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GRAVITY AND MAGNETIC EVIDENCE FOR A GRANITIC INTRUSION NEAR WAHMONIE SITE, NEVADA TEST SITE, NEVADA

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Abstract. Gravity and magnetic data outline a broad anomaly near Wahmonie Site, Nye County, Nevada. A positive 15-mGal gravity anomaly with a steep western gradient and a broad magnetic anomaly coincident with the gravity high characterize the area. Two-dimensional computer models of the gravity data were made using magnetic, seismic, and electric data as independent constraints. The models indicate the presence of a shallow, relatively high density body of 2.65 kg m^{-3} buried near Wahmonie Site. Aeromagnetic and ground magnetic data also indicate the presence of a large, shallow body. Two smaller local magnetic highs that occur along a magnetic prominence extending northward from the broad anomaly directly correlate to granodiorite outcrops. This indicates that the main anomaly is produced by a large shallow intrusion.

Introduction

Wahmonie Site is located on the Nevada Test Site (NTS) about 112 km northwest of Las Vegas, Nevada (Figure 1). The NTS is near the southern border of the Great Basin and lies near the thickest parts of the Paleozoic Cordilleran miogeosynclinal section. Outcrops in the Wahmonie Site are predominantly composed of Tertiary volcanic rocks. These volcanics consist of a series of ashfall and ash flow tuffs that are dominantly rhyolitic in composition and range in age from 26 to 7 Ma [Ekren, 1968]. The Wahmonie volcanic center (Figure 2) erupted andesite, dacite, latite, and tuff. Lower and upper parts of the Wahmonie Formation are dated at 12.9 and 12.5 Ma, respectively [Kistler, 1968, p. 255]. A conspicuous feature near Wahmonie Site is a horst trending north-northeast about 1.6 km wide and 4.8 km in length (Figure 2). The Wahmonie horst is predominantly composed of rhyodacite of the late Miocene Salyer Formation. Two small Tertiary granodiorite intrusive bodies crop out on the east marg n of the horst. The northern body is closely associated with and nearly encircles a small outcrop of the Eleana Formation of Carboniferous age. The Eleana outcrop consists of tan quartzite, calcareous sandstone, and conglomerate. Other, smaller intrusive bodies are present within the horst and are composed of andesite, rhyodacite, and intrusive breccia.

The chemical and mineralogic similarities of the Salyer and Wahmonie formations indicate they are comagmatic and probably are the extrusive equivalents of the granodiorite.

Previous geologic work was done by Ball [1907], Johnson and Hibbard [1957], Poole et al. [1965], Ekren and Sargent [1965], and Cornwall [1972]. Geophysical work includes regional gravity [Healey et al., 1980], detailed gravity [Ponce, 1981], aeromagnetic [Boynton and Vargo, 1963a, b; U.S. Geological Survey, 1979], ground magnetic [Bath, G. D., personal communication 1980], electrical [Smith et al., 1981; Hoover et al., 1982], and seismic [Pankratz, 1982]. These studies were initiated by the U.S. Geological Survey as part of an effort on behalf of the U.S. Department of Energy (Interagency Agreement DE-AI08-78ET44802) to characterize a possible nuclear waste repository in granitic rocks.

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Density Data

More than 250 density measurements of surface samples were used to compute the gravity models. In general, rock densities at the NTS fall into three broad groups: (1) Paleozoic, Mesozoic, and intrusive rocks, (2) Cenozoic volcanic rocks, and (3) ash flow tuff and alluvium. The three groups have approximate average dry bulk densities of 2.67, 2.40, and 2.00 kg m^{-3} respectively. Alluvial densities range from 1.30 to 2.12 kg m^{-3}, partly dependent on the lithology of the source rocks. Densities of rock types in the area are presented in Table 1.

Gravity Data and Regional Trend Separation

Standard gravity corrections were made on all the data and include (1) the earth tide correction, which removes the effect of the tidal attraction of the sun and moon, (2) the instrument drift correction, (3) the free-air correction, which accounts for the fact that each station is at a different elevation, (4) the simple Bouguer correction, which accounts for the attraction of rock material between the station and sea level, (5) the latitude correction, which takes into account the variation with latitude of the earth's gravity at sea-level, (6) the curvature correction, which corrects the Bouguer correction for the effect of the earth's curvature, and (7) the terrain correction, which removes the effect of topography to a radial distance of 166.7 km. Data were reduced using the Geodetic Reference System of 1967 [International Union of Geodesy and Geophysics, 1971] and referenced to the IGSN 1971 gravity datum [Morelli, 1974].

Two regional gravity gradients were removed from the gravity data at Wahmonie Site by determining residual and isostatic corrections. The residual gravity values were computer calculated by removing a planar regional gravity gradient from the complete Bouguer values. The gradient is based on data from gravity stations on pre-Tertiary rocks and was determined from Diment et al.'s [1961, Figure 2] regional gravity

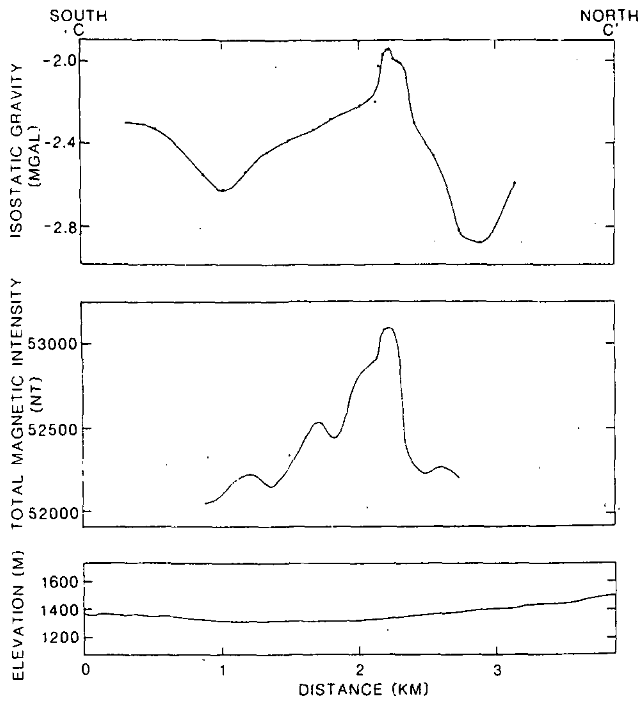

Fig. 6. North-south ground magnetic traverse CC' with isostatic anomaly profile reduced for a density of 2.67 kg m^{-3}. Circles indicate gravity stations.

map of Nevada. Their map is inferred to reflect density contrasts solely within the basement rocks and excludes anomalies caused by near-surface low-density rocks.

Isostatic anomalies were computed to remove long-wavelength variations of the gravity field in the shallow crust. The isostatic correction is based on complete Airy-Heiskanen isostatic compensation [Heiskanen and Vening Meinesz, 1958, pp. 135-137] using a program by Jachens and Roberts [1981] with an assumed upper crustal density of 2.67 kg m^{-3}, a crustal thickness at sea level of 25 km, and a density contrast between the lower crust and upper mantle of 0.40 kg m^{-3}.

The similarity of complete Bouguer, residual, and isostatic anomaly maps (Figure 3) suggests that the gravity anomaly near Wahmonie Site is produced primarily by near-surface structures and is minimally related to regional or isostatic effects. The gravity models presented were derived from the isostatic anomaly values.

Magnetic Data and Interpretation

Magnetic data in the vicinity of Wahmonie Site include two aeromagnetic surveys, a high level and a low level, and a ground magnetic traverse. A high-level aeromagnetic survey at a constant barometric elevation of 2400 m shows that a magnetic high at Wahmonie site is located at the easternmost edge of a magnetic ridge extending from Yucca Mountain, across Calico Hills to Wahmonie Site (Figure 4). This east trending aeromagnetic anomaly may be part of a large, deep, and intrusive complex beneath south west NTS. However, the only exposures of granitic rocks associated with this anomaly are on the east edge of the Wahmonie horst.

A low-level aeromagnetic survey at a constant terrain clearance (drape) of 120 m (Figure 5) shows that the high-level survey includes discrete near-surface components particularly at

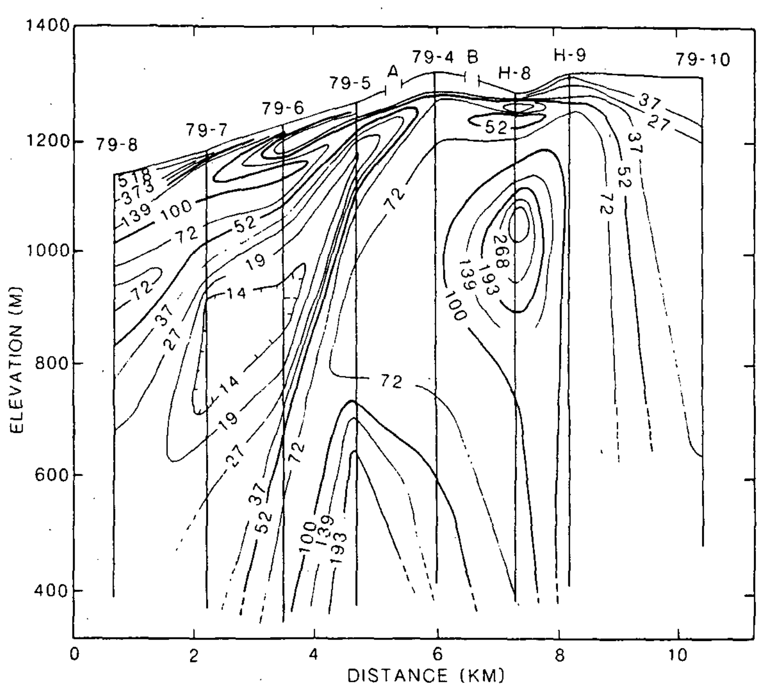

Fig. 7. Vertical electrical sounding geoelectric cross section. Contour interval is logarithmic. Resistivity is in ohm meters. (Modified from Hoover et al. [1982, Figure 5]). Station locations are shown in Figure 2. Major bends in the section are labeled A and B.

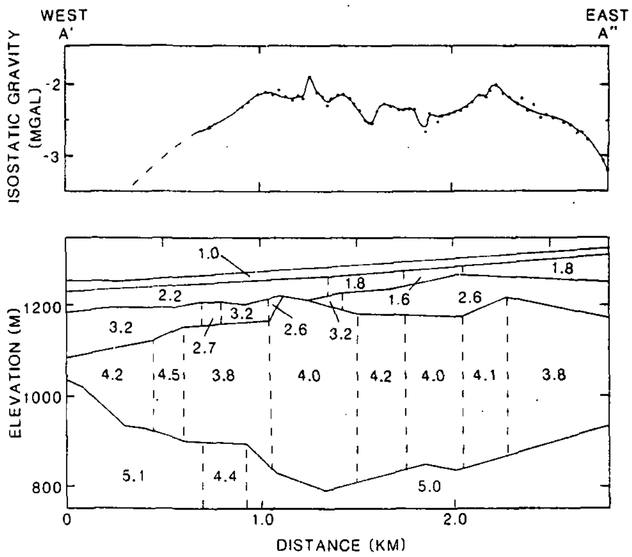

Fig. 8. Seismic refraction model (Modified from Pankratz [1982, Figure 7]) along profile A with isostatic anomaly data reduced for a density of 2.67 kg m^{-3}. Velocity in kilometers per second. Gravity stations are represented by circles.

Wahmonie Site and Calico Hills. The low-level data show a 400-nT high outlined by the 5000-nT contour at Wahmonie Site near the Horn Silver Mine that extends northeast along the eastern margin of the Wahmonie horst. The two smaller magnetic highs that occur at the eastern edge of the horst directly correlate to two small granodiorite outcrops. This correlation to granitic rocks suggests that the larger anomaly to the south may be associated with a large granitic mass at depth.

Other magnetic anomalies in the vicinity of Wahmonie Site are related to normally and reversely polarized tuffaceous rocks and to outcrops of basalt. Anomaly-producing tuffaceous rocks of Skull Mountain include the normally polarized Topopah Spring Member of the Paintbrush Tuff and Ammonia Tanks Member of the Timber Mountain Tuff and the reversely polarized Rainier Mesa Member of the Timber Mountain Tuff. Magnetic susceptibility of the anomaly-producing volcanic rocks near Wahmonie Site range from 3 to 9 x 10^{-3} SI [Bath, 1968]. A magnetic high at Kiwi Mesa appears to be associated with basalt having an outcrop thickness of about 76 m.

A north-south magnetic traverse (CC') across the aeromagnetic high and the Horn Silver Mine (Figure 6) suggests that the causative body is near the surface at a depth of about 100 m and may have a cupola at a depth of less than about 50 m that also correlates with a small gravity peak.

Other Geophysical Data

Constraints from several other geophysical methods were used to discriminate between possible gravity models. Additional constraints are needed because a given gravity distibution can be produced by many mass or density distributions.

There are several Schlumberger vertical electrical soundings (VES) and two induced polarization traverses at Wahmonie Site [Hoover et al., 1982]. Hoover's geoelectric cross section of the VES data interpreted from inverted sounding curves is shown in Figure 7. One-dimensional inversion of the VES data was done using programs of Zohdy [1974, 1975]. The geoelectric cross section shows a major resistivity boundary between soundings 79-6 and 79-5. This boundary coincides with the outer limit of hydrothermal alteration surrounding

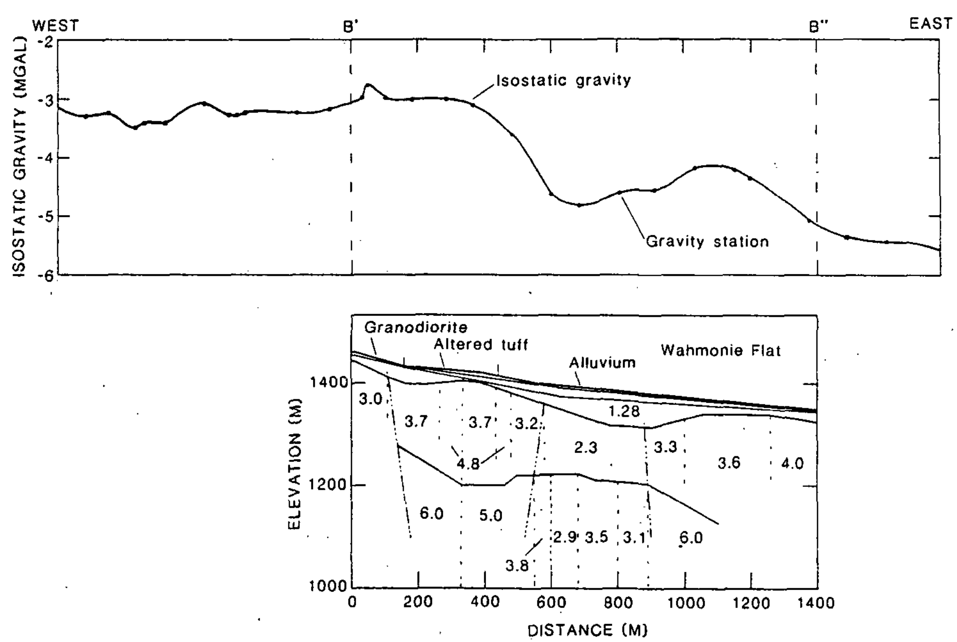

Fig. 9. Seismic refraction model (Modified from Pankratz [1982, Figure 6]) along profile B with isostatic anomaly data reduced for a density of 2.67 kg m^{-3}. Velocity is in kilometers per second.

TABLE 2. Comparison of Seismic Velocity and Density to Lithology

Layer Lithology	Seismic Velocity, km/s Profile A	Seismic Velocity, km/s Profile B	Modeled Density, kg m^{-3}, for Profiles A and B
Alluvium	1.0-2.2	1.0-1.28	1.90-2.10
Tuff	2.6-3.2	2.3-4.8	2.20-2.40
Fractured granite or rhyodacite	3.8-4.5	---	2.55
Granitic rocks	5.0	5.0-6.0	2.65

Wahmonie Site. Sounding 79-6 is outside this zone, while 79-5 is inside this zone and probably overlies the inferred intrusive (Figure 2). At VES 79-5 the presence of an intrusive body is suggested where the resistivity begins to increase with depth, at about 150 m below the surface. The absence of a sharp gradient suggests that the upper part of the intrusive is altered or fractured, which reduces its resistivity. The section below VES H-8, nearer the center of the gravity and magnetic highs, shows a resistive body of 268 to 373 ohm m at depths of 200 to 350 m. According to Hoover et al. [1982] this higher-resistive body may represent a less altered or fractured part of the intrusive body. Also, their two induced polarization dipole-dipole lines at Wahmonie Site support the VES data and give evidence for disseminated sulfide mineralization at depth.

There are two seismic refraction spreads in the vicinity of Wahmonie Site, A'A" and B'B" (Figure 2), with the resulting two-dimensional models by Pankratz [1982] shown in Figures 8 and 9. The velocities and layer configurations were derived from an inversion program of Ackermann [1979].

The two seismic lines provide near-surface control for the gravity modeling. At least four seismic refraction layers can be correlated to lithologic units in the study area. Densities were determined for each layer based on surface rock sampling, inferred rock type, and conversions of seismic velocity to density based on the empirical values of Nafe and Drake [1963, p. 807]. Table 2 shows the association of seismic velocity to density based on the empirical values for profiles A and B (Figures 8 and 9).

Gravity Modeling

Seismic and gravity models along profiles A and B (Figure 2) show a moderately dense (2.65 kg m^{-3}) body near the surface in the vicinity of Wahmonie Site. Estimation and modification of mass distributions were based on geologic and geophysical information. Computation of gravity effects, comparisons of the calculated and observed gravity anomalies, and the subsequent modification of the mass distributions until a satisfactory fit was achieved were facilitated by the use of a version of Talwani et al.'s [1959] two-dimensional computer modeling program. Gravity models were predominantly based on geology and seismic refraction control.

A two-dimensional gravity model of profile A (Figure 10) shows that a near-vertical contact or fault is necessary to produce the observed gradient at the western edge of the inferred intrusive. The gradient also coincides with the western edge of the hydrothermal alteration zone surrounding the intrusion. The model indicates the presence of a relatively high density body of 2.65 kg m^{-3} buried near the surface at Wahmonie Site.

The gravity model representing data along

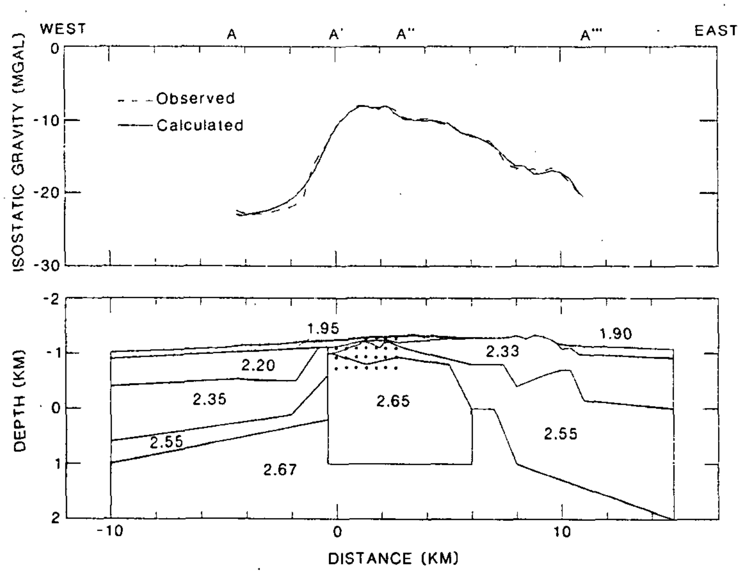

Fig. 10. Isostatic anomaly gravity model along profile A. Densities are in kilograms per cubic meters. Seismic refraction control is shown as stippled area.

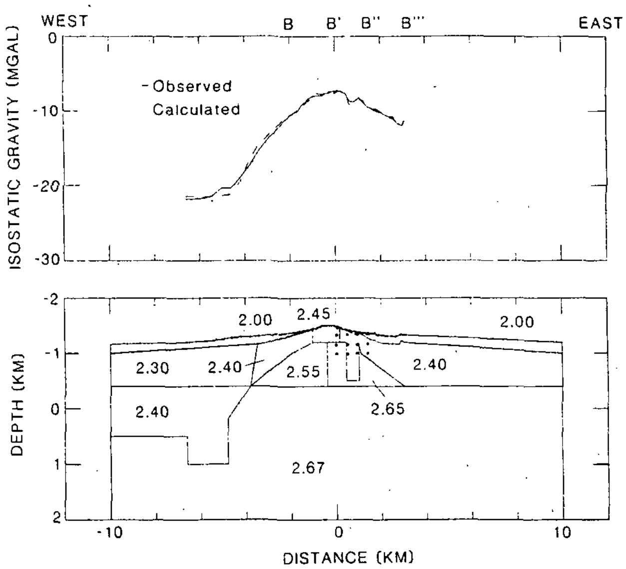

Fig. 11. Isostatic anomaly gravity model along profile B. Densities are in kilograms per cubic meters. Seismic refraction control is shown as stippled area.

profile B (Figure 11) also suggests the presence of a denser body near the surface. Although high seismic velocities greater than 5.0 km/s, characteristic of an igneous intrusive were not detected near the granodiorite outcrops of the Wahmonie horst, gravity data indicate the presence of a relatively dense body. This discrepancy between the seismic and gravity data may be due to starting the seismic spread too close to the edge of the granodiorite body or to weathering [Pankratz, 1982]. Both the gravity model and the seismic section (Figure 9) show a body with a density of 2.65 kg m^{-3} extending east of the Wahmonie horst about 200 m below the surface for about 1 km.

Interpretation

The anomalous gravity and magnetic highs at Wahmonie Site are probably caused by an intrusion that is denser and more magnetic than the surrounding rocks. Other geophysical evidence that supports an intrusion includes data from electric and seismic methods. In addition, Wahmonie Site is surrounded by a zone of hydrothermal alteration that coincides with a steep gravity gradient which appears to mark the outer limit of the buried causative body. While gravity data alone cannot determine the composition of the intrusion, the presence of granodiorite outcrops at Wahmonie horst and their association with local gravity and magnetic highs suggest that the intrusion may be of similar composition. Also, the density of the modeled intrusive and the granodiorite outcrops of about 2.65 kg m^{-3} is consistent.

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Geophysical Characterization of Mineral and Energy Resources at Yucca Mountain and Vicinity, Nevada

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GEOLOGICAL SURVEY OPEN-FILE REPORT 91-620

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INTRODUCTION

This report was prepared for the Yucca Mountain Project (Department of Energy) as part of the study of the mineral and energy resource potential of the site (Activity 8.3.1.9.2.1.5) under the Human Interference part of the program. Most of the 1991 geophysical scoping activities in the Mineral Resources Study were involved with the acquisition and evaluation of existing data. This report presents an overview of how geophysical data (existing and planned) will aid in the evaluation of the potential for mineral and energy resource potential at Yucca Mountain and vicinity.

In the assessment and the exploration for mineral resources, geophysics along with geology and geochemistry constitute a triumverate association required for the identification and classification of favorable areas for undiscovered mineral deposits. Geophysical methods play a particularly important role in current exploration and assessment of mineral resources because, short of drilling, they provide direct and indirect measurement of a wide range of physical properties or contrasts that are important for evaluation of mineral and energy potential. Geophysical data have relevance at all scales of investigation, ranging from the regional scale for identification of terranes and large structures that have a high potential for mineralization, to very local scales, borehole geophysics being one example. Although relatively few geophysical methods directly detect particular types of mineral deposits, geophysics can identify structures, lithologies, and alteration, which may then be used to infer potential mineralization. Geological, geochemical, and some geophysical methods are able to provide informaton at shallow depths through cover. These methods rely on extrapolation to infer conditions at depth. The deep-looking geophysical methods are especially important at Yucca Mountain because (1) they provide important constraints for extrapolation of geologic and geochemical data and (2) any potential significant mineralization is in the subsurface.

Modern assessment and exploration work is being aided by the codification of experience into discrete descriptions of mineral deposit models such as those presented by Cox and Singer (1986). These deposit models present what are believed to be the essential features of a particular class of deposits, and are descriptive in nature but due to our limited knowledge do not necessarily reflect the genetic parameters, due to our limited knowledge. These models will play an important role in the assessment work to be done. Unfortunately, models published to date have very limited information on geophysical attributes of the individual deposit models. This problem is being addressed, but these limitations of the existing deposit models need to be considered.

DESCRIPTION OF GEOPHYSICAL METHODS

One of the geophysical methods that can directly detect particular types of mineral deposits is gamma-ray spectrometry. Aerial and ground gamma-ray surveys measure the gamma radiation emitted by radioisotopes at and near the surface of the ground. These measurements are sensitive to naturally-occurring radioisotopes, particularly the members of the uranium-238 decay series, thorium-232 decay series, and potassium-40. Gamma-ray spectrometry is thus capable of locating uranium deposits if the deposit is near the surface or intercepted by a borehole. This method is also capable of detecting artificial isotopes such as cesium-137 and cobalt-60 that result from human activities.

Another geophysical method capable of directly detecting a particular type of mineral deposit is induced polarization (IP). The method measures the extra voltage (overvoltage) needed to drive an electric current through materials containing metallic minerals. The ratio between the amplitude of the overvoltage before and after the moment the current is stopped gives a measure of the concentration of metallic minerals in the material through which the current flows. Thus, induced polarization can detect sulfide deposits and has been extensively used in the search for disseminated sulfide ores by mining companies since the 1960's (Dobrin and Savit, 1988).

Most geophysical methods, however, provide only indirect evidence for the presence of mineral and energy deposits, which when combined with necessary geologic and geochemical information, can identify terrains or regions where the probability of mineral occurrence is likely. For example, mineralization often occurs in fault zones. Gravity and magnetic methods can often detect subsurface faults because the faults have juxtaposed rocks of different densities or magnetic susceptibilities. The resulting gradients in the gravity and magnetic fields indicate possible targets for mineral deposits. Faults may also be imaged with seismic methods. Seismic reflection and refraction methods are useful in determining the subsurface geometry under Yucca Mountain and vicinity. Seismic reflection has shown the existence of faulted blocks mostly buried by alluvium under Amargosa Valley (Oliver and others, 1990, p. 72). The integrated use of the seismic and potential field methods can pinpoint buried fault systems that may have associated mineralization.

Geophysical methods are important in defining the extent of buried intrusives which may be the source of mineralization, or constitute a heat source for a hydrothermal system to transport and deposit minerals in favorable host rocks. Paleozoic calcareous rocks present below the volcanic rocks at Yucca Mountain could host a variety of deposit types, as could various lithologies along detachment and related listric faults in the region. Certain mineral deposits, such as porphyry copper, molybdenum, gold, and skarn deposits, are often spatially associated with felsic intrusives. These plutons tend to be fairly magnetic, but not very dense. Thus, the combination of a gravity low and magnetic high may delineate possible buried plutons, which then may be associated with mineral deposits.

PREVIOUS WORK

A large body of geophysical literature is available for Yucca Mountain and vicinity, but little of it has been obtained for the express purpose of mineral assessment. This large amount of data constitutes an important resource for assessment investigations, but it needs to be evaluated in terms of its significance to potential mineralization with close coordination with relevant geologic and geochemical data.

Mineralization in the vicinity of Yucca Mountain has been known and described for many years (Ball, 1906; 1907; Cornwall, 1972), but this early literature does not include references to geophysical studies if any were made. The recent literature, while not directly addressing mineralization, does make reference to indications of potential mineralization in a few cases. Hoover and others (1982) and Ponce (1984) presented IP, gravity and magnetic studies in the Wahmonie area (Fig. 1). A strong IP response combined with evidence for extensive alteration in the surrounding volcanics suggests the likelihood of a porphyry system at depth below Wahmonie, the site of the Hornsilver Mine operating prior to World War II. One question that geophysics can help answer is whether this system extends westward along the axis of a mostly buried intrusive to Yucca Mountain in a manner analogous to the distribution of mineralization at the Twin Ridge pluton (Maldonado, 1981). A magnetic anomaly does trend from the Wahmonie-Calico Hills area west to Yucca Mountain. This anomaly has been interpreted both as a buried intrusive and as altered Eleana argillite metamorphosed by an intrusive body at greater depth (Kane and Bracken, 1983; Bath and Jahren, 1984; Baldwin and Jahren, 1982). Both interpretations indicate potential for mineralization below Yucca Mountain, though without additional data the significance for resource potential cannot be evaluated. On the basis of magnetic data, Kane and Webring (1981) have suggested that alteration may also be present in the central graben of Timber Mountain.

This is questionable. See USGS OFR 89-446 (see also USGS OFR 88-664 for gravity)

The possibility of past hydrothermal activity at Yucca Mountain is supported by existing drill core data. Maldonado and Koether (1983) note the presence of barite, fluorite, calcite, chlorite and pyrite in lavas in drill hole G-2, suggesting hydrothermal alteration. Fluorite and pyrite are also common in Paleozoic dolomites from drill hole UE25P#1 (Carr and others, 1986). Existing geophysical data in these drill holes need to be examined very closely to detemine whether geophysical evidence for the observed alteration exists and if so, what evidence there may be for its presence in other drill holes.

In-hole gamma-ray spectrometric data have been acquired in many of the drill holes but used only for correlation of lithologies. These data are invaluable in providing evidence for movement of potassium, uranium, and thorium either into or out of the rock units at Yucca Mountain. D. Muller (oral commun., 1988) has observed high potassium values at the top and bottom of the Bullfrog member of the Crater Flat Tuff in some areas, possibly indicating potassium-metasomatism.

Airborne gamma-ray data exist for the Yucca Mountain area and were obtained as part of the National Uranium Resource Evaluation (NURE) program at a 1- and 3-mile line spacing. These data have apparently not been considered in previous studies at Yucca Mountain. The area covered by the 1-mile spaced data include mineralized areas west of Yucca Mountain and the Calico Hills-Wahmonie region to the east, and warrant examination and analysis.

CONCLUSION

Geophysical methods, integrated with geologic and geochemical data, can help constrain the likelihood of mineralization in the vicinity of Yucca Mountain. Although most geophysical methods do not yield a direct measurement of mineralization, geophysics can define areas with higher potential for mineralization. Because geophysical methods can delineate the subsurface geometry of various physical properties, the assessment of mineral deposits within the Paleozoic section (below the potential repository depth) will rely heavily on the interpretation of borehole and geophysical data. Although geophysical methods may have difficulty in defining relatively small or localized structures at great depth, the maximum depth at which modeled structures can be defined can be calculated using estimates of physical property contrasts.

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NOTE: Parenthesized numbers following each cited reference are for U.S. Department of Energy OCRWM Records Management purposes only and should not be used when ordering the publication.

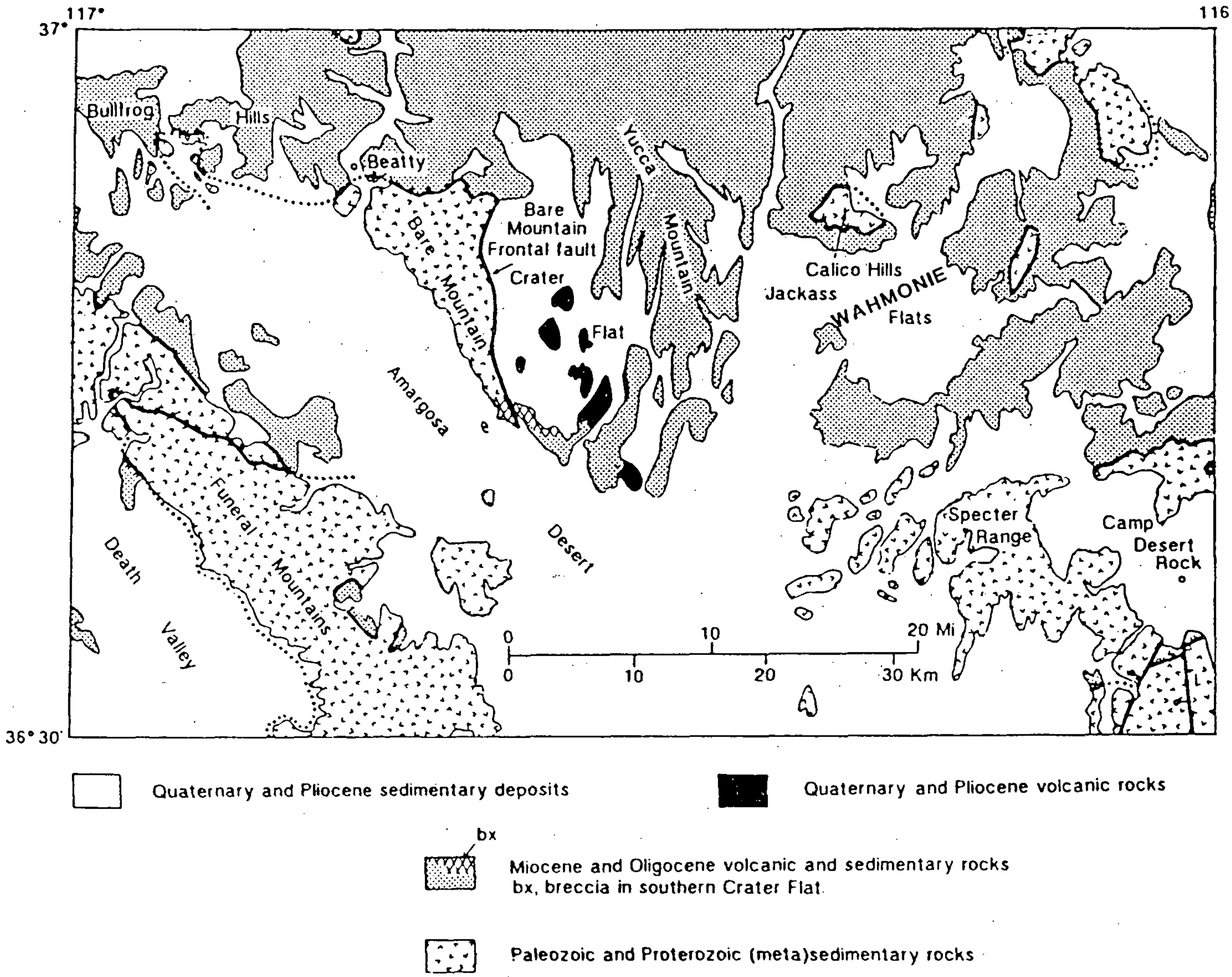

Figure 1. Simplified geologic map of the Beatty quadrangle, Nevada, showing location of Yucca Mountain, Calico Hills, and Wahmonie.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. B12, PAGES 10,193–10,206, NOVEMBER 10, 1984

Interpretation of Gravity Data in a Complex Volcano-Tectonic Setting, Southwestern Nevada

DAVID B. SNYDER[1]

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W. J. CARR

U.S. Geological Survey, Denver, Colorado

This regional gravity study, based on an irregular 2-km data grid, was conducted during the past few years at Yucca Mountain, southern Nye County, Nevada, as part of a program to locate a suitable repository for high-level nuclear waste. About 100 surface rock samples, three borehole gamma-gamma logs, and one borehole gravity study provide excellent density control. A nearly linear increase in density of 0.26 g/cm^3 per kilometer of depth is indicated in the thick tuff sequences that underlie the mountain. Isostatic and 2.0-g/cm^3 Bouguer corrections were applied to the observed gravity values to remove regional gradients and topographic effects, respectively. The Bare Mountain gravity high, with an isostatic anomaly maximum of 48 mGal, is connected with a greater gravity high over the Funeral Mountains, to the southwest; together, these highs result from a continuous block of dense, metamorphosed Precambrian and Paleozoic rocks that stretches across much of the Walker Lane from the east edge of Death Valley to Bare Mountain. The Calico Hills gravity high appears more likely to originate from a northeast trending buried ridge of Paleozoic rocks that extends southwestward beneath Busted Butte, 5 km southeast of the proposed repository, where two- and three-dimensional modeling indicates that the pre-Cenozoic rocks lie less than 1000 m beneath the surface. Tuff, at least 4000 m thick, fills a large steep-sided depression in the pretuff rocks beneath Yucca Mountain and Crater Flat. The gravity low and the thick tuff section lie within a large collapse area that includes the Crater Flat–Timber Mountain–Silent Canyon caldera complexes. Gravity lows in Crater Flat itself are interpreted to coincide with the source areas of the Prow Pass Member, the Bullfrog Member, and the Tram Member of the Crater Flat Tuff; these source areas add nearly 350 km^2 to the previously recognized extent of the local caldera complexes. Southward extension of the broad gravity low associated with Crater Flat into the Amargosa Desert is evidence for sector graben-type collapse segments related to the formation of the Timber Mountain caldera and superimposed on the other volcanic and extensional structures within Crater Flat.

INTRODUCTION

This gravity study is concentrated in southwest Nevada near the California border and Death Valley (Figure 1) and on the southwest side of the southwestern Nevada volcanic field (Figure 2*a*). This volcanic field includes the Timber Mountain caldera complex [*Byers et al.*, 1976] and the Crater Flat–Prospector Pass caldera complex [*Carr et al.*, 1984], the sources of numerous, voluminous eruptions from about 16 to 10 Ma ago. A general understanding of the near-surface structure of this volcanic field has existed for more than a decade. In the last few years and as a result of exploration at Yucca Mountain for a repository to hold high-level nuclear waste, geologic and geophysical studies have outlined the complex crustal structures and tectonic history of the region in greater detail.

Gravity investigations play an important role in the characterization of Yucca Mountain as a possible nuclear waste repository. In and near the mountain Cenozoic sedimentary and volcanic rocks obscure the more complex pre-Tertiary geology, and therefore obtaining information about subsurface rock geometry is critical to fully characterize the water flow patterns in the area. The candidate repository site (Figure 1) lies within tuff composing the northern part of Yucca Mountain, a relatively coherent block of rocks within a stratigraphically and structurally complex region. This study explores and interprets the three-dimensional structure and geometry of the rocks surrounding the candidate site; it updates a preliminary report [*Snyder and Carr*, 1982] and earlier work by *Healey and Miller* [1971].

Numerous deep (750–1830 m) holes have been drilled at Yucca Mountain; most have a full suite of geophysical logs. All but three of the holes (Figure 1) are in or near the candidate site area and include USW-G1 [*Spengler et al.*, 1981], USW-G2 [*Maldonado and Koether*, 1983], USW-G3, UE25P-1, and USW-H1. Other holes drilled a little farther outside the site area include J-13 near Fortymile Wash, UE25a-3 in the Calico Hills [*Maldonado et al.*, 1979], and USW-VH-1 [*Carr*, 1982] and USW-VH-2 in Crater Flat. Geologic, geophysical, and hydrologic data have been obtained from these holes, and this information has been used both directly and indirectly in interpreting the structure of the area. Drill holes UE25a-3 and UE25P-1 reached pre-Tertiary rocks, at depths of 1 and 1240 m, respectively, but several holes in the area (G1, G2, G3, and H1) were drilled to depths of about 1830 m without reaching the base of the volcanic rocks (Figure 3). Alteration was especially notable in the lower part of the section penetrated by these deep holes [*Waters and Carroll*, 1981], and metamorphic effects, including density change, increase steadily downward.

Four aeromagnetic surveys are encompassed by the area of the gravity study. Constant-barometric-elevation surveys [*Boynton and Vargo*, 1963; *U.S. Geological Survey*, 1971], flown at 2440 and 2740 m, respectively, indicate a strong gradient across northern Yucca Mountain that increases in total intensity to the north. The breadth and slope of this gradient suggest that the source lies at a minimum depth of

[1]Now at Department of Geological Sciences, Cornell University.

Paper number 4B0782.

A.

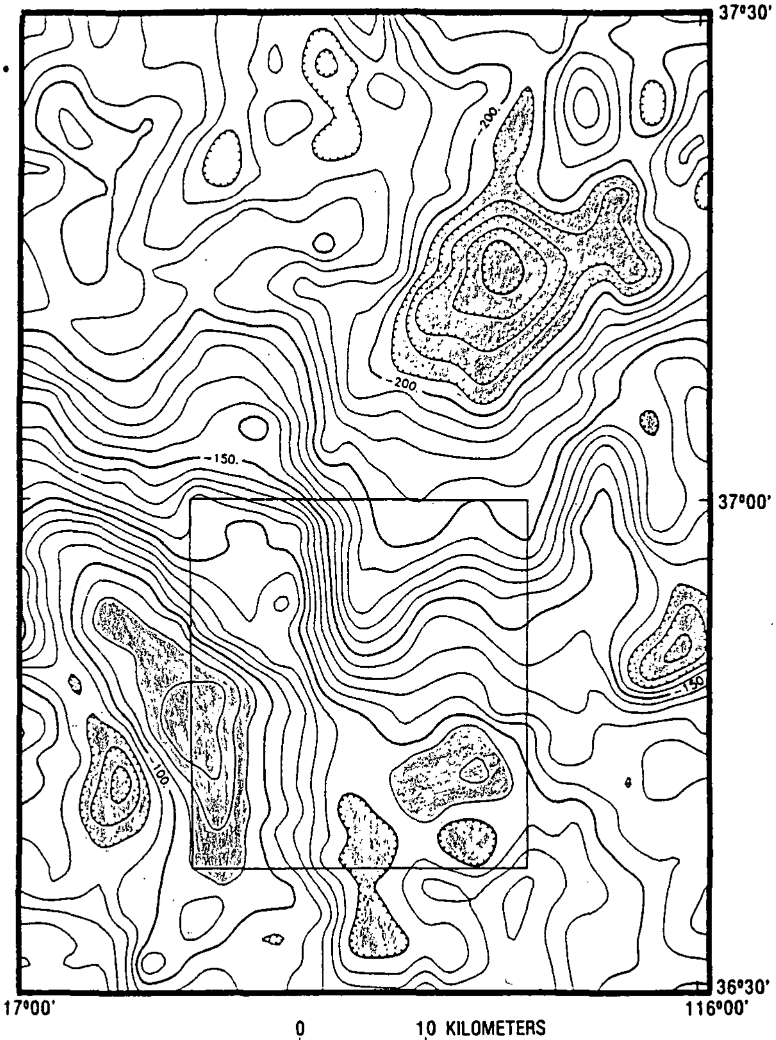

Fig. 4*a*. Complete Bouguer anomaly map of the region surrounding Yucca Mountain. Area of Figures 4*b* and 4*c* is indicated by the rectangle.

The density of saturated pre-Tertiary rock samples ranges from 2.60 to 2.82, with a mean of 2.66 ± 0.06 (1σ) g/cm^3, on the basis of samples taken from outcrops at Bare Mountain and the Striped Hills (Table 2); values in Table 1 are averages of the samples from each rock group listed.

Gamma-gamma density logs were obtained in drill holes USW-G1, H1, and VH-1. These logs have been borehole compensated; that is, any variations in hole diameter caused by wall collapse or the drilling process have been accounted for in the density determinations. The compensated density log curves were then integrated within specified depth intervals to produce an average value for each interval. This analysis further smoothed irregularities caused by fractures in the drill hole walls. The observed downward increase in density (Figure 3) appears to be related to the closing of pore space due to alteration and compaction rather than to primary density variations in the tuff. Nearly linear density increases within individual tuff units (for example, Tram Member in Figure 3) are clearly attributable to the degree of welding and cooling history of the tuff at the time of emplacement.

A downhole gravity study was made in drill hole USW-H1 [*Robbins et al.*, 1982]. Values agree well with the gamma-gamma measurements (Figure 3). This agreement is significant, because borehole gravity measurements sample a much greater lateral volume than do the density logs and include fractures, cavities, and other large irregularities in the rock.

The three drill holes with gamma-gamma logs provide excellent constraints on the densities of the Cenozoic tuff, basalt, and alluvium. The linear gradient of 0.26 g/cm^3 per kilometer of depth, if it is indeed due to alteration and lithostatic loading, is applicable to all the thick tuff sequences within the study area.

Structure

The area of this study is near the axis of the Walker Lane and near the southern margin of the southwestern Nevada volcanic field (Figure 2*a*; *Carr et al.* [1984]). The nearly linear basins and ranges of central Nevada are interrupted in southwestern Nevada by several northwest striking right-lateral fault zones; these fault zones combine with northeast striking fault zones and structures related to numerous nearby calderas to produce a 50- to 100-km-wide, northwest trending zone of diverse topography and structure here included in the Walker Lane [*Carr*, 1974]. Large-scale drag folds or oroclinal bends [*Albers*, 1967] are associated with parts of the Walker Lane, but in the study area these structures are obscured by

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February 8, 1995

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QA: L

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Mark Tynan, YMP WBS Manager, DOE, Las Vegas, NV

SUBJECT: PUBLICATIONS--Transmittal of abstract entitled, "Geophysical expression of the Ghost Dance fault, Yucca Mountain, Nevada", by D.A. Ponce and V.E. Langenheim

Interagency Agreement No. DE-AI08-92NV10874

Dear Wesley:

One copy of the subject abstract is enclosed for review in your office and concurrence for presentation and publication in the proceedings volume for the International High-Level Radioactive Waste Management Conference to be held May 1-5, 1995 in Las Vegas, Nevada

This report received technical review by Andrew Griscom and Robert Morin who were chosen because of their general knowledge of the work and techniques. A QA review was performed by Bob Scavuzzo, YMPB-QA Office, and a preliminary Policy review was performed by Bob Lewis, YMPB.

Technical data for this report have been submitted in accordance with YAP-SIII.3Q. The tracking number for the TDIF associated with these data is GS950208314212.003

This report was prepared under WBS number 1.2.3.2.2.1. There are no milestones associated with this report. Upon publication, this report will be submitted to OSTI in accordance with DOE order 1430.2, under distribution category UC-814.

Robert E. Lewis, Reports Improvement Officer
Yucca Mountain Project Branch
For: Larry R. Hayes, Chief YMPB

Enclosures

cc w/o enclosures:
LRC File 3.304-9 (P)
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D.A. Ponce, USGS, GD, Menlo Park, CA
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CC: Jones
CC: Tynan
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May 1-5, 1995 ... Las Vegas, Nevada

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Summary deadline:
Postmarked by Friday November 11, 1994

Conference Host:

Howard R. Hughes College of Engineering, University of Nevada, Las Vegas

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This is the official call for summaries for the 1995 International High-Level Radioactive Waste Management Conference. You are encouraged to submit summaries of papers describing work that is NEW, SIGNIFICANT and RELEVANT to the theme of the meeting. To facilitate an adequate review, your summary must be received at ANS Headquarters by November 11, 1994. The Technical Program Committee will then review your summary and will notify you of their decision by the middle of December. Authors of accepted summaries will be sent guidelines for preparation of final summaries on camera-ready mats. Summaries, on camera-ready mats, will be due at ANS Headquarters no later than February 1, 1995. You will present your work in an oral or poster session at the meeting and are expected to register for the meeting. Camera-ready summaries will be required for presentation and inclusion in the conference proceedings. It is your responsibility to protect classified or proprietary information.

Program:

The conference will be an international forum for presentation and discussion of scientific and technical information related to progress in understanding the characteristics of systems that will receive, transport, store, and dispose of wastes within the purview of the Office of Civilian Radioactive Waste Management and similar organizations in other nations. The program will include technical sessions and substantive plenary sessions that discuss technical issues and applications of professional disciplines in natural, engineered, institutional and integrated systems. Summaries will be presented in both oral and poster sessions.

Reviewed by C. Hunter 1/24/95 W. Clay Hunter

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GEOPHYSICAL EXPRESSION OF THE GHOST DANCE FAULT, YUCCA MOUNTAIN, NEVADA

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ABSTRACT

Gravity and ground magnetic data collected along surveyed traverses across Antler and Live Yucca Ridges, on the eastern flank of Yucca Mountain, Nevada, reveal small-scale faulting associated with the Ghost Dance and possibly other faults. These studies are part of an effort to evaluate faulting in the vicinity of a potential nuclear waste repository at Yucca Mountain.

I. INTRODUCTION

Gravity and ground magnetic data were collected along surveyed traverses across Antler and Live Yucca Ridges, on the eastern flank of Yucca Mountain, Nevada, as part of an effort to evaluate faulting in the vicinity of a potential nuclear waste repository at Yucca Mountain. Gravity and magnetic data reveal small-scale faulting associated with the

Ghost Dance fault (Fig. 1). Because the Ghost Dance fault has been identified within the potential repository area, its geophysical expression becomes important to the design and construction of underground facilities. The largest gravity and magnetic anomalies in the study area are associated with larger-scale north-south trending faults[1] such as the Solitario Canyon, Bow Ridge, and Paintbrush Canyon faults on the west and east flanks of Yucca Mountain.

II. GRAVITY AND MAGNETIC DATA

Detailed gravity data were collected along Antler and Live Yucca Ridges on the east flank of Yucca Mountain (Fig. 1) using LaCoste and Romberg gravity meters. Gravity meter performance and calibration factors were checked over a mountain gravity meter calibration loop. Gravity data were reduced using the Geodetic Reference System of 1967 and referenced to the International Gravity Standardization Net 1971 gravity datum. Gravity data were reduced to complete Bouguer anomalies using a reduction density of 2.00 g/cm^3.

Ground magnetic data with the sensor at 8 ft (2.4 m) above the surface were also gathered along the two profiles (Fig. 1). A Geometrics portable proton precession magnetometer, model G-816, was used to collect data. Because the anomalies of interest were expected to be small (20 to 50 nT) and the profile lines were long, a base station was periodically reoccupied to make corrections for diurnal time variations of the Earth's magnetic field.

III. RESULTS

Previously collected magnetic data along traverse J82[2] (Fig. 1) and gravity and magnetic data collected along traverse WT-2[3] in washes that cross the Ghost Dance fault indicate that the Ghost Dance fault is characterized by both gravity and magnetic anomalies. Gravity and magnetic data along the WT-2 traverse (Fig. 2) indicate a small-amplitude gravity low in a broad area ~~that~~ encompasses the Ghost Dance fault that may reflect a much broader zone of brecciation. Magnetic data (Fig. 2) reveal a distinctive low of about 400 nT (~~nanoteslas~~) associated with the fault.

Recently collected gravity and magnetic data along Antler Ridge and Live Yucca Ridge (Fig. 3) also indicate that the Ghost Dance fault is characterized by gravity and magnetic anomalies. Gravity data along the crest of Antler Ridge (Fig. 3) reveal a small-amplitude gravity low associated with the Ghost Dance fault similar to that along the WT-2 Wash traverse. In addition, gravity data reveal other possible faults such as the anomaly about 240 m east of the Ghost Dance fault (Fig. 3).

Magnetic data collected along the crest of Antler and Live Yucca Ridges (Fig. 3) reveal a magnetic low of about 80 nT associated with the Ghost Dance fault which is much smaller in amplitude than the J82 or WT-2 traverses. This discrepancy suggests that the magnetic signatures of the Ghost Dance fault along traverse J82 and WT-2 (Fig. 1) are in part caused by magnetic terrain effects resulting from reversely magnetized rocks of the Tiva Canyon ~~Formation~~ in the canyon walls. In addition, gravity and magnetic data along Antler and Live Yucca Ridges indicate the presence of other small-amplitude anomalies that may reflect other small-scale faults.

V. CONCLUSIONS

Gravity data combined with ground magnetic data can provide an effective exploration tool for delimiting small- and large-scale faulting and for tracing such faults under alluvial cover. These data supplemented with density data, magnetic property data, and two- and three-dimensional modeling can provide additional structural information such as dip and vertical offset of faults.

ACKNOWLEDGMENTS

Prepared in cooperation with the U.S. Department of Energy (Interagency Agreement DE-AI08-~~78ET44802~~ 92NV10874). R.F. Sikora assisted in gravity data processing. The processed data are preliminary.

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1. D.A. Ponce, V.E. Langenheim, and R.F. Sikora, Gravity and magnetic data of Midway Valley, southwest Nevada: U.S. Geological Survey Open-File Report 93-540-A, documentation, 9 p. (1994). (NNA.940418.0157)

2. G.D. Bath, and C.E. Jahren, Interpretations of magnetic anomalies at a potential repository site located in the Yucca Mountain area, Nevada Test Site: U.S. Geological Survey Open-File Report 84-120, 40 p. (1984).

3. H.W. Oliver, and R.F. Sikora, 1994, Gravity and magnetic data across the Ghost Dance Fault in WT-2 Wash, Yucca Mountain, Nevada: U.S. Geological Survey Open-File Report 94-413-A, 22 p. (1994).

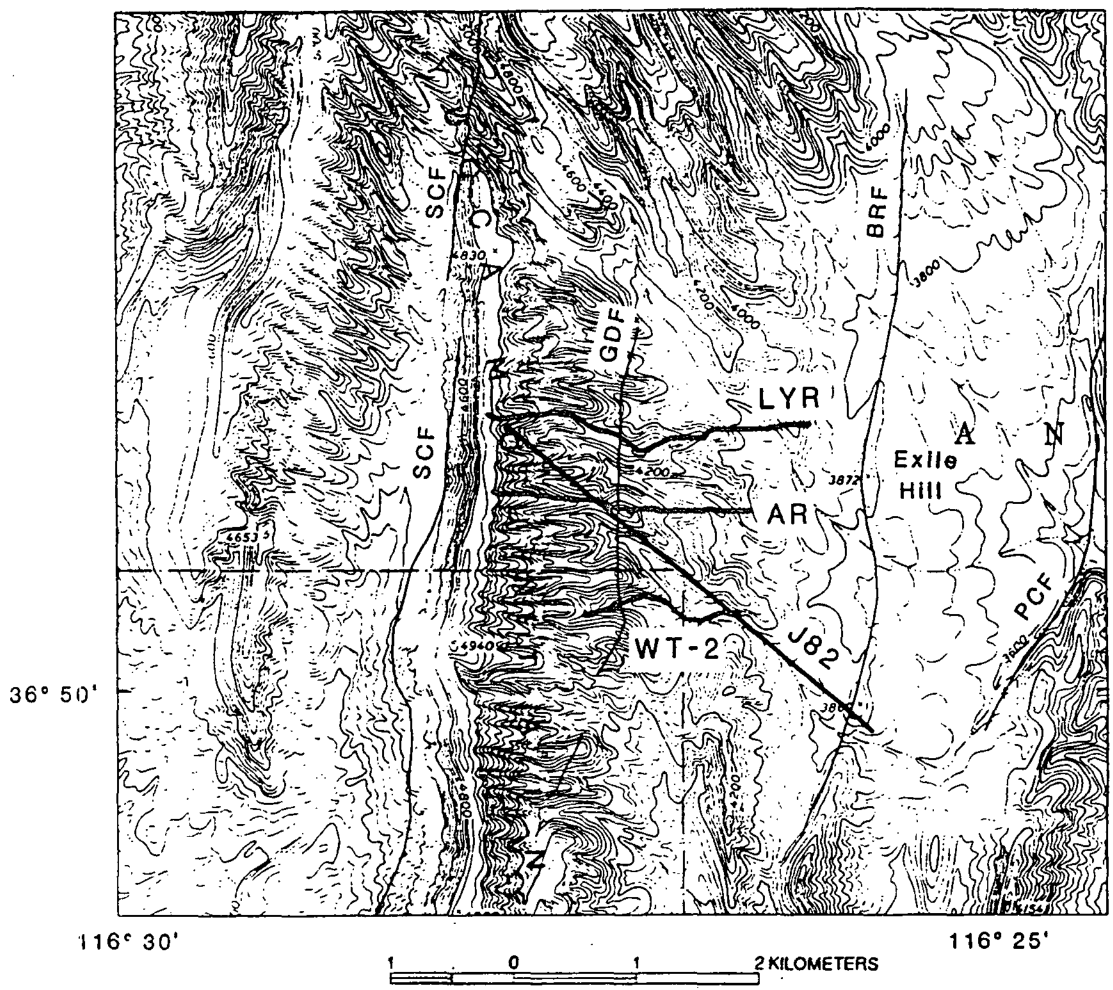
I think an effort should be made to incorporate previous papers on the detailed mapping along the GDF
Spengler + others 1993 Spengler + others 1994
(ANS papers) and list when appropriate
Ref. [illegible] + text.

FIGURE CAPTIONS

Figure 1 Index map of Yucca Mountain and vicinity showing locations of gravity and magnetic traverses across the Ghost Dance fault. AR, Antler Ridge traverse; BRF, Bow Ridge Fault; GDF, Ghost Dance fault; J82, J82 traverse; LYR, Live Yucca Ridge traverse; PCF, Paintbrush Canyon fault; SCF, Solitario Canyon fault; and WT-2, WT-2 Wash traverse.

Figure 2 Gravity, and magnetic profiles along WT-2 Wash traverse. GDF, Ghost Dance fault. Reference source for WT-2 traverse? It is in text, of source.

Figure 3 Gravity, and magnetic profiles along Antler Ridge. GDF, Ghost Dance fault.



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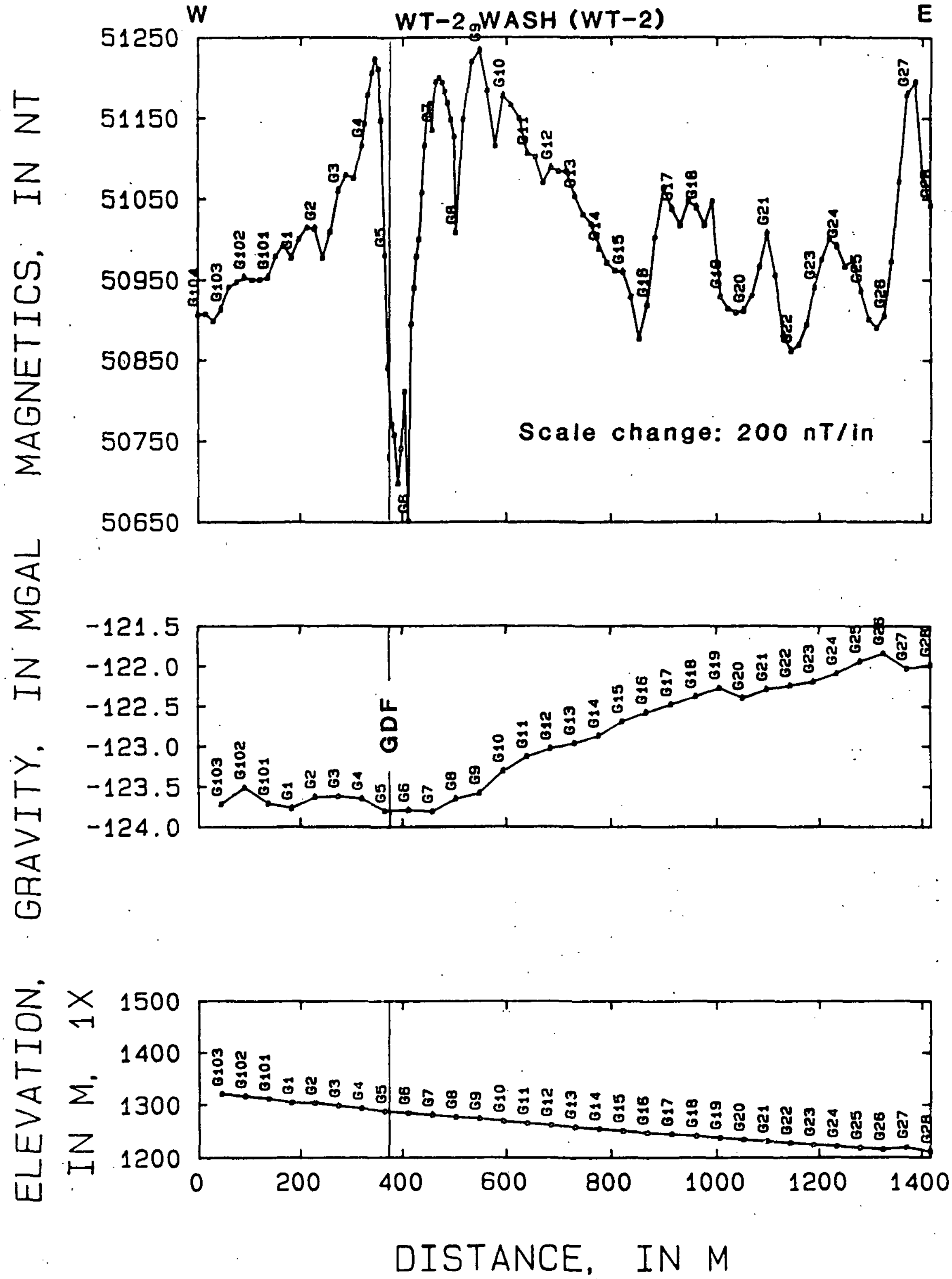

Figure 2 Gravity, and magnetic profiles along WT-2 Wash traverse. GDF, Ghost Dance fault. Oliver and Sikora, 1994. Reference Source?

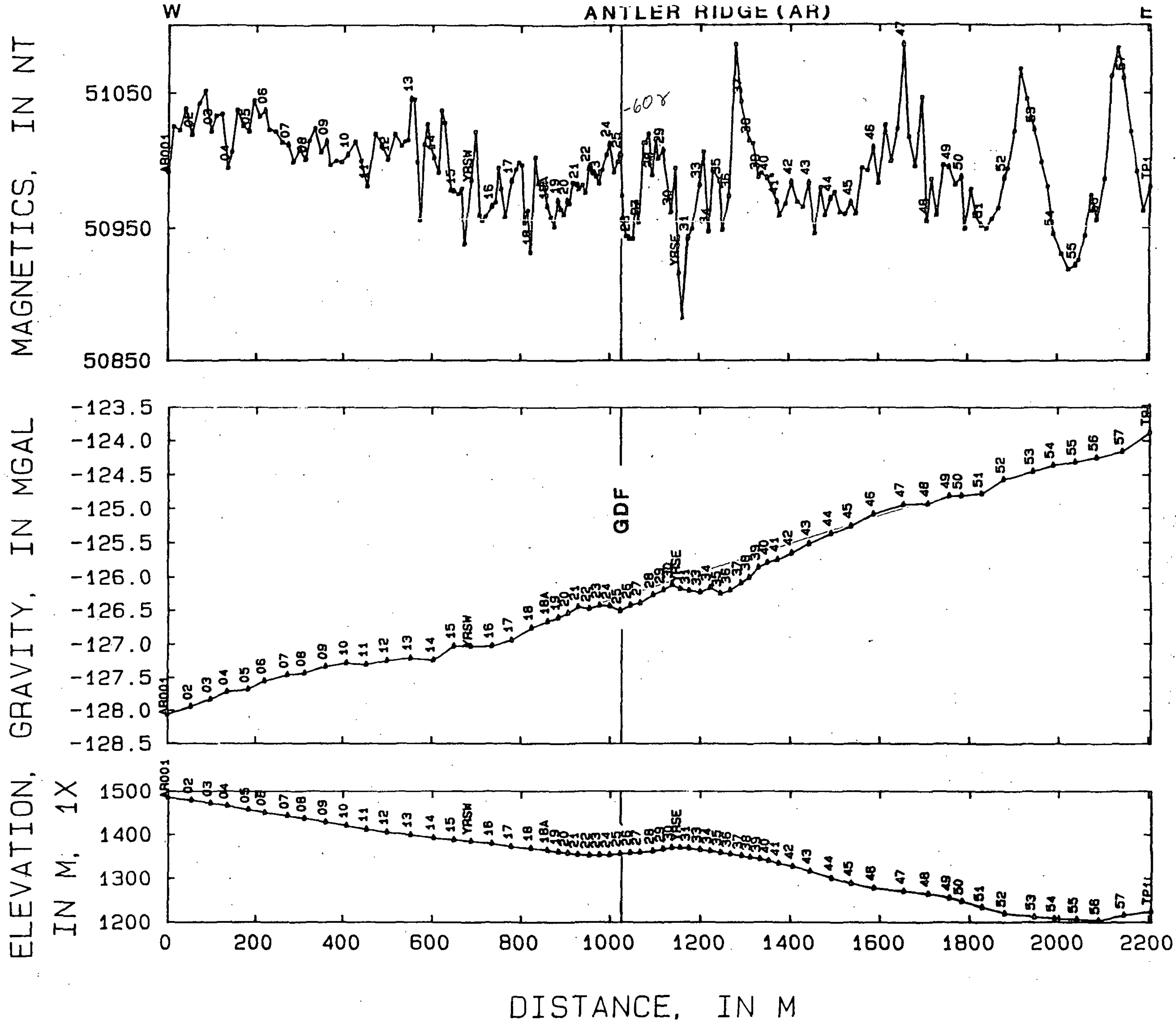

Figure 3 Gravity, and magnetic profiles along Antler Ridge. GDF, Ghost Dance fault.

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I-366906

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January 31, 1995

Robert M. Nelson, Jr., Acting Project Manager
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Nevada Field Office
U.S. Department of Energy
P.O. Box 98608

WBS: 1.2.3.2.5.2.1
QA: L

Attn: Peter M. Stephan, REECo, MS 523, Las Vegas, NV

SUBJECT: PUBLICATIONS--Transmittal of abstract entitled, "Depth to pre-Cenozoic basement in southwest Nevada", by V.E. Langenheim and D.A. Ponce

Interagency Agreement No. DE-AI08-92NV10874

Dear Bob:

One copy of the subject abstract is enclosed for review in your office and concurrence for presentation and publication in the proceedings volume for the International High-Level Radioactive Waste Management Conference to be held May 1-5, 1995 in Las Vegas, Nevada

This report received technical review by Robert C.Jachens and Robert F. Sikora who were chosen because of their general knowledge of the work and techniques. A QA review was performed by Bob Scavuzzo, YMPB-QA Office, and a preliminary Policy review was performed by Bob Lewis, YMPB.

Technical data for this report have been submitted in accordance with YAP-SIII.3Q. The tracking number for the TDIF associated with these data is GS950100123252.001

This report was prepared under WBS number 1.2.3.2.5.2.1. There are no milestones associated with this report. Upon publication, this report will be submitted to OSTI in accordance with DOE order 1430.2, under distribution category UC-814.

Robert E. Lewis, Reports Improvement Officer
Yucca Mountain Project Branch
For: Larry R. Hayes, Chief YMPB

Enclosures

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- M.P. Chornack, USGS, YMPB, Denver, CO
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DEPTH TO PRE-CENOZOIC BASEMENT IN SOUTHWEST NEVADA

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I. Introduction

The composition of and depth to pre-Cenozoic basement are poorly known at Yucca Mountain and vicinity because of the thick sequence of tuff that was erupted between 15 and 7 Ma. (cite Sawyer and others 1994 (GSA Bulletin, v. 106, no 10, p. 1304-18).) Only one well (UE-25 p#1) of many deep wells drilled to characterize the Yucca Mountain site penetrated basement. Gravity data can be used to estimate the thickness of Cenozoic deposits because of the large density contrast between low-density volcanic and alluvial deposits and high-density pre-Cenozoic basement rock. We use an iterative procedure based on the gravity data, the surface geology, and an estimated density-depth function for the Cenozoic deposits to separate the gravity field into a "basement" gravity component and a "basin" gravity component[1]. We present a preliminary isopach map of Cenozoic deposits at Yucca Mountain and vicinity based on the "basin" gravity field.

II. Method

The method[1] separates gravity observations into two sets, one consisting of observations on basement outcrops and the other consisting of observations taken on Cenozoic outcrops. The second set of observations is inverted for thickness of Cenozoic deposits based on an estimate of the density-depth curve (from Jachens and Moring[1]) between these deposits and pre-Cenozoic basement. This inversion is complicated by two factors: (1) basement gravity stations are influenced by the gravity anomaly caused deposits in western and southern Crater Flat and under northern Yucca Mountain. These local lows within Crater Flat and Yucca Mountain may indicate grabens that formed before the advent of voluminous silicic volcanism about 17 Ma[5]. This model predicts about 600 m of Cenozoic deposits at drillhole UE-25 p#1, which penetrated basement at a depth of 1244 m. Cenozoic deposits in Amargosa Desert and Jackass Flats are generally less than 1.5 km thick, in agreement with interpretations of electrical resistivity data[6] and with limited drill-hole data.

obs 600m vs 1244m

← VES ??

IV. Conclusions

Although the results of the iterative modeling procedure agree fairly well with other data, the preliminary isopach map has several inherent limitations arising from the procedure and data used to create the map. Better gravity coverage on basement outcrops would better constrain the known basement gravity field. However, uncertainties in the density-depth function, lateral variations in density within the volcanic sequence, and the presence of concealed basement sources (e.g., a hypothetical pluton underlying the Cenozoic sequence in Crater Flat) could all affect the predicted cover thicknesses. Nonetheless, the isopach map does provide target basement depths for deep drilling in Crater Flat and Yucca Mountain. Differences between the predicted thicknesses and thicknesses determined by other methods can be used to refine the model.

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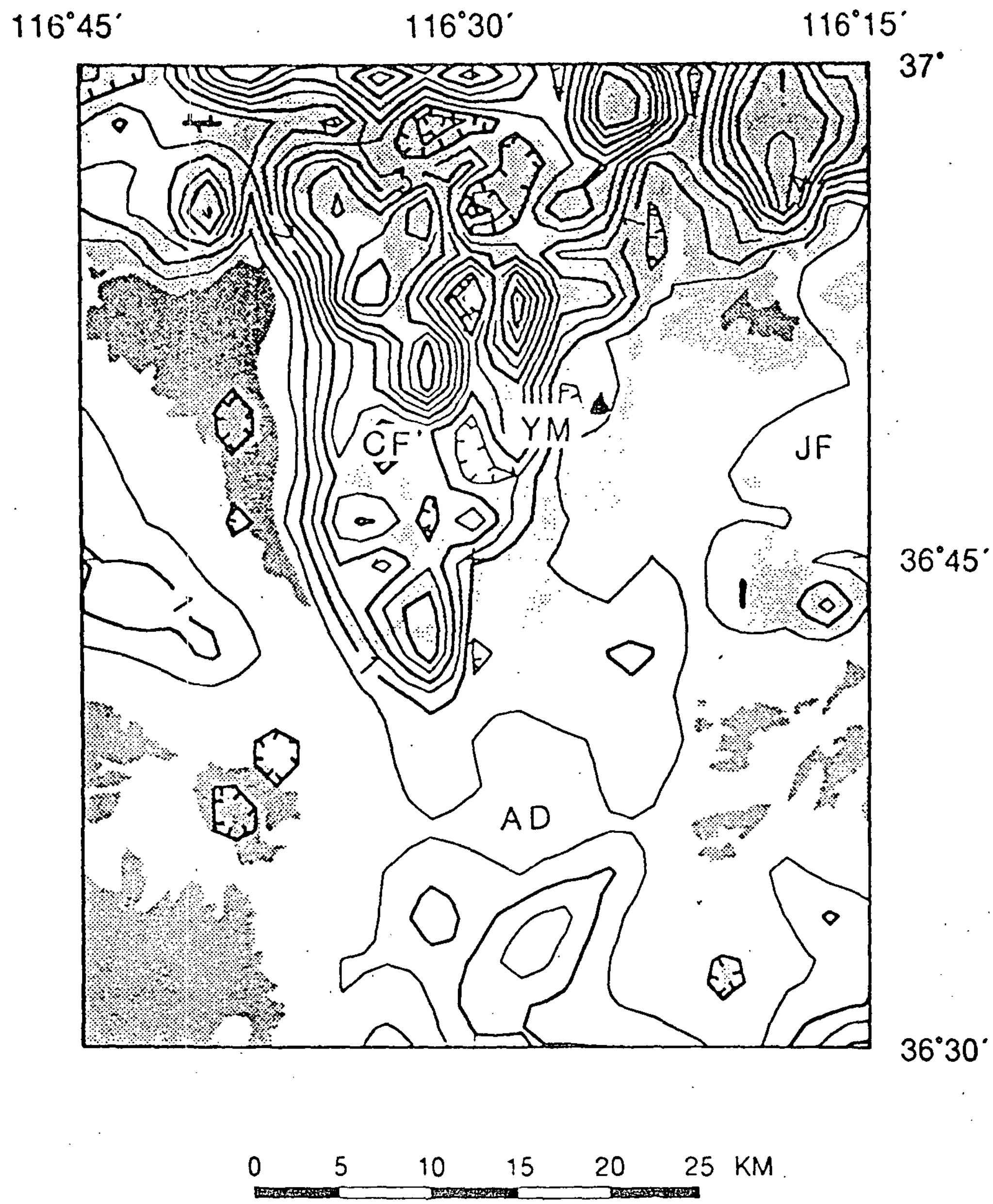
Fig. 1 Schematic representation of the gravity separation procedure. "n" represents final iteration of basin-fitting procedure.

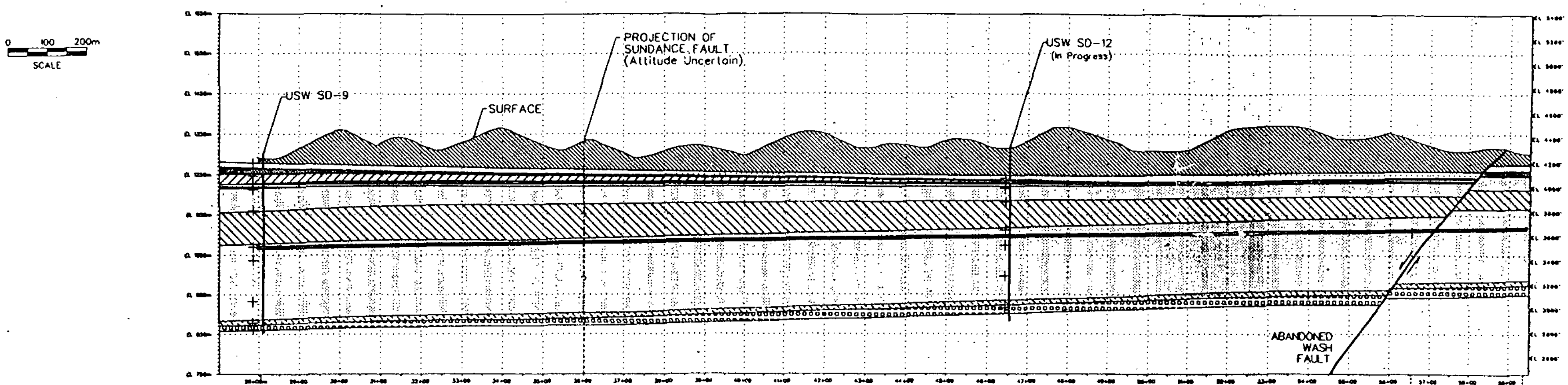
Fig. 2 Preliminary isopach map of Cenozoic sedimentary and volcanic rocks. Contour interval 0.5 km. Dark areas indicate outcrops of pre-Cenozoic rock; lightly shaded areas, Tertiary volcanic rock; unshaded areas, Quaternary and Cenozoic alluvial deposits. YM, Yucca Mountain; AD, Amargosa Desert; CF, Crater Flat; JF, Jackass Flats. Triangle shows location of well UE-25 p#1.



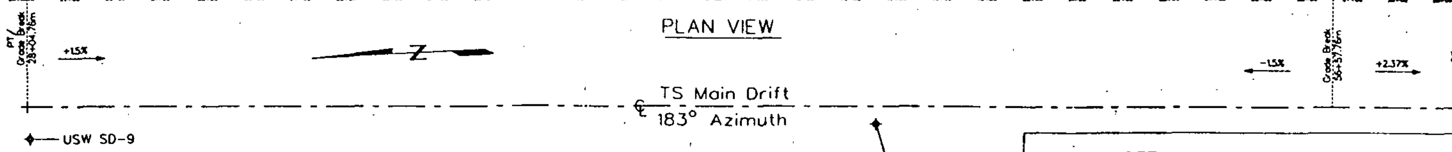
reliminary isopach map of Cenozoic sedimentary and volcanic rocks. Contour interval 0.5 km. Dark areas indicate outcrops of pre-Cenozoic rock; lightly shaded areas, Tertiary volcanic rock; unshaded areas, Quaternary and Cenozoic alluvial deposits. YM, Yucca Mountain; AD, Amargosa Desert; CF, Crater Flat; JF, Jackass Flats. Triangle shows location of well UE25 p#1.

UE-25

SECTION VIEW



PLAN VIEW



STRATIGRAPHY[1]

		LITHO-STRATIGRAPHIC UNITS	SYMBOL	THERMAL-MECHANICAL UNITS
PAINTBRUSH GROUP		Tiva Canyon Tuff; undifferentiated, devitrified	Tpcun	TCw
	TIVA CANYON	Tiva Canyon Tuff; crystal-poor, vitric, nonwelded to moderately welded	Tpcpv	PTn
		Pre-Tiva Canyon tuff bedded tuff	Tpbt4	PTn
	YUCCA MTN.	Yucca Mountain Tuff	Tpy	PTn
		Pre-Yucca Mountain bedded tuff	Tpbt3	PTn
	PAH CANYON	Pah Canyon Tuff	Tpp	PTn
		Pre-Pah Canyon Tuff bedded tuff	Tpbt2	PTn
	TOPOPAH SPRING	Topopah Spring Tuff; crystal-rich, vitric, nonwelded to moderately welded	Tptrv	PTn
		Topopah Spring Tuff; crystal-rich, devitrified, nonlithophysal (includes vitrophyre)	Tptrn	TSw1
		Topopah Spring Tuff; crystal-poor, upper lithophysal (includes crystal-rich lithophysal)	Tptpul	TSw1
		Topopah Spring Tuff; crystal-poor, middle nonlithophysal	Tptpmn	TSw2
		Topopah Spring Tuff; crystal-poor, lower lithophysal	Tptpll	TSw2
		Topopah Spring Tuff; crystal-poor, lower nonlithophysal	Tptpln	TSw2
		Topopah Spring Tuff; crystal-poor, vitrophyre subzone	Tptpv3	TSw3
		Topopah Spring Tuff; crystal-poor, vitric, non-welded to moderately welded	Tptpv1&2	CHn

[1] Stratigraphic and thermal-mechanical units as defined by Buesch, et al, USGS Open File Report 94-469, in press, "Revised Stratigraphic nomenclature and macroscopic identification of lithostratigraphic units of the Paintbrush Group exposed at Yucca Mountain, Nevada.

LEGEND

PROPOSED TS MAIN DRIFT ALIGNMENT

\+ DRILLHOLE CONTACTS BASED ON PROJECTING BOREHOLE ALONG DIP

PRELIMINARY TS MAIN DRIFT DATA
QA:N

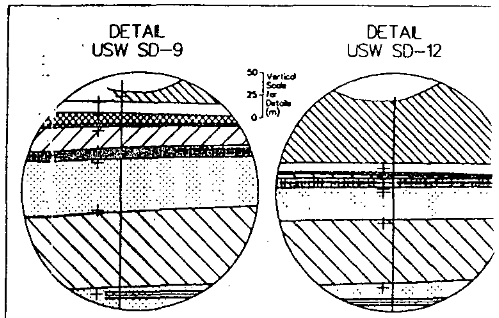
Station (m)	Grade	State Plane Coord. (m) Northing	State Plane Coord. (m) Easting	Elevation (m)
28+04.76 (PT)	+1.5%	231098.7	171213.8	1063.00
56+34.76 (VPI)	+2.37%	231242.6	171164.7	1107.74
59+36.89 (PC)		230940.3	171148.8	1114.41

BOREHOLE PROJECTIONS
QA:L

Borehole	Projected to Section along Azimuth	Ground Elevation (m)	Distance to Section (m)
USW SD-9	90°	1302.28	71.3
USW SD-12	90°	1318.78	39.3

Note: Stratigraphic contacts based on USGS LYNX Model YMP.R1.1 Not qualified data. Projections of stratigraphic contacts from USW SD-9 and USW SD-12. Qualified data.

DETAIL USW SD-9 / DETAIL USW SD-12



REV. NO.	DATE	BY	VERSION	SUPERCEDES
3	12-?-94	CEB	QA1	PRELIM2
2	10-25-94	CEB	PRELIM2	PRELIM1
1	9-27-94	CEB	PRELIM	PRELIMINARY

REVISIONS

QA:L

TS MAIN DRIFT
YUCCA MOUNTAIN SITE
CHARACTERIZATION PROJECT
CROSS SECTION ALONG DRIFT FR
28+04.76m (PT) to 59+36.89 (F

Sandia National Laborator

BASE DRAWING USGS LYNX MODEL VERSION YMP.R1.1 QA:N SEPTEMBER 1994

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CONSTRAINTS ON THE STRUCTURE OF CRATER FLAT, SOUTHWEST NEVADA, DERIVED FROM GRAVITY AND MAGNETIC DATA

V.E. Langenheim

ABSTRACT

Gravity data were modeled across Crater Flat by using three distinct geometries for the Bare Mountain fault: (1) stepped, high-angle normal faults, (2) low-angle normal fault, and (3) a single, high-angle range-front fault with interbedding of high-density alluvium in the Crater Flat basin fill. All three models fit the gravity data well and provide three distinct geometries to test using other geophysical methods, such as seismic reflection and refraction. Magnetic data suggest that a stepped, high-angle normal fault geometry for Bare Mountain is more likely than the other two geometries.

INTRODUCTION

Understanding the structural framework of Crater Flat is essential for assessing seismic hazard to the proposed high-level radioactive waste repository site at Yucca Mountain. Hypotheses to explain the formation of the elliptical, deep basin at Crater Flat fall into three main categories: (1) volcano-tectonic depression or caldera (Snyder and Carr, 1984), (2) detachment faulting (Hamilton, 1988), and (3) graben faulting. Geophysical data, especially gravity data, have been used to support two of these hypotheses, namely the caldera hypothesis (Snyder and Carr, 1984), and the detachment faulting mechanism (Oliver and Fox, 1993). In particular, the gravity data have been used to model the geometry of the Bare Mountain fault, a structure that places folded and faulted Paleozoic and Precambrian sedimentary rocks of Bare Mountain in juxtaposition with the alluvial deposits of Crater Flat. The Bare Mountain fault has generally been linked geometrically to faults underlying Yucca Mountain, faults that are hidden under a thick volcanic pile. This paper will attempt to identify limits on the possible fault geometries of the Bare Mountain fault by using gravity and magnetic data.

GEOLOGIC SETTING

Crater Flat lies in the southern part of the Great Basin section of the Basin and Range physiographic province and within the Walker Lane belt (Carr, 1974). The northern and central Great Basin is characterized by alternating north-trending ranges and valleys, whereas the topography of the Walker Lane belt is more diverse, with lower relief and more arcuate trends. Crater Flat, located on the southwest side of the southwestern Nevada volcanic field, has been interpreted to be a caldera complex (Carr and others, 1984).

Crater Flat is an elliptical basin rimmed by Bare Mountain on the west and Yucca Mountain on the east (fig. 1). Gravity and seismic refraction data indicate that the basin fill reaches thicknesses of 3 to 4 km. Because the basin fill is so thick and the two existing drill-holes in Crater Flat bottom in this fill, one must look to the surrounding geology at Yucca Mountain and Bare Mountain to determine the possible geological configuration below Crater Flat.

FIGURE 1. NEAR HERE

The oldest rocks in the area are exposed at Bare Mountain. These pre-Tertiary rocks consist of Paleozoic and upper Precambrian clastic and carbonate rocks. These rocks are mildly to moderately metamorphosed (Monsen and others, 1992) and complexly faulted and locally folded. One drill-hole on the east side of Yucca Mountain, UE-25 p#1, penetrated Silurian dolomite at a depth of 1244 m (Carr and others, 1986). At the northwest end of Bare Mountain, the sequence is intruded by a Cretaceous granite that is inferred to postdate the ductile deformation observed in the Paleozoic rocks (Monsen and others, 1992). Along the east edge of Bare Mountain north-trending quartz latite dikes dated at 13.9 Ma clearly postdate ductile deformation of the pre-Tertiary sequence (Monsen and others, 1992).

Overlying or in fault contact with these pre-Tertiary rocks are voluminous Tertiary ash-fall tuffs and lava flows extruded from several volcanic centers within and adjacent to the Timber Mountain-Oasis Valley caldera complex, north of Crater Flat. Most of the volcanism occurred between 17 and 7 Ma (Byers and others, 1976). The tuff sequence exposed at Yucca Mountain is cut by numerous west-dipping, north- to northeast-trending normal faults, with consistent down-to-the-west displacement (Scott, 1990). Dips of the tuff are generally shallow, ranging from 10° to 30°. Scott (1990) has argued the existence of a relatively shallow (1-2 km) detachment fault underlying Yucca Mountain based on these structural patterns.

In Crater Flat, these tuffs are overlain by a thin veneer of alluvium. Pliocene cinder cones and basalt flows have a general north-northeast alignment within Crater Flat. Along the southern rim of Crater Flat are exposures of Miocene basalt (dated at 10.5 Ma), overlain by slide breccias composed entirely of Paleozoic debris.

GRAVITY

Densities

Density information is critical to modeling of the gravity data. An abundance of density data are available for the rocks in Crater Flat and vicinity. Density logs from the two drill holes in Crater Flat and density measurements from surface samples indicate that there are significant density contrasts between alluvium, basalt, tuff, and pre-Tertiary rocks. A borehole gravimeter study of USW H-1 at Yucca Mountain gives densities within the tuff sequence consistent with those obtained using the gamma-gamma method (Snyder and Carr, 1984), indicating that the gamma-gamma method is an appropriate technique for measuring densities in this area, although this method samples a smaller volume of rock in the drill hole than the borehole gravimeter technique. Snyder and Carr (1984) found that density and depth had the following empirical relationship

$$\rho = 0.26\, d + 1.9$$

where ρ is density in g/cm^3 and d is depth in kilometers. They attributed the steady increase in density to closure of pore spaces and fractures and increasing alteration rather than any systematic change in lithology. This result generally holds true for the density logs of USW VH-1 and USW VH-2 except where high concentrations of Paleozoic rock fragments were found. At USW VH-2, two intervals (51 and 61 m thick) of Paleozoic slide breccia have densities of 2.5 to 2.6 g/cm^3, which is significantly higher than densities measured for the underlying and overlying tuff (2.0-2.3 g/cm^3) and alluvium (1.8-2.0 g/cm^3)(Carr and Parrish, 1985; Nelson and others, 1991). Similar breccias composed solely of Paleozoic debris crop out along the southern edge of Crater Flat, with exposed thicknesses of at least 100 m (Swadley and Carr, 1987).

Information on the densities of the pre-Tertiary rocks is limited to density log data from UE-25 p#1 (p#1 on fig. 1), where the average density of the carbonate sequence is about 2.75 g/cm^3 (Healey and others, 1984). Densities of 77 hand samples of several different lithologies from Bare Mountain average about 2.76 g/cm^3, ranging from 2.37 g/cm^3 to 2.85 g/cm^3 (table 1).

Table 1. Physical property measurements of Bare Mountain samples

Lithology	Number of samples	Average density (g/cm^3)	Range in density (g/cm^3)	k*
Limestone	27	2.76	2.37-2.85	0-0.08
Dolomite	19	2.78	2.66-2.85	0-0.32
Breccia	3	2.71	2.62-2.83	0-0.09
Meta-carbonate	16	2.75	2.63-2.85	0-0.14
Meta-pelite**	12	2.76	2.70-2.85	0.10-11.2
ALL LITHOLOGIES	77	2.76	2.37-2.85	0.00-11.2

*10^{-3} SI units
**Wood Canyon Formation

Seismic velocities also provide indirect information on densities. Ackermann and others (1988) obtained a relationship between density and velocity, although seismic velocities are considerably more sensitive to fractures than are densities and may give unreasonably low estimated densities, especially for pre-Tertiary rocks in the uppermost 1-2 km of the crust at Yucca Mountain (W.D. Mooney, U.S. Geological Survey, written commun., 1986; see below).

Gravity Data

Over 3,000 gravity stations taken from Saltus (1988) and Harris and others (1989) were used to generate the gravity map (fig. 1). The gravity data were reduced using standard methods to complete Bouguer gravity anomalies at a reduction density of 2.67 g/cm^3 (Telford and others, 1976). This density was chosen to emphasize the contribution to the gravity field from the topography of the Paleozoic surface and may not adequately correct for topography consisting of lower-density volcanic material. The data include earth-tide, instrument drift, free-air, Bouguer, latitude, curvature, and terrain corrections. A regional correction using the principle of isostasy was also applied to the data to model and remove long-wavelength effects deep compensation for topographic loads (Simpson and others, 1986).

Models

The gravity data were modeled using three distinct geometries along a profile A-A′ (fig. 1) that nearly coincides with the Yucca Mountain seismic refraction profile (W.D. Mooney, written commun., 1986). The data were modeled using standard 2-dimensional methods (Saltus and Blakely, 1993). The seismic profile provides constraints on the density structure within the fill. The seismic model called for two different velocities within the pre-Tertiary sequence; the gravity model suggests that one density for the pre-Tertiary sequence is sufficient to model the data, emphasizing the sensitivity of seismic velocities to fractures in the upper 2 km. Drill holes VH-2 and UE-25 p#1 (VH-2, p#1, respectively on fig. 1) provide information on the thickness of Cenozoic deposits (fig. 1). An examination of the gravity field and modeling indicate that high-density Paleozoic rocks must be present near the surface east of the mapped trace of the Bare Mountain fault in order to account for the location of the gravity gradient. If the Bare Mountain fault extended to depth at a dip of 55° east (dips vary from 45° to 75° along its strike; Monsen and others, 1992), the horizontal gradient of the gravity field should be maximized over the contact (Blakely and Simpson, 1986). Instead, three detailed profiles on the west flank of Crater Flat indicate that the maximum horizontal gravity gradient is 0.5 to 1.5 km east of the mapped Quaternary trace of the Bare Mountain fault. At least three geometries can account for the location of the maximum horizontal gravity gradient: (1) one or more steps in the steep, east-dipping fault observed at the range front of Bare Mountain (fig. 2A), (2) a flattening of the dip of the Bare Mountain fault (fig. 2B), or (3) a steeply-dipping fault which incorporates high-density Paleozoic breccia within the fill of the Crater Flat at the base of the fault (fig. 2C).

FIGURE 2 NEAR HERE

The step model (fig. 2A) fits the gravity data quite well. Along the modeled profile, the step is 1 km long and about 400 m high. Modeling along other profiles indicates that the step ranges in length from less than 1 km to more than 2 km. Snyder and Carr (1984) interpreted the geometry of the step model as evidence for a caldera underlying Crater Flat. According to their interpretation, the Bare Mountain fault is a reactivated ring fault of the caldera that was the source of the Crater Flat tuff and the cause of the gravity low. This geometry may also describe a range-front fault that steps inward into the range, perhaps reflecting two major episodes of movement. This inwardly stepping normal fault geometry has been documented in other parts of the Basin and Range where no other evidence for a caldera structure exists (for example, Dixie Valley, Nevada; Okaya and Thompson, 1985; Amargosa Desert, Nevada; Brocher and others, 1993).

The gravity data can also be fit by lowering the dip of the fault surface from 55° to 35° along profile A-A' (fig. 2B). To the north, the fault must dip even more shallowly (20°) to fit the gravity data. Oliver and Fox (1993) modeled the gravity assuming a detachment fault geometry that also includes a step in the detachment surface 3 km east of the mapped range fault. The location of their modelled profile coincides with the profile modeled by Snyder and Carr (1984). The difference between the Snyder and Carr (1984) and Oliver and Fox (1993) models is in part the result of the density distribution chosen for the basin fill. Oliver and Fox (1993) assumed a two-layer density-depth model for all of Crater Flat, whereas Snyder and Carr (1984) and models presented here use the empirical relationship of depth and density found in drill hole USW H-1. Alternatively, the smooth surface of the single, low-angle normal fault may be broken by numerous normal faults with small displacements, all down to the east.

The third geometry suggested for the Bare Mountain fault extends the steep dip measured at the surface along the Bare Mountain range fault to depth, but incorporates higher density alluvium within the basin fill (fig. 2B). The higher density material needs to be concentrated within the upper 1-2 km of section to fit the observed gravity gradient. Monolithologic breccias composed of Paleozoic debris crop out along the southern margin of Crater Flat. Two intervals of breccia were found in drill hole USW VH-2, more than 4 km east of the mountain front. The breccias both underlie and overlie a 10.5 to 11 Ma basalt flow. Presumably these deposits thicken towards Bare Mountain, the nearest exposure of pre-Cenozoic rock. Carr (1984) considers these breccias to be slide breccias whose extent and age is the result of major movement on the Bare Mountain high-angle normal fault that occurred at the same time as faulting at Yucca Mountain. Alternatively, Labotka and Albee (1990) have shown that monolithologic breccias can be the result of tectonic erosion along low-angle normal faults.

The three gravity models (fig. 2) provide alternative explanations for the observed gravity gradient observed over the western edge of Crater Flat. The models provide target depths and geometries that can be tested with seismic reflection and refraction methods and drilling. For example, the seismic reflection method may be able to determine whether extensive landslide breccias are interbedded in the upper 1 to 2 km of the Crater Flat fill. Detailed seismic refraction profiles parallel to the range-front fault may be able to image the proposed step in the range-front fault because of the large velocity contrast between the low-velocity Crater Fill material and the higher-velocity pre-Cenozoic rock.

MAGNETIC FIELD

Magnetic Data

Total-field magnetic data from 3 separate surveys (U.S. Geological Survey, 1979; Langenheim and others, 1991; Grauch and others, 1993) were used to construct the aeromagnetic map shown in figure 3. The data were smoothed by upward continuation (Cordell, 1985) to an effective height of 305 m (1000 ft) above the land surface. Data shown in figure 4 were collected with a proton-precession magnetometer with the sensor 2.4 m (8 ft) above the ground.

Discussion

In general, the Precambrian and Paleozoic rocks are only weakly magnetic, producing a uniform magnetic field marked by broad, low-amplitude anomalies. One exception is an intense magnetic high present over Calico Hills (fig. 3). The source of the high appears to be altered argillite of the Eleana Formation which has an average magnetization of almost 4 A/m (0.004 emu; Baldwin and Jahren, 1982). Bath and Jahren (1984) proposed that an underlying intrusion caused the alteration. The magnetic high present over the Calico Hills extends west over the northern part of Yucca Mountain, suggesting that highly magnetic argillite of the Eleana Formation (and its associated intrusion) is present at depth below Yucca Mountain and northern Crater Flat (Bath and Jahren, 1984).

FIGURE 3 NEAR HERE

The magnetic field over Bare Mountain is characterized by east-west-trending anomalies with amplitudes of more than 50 nanoteslas (nT) (fig. 3). These anomalies appear to correlate with outcrops of the Wood Canyon Formation, a Precambrian to

Cambrian unit containing siltstone, quartzite, limestone, and dolomite. Magnetic susceptibility (k) measurements confirm that the Wood Canyon Formation is indeed moderately magnetic (k=0 to 0.01 SI unit; Table 1) whereas other formations of Paleozoic age in this region are essentially nonmagnetic. The Bare Mountain anomalies, which most likely reflect the east-west trending structures mapped at Bare Mountain (Monsen and others, 1992), are in sharp contrast to the mostly north-south-trending anomalies present to the east and north (fig. 3).

The source of most of the magnetic anomalies in figure 3 is volcanic rock. Magnetic-property measurements of volcanic rocks in this area indicate that the remanent magnetization is the principal cause of the anomalies (Bath, 1967). The two main types of volcanic rock that produce anomalies in the Yucca Mountain area are (1) Tertiary and Quaternary lava flows and (2) Tertiary ash-flow tuff. Buried igneous intrusions are a third possible source. Tertiary and Quaternary lava flows tend to produce intense, irregularly shaped, isolated anomalies (Kane and Bracken, 1983). The tuffs, originally laid down as widespread ash-flow sheets, produce anomalies primarily where abrupt changes in thickness or magnetization occur. This means that vertical offsets of the tuff units produce linear magnetic anomalies that depend on the thickness and magnetization of the individual tuff units. (Bath and Jahren, 1984). North-south-trending anomalies are present over mapped normal faults at Yucca Mountain (Bath and Jahren, 1984). The pattern of north-south trending anomalies extends west of Yucca Mountain (and its mapped faults) halfway across southern Crater Flat and to within 4 to 5 km east of the Bare Mountain range-front fault across northern Crater Flat (fig. 3). This suggests that faults offsetting the underlying tuff units extend at least halfway across Crater Flat. The difference in magnetic anomaly pattern between northern and southern Crater Flat, which is approximately on trend with an east-west-trending gravity gradient (just north of profile A-A′ on Fig. 1), may indicate a change in structural style between northern and southern Crater Flat.

The southwestern edge of Crater Flat is dominated by a magnetic low (marked L on fig. 3). Drill hole VH-2 penetrated 30 m of reversely polarized basalt at 360 m depth (Carr and Parrish, 1985). The age and magnetic polarity of this basalt is the same as basalt exposed along the southern edge of Crater Flat. The continuity of the Crater Flat magnetic low to the south over exposed 10.5 Ma basalt suggests that the Crater Flat low is caused by reversely magnetized basalt. A ground magnetic profile across the magnetic low indicates that the basalt is not offset vertically by more than 50 m (fig. 4). This profile suggests that the low-angle fault shown in fig. 2B cannot be a shallow-dipping surface consisting of multiple normal faults, unless the faults are older than 10.5 to 11 Ma or have offsets smaller than 50 m.

and Tuff

FIGURE 4 NEAR HERE

Magnetic data indicate that the western edge of the buried Crater Flat basalt coincides with the modeled location of the step in the Bare Mountain fault (fig. 2A) as well as with the eastern edge of the east-trending magnetic anomalies associated with the Wood Canyon Formation. Both the magnetic and gravity data indicate that Paleozoic and Precambrian rocks of Bare Mountain extend farther east than the mapped range-front fault. The magnetic data, however, suggest that monolithologic breccias or low-angle normal faults are not the reason for the location of the gravity gradient. Landslide breccias might not preserve the coherence of the east-west-trending magnetic anomalies into the Crater Flat fill. These anomalies would not be abruptly terminated (as the magnetic data suggest) if a low-angle fault were responsible for the presence of pre-Cenozoic rock east of the Bare Mountain fault. The magnetic data thus appear to support the step or caldera model presented in fig. 2A.

Note!

One piece of geophysical evidence used to support the caldera model is the magnetic high (marked H on fig. 3) present over central Crater Flat. Carr (1984, 1990) concluded that the source of the anomaly is a thick accumulation of normally polarized Bullfrog Member of the Crater Flat Tuff. Carr argues that this thickening of the Bullfrog is evidence for a caldera in Crater Flat and that the observed uplift of the Bullfrog between drill holes USW VH-1 and USW VH-2 is evidence of a resurgent dome. The minimum thickness of the Bullfrog Member, as measured in the USW VH-1 drill hole, is nearly the same as the maximum thickness measured in drill holes and outcrops at Yucca Mountain. The top of the Bullfrog is about 573 m higher in drill hole USW VH-1 than in USW VH-2 (Carr, 1982; Carr and Parrish, 1985). Modeling of the anomaly, using an average magnetization of 2 A/m based on measurements by Rosenbaum and Snyder (1984), suggests that Carr's (1990) proposed doming and increase in thickness of the Bullfrog are not enough to account for the magnetic high present over Crater Flat (fig. 5). The gradients of the magnetic high indicate that, if the Bullfrog is the source, there must be an abrupt change in magnetization or thickness within the Bullfrog. Modeling of the anomaly indicates that the top of the source actually may be much deeper than the observed top of the Bullfrog, perhaps as deep as the bottom of the basin fill. The possible source of the magnetic high could be a Tertiary or Cretaceous intrusion.

FIGURE 5 NEAR HERE

CONCLUSION

Three distinct gravity models have been presented. Because of the nonuniqueness of the potential field method, it is impossible to determine which of the three models described is the most appropriate on the basis of gravity alone. Nonetheless, gravity data can provide alternative models that can be tested by other geophysical data. Analysis of the magnetic field over Crater Flat supports the stepped normal fault model rather than the low-angle normal fault or high-density alluvium models, although the magnetic data do not eliminate these alternative models. Modeling of the Crater Flat magnetic high, previously cited as evidence for a resurgent dome within Crater Flat, suggests that the source of the anomaly may not be doming of the Bullfrog Member of the Crater Flat Tuff; the top of the source of the anomaly may be as deep as the floor of the basin fill and could be a Tertiary or Cretaceous intrusion.

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FIGURE CAPTIONS

Figure 1. Isostatic gravity map of Crater Flat (CF) and vicinity. Contour interval, 2 milligals. Hachures indicate gravity lows. Lightly shaded regions indicate exposures of Tertiary and Quaternary volcanic rock; darker regions, rocks of Precambrian and Paleozoic age; unshaded regions, Quaternary alluvium. Boxes show locations of drill holes USW VH-1 (VH-1), USW VH-2 (VH-2), and UE-25 p#1 (p#1). A-A' shows location of profiles modeled in Figures 2A-C. BM, Bare Mountain; CF, Crater Flat; CH, Calico Hills; FM, Funeral Mountains; YM, Yucca Mountain.

Figure 2. Two-dimensional gravity models across Crater Flat along profile A-A'. Numbers in models indicate densities in g/cm^3. Gridded values are observed data. Abbreviations are same as in figure 1. A) step model, B) detachment fault, C) higher-density alluvium in shaded region.

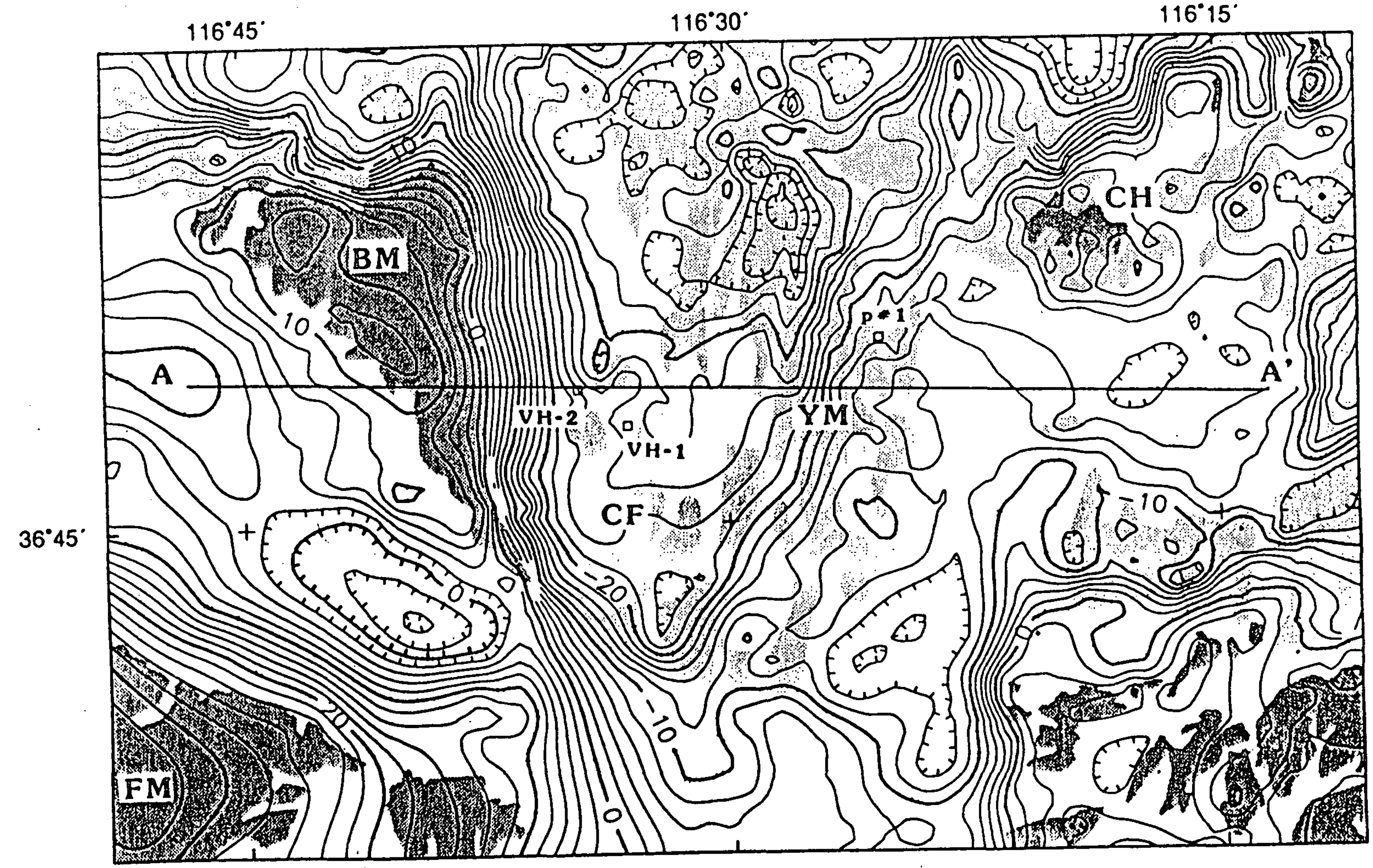
Figure 3. Aeromagnetic map of Crater Flat and vicinity. Shading and abbreviations same as in figure 1. Contour interval, 50 nanoteslas. Hachures indicate magnetic lows. Data from U.S. Geological Survey (1979), Langenheim and others (1991), and Grauch and others (1993). Data were smoothed by analytically continuing upward to an effective height of 305 m (1000 ft) above ground surface. Region marked NO DATA has no high-resolution aeromagnetic coverage. L marks magnetic low discussed in text; H, magnetic high. B-B' and C-C' show location of profiles in Figures 4 and 5 respectively.

Figure 4. Ground magnetic profile across magnetic low (marked L here and on fig. 3) east of the Bare Mountain fault. Sensor 2.4 m (8 feet) above ground surface. Eastern end of profile terminates at drill USW VH-1. The smoothness of the anomaly suggests that the source of the anomaly (most likely Tertiary basalt) has not undergone major (greater than 50 m) vertical offsets.

Figure 5. Simplified magnetic model across Crater Flat along profile B-B′ (see fig. 3). Tb, Tertiary basalt; Tpc, Tiva Canyon Member of the Paintbrush Tuff; Tpt, Topopah Spring Member of the Paintbrush Tuff; Tcp, Prow Pass Member of the Crater Flat Tuff; Tcb, Bullfrog Member of the Crater Flat Tuff (shaded); Pz, Paleozoic and Precambrian rock. Numbers in parentheses are remanent magnetizations in A/m from Rosenbaum and Snyder (1984). Abbreviations same as in fig. 1. Location of USW VH-2 projected onto profile. Gridded values are observed data. Basement geometry inferred from gravity. The uplift and increase in thickness of the Bullfrog Member suggested by Carr (1984) do not account for the amplitude of the magnetic high (H).

In this paper all magnetic units are given in the International System of units (SI). Conversions to the older electromagnetic units (emu) are given in the following table:

Quantity	SI unit	Equivalent unit (in emu)
Magnetic field	nanotesla (nT)	1 nT = 1 gamma
Magnetization	ampere/meter (A/m)	1 A/m = 10^{-3} gauss
Susceptibility	dimensionless	$(4\Pi)^{-1}$
Gravity field		1 milligal (mGal)= 10^{-3} cm/s^2



0 5 10 15 20 25 KM

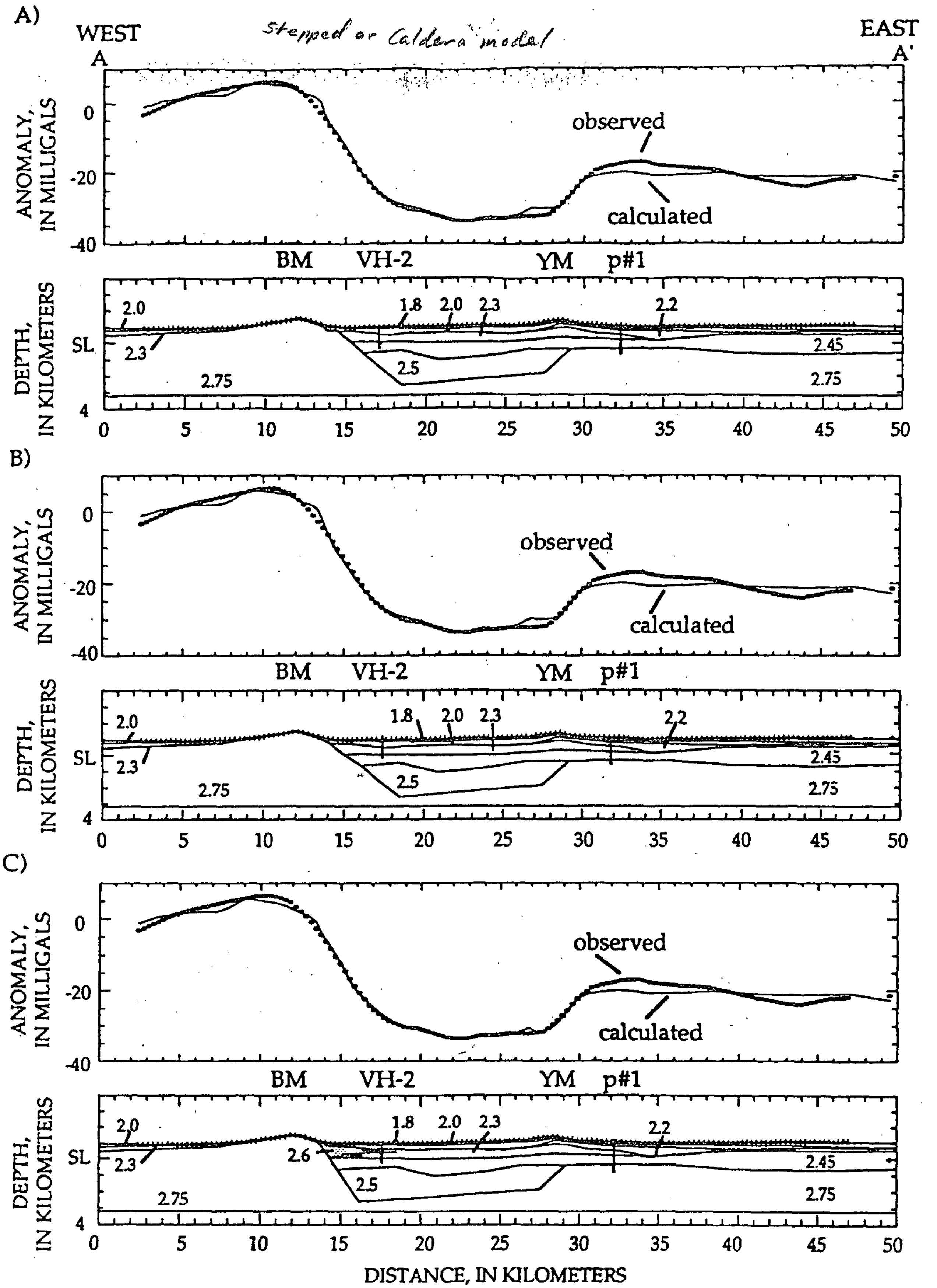
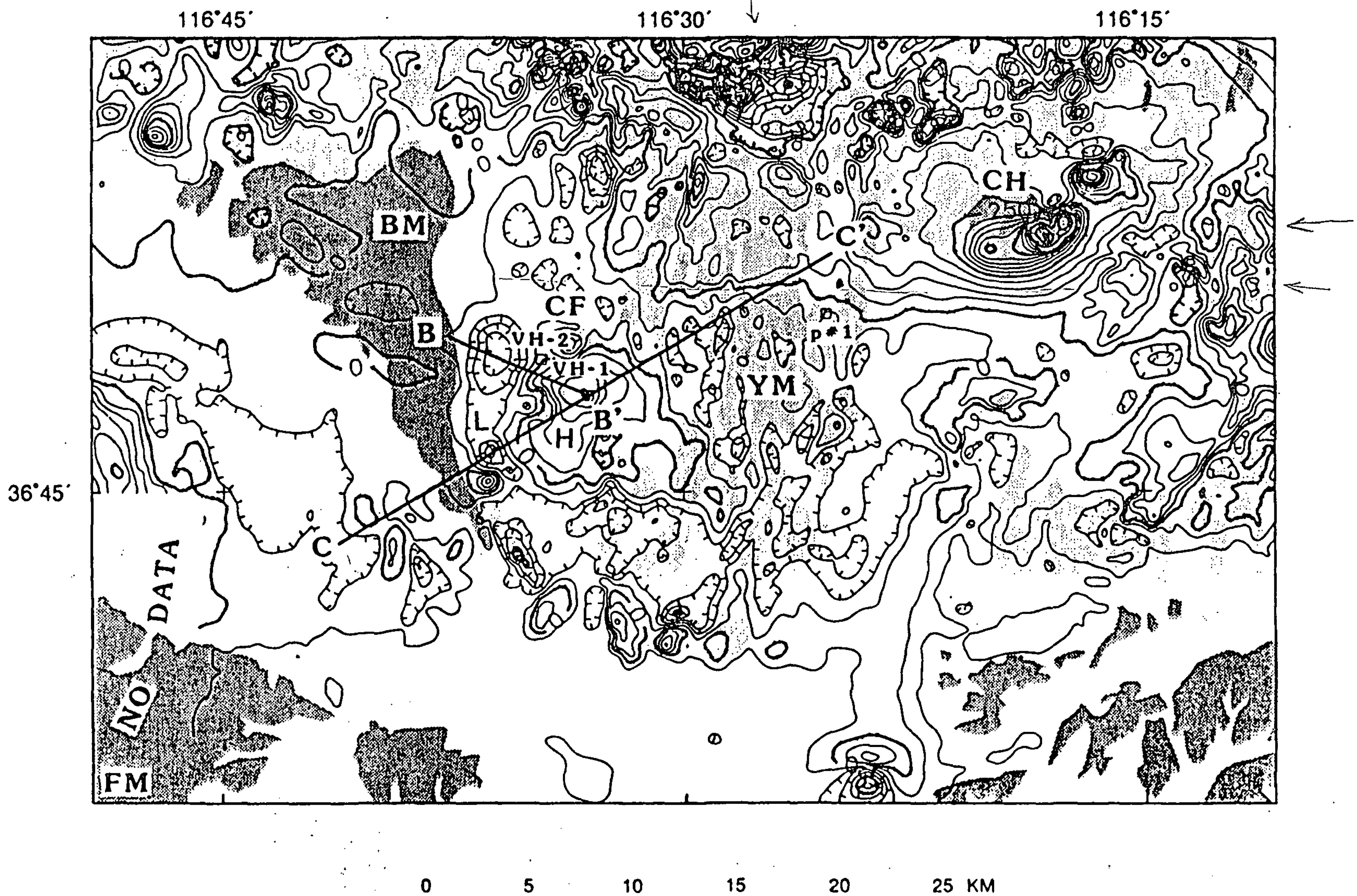


Figure 2. Two-dimensional gravity models across Crater Flat along profile A-A'. Numbers indicate densities in g/cm^3. Gridded values are observed data. Abbreviations are same as in figure 1. (A) step model, (B) detachment fault, (C) higher-density alluvium in shaded region.



116°45′
116°30′
116°15′
36°45′
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CH
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C′
CF
B
VH-2
VH-1
P#1
YM
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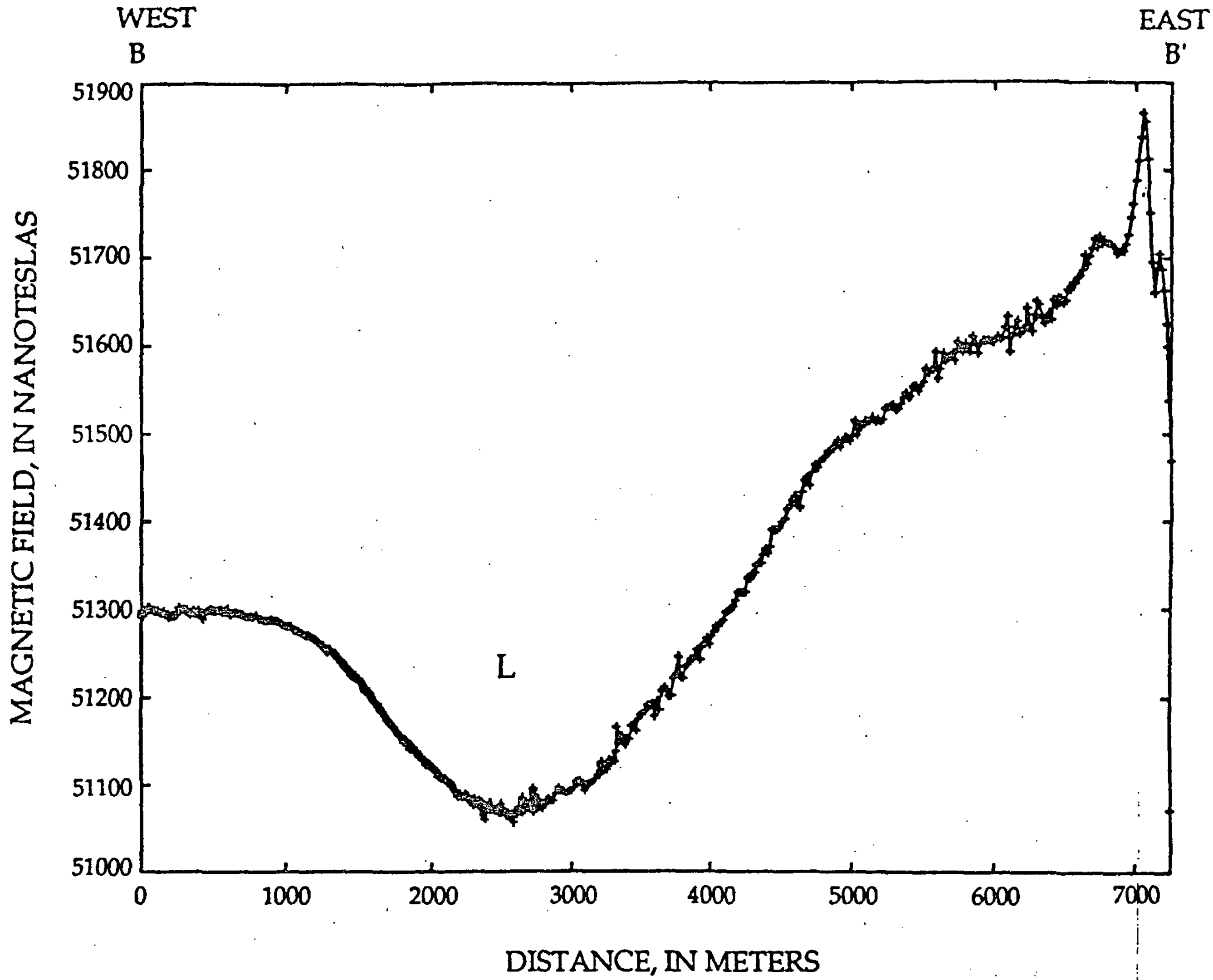

Figure 4. Ground magnetic profile across magnetic low (marked L here and on fig. 3) east of the Bare Mountain fault. Sensor 2.4 m ~~(8 feet)~~ above ground surface. Eastern end of profile terminates at drill hole USW VH-1. The smoothness of the anomaly suggests that the source of the anomaly (most likely Tertiary basalt) has not undergone major (greater than 50 m) vertical offsets.

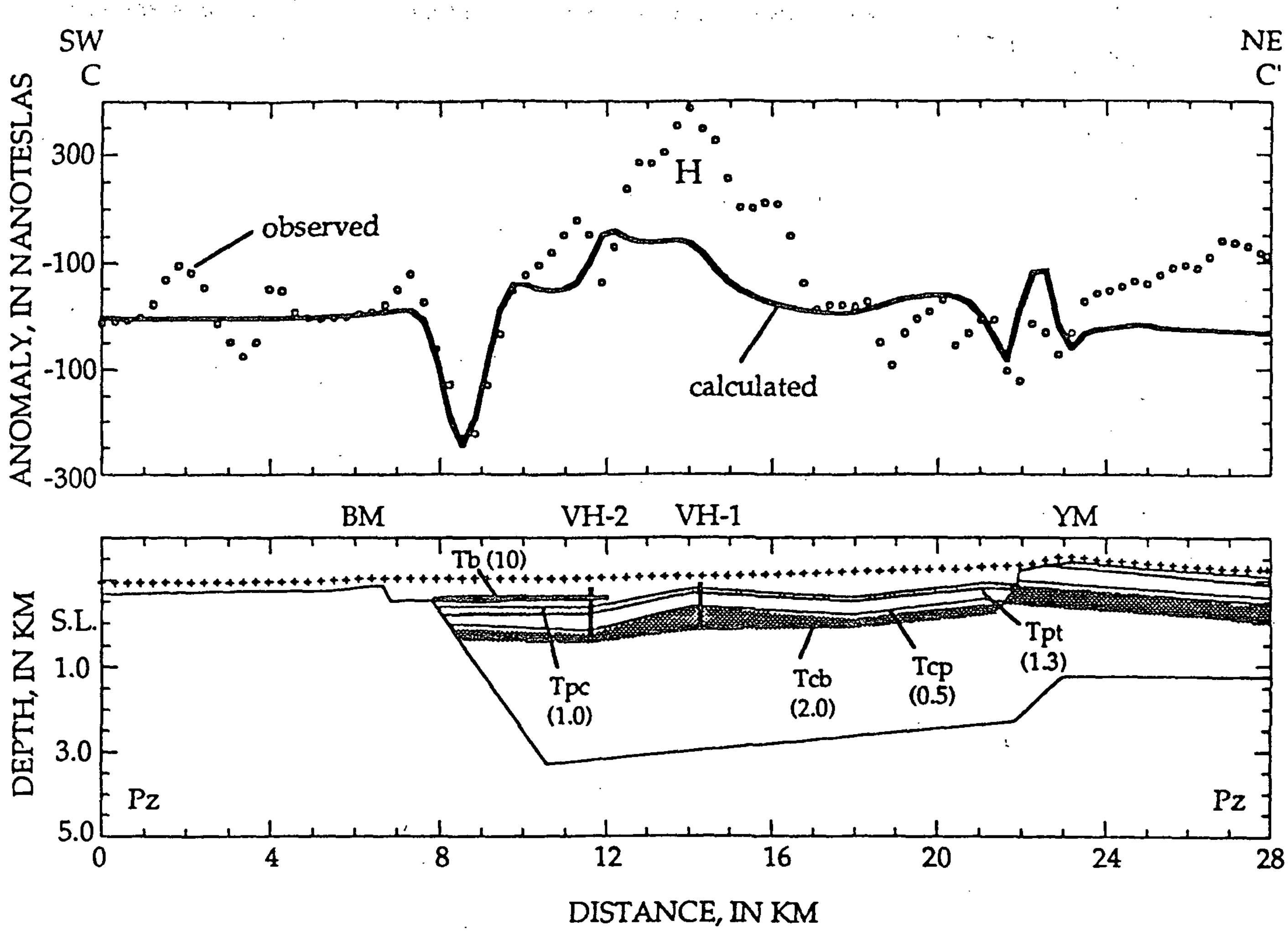

Figure 5. Simplified magnetic model across Crater Flat along profile C-C' (see fig. 3). Tb, Tertiary basalt; Tpc, Tiva Canyon Member of the Paintbrush Tuff; Tpt, Topopah Spring Member of the Paintbrush Tuff; Tcp, Prow Pass Member of the Crater Flat Tuff; Tcb, Bullfrog Member of the Crater Flat Tuff (shaded); Pz, Paleozoic and Precambrian rock. Numbers in parentheses are remanent magnetizations in A/m from Rosenbaum and Snyder (1984). Abbreviations same as in fig. 1. Location of USW VH-2 projected onto profile. Gridded values are observed data. Basement geometry inferred from gravity. The uplift and increase in thickness of the Bullfrog Member suggested by Carr (1984) do not account for the amplitude of the magnetic high (H).

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United States Department of the Interior

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November 18, 1994

Robert M. Nelson, Jr., Acting Project Manager
Yucca Mountain Site Characterization Project Office
Nevada Field Office
U.S. Department of Energy
P.O. Box 98608

WBS: 1.2.3.2.2.1.1
QA: QA

Attn: Jerry J. Lorenz, REECo, Technical Information Section

SUBJECT: PUBLICATIONS--Transmittal of Report entitled, "Constraints on the structure of Crater Flat, southwest Nevada, derived from gravity and magnetic data", by V.E. Langenheim

Interagency Agreement No. DE-AI08-92NV10874

Dear Bob:

One copy of the subject report is enclosed for review in your office and concurrence for publication as a chapter in a U.S. Geological Survey Circular.

This report received technical review by Rick Saltus and Chris Fridrich who were chosen because of their general knowledge of the work and techniques. A QA review was performed by Bob Scavuzzo, YMPB-QA Office, and a preliminary Policy review was performed by Bob Lewis, YMPB.

Technical data for this report have been submitted in accordance with YAP-SIII.3Q. The tracking number for the TDIF associated with these data is GS940808314212.006

This report was prepared under WBS number 1.2.3.2.2.1.1. There are no milestones associated with this report. Upon publication, this report will be submitted to OSTI in accordance with DOE order 1430.2, under distribution category UC-814.

Robert E. Lewis
Robert E. Lewis, Reports Improvement Officer
Yucca Mountain Project Branch 250
For: Larry R. Hayes, Chief YMPB

Enclosures

cc w/o enclosures:
- LRC File 3.304-9 (P)
- M.P. Chornack, USGS, YMPB, Denver, CO
- V.E. Langenheim, USGS, GD, Menlo Park, CA
- B.T. Brady, YMPB, Denver, CO
- R. Ritchey, YMPB, Denver, CO
- YMP WBS Manager: T. Sullivan, DOE, Las Vegas, NV

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Lindenburg
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REC'D 11/21/94