A new gravity interpretation: A case study from Pahute Mesa, Nevada test site

K. Mallick*[‡], V. K. Rao* and K. K. Sharma[†]
*National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India
[†]Department of Applied Geology, University of Madras, Chennai 600 025, India

The separation of regional and residual components from observed Bouguer gravity anomaly is crucial in gravity intepretation. A new approach is applied in this study to compute the residual anomaly of the Pahute Mesa region lying on the north-west corner of Nevada test site. The drilling in Pahute Mesa revealed a structural depression, which in fact, is a caldera, known as Silent Canyon. This region is topographically very high (> 2000 m) and yet the lowest gravity values (~ – 220 mGal) are observed here. This appears to be an exceptional case in the Nevada test site. Geologically, the low-density Cenozoic sedimentary and volcanic rocks in the Silent Canyon overlie the denser pre-Cenozoic basement. The thickness of the top sedimentary and volcanic rocks needs to be redefined for the conduction of nuclear tests. The basement depth determination by a previous USGS study in the Pahute Mesa region appears to be inconclusive. The basement thickness was predicted to be 7000 ft, whereas the drill hole UE 20f in the central region up to a depth of 13,686 ft did not encounter the basement rocks.

In sharp contrast, the thickness of the Cenozic sedimentary and volcanic sequences not too far from the drill hole UE 20f in the Silent Canyon, was estimated to be 17,000 ft by interpreting residual gravity anomaly obtained by our new approach, based on the finite element concept. This depth estimate seems to be geologically more realistic. The basement configuration of the Pahute Mesa site has been constructed by interpreting a number of residual gravity profiles.

THE Nevada test site has a thick cover of alluvium and Cenozoic volcanic rocks overlying the basement that consists of Precambrian and Paleozoic sedimentary and metamorphic rocks. As far as gravity data interpretation is concerned, there are essentially two broad sequences – Cenozoic and underlying pre-Cenozic basement rocks. The objectives of the gravity measurements were to determine (1) the thickness of the test media; (2) the lateral extent of the test media; (3) the fault geometry; and (4) the basement configuration. Several core drillings and seismic refraction studies on the test site provided bulk density of rocks at varying depths and the thickness of different layers, respectively to facilitate the gravity interpretation[1].

Here we apply a new technique to answer questions related only to the thickness of the test media and the basement configuration. To achieve this we have interpreted three profiles – E–W profile AA′ at 37°15′ N, NE-SW profile BB′ and NW-SE profile CC′, all crossing over the Silent Canyon. The E–W profile AA′ passes very near the deepest drill hole in this region (see Figure 6).

Pahute Mesa in the north-west corner of the Nevada test site[2] (Figure 1) has high topography and at the same time recorded the lowest Bouguer gravity values. The deep gravity low made Pahute Mesa suitable for nuclear testing. Based on the drilling data, a structural depression or caldera was discovered in this region. This caldera is called the Silent Canyon. The depth determination of Silent Canyon was inconclusive; a preliminary depth estimate of 7000 ft by USGS based on the interpretation of residual gravity anomaly derived by first-order surface approach was far less. The drilling up to 13,686 ft at site UE 20f could not encounter the basement. It was thereafter speculated to be 16,000 ft or more.

Measurements of rock samples taken from the cores of the drill holes showed variations in density[1]. However, following the assumptions of the USGS study, the average densities of the Cenozoic and pre-Cenozoic rocks were taken as 2.22 g/cm^3 and 2.67 g/cm^3, respectively in the present study. The density contrast is therefore 0.45 g/cm^3.

Besides complex geology and density variations with depth, the key to the interpretation of gravity data is the construction of a satisfactory residual anomaly map. The high topography in Pahute Mesa is likely to be associated with isostatic compensation at depth. Drilling, in fact, has established the presence of a crustal depression in this region. The regional gravity approximated by a first-order surface, a plane, was subtracted from the observed gravity

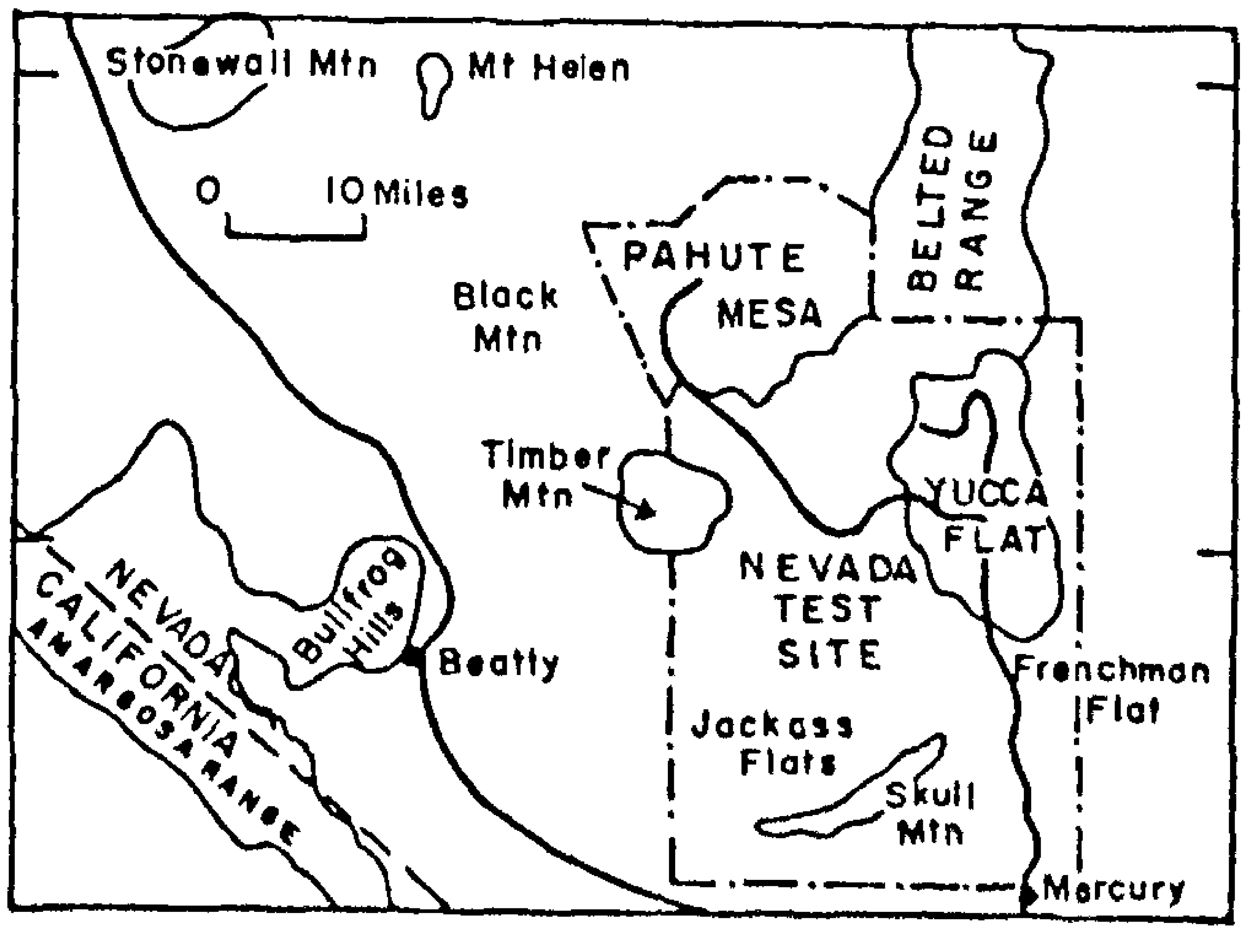

Figure 1. Location map of Nevada test site: Pahute Mesa in the north-west and Yucca Flat in the central region.

[‡]For correspondence. (e-mail: postmast@csngri.ren.nic.in)

values, to derive the residual gravity map in this region. However, an early synthetic experiment[3] showed that a first-order surface retained a part of the residual. Further, the regional anomaly approximated by the first-order and second-order surfaces in Raguba oil field, Libya[4] was rejected, since it produced negative pseudo-residual anomalies.

With this background, a new approach[5,6] was applied to recompute the regional and residual components of the synthetic gravity fields[3] and the field data in the Raguba oil fields. It is interesting that the new technique could successfully recover the assumed model regional and the intuititive regional in the Raguba oil fields. Figure 2 shows the observed gravity field profile in Raguba oil field, along with four approximations for regional anomaly. The first-order and second-order surfaces produced negative residuals at both the ends of the profile. It is believed that these negative residuals are pseudo-anomalies[4], and therefore a regional of – 20 mGal approximated by intuition. The regional derived by finite element anlysis[5,6], (FEA regional), was satisfactory. The computations showed that the new technique accounts also for the isostatic effects.

Before the regional and residual components of the Pahute Mesa region are computed, a few lines on the new approach are described. The gravity map is superimposed by an eight-node finite element. The observed gravity values at these nodes of the element approximate the regional field. The regional gravity, $g_d(x, y)$ at any point (x, y) in the map space is expressed as:

$$g_d(x, y) = \Sigma N_i(x, y) g_i, \quad i = 1, 2, ..., 8, \tag{1}$$

where d refers to deeper regional structure and the weights, $N_i(x, y)$ are the shape functions of the element[7–9]. For the sake of computational convenience, we replace the cartesian $x - y$ space by a non-dimensional $\xi - \eta$ space, ξ and η varying between – 1 and 1. Equation (1) is rewritten as:

$$g_i(\xi, \eta) = \Sigma N_i(\xi, \eta) g_i \quad i = 1, 2, ..., 8. \tag{2}$$

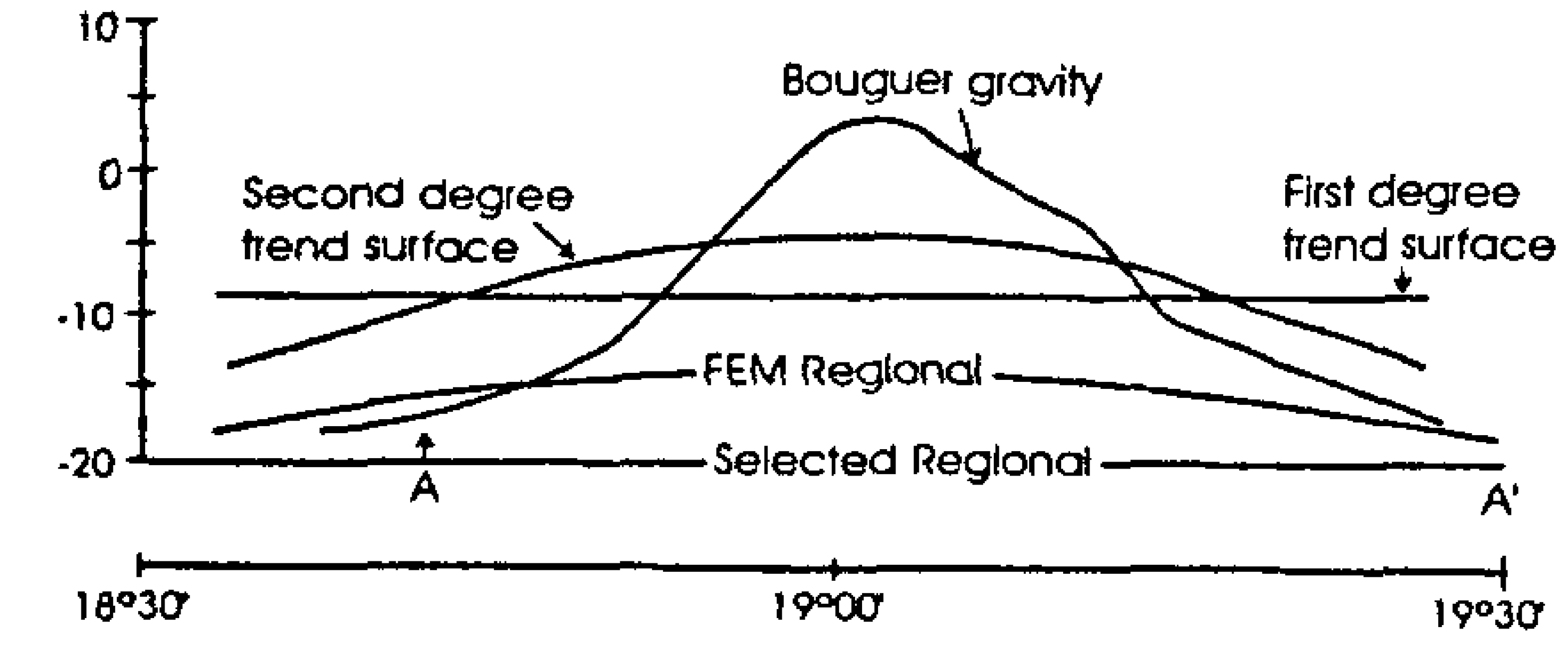

Figure 2. Bouguer and regional gravity profiles in Raguba oil field, Libya. The first- and second-order surface regional produced pseudo-residual anomaly.

The above transformation enables one to process gravity maps of any size and of any orientation in ξ–η reference space. More details of this new technique are available in recent papers[5,6]. Although we have described an eight-node isoparametric quadratic element, one can also use a 12-node cubic element. The shape function, $N_i(\xi, \eta)$, used as weighting functions, are defined without ambiguity.

Figure 3 shows the residual gravity map of the Pahute Mesa region obtained by removing the regional approximated by a first-order surface[1]. The residual map is dominated by a central low of the order of – 30 mGal, mainly due to the volcanic fill in the Silent Canyon. The outer ring of the Silent Canyon is marked by steep contour gradient. The western edge appears to be steeper. With 0.70 g/cm^3 as the density contrast, a preliminary depth estimate of 7000 ft was made. However, the drilling, the deepest in Pahute Mesa, at UE 20f up to a depth of 13,686 ft continued to meet volcanic rocks. It revealed two important facts – the density contrast of 0.70 g/cm^3 was too high and the residual gravity anomaly was too less to yield a depth estimate of 7000 ft for the Silent Canyon. Subsequently, the density contrast was revised to 0.45 g/cm^3 and the maximum depth of the Cenozoic volcanics was speculated to be at least 16,000 ft.

It is, however, believed that the regional component approximated by a first-order surface retained a part of the gravity effects of the shallower structures, thereby producing less residual gravity anomaly. With this background we attempted to compute the residual anomaly by the new technique and once again estimate the basement depth in Pahute Mesa region.

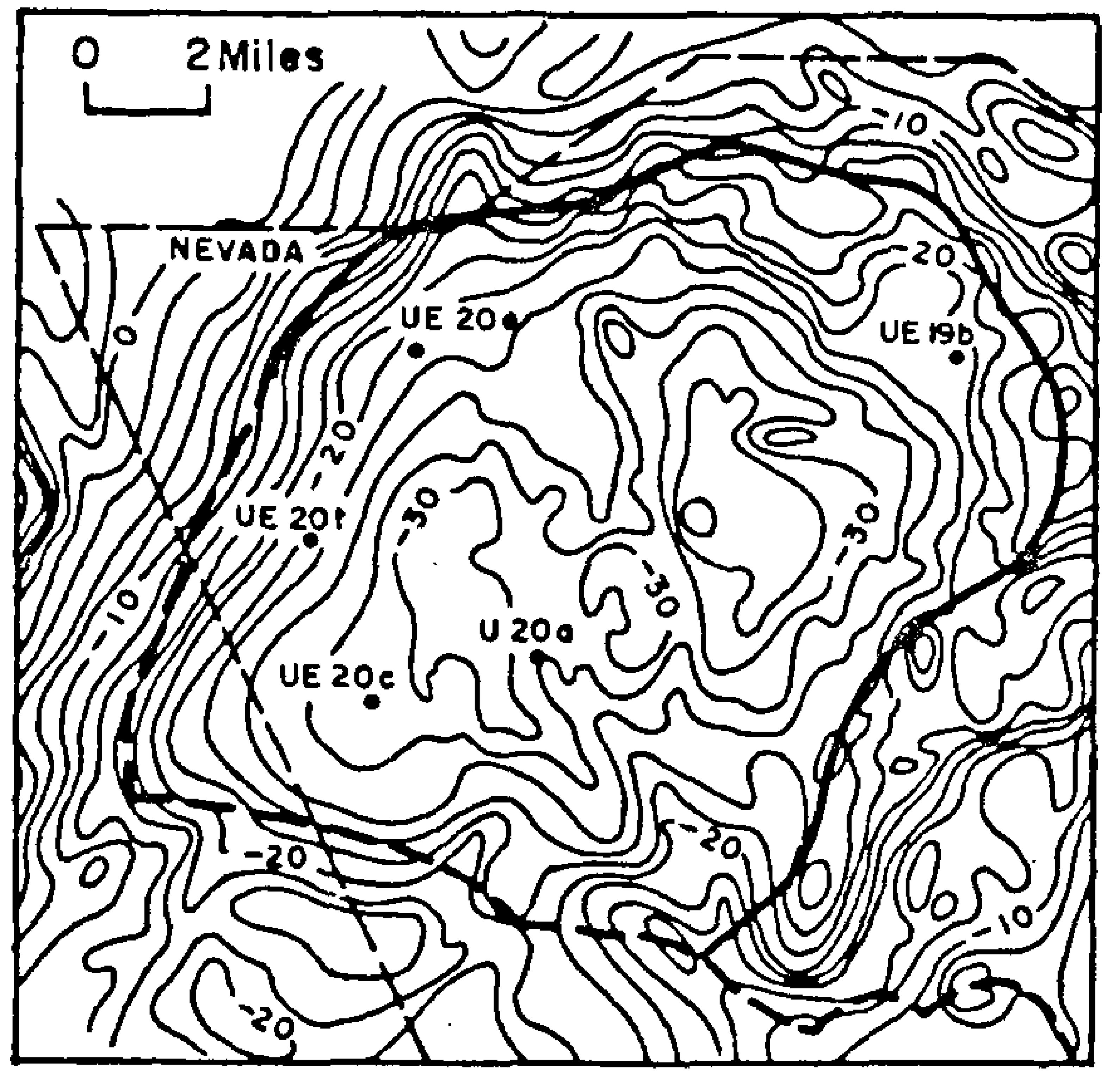

Figure 3. Residual gravity anomaly map of Pahute Mesa[1]. The regional is approximated by a first-order surface. The boundary of the Silent Canyon is shown. The drilling sites are shown by solid circles. The contour interval is 2 mGal.

Figure 4 is the residual gravity map of the Pahute Mesa and the neighbouring regions obtained by the new approach. The Silent Canyon is associated with much lower residual anomalies, the lowest being – 57 mGal. In contrast, it was – 30 mGal in a previous USGS study[1]. The steep gradient, much steeper on the western edge, defines the Silent Canyon rim clearly.

We assumed the density contrast of 0.45 g/cm^3 from the previous study and interpreted the new residual gravity anomaly to determine the thickness of the Cenozoic volcanic rocks. Figure 5 shows the residual gravity and the corresponding depth estimate of the Cenezoic volcanics in Pahute Mesa along a profile AA′ at 37°15′ N.

Figure 5 *a* shows the residual anomaly obtained earlier[1], the FEA residual and the computed residual (open circles) anomalies corresponding to the assumed earth model (Figure 5 *b*) consisting of the Cenozoic and Pre-Cenozoic rocks. Important observations made from this figure are as follows: (i) there is a considerable difference between the FEA and the trend surface residual anomalies; (ii) the FEA residual and the computed residual for the assumed basement structure show close match, excepting over a short portion on the western edge. The RMS difference is 2.915; and (iii) the maximum depth of the pre-Cenozoic basement by our scheme is 17,000 ft. This appears to be a more realistic estimate considering the results of the drilling at UE 20f. The profile AA′ at 37°15′ N is not very far from the drilling site.

The basement configuration of the Silent Canyon is required from the viewpoint of nuclear tests. To achieve this, two additional residual gravity profiles BB′ and CC′ (Figure 6) were interpreted. All the three profiles showed the maximum basement depth to be 17,000 ft in the central region of Pahute Mesa. There were three options to match the observed residual gravity profiles with the computed gravity effects of the assumed geological structures; (i) by varying the density contrast between the top sedimentary and volcanic rocks and the basement rocks; (ii) by varying the depth of the basement; and (iii) by varying both the density contrast and the basement depth. It was observed that for a satisfactory interpretation of the residual gravity profiles the third option was required. For example, to get a closer match between the observed and the computed responses, the density contrast was reduced from 0.45 g/cm^3 to 0.30 g/cm^3 over certain parts of the profile BB′. This is in confirmity with the variation of density with depth as revealed by drilling[1]. The resulting basement configuration is shown in Figure 6. It is elongated along NE-SW direction and the maximum depth is about 17,000 ft. The spot values of 17,000 ft for the basement depths are shown by filled circles. Besides the drill hole UE 20f located in the central zone of Silent Canyon, the borehole PM2 drilled up to 9000 ft on the north-west corner of Pahute Mesa did not encounter the basement. In the present study, the depth contour 12,000 ft passes very near the borehole PM2, further confirming that the basement depth estimation is more realistic.

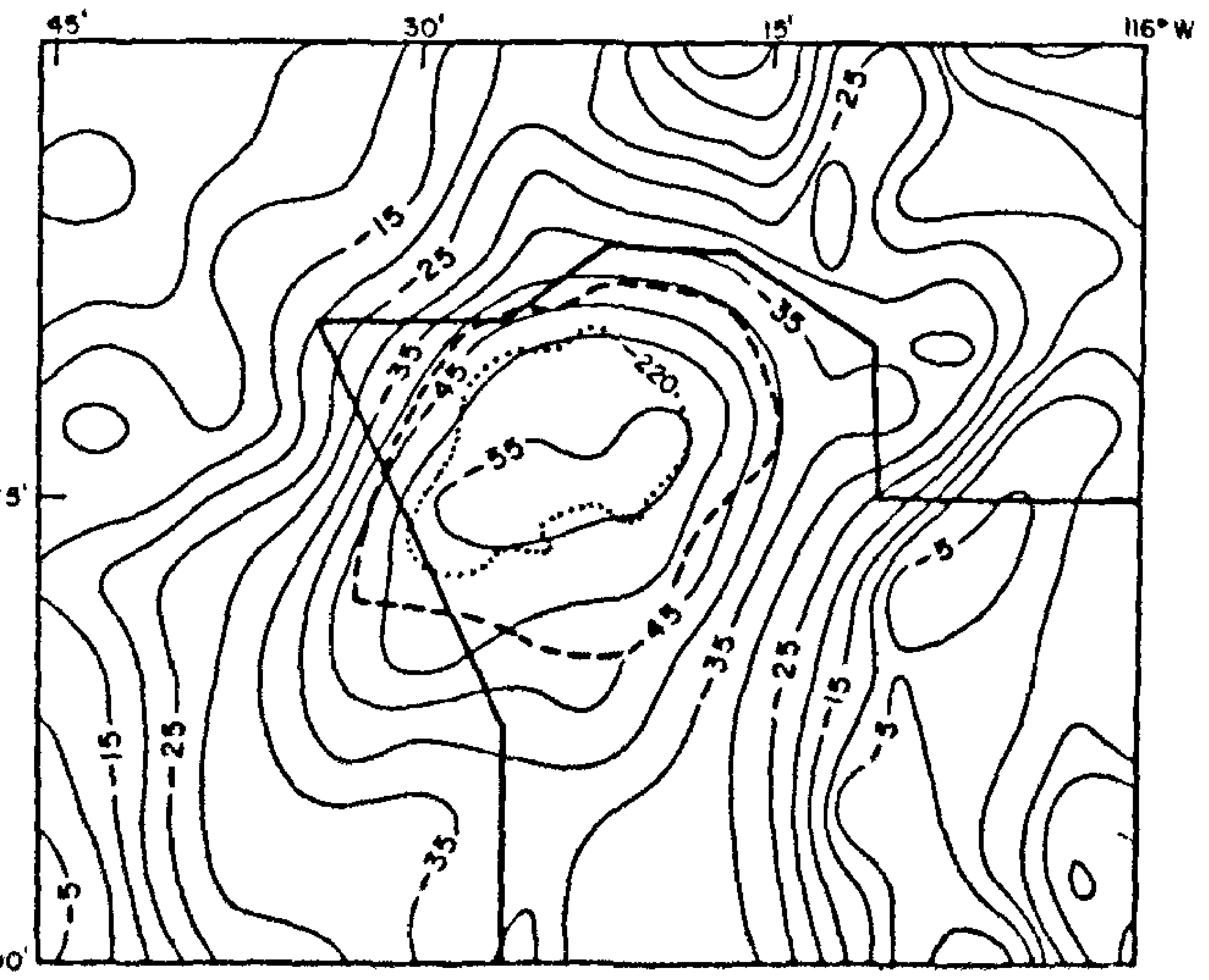

Figure 4. Residual gravity anomaly map of Pahute Mesa obtained by finite element analysis. The maximum anomaly in Silent Canyon is – 57 mGal. The contour interval is 2 m Gal.

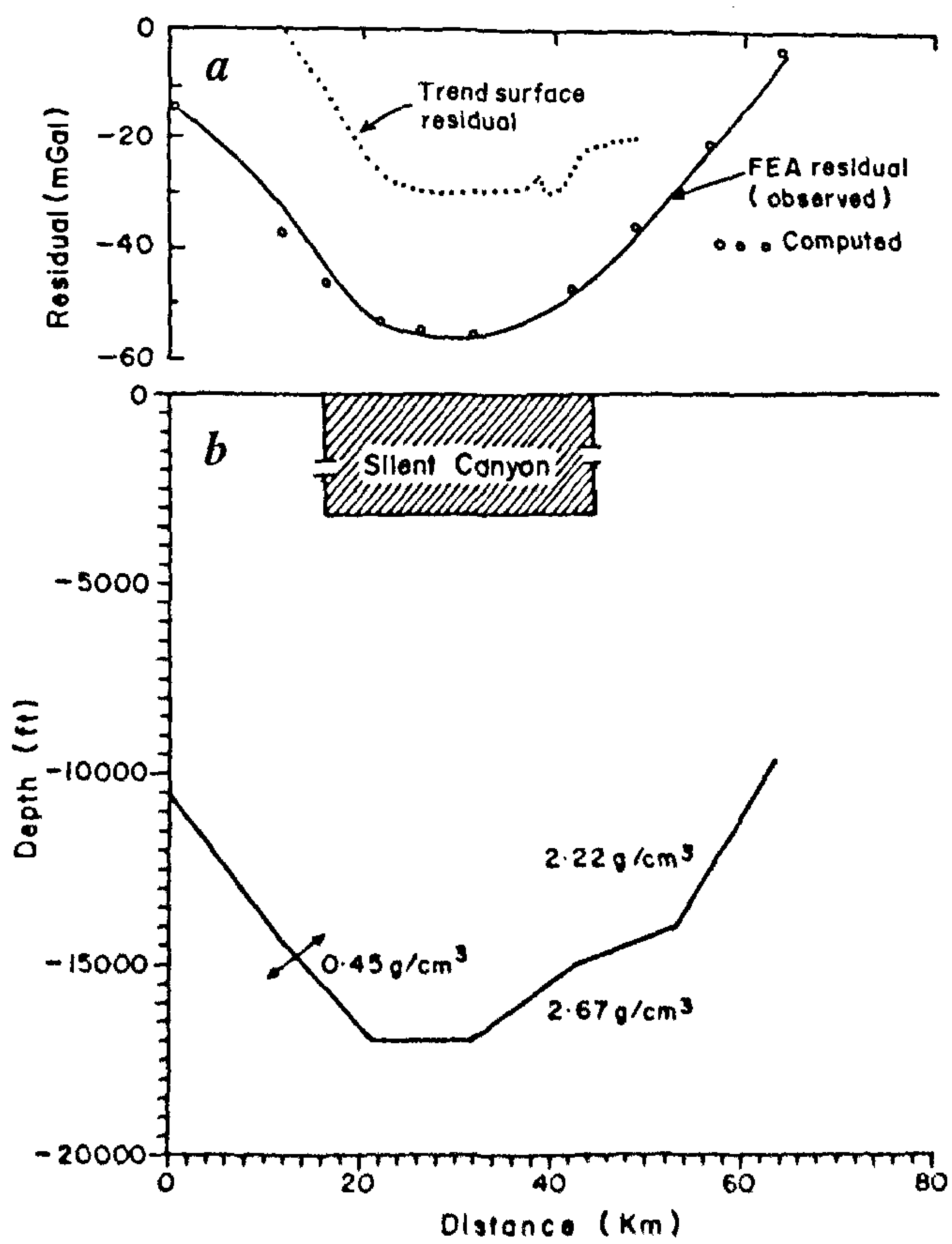

Figure 5. *a*, Bouguer residual gravity profile along 37°15′N in Figure 4. The residual anomaly in dotted line[1], FEA residual in continuous curve and the computed gravity effects in open circles of the type-model shown in *b*; *b*, The type basement configuration between Cenozoic and Pre-Cenozoic rocks. The maximum depth is 17,000 ft.

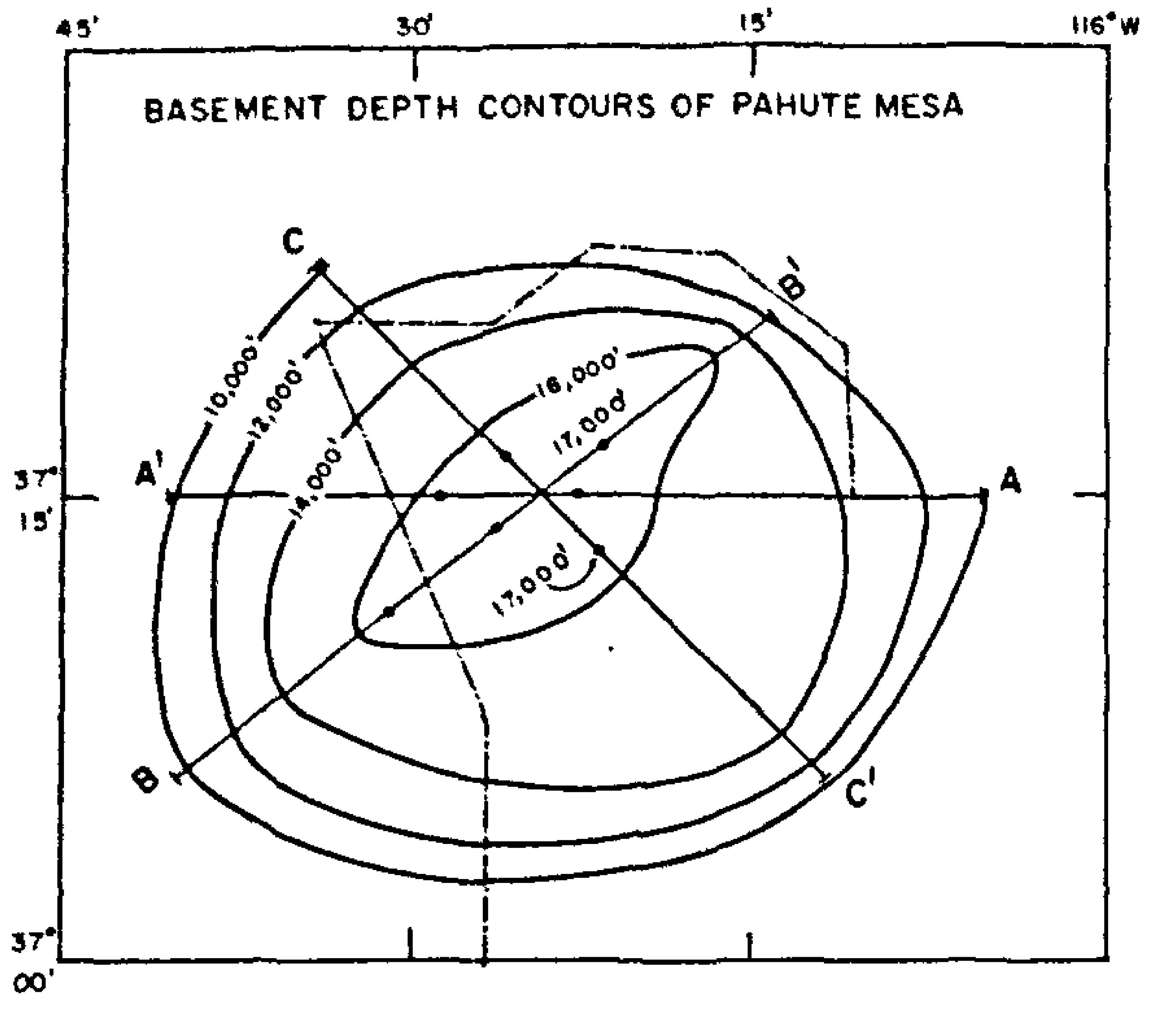

Figure 6. Basement configuration of the Silent Canyon. Profiles AA', BB' and CC' are interpreted. Filled circles show depths of 17,000 ft. Contour interval is 2000 ft. The Nevada test site is shown by the dotted and dashed line.

The new approach, based on finite element concept to derive the regional and residual gravity anomalies, has some unique features. In the present example, just eight gravity values have been used to compute the regional component. The effects of the shallower features inside the survey space do not enter into the regional computations. The FEA regional automatically takes care of isostatic effects, i.e. the isostatic compensation due to the high topography at Pahute Mesa, therefore, is implicitly incorporated into FEA regional. The results of the new approach are not only the residual map and the more acceptable basement configuration, but a method with several new features for future gravity interpretation.

1. Healey, D. L., *Geol. Soc. Am. Mem.*, 1968, **110**, 147–156.
2. Houser, F. N., *Geol. Soc. Am. Mem.*, 1968, **110**, 21–33.
3. Agocs, W. B., *Geophysics*, 1951, **16**, 686–696.
4. El-Batroukh, S. I. and Zentani, A. S., *Geophysics*, 1980, **45**, 153–163.
5. Mallick, K. and Sharma, K. K., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1997, **106**, 55–59.
6. Mallick, K. and Sharma, K. K., *Geophysics*, 1999, **64**, 461–469.
7. Zienkiewicz, O. C., *The Finite Element Method*, McGraw-Hill, New York, 1979, p. 618.
8. Cheung, Y. K. and Yeo, M. F., *A Practical Introduction to Finite Element Analysis*, Wiley, 1979, p. 180.
9. Sarma, G. S., Mallick, K. and Gadhinglajkar, V. R., *Geophysics*, 1998, **63**, 1006–1016.

ACKNOWLEDGEMENTS. We thank Dr H. K. Gupta, Director, National Geophysical Research Institute, Hyderabad for his keen interest and permission to publish this paper. We also thank Mr Ch. Venkateswarlu, Mr G. Ramakrishna Rao and Mr S. Jamaluddin for help in preparation of the manuscript. We thank the anonymous reviewer for his constructive suggestions to improve the paper.

Received 22 July 1998; revised accepted 20 March 1999

Coralline algae from the Kakana Formation (Middle Pliocene) of Car Nicobar Island, India and their implications in biostratigraphy, palaeoenvironment and palaeobathymetry

Anil Chandra*, R. K. Saxena and Amit K. Ghosh
Birbal Sahni Institute of Palaeobotany, 53 University Road, Lucknow 226 007, India

Coralline algae are reported here for the first time from the Kakana Formation (Middle Pliocene) of the Car Nicobar Island. The algal assemblage is represented by 10 species of crustose and articulated coralline red algae belonging to 7 genera, viz. *Lithothamnion*, *Mesophyllum*, *Lithophyllum*, *Porolithon*, *Amphiroa*, *Corallina* and *Arthrocardia*. Biostratigraphical, palaeoenvironmental and palaeobathymetrical implications of this assemblage are also highlighted.

THE first record of fossil algae from the Andaman and Nicobar Islands in Bay of Bengal was by Gee[1]. This included *Lithothamnion nummuliticum* and *L. suganum* from the Middle Andaman and fragments of *Lithothamnion* from the foraminiferal limestone of Hut Bay, Little Andaman and Wilson Island (Ritchie's Archipelago). All these occurrences were reported from the post-Eocene sediments. Narayana Rao[2] reported *Amphiroa oceanica* and *Corallina andamanica* from the Lepidocyclina Limestone of the Long Island, Middle Andaman and assigned a Late Oligocene or Early Miocene age to this limestone bed. Chatterjee and Gururaja[3] published an illustrated account of the coralline algae from the Andaman Islands which were described as *Lithothamnion andamanensis*, *Lithoporella melobesoides* and *Distichoplax biseriales* from the Palaeocene sediments of Cheria Tapu, South Andaman and *Lithothamnion wilsonensis*, *Lithophyllum* aff. *L. prelichenoides*, *Lithothamnion* sp., *Corallina raoi* and *Jania* sp. from the Early Miocene sediments of Wilson Island (Ritchie's Archipelago). Besides, *Amphiroa* sp. was also recorded by them from the Early Miocene sediments of the Little Andaman Island[3]. However, Lemoine[4] and Lemoine[5] questioned the validity of *Distichoplax* as an alga. They showed analogies between chitinous parts of the living and fossil Pterobranchia belonging to *Rhabdopleura* and suggested exclusion of *Distichoplax* from the algal group. Badve and Nayak[6] and Ghosh *et al.*[7] also agree with the above contention. Gururaja[8] reported *Neosolenopora* from the Miocene sediments of Hut Bay,

*For correspondence.