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AN INTEGRATED GEOPHYSICAL STUDY OF THE KNIGHT PEAK GRABEN

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Abstract—An integrated geophysical study using seismic refraction and gravity data was performed in the Knight Peak graben area in southwestern New Mexico. The objective of the study was to model the graben structure, with special attention to the location of the unexposed northeastern bounding fault, the extent of the buried Tertiary tuffs and the maximum depth to the Precambrian basement.

Seismic refraction data were taken along a 12 km long and two shorter profiles, all of which spanned the graben perpendicular to its strike. Delay times for distant quarry blasts were observed at 26 stations distributed along the entire length of the profile. The two shorter refraction lines were sited near the center of the long profile: one, 2.2 km in length, was a reversed explosion line; the other, 100 m in length, was an unreversed hammer line. Gravity data were also obtained at 68 stations along the 12 km profile.

Joint modeling of the seismic and gravity data indicates a half graben, formed by a block of granite and volcanic tuff which has rotated downward to the northeast against a subsurface fault. The graben has a width of about 2 km, and structural relief of about 400 m, making it smaller than has been indicated in the literature.

INTRODUCTION

The study area is located in southwestern New Mexico (Fig. 1) in an unnamed structural depression lying between the Big Burro Mountain block (on the north) and the Gold Hill block (on the south) referred to here as the Knight Peak graben. Although the location of this graben is well defined, its subsurface structural geometry is not. Bounding the graben on the northeast is the Knight Peak fault, which is inferred to extend over a distance greater than 15 km (Hedlund, 1978a, b). To the southwest, the graben is bounded by a distinct outcrop of Tertiary volcanic tuffs which lie unconformably on the Precambrian granite of Gold Hill. Tertiary clastics derived from the tuffs and exposed granites are buried within the graben and are overlain by Quaternary alluvium.

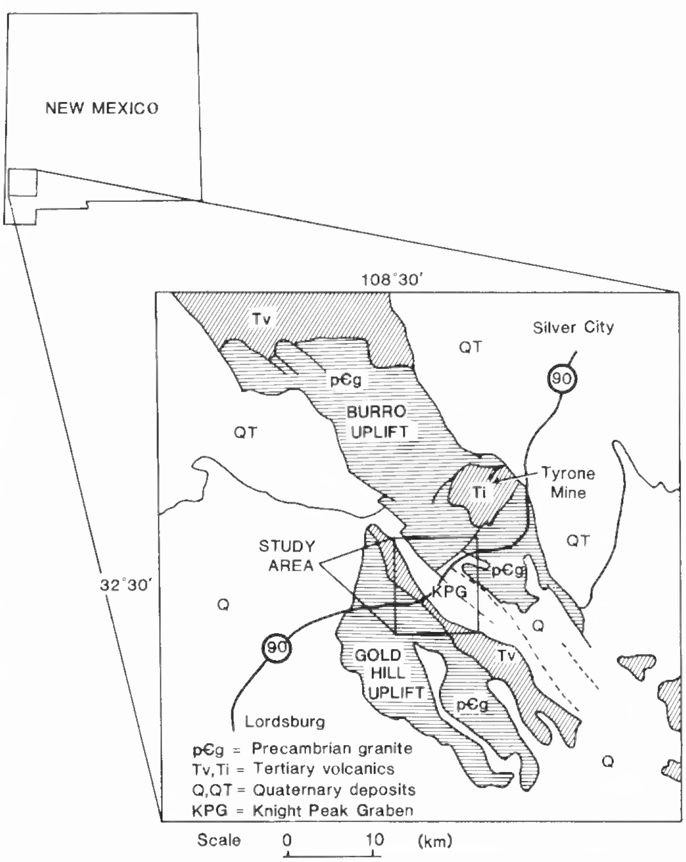

FIGURE 1. Location map showing the study area and regional geology adapted from the New Mexico Highway Geologic Map (NMGS, 1982).

In order to investigate the subsurface structure of the Knight Peak graben, gravity and seismic refraction surveys were carried out in the fall of 1983 and during the spring and summer of 1985. The 1983 surveys succeeded in the collection of data directly over the graben, but interpretation proved difficult due to poor regional gravity control and insufficient seismic data. The 1985 surveys filled gaps in the previous data and allowed their interpretation. Results of geophysical surveys indicate the Knight Peak graben is much narrower than indicated by surface geology.

The study area is located approximately 17 km to the southwest of the Phelps-Dodge open pit copper mine at Tyrone, New Mexico (Fig. 1). The quarry blasts from the mine were used as energy sources for an in-line refraction profile, which obtained 26 data points spanning 12 km. The mine is situated on the northeastern boundary of the Burro uplift, so that the seismic travel path from the mine to the Knight Peak graben is almost entirely through Precambrian granite. Interpretation of depths and geometry by delay time analysis (or other methods) requires reliable estimates of seismic velocities in the subsurface. These intergraben velocity data were obtained by means of a reversed refraction line 2.2 km in length, which also yielded information on basement depth and fault geometry. One short unreversed refraction line determined the near surface seismic velocity, which was used to make elevation corrections for the longer lines.

The general graben structure was further constrained by interpretation of gravity data obtained at 68 stations. These stations lay along the same profile line utilized for the seismic refraction measurements which lies along New Mexico highway 90 between Lordsburg and Silver City.

GEOLOGIC SETTING

The Burro Mountains, located in southwestern New Mexico, are a structural and topographic high underlain predominantly by Precambrian granite. They appear as block uplifts bounded by northwest-trending faults. Physiographically, the area is located in the Mexican Highland section of the Basin and Range Province. The Datil-Mogollon volcanic field, located north of the study area, marks a zone transitional between the Basin and Range Province and the Colorado Plateau. The Rio Grande Rift, dominated by north-trending block faulted ranges separated by broad intermontane basins, lies to the east. The area south of the Burro Mountains contains a series of north- and northwest-trending horsts and grabens. Northwest-trending structures of the Basin and Range Province lie to the west and extend into Arizona.

Three main rock units crop out in the study area: Precambrian granite, Tertiary tuffs and Tertiary and Quaternary unconsolidated sediments (Fig. 2). Three of the Precambrian rock units of the Burro Mountains

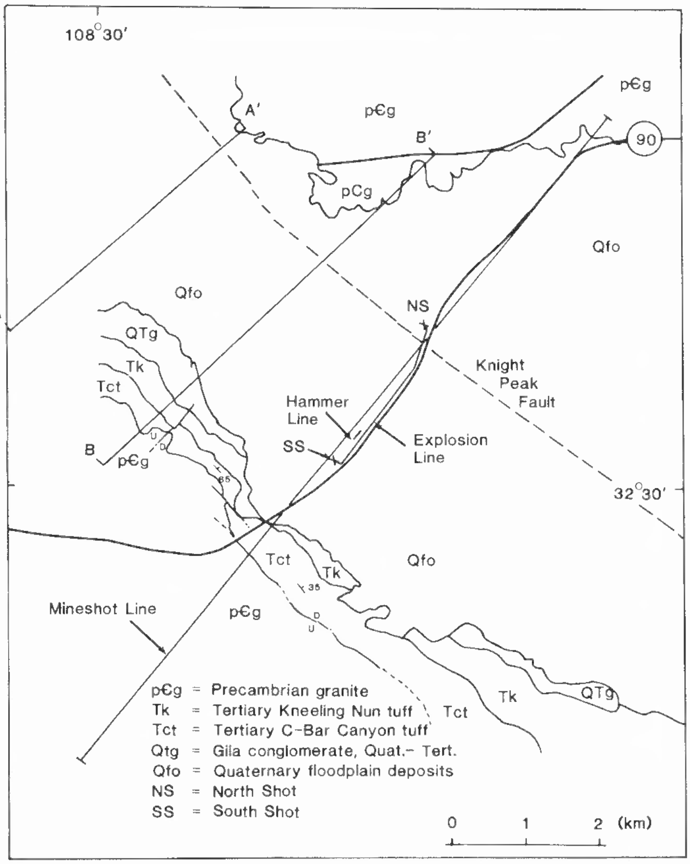

FIGURE 2. The study area showing simplified geology (from Hedlund, 1978a, b and Ballmann, 1960) and the locations of the hammer line, explosion line and mineshot line.

have been dated by U-Pb and K-Ar methods (Hedlund et al., 1981). These are the older gneissic rocks of the Bullard Peak Series (1,560 to 1,570 my), which are intruded by the Burro Mountain batholith plagiogranites (1,450 ± 50 my). The youngest Precambrian rocks are granodioritic stocks (1,380 ± 45 my) which intrude the batholith. Discordant dikes of diabase of unknown age cut both the granite of the Burro Mountains and the granodiorites.

Tertiary volcanic rocks in the area form the 40 km long, northwest-trending Knight Peak range. The volcanic rocks are a sequence of andesite, tuff, rhyolite and latite flows with maximum thickness of 2000 m (Hedlund, 1978c), although it is much thinner in the study area. The volcanic section in the study area consists primarily of two units: the Tuff of C-Bar Canyon and the Kneeling Nun Tuff. The Tuff of C-Bar Canyon, which is Oligocene (Hedlund, 1978b) is composed of non-welded, rhyolitic ash-flow tuff with pumice fragments, and unconformably overlies the Precambrian granite as well as thin, localized lenses of Tertiary sandstone. This unit is overlain by the Kneeling Nun Tuff (Oligocene), a densely welded ash-flow tuff with a Ar/Ar age of 35.3 my (McIntosh et al., 1986). Thicknesses are difficult to estimate due to structural variations, but field observations suggest that the entire unit is less than 200 m thick where crossed by the geophysical lines in this study.

The graben is partially filled by the Gila Conglomerate (Miocene to Pleistocene in age), a poorly sorted fanglomerate derived from Precambrian granite and Tertiary tuffs (Hedlund, 1978a). The Gila Conglomerate has been faulted and is dipping approximately 10° to the northeast in the graben (Ballmann, 1960). The entire area is covered by a veneer of Quaternary sheetflood fan deposits, and Holocene alluvium occurs locally in drainages.

Contact relations between the tuffs and the Precambrian granites have been an uncertain matter. Ballmann (1960) first mapped the entire contact as a fault, extending the entire length of the Knight Peak range, but Hedlund (1978a, b) later mapped the contact as an unconformity with faulting present only locally. Field reconnaissance suggests an unconformity. Evidence for an unconformable contact consists of inclusions of granitic rock fragments in the basal Tertiary tuffs, the appearance of a lithified regolith at the Tertiary/Precambrian contact and lack of an exposed fault.

The Knight Peak graben, actaully a half graben, is formed by rotation along a major northwest-trending fault, named the Taylor fault by Ballmann (1960) and renamed the Knight Peak fault by Hedlund (1978a) as seen in Figure 3. This fault is inferred within the study area. Movement on this fault has rotated the Tertiary tuffs and Gila Conglomerate approximately 30° down to the northeast to form the half graben. The volcanic section forms the up-dip outcrop and the crest of the Knight Peak range. The graben has been filled by conglomerates of the Gila Conglomerate eroded from Precambrian granites and Tertiary tuffs. At least the upper part of the clastics cover the inferred Knight Peak fault on the northeastern edge of the graben. The faulting and tilting is dated as late Tertiary-early Quaternary because the Gila Conglomerate is the youngest unit involved (Ballmann, 1960), although this movement may be due to reactivation of older faults. The Burro Mountains have undergone several periods of uplift (Ballmann, 1960), and repeated motion along faults may be commonplace.

SEISMIC REFRACTION

Locations of the seismic refraction lines are shown in Figure 2. The term "line" will be used to mean a seismic refraction line. The "hammer line" used a sledge hammer as a seismic energy source and was employed to determine the near surface seismic velocity of the graben fill. The hammer line was unreversed. The "explosion line," a reversed profile, employed two sources, the "north" and "south" shots, each of which used high energy explosives. The explosion lines had two purposes: (1) to resolve the geometry of the Knight Peak fault and (2) to establish seismic velocity control in the area. The "mineshot line" utilized quarry blasts from the Tyrone copper mine as seismic energy sources. This line was employed to obtain general subsurface structure in the study area.

First break analysis of the hammer line record section (Fig. 4) yielded two velocities, thus the data were interpreted as a single layer over half space. Linear regression of the data in Figure 4 indicates a velocity of 1.1 ± 0.02 km/s for the surface layer and an apparent velocity of 4.9 ± 1.3 km/s for the half space below the surface layer. Since this refraction line was not reversed, true velocities of the half space cannot be determined. An intercept time of 0.055 ± 0.004 s indicates a basement detph of 31 ± 2 m, if the basement is not dipping.

Travel times of the first arrivals (or first breaks) for the explosion

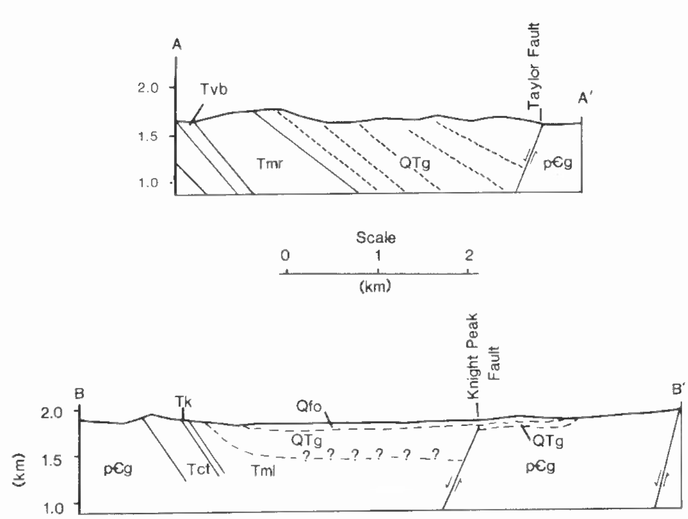

FIGURE 3. Geologic cross sections of the Knight Peak graben (A-A′ from Ballmann, 1960 and B-B′ from Hedlund, 1978a).

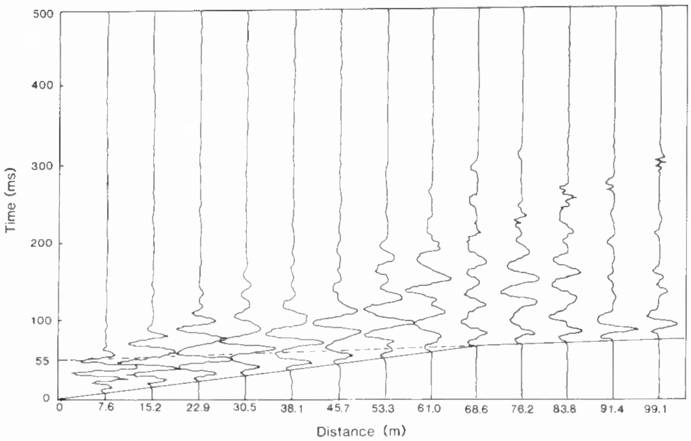

FIGURE 4. Seismic record section of the hammer line.

line are plotted as a function of distance in Figure 5. Velocity determinations were made from these picks using linear regression. If the basement were a simple planar surface covered with a layer of alluvium of uniform thickness each travel time curve would be composed of two segments. The direct segment which would have a slope equal to the reciprocal of the velocity in the alluvium and would intercept the time axis at zero time. The second segment would have a slope equal to the reciprocal of the velocity in the basement and intercept the time axis at a time which would correspond to the thickness of the alluvium. The slopes and intercepts would be equal in both directions in the flat lying case. If the basement surface is planar and dipping the slopes and intercept times will increase in the down-dip direction and decrease in the up-dip direction. If the basement surface is nonplanar then the second segments of the travel time curves are not straight lines but curves which reflect the topography on the basement. Since seismic velocity of the alluvium is lower than that of the basement the first arrivals will be delayed if the alluvium is thick or will arrive earlier than expected if the alluvium is thin. In this way the depth to the basement can be mapped assuming the velocity of the alluvium and the basement are known. The detail of this method are described by Davis (1986).

The direct segment from the south shotpoint (SSP) in Figure 5 indicates the velocity of the alluvium filling the graben is 1.4 km/s. The intercept time of 0.13 s is a result of elevation corrections which have been applied to the data set. The derivations of the second segment of the travel time curve from SSP indicate the basement surface is not planar but has a great deal of topography on it. The two layered model shown below the travel time plot (Fig. 5) is a best fit model to the data in the travel time plot. The model was obtained by adjusting the topography of the basement surface assuming the velocity in the alluvium is 1.4 km/s and the velocity in the basement is 4.5 km/s. Fill thickness of 48 m at the south shotpoint (SSP) and 31 m along the hammer line (HL) together indicate a slight southwesterly dip of the basement in the 0.0 to 0.2 km segment. The 0.1 s advance in travel time of the 3S segment and the 0.1 s delay in travel time of the 3N segment are interpreted to represent a fault of approximately 100 m throw on the basement surface at the 1.2 km position. A dip of 60° to the southwest was assumed for this fault. Using the control points found from the hammer and explosion lines a boundary was drawn between horizontal positions 0.2 km and 1.1 km with a northwesterly dip. The boundary is probably irregular, based on scatter of data points along the 2S segment. The fault at 1.2 km forms the southwestern side of a small uplifted block. This block is bounded on the northeast by another fault at 1.7 km as indicated by the 0.2 s delay of the 4S segment relative to the 3S segment. The interval from 1.7 to 2.2 km is difficult to interpret, but the 0.2 s delay in travel-time of 4S relative to 3S indicates a much deeper structure than the 68 m thickness calculated from the 2N segment. There may be a deep, narrow structure in the basement in this interval; however, this segment is poorly constrained.

The mineshot line (Fig. 2) was established along New Mexico State Highway 90 in order to determine the general subsurface structure of the graben perpendicular to strike. Quarry blasts from the Phelps-Dodge open pit copper mine at Tyrone, New Mexico, were used as the seismic energy source. The orientation of the profile line lies within 10° of azimuth from the mine. Shot-receiver distances range from 11 to 23 km. The seismic traces were all recorded with Sprengnether DR-100s. The specific delay time method employed here is also described by Davis (1986). It is used to interpret the data (Fig. 6) utilizing differences in travel times for raypaths passing through an all granite model versus those through a model of granite overlain by graben fill sediments.

Features of the mineshot line are discussed in terms of distance from the shot (the horizontal axis in Fig. 6). Analysis indicates that fill with a thickness of approximately 66 m overlies a 150-m-thick tuff unit at kilometer 19. This indicates that the maximum depth to the underlying granite is on the order of 400 m to the southwest of kilometer 18. The

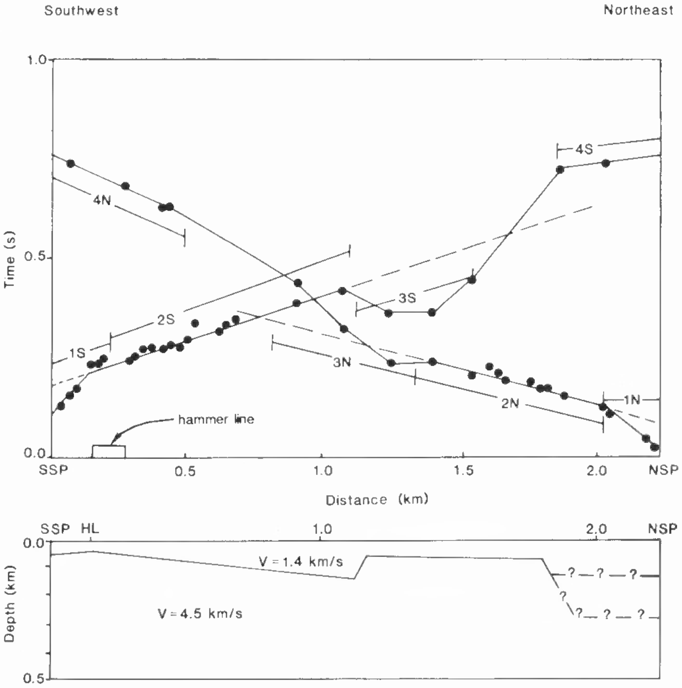

FIGURE 5. Travel-time versus distance for the first arrivals from the north (NSP) and south (SSP) shotpoints. Note that curves are divided into segments discussed in text. Lower diagram is the model derived from the travel-time curves.

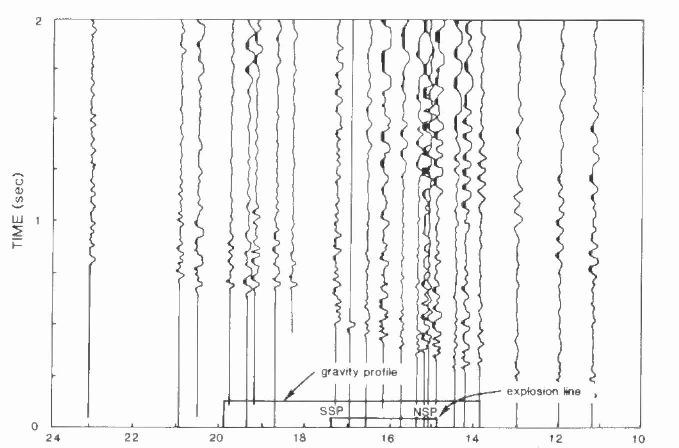

FIGURE 6. Seismic record section obtained using mine shots.

transitional zone at kilometer 18 is interpreted to represent the master fault of the graben. Some detail was lost due to the inability to recover data in this area. Throw on the master fault is on the order of 350 m. The granitic block underlying the tuff unit is interpreted to have rotated along this fault and the tuffs appear to be truncated by this fault.

GRAVITY

A gravity survey was conducted to obtain information on the structure of the graben. The residual gravity anomaly was modeled using a 2-D Talwani program (Talwani et al., 1959). The computer program calculates potential field anomalies over horizontal prismatic bodies taken to be infinitely long in the strike direction. This is a suitable first order approximation for the geometry of the study area. Densities used in the model are established using velocity data obtained in the seismic experiments and the Nafe-Drake curves (Bott, 1982) and also from water bath specific gravity measurements of hand specimens. The following densities were assigned: 2.5 gm/cm^3 for the granite; 1.7 gm/cm^3 for the graben fill; and 1.6 gm/cm^3 for the tuffs.

The residual Bouguer gravity and the computer generated model field are shown together with the model body construction in Figure 7. The model assumed a body of graben fill overlying granitic basement, and included an intervening prism of tuffs to the southwest. Features of the model and the gravity fields will be discussed by segment, according to position along the distance scale at the bottoms of the diagrams.

The tuff segment exhibits a negative 3.8 mgal residual anomaly as seen from 0.5 to 1.6 km on Figure 7. This was modeled by a northeast-dipping tabular body representing the Tertiary tuffs. The tabular body has a maximum depth of 160 m and is truncated at depth by a fault at kilometer 1.6 on the profile. Modeling also indicates a wedge of denser material (1.7 g/cm^3) which is assumed to represent the Quaternary graben fill sediments.

The remaining residual gravity was fitted by adjusting the depth to the basement along the profile. The deep fill segment is modeled with a distinct corner in basement at 2.2 km, interpreted to represent a step fault in the underlying granite. This feature fits the 1.0 mgal perturbation in the observed field at 1.6 km to 2.8 km in Figure 7. This segment is interpreted to be overlain with graben fill 150 m thick at 1.8 km, 90 m at 2.2 km and 90 m at 2.8 km, below the lowest part of the surface topography.

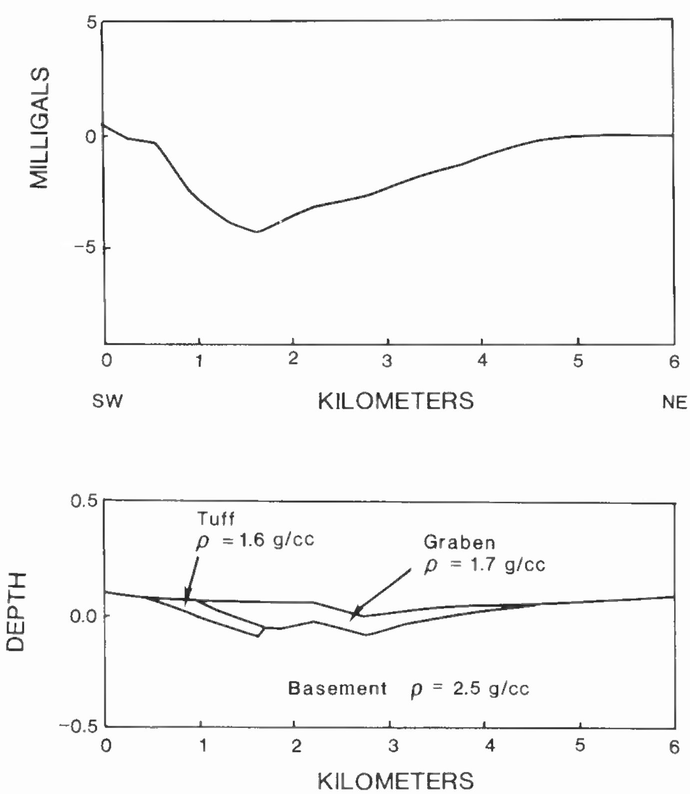

FIGURE 7. Upper diagram is the residual Bouguer gravity values observed along the profile (solid line) and the values obtained from the model shown in the lower diagram.

The shallow fill segment is modeled as slight uplift in the granitic basement from kilometers 2.8 to 3.1 on the profile. The graben fill thickness of 90 m at 2.8 km decreases to only 50 m at 3.1 km. The graben fill thickness gradually decreases to zero from 3.1 km to 4.7 km. This thin wedge of fill does not include the faults observed in the seismic data. A small (10 m thick) lens of graben fill is modeled at 4.7 to 5.1 km.

THE INTEGRATED MODEL

The final model (Fig. 8) of the Knight Peak graben is a synthesis of the geological and geophysical interpretations already presented in this paper. The mineshot seismic model yielded the general structure of the graben and was consistent with the gravity data. The explosion and hammer seismic lines detailed the area to the northeast of the master fault as well as producing velocity control. The most significant feature of the model is the location of the master fault. The fault, possibly a fault zone, is located 1.5 km from the granite-tuff contact to the southwest. This indicates that the width of the Knight Peak graben along this profile is about one-third of that believed previously (Ballmann, 1960), and that the Knight Peak fault does not form its northeastern boundary. The location of the fault was determined by the large offset in arrival times at kilometer 18 on the mineshot line (Fig. 6) and by the gravity data in this segment. The gravity model requires a distinct step in basement structure and the introduction of a step fault. The results of the seismic refraction interpretation indirectly support the master fault location. These data indicate a shallow depth to basement on the northeast, which is interpreted as an upthrown granite block.

Vertical throw across the master fault is estimated at 350 m, subject to two major uncertainties: (1) it is unknown how much of the uplifted northeastern block has been eroded away and (2) the maximum depth to basement, from which the throw is determined, is not well constrained. Maximum depth was estimated from the mineshot line using velocities that were extrapolated from near surface measurements close to the granite-tuff contact. Because densities were determined from the above described velocities, depths in the gravity model were also uncertain. The depth (less than 200 m) indicated in the gravity model is believed to be too shallow.

The Tertiary tuffs are modeled as a prismatic body located southwest of the fault. The mineshot model and the gravity model indicate low velocity and low density for this prism. The tuffs appear to be truncated by the master fault, where they have a depth of approximately 400 m. The tuff-granite block is interpreted to have rotated along this fault to its present position. Estimation of the subsurface dip of the tuffs suffers from the depth uncertainties described above. Nevertheless, average dip of less than 20° is less than that observed in a surface exposure (35°), suggesting a decrease of dip with depth.

The shallow fill segment (2.5–4.2 km in Fig. 8), interpreted from seismic and gravity models, appears as an uplifted block of Precambrian granite with a covering of Quaternary alluvium. The explosion and hammer seismic data indicate that the upper surface of this block has a slight southwesterly dip in the 2.6 to 3.0 km interval and a northeasterly dip in the 3.0 to 4.2 km interval.

A small horst block is bounded on the southwest by a fault at the 4.2 km position and on the northeast by a fault at the 4.7 km position. A minimum depth of 16 m to the top of the horst block is indicated by the mineshot data. The top of the horst appears to have a southwesterly dip. The southwest bounding fault is interpreted from the explosion seismic data to have a throw on the order of 100 m. The mineshot line model also indicates this feature, but with a lesser throw (50 m). The mineshot data also indicate a narrow trench bordering the horst on its northeast side; this interpretation is supported by the delay in travel-time observed in the 4S segment of the explosion line. This feature was not seen on the gravity profile suggesting either that the trench has limited lateral extent or that its density is quite small.

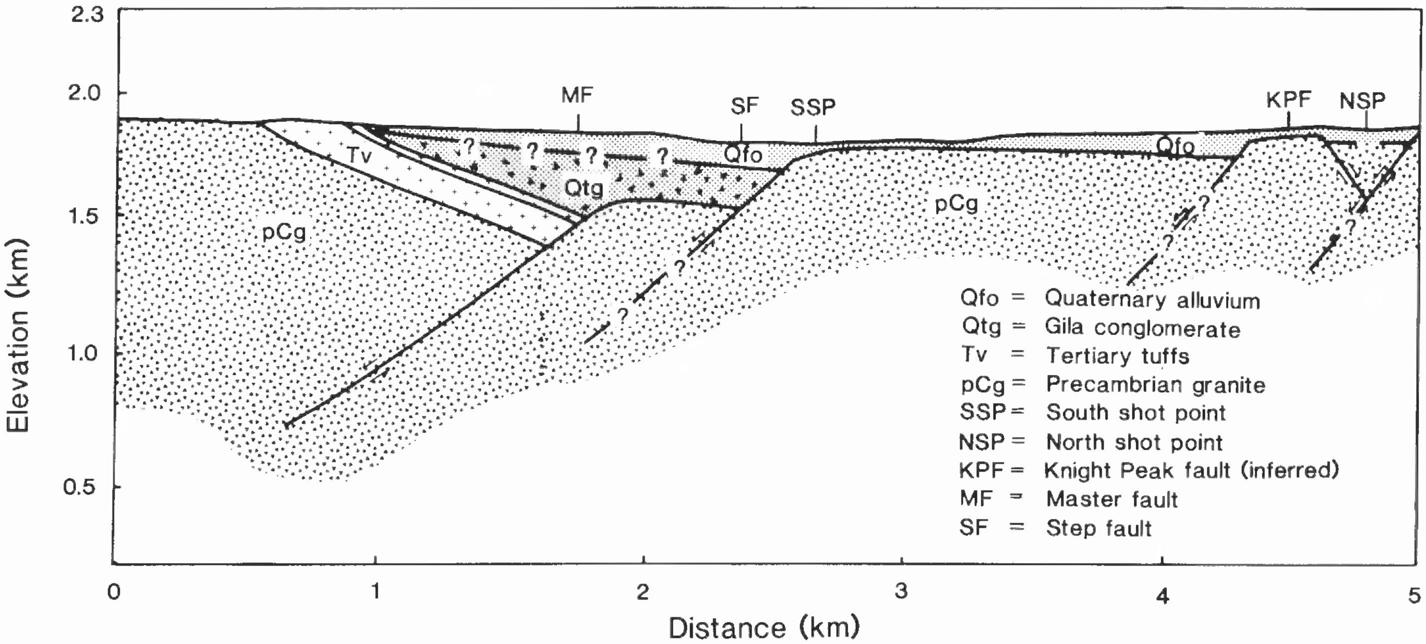

FIGURE 8. Geologic cross section of the Knight Peak graben obtained from the analyses of geophysical data presented in this paper.

Denser seismic data are required to better determine the structural details of the study area. A refraction line similar to the mineshot line but with shots to the southwest, or a seismic reflection line, would be useful. Lines perpendicular to this profile would indicate structure along the strike of the graben.

ACKNOWLEDGMENTS

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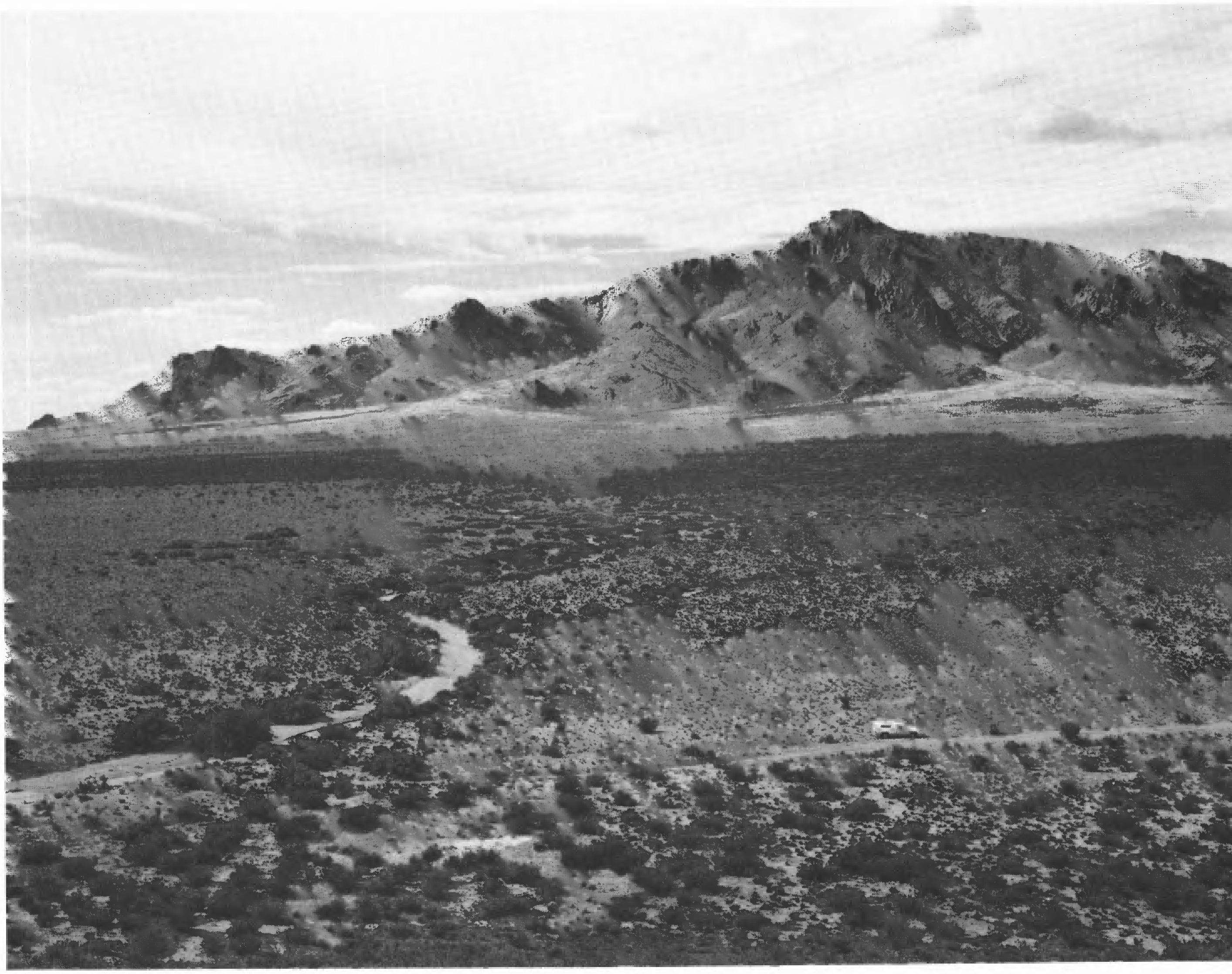

South Peak (2159 m) and southern end of Florida Mountains. View is N2°W. The mountains visible here are composed of interlayered Upper Cambrian granite and hornfels. The layering dips about 30° northeast. Several northwest-trending rhyolite dikes parallel the rather linear southern end of the Florida Mountains and suggest probable northwest-trending faults along which the mountain block was uplifted. Note the two large alluvial fans. Mesquite is present in foreground, along wash, and on small coppice dunes to the left of the wash. The dark band of vegetation in the middle distance is composed mainly of creosote. Camera station is in S1/2, sec. 34, T26S, R8W. Altitude about 1311 m. W. Lambert photograph No. 87L16. 19 July 1987, 5:19 p.m., MDT.