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GEOPHYSICAL INTERPRETATION OF SUBSURFACE GEOLOGY, PEDIMENT OF THE SAN ANDRES MOUNTAINS TO THE JORNADA DEL MUERTO BASIN, NEW MEXICO

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Abstract—Beginning in 1985, detailed studies of the geology and hydrology in the vicinity of the NASA White Sands Test Facility (WSTF) on the pediment slope of the San Andres Mountains have been undertaken in an effort to define the controls on groundwater movement in the subsurface. Here we present results from a study undertaken in 1995 in which geophysical data sets are integrated with extensive well data in the vicinity of the WSTF to produce new information on the subsurface geology of the region. Our study includes the re-interpretation of 42 mi of shallow seismic reflection data, originally shot in 1987, in conjunction with data from 100 wells that have been drilled since the seismic data were originally acquired. This effort has resulted in a new depth to bedrock structure map that shows that there are two major fault zones trending north-northwest-south-southeast that offset bedrock beneath the study area. Well data and gravity modeling show that Tertiary volcanics have been juxtaposed against Paleozoic sedimentary rocks along the subsurface extension of a fault mapped in outcrop at Hardscrabble Hill and that displacement across this fault is at least 6400 ft.

INTRODUCTION

Beginning in 1985, detailed studies of the geology and hydrology in the vicinity of the NASA White Sands Test Facility (WSTF) (Fig. 1) have been undertaken in an effort to define the controls on groundwater movement in the subsurface (Giles and Pearson, this guidebook). These studies have also provided useful new information on the subsurface geology of the San Andres pediment and eastern Jornada del Muerto Basin.

Here we present results from a study undertaken in 1995 in which geophysical data sets are integrated with extensive well data in the vicinity of the WSTF to produce new information on the subsurface geology of the region. Our study includes the re-interpretation of 42 mi of shallow seismic reflection data, originally shot in 1987 (Reynolds and Associates, unpubl. report for NASA, 1987; unpubl. report to NASA, 1988), in light of data from 100 monitoring wells that have been drilled since the seismic data were originally acquired. This effort has resulted in a new depth to bedrock map that constrains the location of faults and other features that may influence groundwater flow in the subsurface. In addition, we present results from a gravity survey, which together with the seismic results helps constrain displacement on basin-bounding faults on the west side of the study area.

GEOLOGIC AND HYDROLOGIC SETTING

The study area lies on the western pediment slope of the southern San Andres Mountains and incorporates the eastern half of the Jornada del Muerto Basin (Fig. 1). The region is characterized by north-south-trending, fault-bounded mountain ranges, including the San Andres and Organ Mountains, and intermountain basins, including the Jornada del Muerto Basin. This physiography has developed primarily since late Oligocene time in response to extensional tectonism along the Rio Grande rift (Seager, 1981). The geologic structure of the region has also been significantly affected by late Cretaceous to early Tertiary shortening during the Laramide orogeny. This event produced northeast-southwest-trending structures including the Bear Creek thrust that crops out in the northern portion of the study area (Fig. 1, Seager, 1981; Seager et al., 1986).

Bedrock is composed of Paleozoic sedimentary rocks that are locally intruded or unconformably overlain by Tertiary volcanic rocks. The volcanics originate from the Organ Mountains volcanic complex (Seager, 1981), whereas Paleozoic rocks outcrop primarily in the San Andres Mountains. These lithologic differences can be seen clearly in the Landsat Thematic Mapper image of the region (inside cover of this guidebook) where Paleozoic bedrock is purple and the volcanic rock is green. Within the Jornada del Muerto Basin, significant thicknesses of Love Ranch Formation, the product of erosional unroofing of Laramide uplifts, are known to occur (Seager, 1981). Rift basin fill in the Jornada del Muerto Basin is

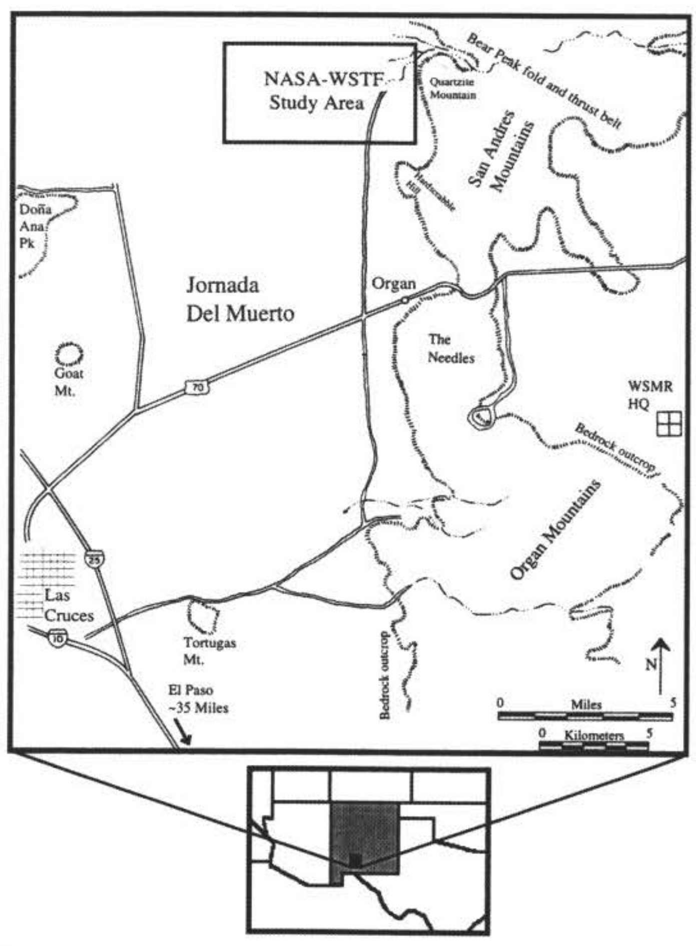

Figure 1

FIGURE 1. Index map showing the study area in relation to surrounding landmarks. The NASA White Sands Test Facility lies on the western slopes of the southern San Andres Mountains and the study area extends into the Jornada del Muerto Basin. Study area outline corresponds to large black rectangle in subsequent figures.

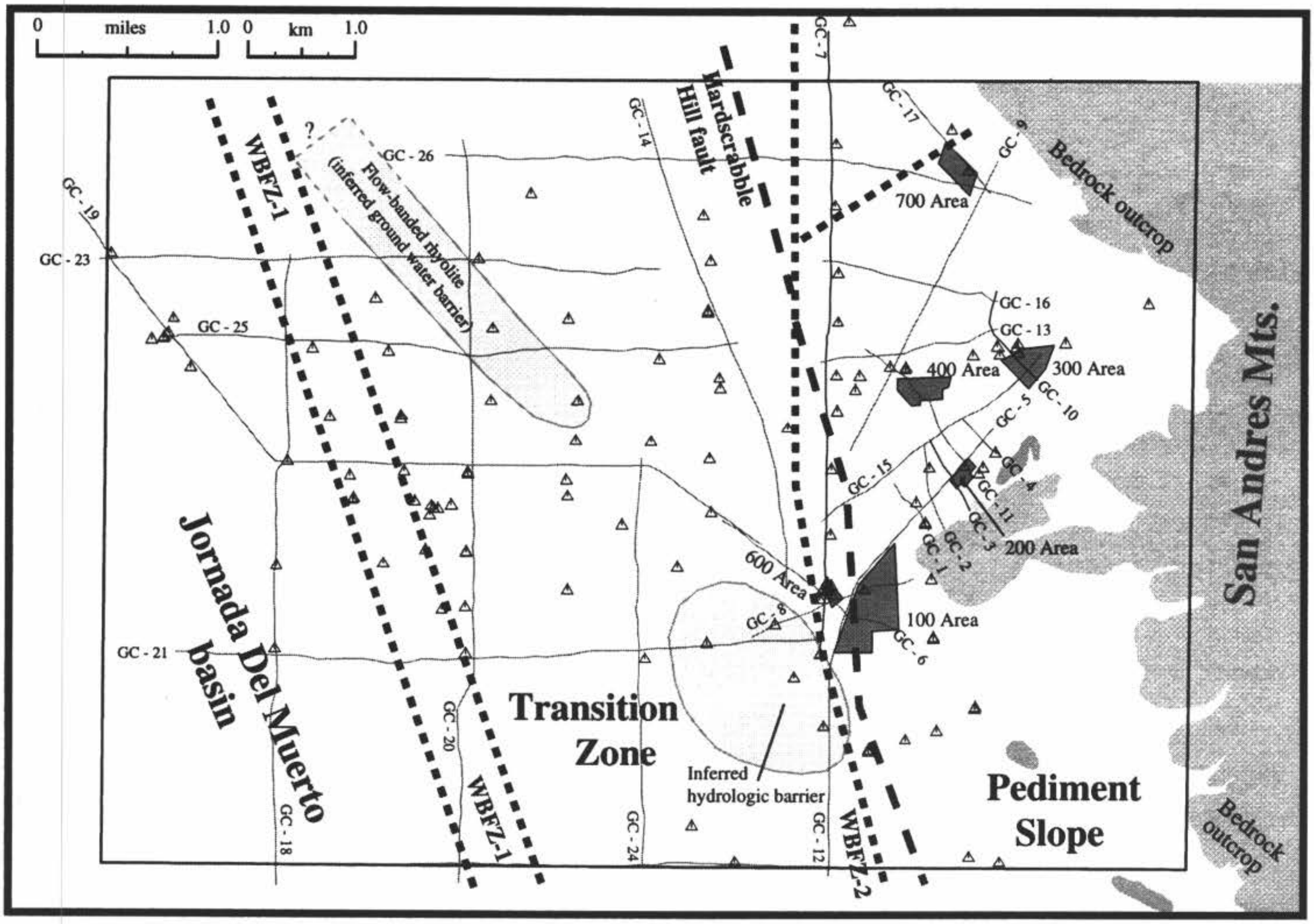

FIGURE 2. Map showing locations of wells (triangles) and seismic lines (thin black lines) used in the study. Buildings on the WSTF are found within the 100 and 700 Areas and are used as a geographic reference. Major fault zones defined by this study include the WBFZ-1, WBFZ-2, and the Hardscrabble Hill fault. Bedrock lithology changes from Paleozoic sedimentary rock to Tertiary volcanic rock, west of the Hardscrabble Hill fault. The locations of two groundwater flow barriers within the volcanic section are also shown.

capped by alluvial fan and fluvial deposits of the upper Santa Fe Group. These deposits blanket most of the study area and thicken westward into the Jornada del Muerto Basin (Seager, 1981). The compositional differences due to changes in source rock for the surface alluvium can be seen clearly in the Landsat Thematic Mapper image, where alluvium composed of clasts of Paleozoic bedrock is purple, and alluvium composed of igneous clasts is green (Maciejewski, 1996; inside cover of this guidebook).

Structurally, the study area is best divided into 3 zones: the Jornada del Muerto Basin to the west, the pediment slope area of the San Andres Mountains, and a transition zone in the middle. Faults defined by wells and seismic data presented in this study demark the boundaries for these zones (Fig. 2). Two fault zones within the NASA-WSTF, the Hardscrabble Hill fault and the western boundary fault zone-2 (WBFZ-2), account for the majority of the displacement along the eastern basin boundary of the Jornada del Muerto Basin and form the boundary between the pediment and the transition zone. A third fault, the western boundary fault zone-1 (WBFZ-1), downdrops bedrock further into the basin, and forms the boundary between the basin and the transition zone. These faults probably correspond to the west-side boundary fault of Seager (1981). The Hardscrabble Hill fault, so named because we believe it to be continuous with a normal fault seen in outcrop at Hardscrabble Hill, 1.2 mi south of our study area (Seager, 1981). The pediment slope consists of a thin veneer, 0–200 ft, of coalescing alluvial deposits overlying faulted bedrock. The alluvium in the transition zone is 350–750 ft thick, and exceeds 2000 ft west of WBFZ-1 in the Jornada del Muerto Basin. Gravity modeling (Dagget et al., 1986; Gilmer et al., 1986) combined with P-wave delay studies (Harder et al., 1986) suggests that rift basin fill may reach 2600 ft in the center of the basin and that the total Cenozoic fill may reach 10,000 ft in depth.

The main source of the groundwater in the study area is from mountain front recharge through fractures and faults zones exposed in the San Andres Mountains. Current flow models suggest that groundwater moves primarily through the fractured bedrock until it intercepts coarse-alluvium in the Jornada del Muerto Basin. From a hydrostratigraphic point of view, the area can be broken into two units: porous alluvium with high hydraulic conductivity and fractured bedrock with a lower hydraulic conductivity. Bedrock lithology itself is not an important predictor of hydraulic conductivity. At least two hydrologic barriers with extremely low hydraulic conductivity occur within the bedrock on site (Fig. 2). One corresponds to a flow-banded rhyolite in subcrop. The other also occurs within the volcanics in subcrop and is associated with a porphyritic latite. Some remaining questions concerning groundwater movement in the study area include: how does the geometry of the bedrock-alluvium interface affect flow rates and directions, and how do faults within the bedrock influence fluid migration?

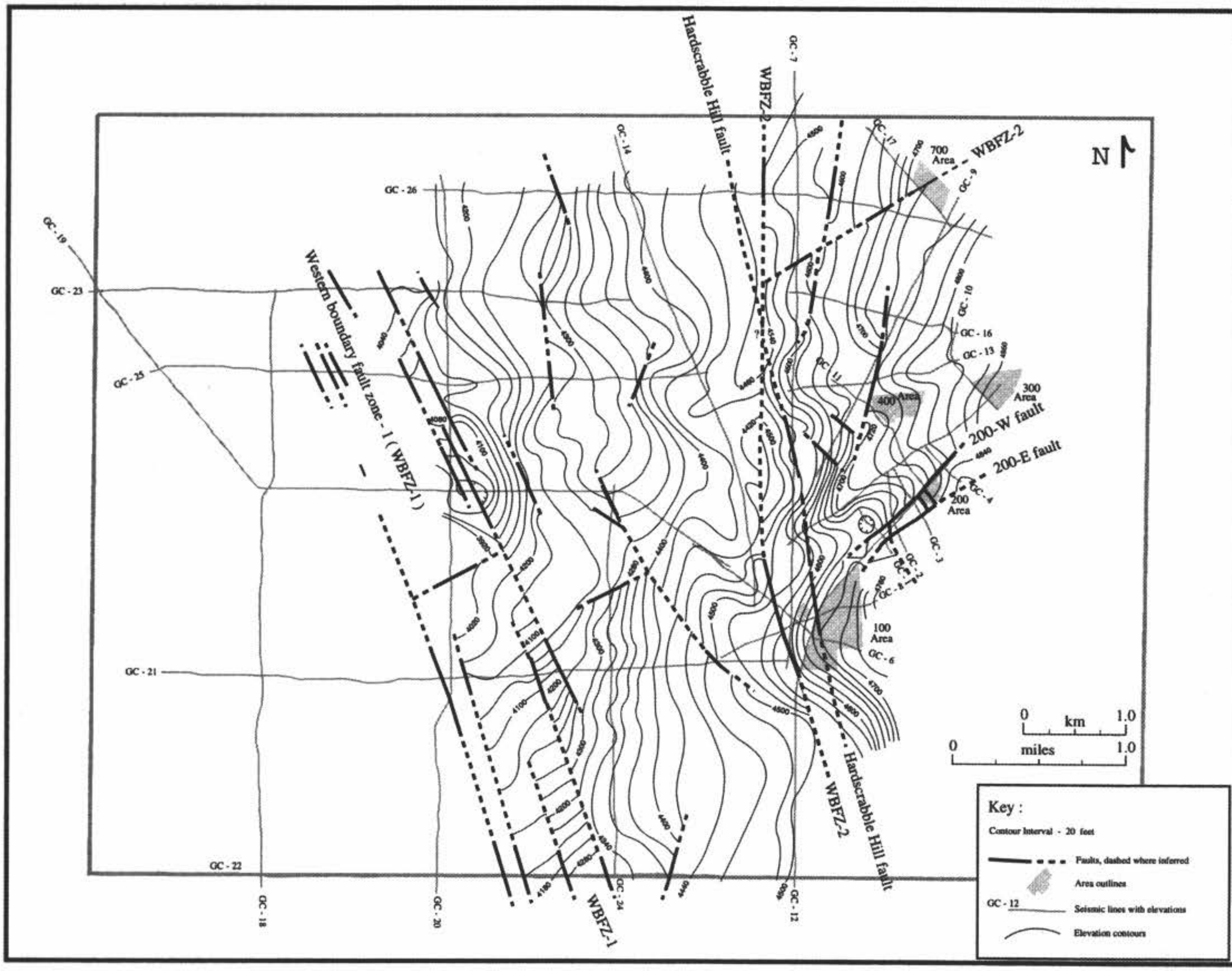

FIGURE 3. Map of bedrock elevation showing primary structures in the study area including the WBFZ-1, WBFZ-2, and the Hardscrabble Hill faults. The bedrock surface dips to the southwest at approximately 3°.

SEISMIC DATA INTERPRETATION

Methodology

In an effort to obtain better constraints on the location of faults and other structures that may influence groundwater flow in the subsurface, 42 mi of seismic reflection data were interpreted together with data from over 100 wells in the study area to produce a top of bedrock map for the area (Fig. 3). In the process of producing the map, well data were projected along dip into the nearest seismic line in order to constrain the top of the bedrock. Time-to-depth conversions were performed using the velocity function in Table 1. This function is consistent with a large number of wells on the site and with the few sonic logs available.

Overall, the seismic data were not of especially good quality (Fig. 4), but by carefully tying the seismic data to well top information, we believe a reliable map was produced for the top of bedrock. Because little seismic energy appeared to penetrate into bedrock and because processing steps that enhanced sub-horizontal reflectors were applied to the data, we consider the data unreliable for interpretation of both interfaces within bedrock and fault dip. Bedrock outcrop exhibit dips as great as 30° and the faults, which are primarily down-to-the-west normal faults, are probably more steeply dipping. Faults were identified primarily by observed truncations of bedrock reflectors in the seismic data. In addition, apparent leakage of surface waves into the stacked record section was used as a tool for identifying large faults. Near single fault strands, noise interpreted as surface wave energy trapped within the fault zone is seen in the data (Fig. 4). In areas of multiple fault strands, a dead zone between the two faults strands was commonly observed.

Results

The primary product of the seismic interpretation is a structure map on the top of bedrock (Fig. 3). A cross-sectional view (Fig. 5) also highlights the main bedrock features. The structure map shows that bedrock surface dips to the west at ~3° and that two major north-northwest-trending fault zones cross the site. A number of less significant faults were also delineated by the data (Maciejewski, 1996), but these have been left off of this map so as not to obscure the primary structural features.

The main fault zones identified in the subsurface of the study area are: (1) the western boundary fault zone-1 (WBFZ-1), the western most fault zone that trends north-northwest through the western part of the study area; (2) the western boundary fault zone-

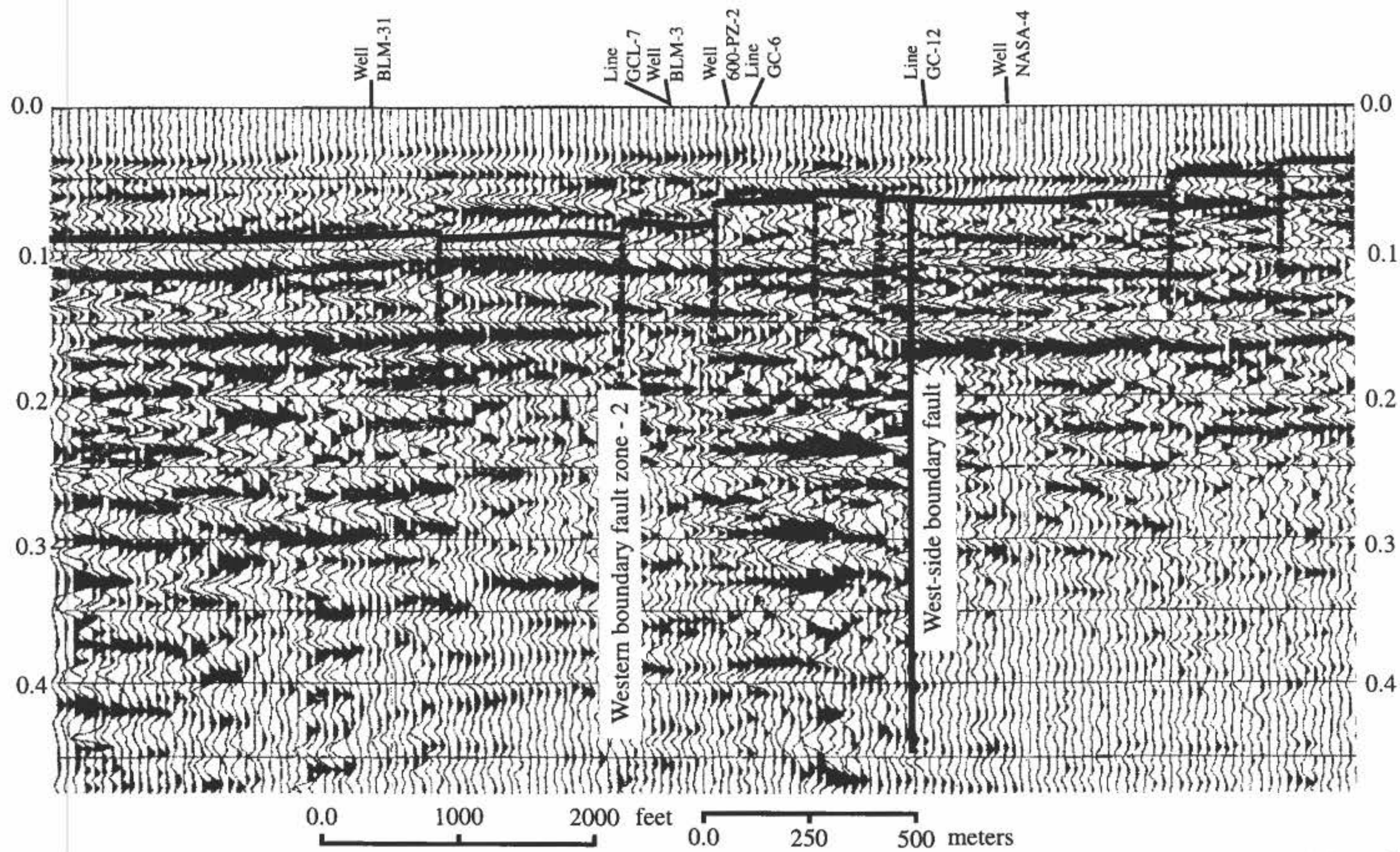

FIGURE 4. Example of an interpreted seismic-record section from line GC-8. Black lines mark interpreted top of bedrock. Top of bedrock is tied to well data. Dashed lines mark interpreted faults. Faults were identified primarily by observed truncations of bedrock reflectors in the seismic data. Apparent leakage of surface waves into the stacked record section was used as a tool for identifying large faults. Near single fault strands, noise interpreted as surface wave energy is commonly observed. In areas of multiple fault strands, a dead zone between faults strands is sometimes seen.

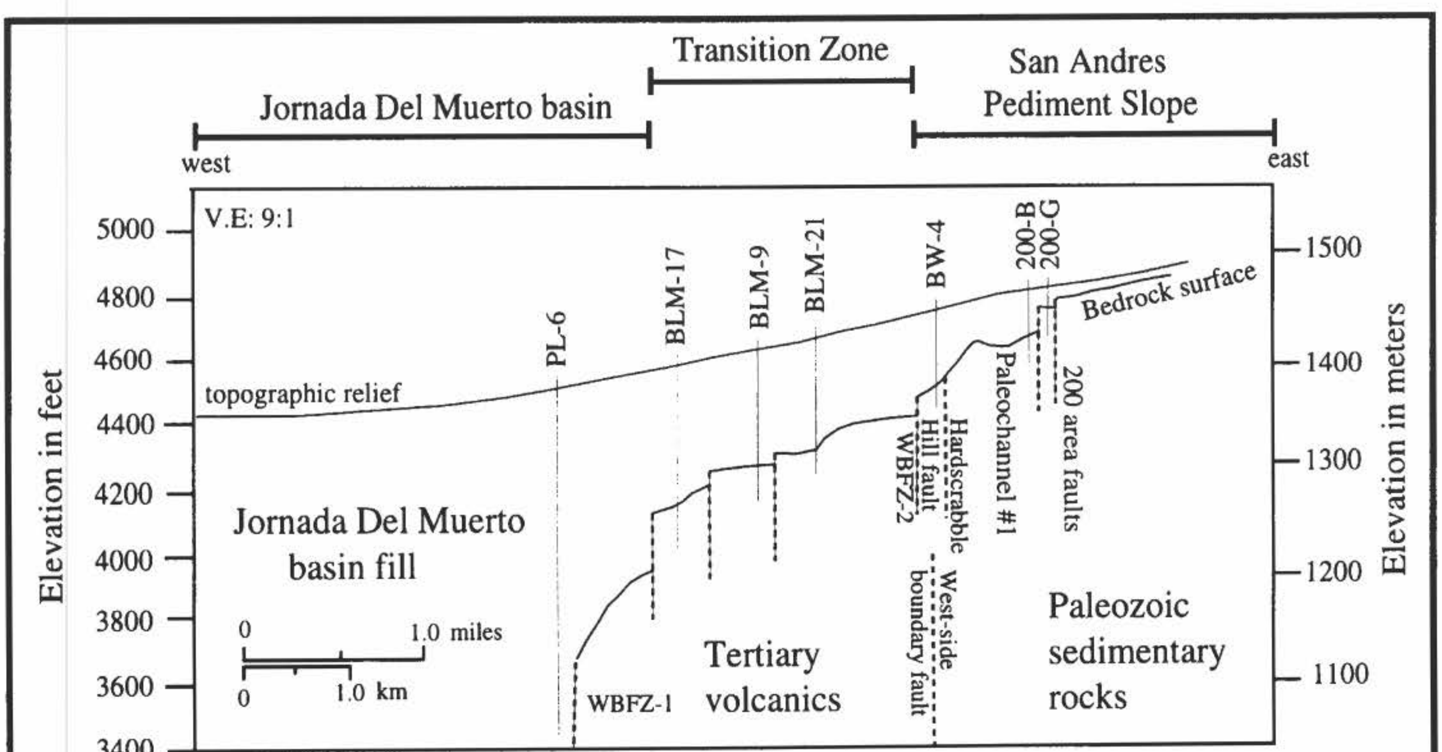

FIGURE 5. Cross section showing bedrock surface and major faults in the study area. Major fault zones defined by this study include the WBFZ-1, WBFZ-2, and the Hardscrabble Hill fault. Bedrock lithology changes from Paleozoic sedimentary rock to Tertiary volcanic rock west of the Hardscrabble Hill fault.

TABLE 1. Velocity function for time-to-depth conversions.

Depth (ft)	Velocity (ft/s)
0–12	1200
12–50	4000
50–100	5000
100–200	6000
>200	6200

2 (WBFZ-2), which trends NNW through the center of the area; and (3) the Hardscrabble Hill fault, which is nearly coincident with the WBFZ-2 (Fig. 2, 3, and 6). A combination of the Hardscrabble Hill fault and the WBFZ-2 appear to constitute the eastern boundary of the Jornada del Muerto Basin.

The WBFZ-1 consists of multiple down-to-the-west normal fault segments that downdrop the bedrock surface into the Jornada del Muerto Basin. Total displacement on the fault system cannot be determined from the seismic data due to poor energy penetration and short record time. However, well data suggest that displacement must exceeds 1700 ft and gravity modeling suggests that the basin fill exceeds 2600 ft in thickness.

The WBFZ-2 lies 1.5 mi east of the WBFZ-1. This fault zone displaces the top of bedrock displacement by 40 ft in the south, to 80 ft in the central portion of the study area. To the north, this single fault splits in two with one branch continuing along the same trend and the other trending northeast-southwest through the 700 Area.

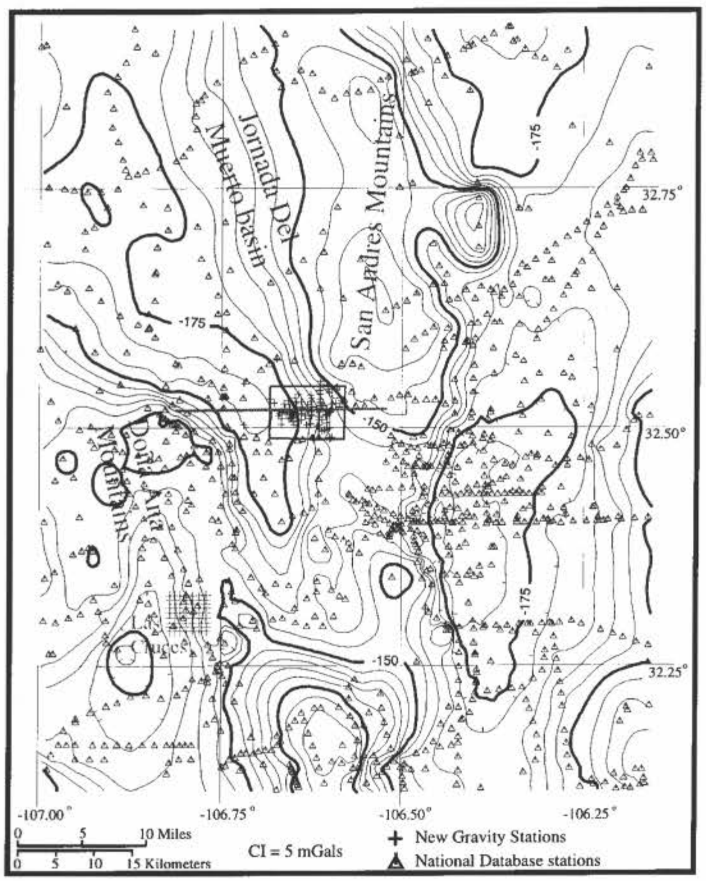

FIGURE 6. Regional Bouguer gravity map contoured at 5 mGal. Map is based on gravity readings from the database maintained at UTEP (triangles) and new readings taken as part of this study (crosses). The gravity model of Figure 7 crosses through the study area (rectangular outline) and was constructed along the profile marked by the gray line. Low gravity values in the northwest corner of the map suggest that the basin fill is thickest in this region.

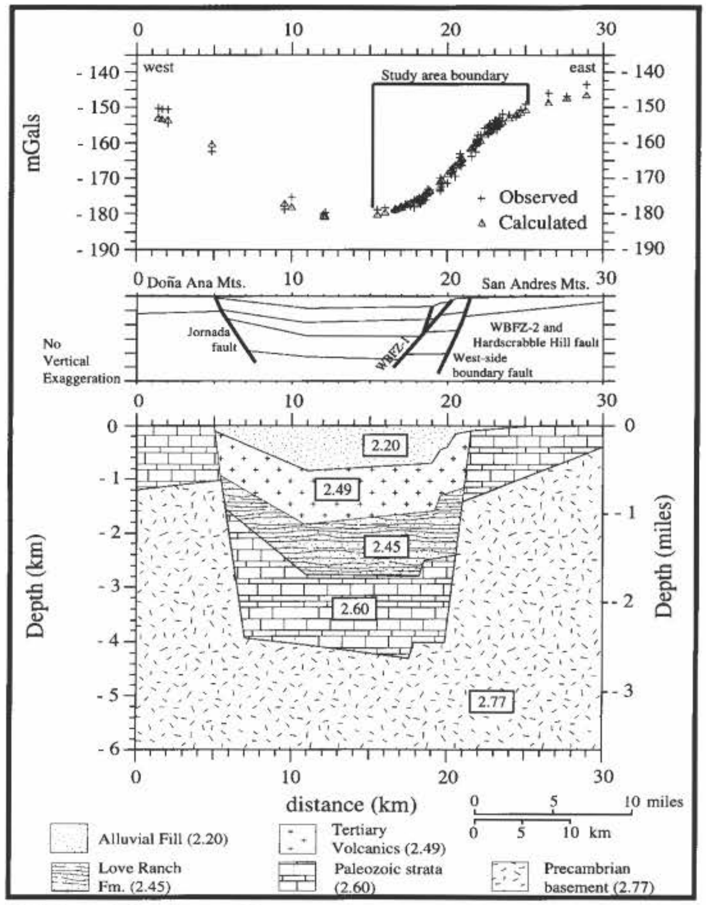

FIGURE 7. Gravity model across the Jornada del Muerto Basin including the NASA-WSTF. See Figure 6 for profile location. The large gradient in the gravity field can be attributed to at least 6400 ft of throw on the fault system at the eastern edge of the Jornada del Muerto Basin.

The Hardscrabble Hill fault is adjacent to the WBFZ-2 and is thought to represent an extension of a normal fault mapped in outcrop 1.2 mi to the south. This fault does not appear to offset the bedrock surface, but is recognized on the seismic data by a character change at depth where "reflectors" (possibly surface wave energy) truncate at a dead zone in the data. This character change is attributed to the juxtaposition of Tertiary volcanic rocks against Paleozoic sedimentary rocks along the fault zone. Slip on the Hardscrabble Hill fault probably predates slip on the WBFZ-1 and WBFZ-2 since the Hardscrabble Hill fault does not offset the bedrock surface. Total vertical displacement on this fault is not constrained by the seismic data, but gravity modeling suggests that the Hardscrabble Hill fault and WBFZ-2 combine for around 6400 ft of vertical displacement.

Two other faults of note are the 200-east and 200-west faults that trend northeast-southwest on the east side of the study area and have vertical displacements of 40–100 ft. Between these two faults, bedrock is broken up into small blocks, suggesting a complex faulting regime. The 200-east and 200-west faults may have a left-lateral strike-slip component of motion associated with them, as they are oriented obliquely to the presumably east-west-trending minimum principal stress.

GRAVITY MODELING

We also constructed a gravity model in order to constrain depth to bedrock and fault geometry and displacement in parts of the study area that lacked wells or seismic data. As part of this effort 95 new gravity measurements were taken on the NASA-WSTF and merged with the stations from the national gravity database maintained at the University of Texas at El Paso. A regional Bouguer gravity anomaly map (Fig. 7) shows that the gravity field in the study area is characterized by a strong north-northwest–south-southeast gradient (-146 to -179 mGals) that can be attributed to the transition between high-density bedrock in the San Andres Mountains and low-density fill in the Jornada del Muerto Basin.

The gravity profile trends west-east, begins at the Doña Ana Mountains, crosses the Jornada del Muerto Basin, and terminates 2.8 mi east of the NASA-WSTF (Figs. 6 and 7). An initial density model was constructed based on a previously published gravity model that crosses our profile with a northeast-southwest trend (Gilmer et al., 1986), and the shallow bedrock constraints from this study. Density units incorporated into the model include basin fill (2.20 g/cc), Tertiary volcanics (2.49 g/cc), Love Ranch Formation (2.45 g/cc), Paleozoic strata (2.60 g/cc), and Precambrian basement (2.77 g/cc). These values are similar to those used by Gilmer et al., (1986) and are consistent with those obtained in density logs in wells in the study area. Thickness of individual units are also consistent with those reported by Seager (1981).

The gravity model (Fig. 7) shows that the eastern boundary of the Jornada del Muerto Basin corresponds to the location of the WBFZ-2 and the Hardscrabble Hill fault in the study area. Together these two faults account for over 6400 ft along a zone dipping at ~65–75°. Since the WBFZ-2 and the Hardscrabble Hill faults are nearly coincident and the WBFZ-2 only offsets bedrock by 40–80 ft or the equivalent of a 2 mGal anomaly, the gravity model can not determine which of the two faults takes up the displacement at the basin boundary. The fact that the Hardscrabble Hill fault is responsible for the juxtaposition of two different bedrock lithologies of very different age, the Tertiary volcanics and Paleozoic rocks, both on the WSTF and in outcrop to the south (Seager, 1981), suggests that it is the more important of the two. However, the Hardscrabble Hill fault does not appear to offset the bedrock surface, whereas the WBFZ-2 is a series of normal faults that clearly offset the bedrock surface, suggesting that it has been active relatively recently. One interpretation of these relationships is that Hardscrabble Hill fault is the main basin-bounding fault and that the WBFZ-2 represents splays that join that fault at depth.

The model also shows that the WBFZ-1 probably displaces bedrock down to the west by 1800–2000 ft on the west side of the study area. This observation provides a constraint on the depth range over which groundwater may be entering the basin fill. The model also shows that the maximum thickness of fill in the Jornada del Muerto Basin is 2600 ft.

CONCLUSIONS

Interpretation of shallow seismic reflection, well, and gravity data from the Jornada del Muerto Basin and pediment slope of the San Andres Mountains has resulted in new information on the geology of this region. The results show that there are two major fault zones trending north-northwest-south-southeast that offset bedrock beneath the study area. Well data show that Tertiary volcanics have been juxtaposed against Paleozoic sedimentary rocks along one of these fault zones at the Hardscrabble Hill fault. This fault may represent the extension of a normal fault mapped in outcrop at Hardscrabble Hill that also juxtaposes Tertiary volcanics with Paleozoic rocks (Seager, 1981). Gravity modeling suggests that the fault zones in the study area dip at ~65–75° and combine for at least 6400 ft of normal separation. Thus the fault zones mapped in the study area appear to represent the eastern boundary of the Jornada del Muerto Basin, and probably correspond to the west side (of the Organ Mountains) boundary fault inferred by Seager (1981).

The well and seismic data show that the Hardscrabble Hill fault does not offset bedrock within the study area, suggesting that it has not been active recently. However, this fault is nearly coincident with the WBFZ-2 that clearly does offset bedrock. Two possible interpretation of these relationships are that that the WBFZ-2 is a fault zone separate from the Hardscrabble Hill fault that represents the zone along which the most recent slip has occur, or that the WBFZ-2 represents splays of the Hardscrabble Hill fault that join it at depth. Neither the gravity modeling nor the seismic data are of sufficient resolution for distinguishing between these two models.

ACKNOWLEDGMENTS

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