GL03166.2 of 8

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. B5, PAGES 3627-3636, APRIL 10, 1985

THE SUBSURFACE STRUCTURE OF LONG VALLEY CALDERA, MONO COUNTY, CALIFORNIA: A PRELIMINARY SYNTHESIS OF GRAVITY, SEISMIC, AND DRILLING INFORMATION

Geoffrey Abers

Department of Geological Sciences, Brown University, Providence, Rhode Island

Abstract. Long Valley Caldera is a 0.7 m.y. old volcanic eruptive center associated with an elliptical collapse structure on the eastern margin of the Sierra Nevada. Two-dimensional models of caldera fill are presented in this study resulting in structures compatible with existing seismic refraction and gravity data. Modifications to previous seismic models include shifting the north caldera rim to the south and decreasing the dip of the west and south boundaries. Densities in the model are not varied independently but are based on empirical velocity-density relationships and measured densities from surface outcrops and drill cores. These density values are adequate to account for observed gravity anomalies, indicating that the assumed subsurface lithologies are approximately correct. The large gravity anomaly in the shallow eastern caldera is modeled by assuming that the area is underlain by a layer of exceptionally low density.

Introduction

Scope of Present Investigation

Recent developments have highlighted the importance of an improved understanding of Long Valley Caldera. As the Long Valley/Mono Craters Complex is a recently active volcanic system (evidenced by hot spring activity and volcanic rocks considerably less than 1000 years old; [Bailey et al., 1976]), there is considerable interest in understanding its thermal regime. Another, perhaps more urgent development in the area is a heightened earthquake and volcanic hazard suggested by the recent increase in seismic activity and ground deformation. Following a series of large earthquakes in 1980, frequent seismic swarms have occurred in the Mammoth Lakes area [Ryall and Ryall, 1981, 1983]. Evidence for 10-25 cm of uplift between 1975 and 1980 associated with the resurgent dome was detected in the central caldera [Savage and Clark, 1982] and other signs of possible imminent volcanism of uncertain scale have emerged. As a result, a Notice of Potential Volcanic Hazard was issued by the U. S. Geological Survey in May 1982 for the area surrounding the town of Mammoth Lakes [Miller et al., 1982]. A better understanding of the structure of the caldera will contribute to a more accurate estimation of the thermal state of the area as well as an improved assessment of possible volcanic and earthquake risks.

The following discussion attempts to synthesize gravity data with seismic and other information for gaining insight into the nature of the structure of Long Valley Caldera that cannot be obtained using any single method alone. The data used include a complete Bouguer gravity map of the area [Oliver and Robbins, 1978] and the results from a seismic refraction experiment [Hill, 1976], supplemented with detailed geologic mapping [Bailey and Koeppen, 1977] and drill hole information [Smith and Rex, 1977; Sorey et al., 1978; Gambill, 1981; Heiken et al., 1982].

Paper number 5B0030.
0148-0227/85/005B-0030$05.00

Geologic Setting

The Long Valley Caldera is adjacent to the eastern front of the Sierra Nevada Mountains, intersecting the east Sierra fault boundary in central California (Figure 1). It is surrounded on all sides by typical Jurassic and Cretaceous granitic rocks of the Sierra Nevada Batholith as well as earlier metasedimentary and metavolcanic rocks. The caldera itself was formed in an explosive eruption of rhyolitic magma 0.7 m.y. ago, producing about 500 km^3 of Bishop tuff both within and outside the caldera and about 300 km^3 of ash dispersed over much of the western United States. Allowing for various differences in porosity, Bailey et al. [1976] estimated a total volume of erupted magma of 600 km^3. Collapse of the roof of the magma chamber accompanied the eruption, with subsidence of about 2-3 km along an arcuate fracture zone. The caldera outlined by this fracture zone is elliptical in shape, with its long axis extending roughly 30 km E-W and the short axis about 15 km N-S.

Immediately following the eruption of the Bishop tuff, a resurgent dome began developing in the west-central caldera, accompanied by extrusion of rhyolitic tuffs and flows onto the caldera floor. Over the last 0.5 m.y. there have occasionally been further eruptions of rhyolites and basalts, largely in the caldera moat and rim, although some basalt eruptions occurred to the south and north of the western caldera margin. In the western sector of the caldera, volcanic activity in the Inyo craters may have been as recent as 550 years ago. The eastern caldera is composed largely of lake beds with ash layers intermixed, deposited by a Pleistocene Long Valley Lake that occupied this site for most of the caldera's posteruptive history [Bailey et al., 1976].

Previous Geophysical Studies

Recent caldera models include one which relies only on gravity data [Kane et al., 1976], two [Muffler and Williams, 1976; Sorey et al., 1978] that are based primarily on the seismic data of Hill [1976]. Two of the models treat the caldera fill as one homogeneous body, extending from basement to surface [Muffler and

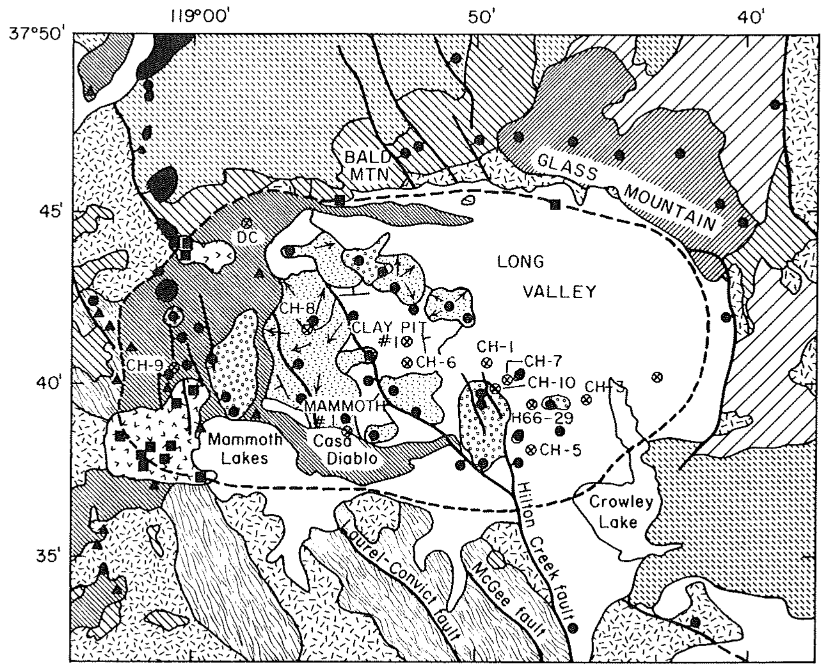

Fig. 1. Geologic map of Long Valley Caldera, showing rock types, inferred caldera ring fracture, faults, locations of drill holes, and other information. Modified after Bailey et al. [1976, Figure 3], with shallow drill hole locations from Sorey et al. [1978, Plate 1] and deep hole sites from Heiken et al. [1982, Figure 5]. Deep hole sites are labeled 66-29, Mammoth 1 and Clay Pit 1.

Williams, 1976; Kane et al., 1976]. Hermance [1983] has pointed out that gross differences exist between these various interpretations (see, for example, Hermance's Figure 13). A comparison of these models along seismic profiles A-A′ and B-B′ (located on Figure 2 [from Hill, 1976]) shows significant discrepancies in the size and shape of the interpreted subsurface caldera structure (the bottom panels of Figures 3 and 4).

As can be seen in these figures, the thickness of caldera fill along both profiles varies dramatically between models. As a further comparison, a two-dimensional gravity anomaly was calculated for each of these cross sections (using the bulk densities given with each published model) and compared to the others (the top panels in Figures 3 and 4). For a total anomalous field of 40 mGal, the resulting anomalies show differences of 5-10 mGal between the various models. The largest differences are between the model based solely on gravity data [Kane et al., 1976] and those constrained largely by the seismic data [Sorey et al., 1978; Muffler and Williams, 1976], and the discrepancies are largest near the caldera boundaries.

Data Base

Seismic Interpretations

In this study, primary constraints on the subsurface structural models of Long Valley Caldera are the two seismic refraction sections interpretated by Hill [1976]. One of the seismic profiles (B-B′) runs approximately N-S from near Mono Lake to Convict Lake, while the other (A-A′) transects Long Valley roughly E-W (Figure 2). Error estimates of 10% in P wave velocities (V_p) and 20% in interface depths are suggested [Hill, 1976]. The interpreted seismic sections are shown in the top panels of Figures 5 and 6.

Although the seismic sections are uncertain in several areas, four distinct layers are resolvable. The deepest, inferred to be a basement layer at 2-3 km depth, has a V_p of 6.0 km/s based on averaging a series of reversed travel time curves in the area, although lateral velocity variations cast an uncertainty of 0.4 km/s on this value [Hill, 1976]. The next layer, found throughout the caldera, has a V_p of 4.0-4.4 km/s and maintains a fairly constant thickness. Near the surface, it is possible to separate two additional layers: a lower one with a velocity of 2.7-3.4 km/s that is generally thickest where the basement is deepest and a thin top layer thickening in the east with a 1.5-1.7 km/s velocity within the caldera. Although all of these layers are not defined everywhere on the profiles and there is some uncertainty in these velocity ranges, these sections represent a reasonable approximation to the velocity structure in the caldera.

Gravity Data

Values for the gravity anomaly associated with the caldera are taken from a number of sources. An initial attempt was made to use the local anomaly calculated by Kane et al. [1976, Figure 2], but this was abandoned due to difficulties in using the published contour map. The bulk of the available gravity values are from a survey conducted in 1955 and 1956,

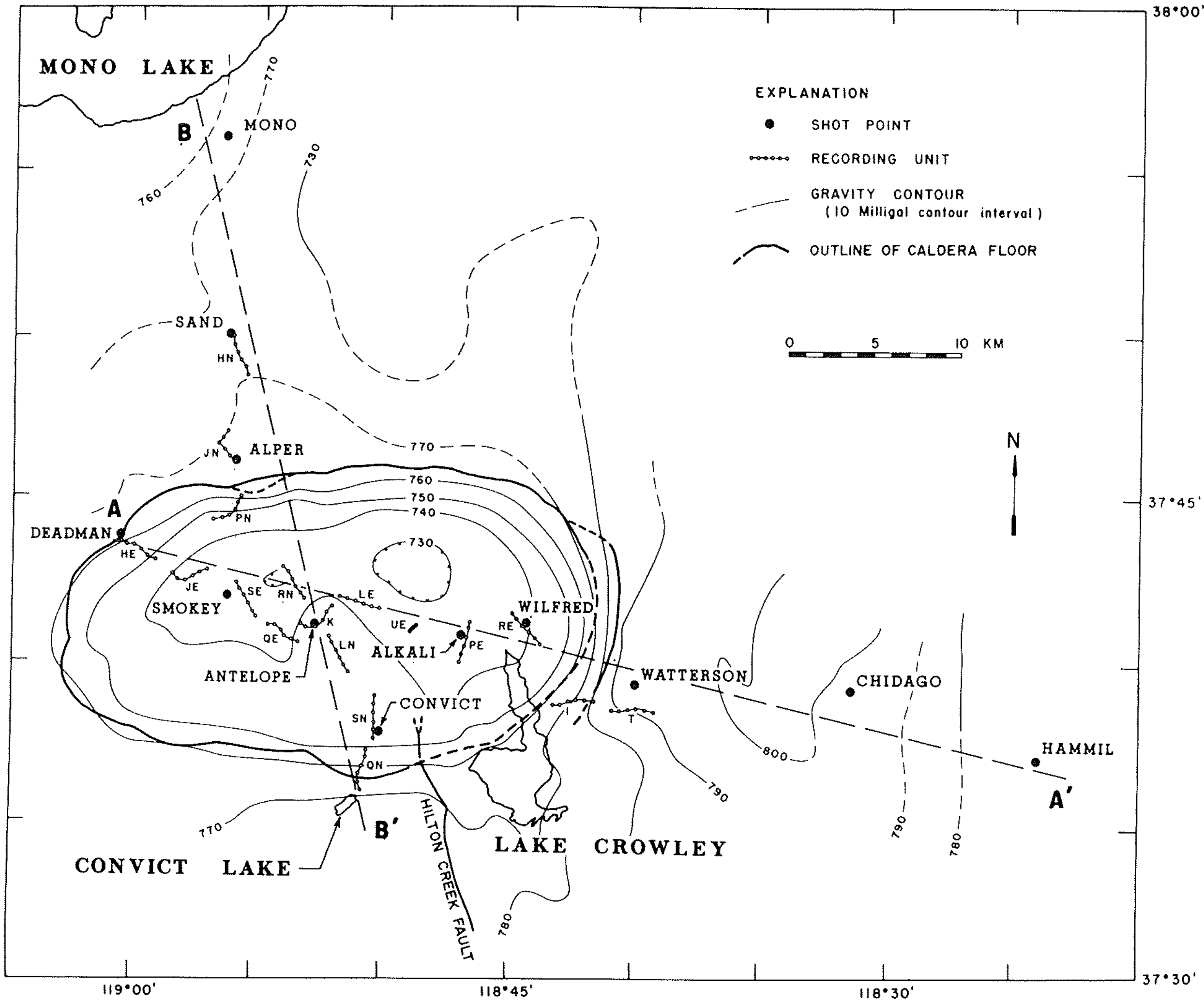

Fig. 2. Map of Long Valley area showing locations of seismic profiles, including shot point, recorder locations, and Bouguer anomaly [from Hill, 1976, Figure 1].

contoured on a 1:96,000 map with a 2-mGal contour interval [Pakiser et al., 1964, Plate 1]. This map served as an observed gravity data base for most modeling. However, it does not cover enough area to determine regional gradients, so a less detailed, more recent 1:250,000 map was also used [Oliver and Robbins, 1978], which in the vicinity of Long Valley is still largely based on the 1955-1956 survey.

The gravity map (Figure 7) shows a well

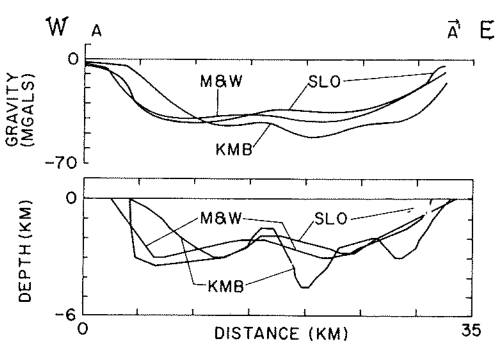

Fig. 3. Cross sections of caldera floor models and resulting two-dimensional anomaly from previous studies along seismic profile A-A′. (Top) Gravity anomaly. (Bottom) The basin models. Lines labeled "SLO" refer to the model of Sorey et al. [1978, from Figure 3], lines "KMB" are from the model of Kane et al. [1976, Figure 3], and the model of Muffler and Williams [1976, Figure 2] is represented by "M&W."

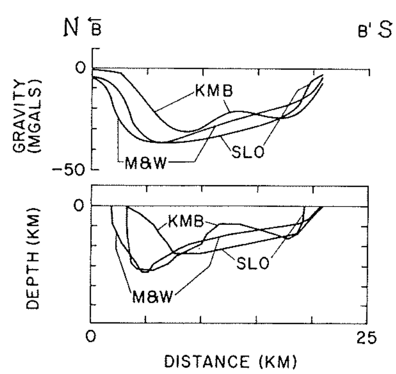

Fig. 4. Previous basement models along B-B′. (Top) Calculated gravity from models. (Bottom) The basin models. Notations are the same as in Figure 3.

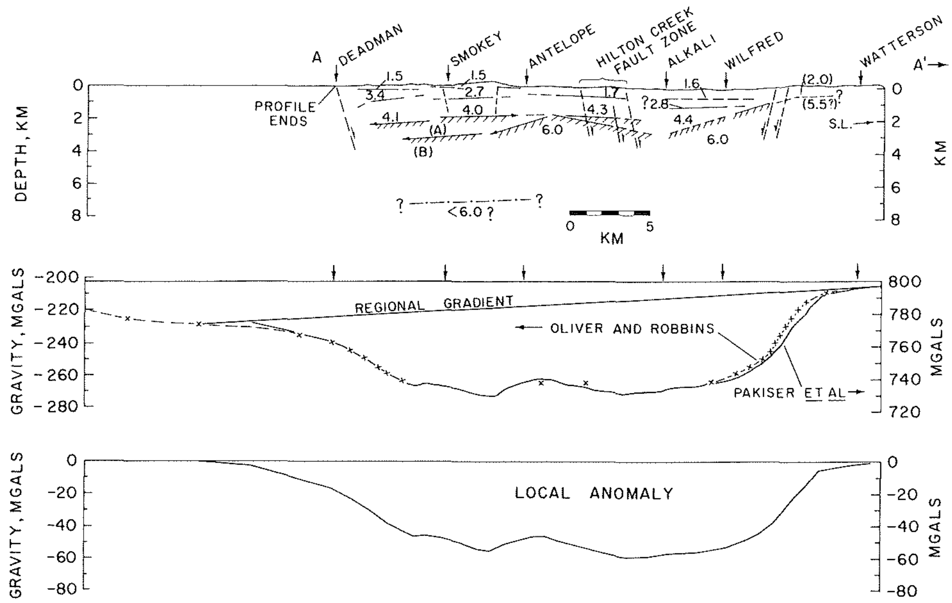

Fig. 5. Profile A-A′, as located in Figure 2. (Top) Seismic section from refraction experiment (modified after Hill [1976, Figure 7]. (Middle) Observed gravity with selected regional datum drawn. Data from Oliver and Robbins [1978] and Pakiser et al. [1964, Plate 1] as labeled. (Bottom) Local anomaly with above regional datum subtracted from Pakiser et al. [1964].

defined negative anomaly associated with Long Valley Caldera, having a 40-mGal amplitude and steep horizontal gradients associated with the inferred ring fracture zone. The slope of the anomaly is greatest along the north and east caldera walls and is less well defined at the south and west margins. The lowest anomalous values lie in the north caldera, and a local high protrudes into the caldera from the south-central wall which may be associated with a continuation of the Hilton Creek fault zone.

Surface Geology

A maximum size for the caldera structure is constrained by surrounding outcrops of pre-Tertiary granitic and metamorphic basement rocks. From inside the caldera, the closest of these basement rocks are found just outside of the inferred boundary faults and in many places are truncated by the ring fracture (see Figure 1). These outer caldera boundaries appear on the seismic interpretations as the near vertical inferred faults (Figures 5 and 6), so that the outside boundaries of the profiles are constraints on the maximum caldera width.

Surface geology (Figure 1) shows extensive covering of Quaternary sedimentary deposits over the eastern half of the caldera, suggesting the presence of low-density, low-velocity fill. A variety of postcollapse volcanic tuffs and flows (mostly rhyolitic and basaltic) dominate the western caldera, suggesting a different subsurface structure in this area. Large areas

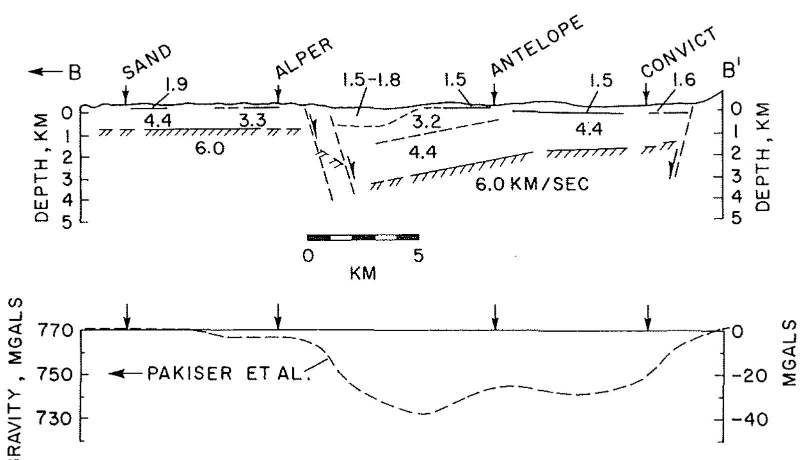

Fig. 6. Profile B-B′, as located in Figure 2. (Top) Seismic section from refraction experiment (modified after Hill [1976, Figure 8]. (Bottom) Observed gravity data from Pakiser et al. [1964]. Scale on left is from original map, scale on right has datum employed in this report subtracted. "PAK" is same as in Figure 5.

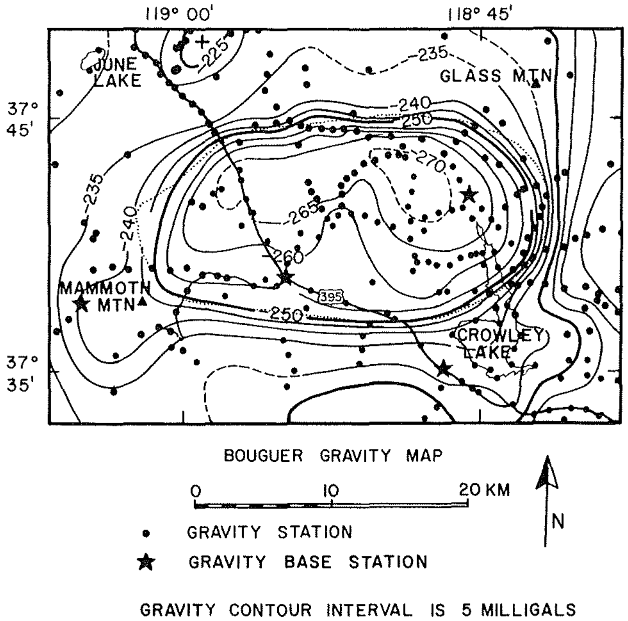

Fig. 7. Bouguer anomaly map of Long Valley region [after Oliver and Robbins, 1978]. Reduction density is 2.67 g/cm^3; terrain and curvature corrections are made to 166.7 km.

outside the caldera are covered by the Bishop tuff, and in the Owens River gorge a sizable vertical section of the tuff is exposed. Density measurements of the Bishop tuff range from 1 g/cm^3 for nonwelded pumiceous ash, to 2.4 g/cm^3 for the densest welded tuff [Ragan and Sheridan, 1972)]. Inclusions of Bishop tuff in early postcollapse rhyolites and in samples from deep drill holes indicate that the tuff at depth in the caldera is almost all densely welded [Smith and Rex, 1977; Sorey et al., 1978].

Drill Holes

A set of shallow test holes (CH-1 to CH-9 and DC on Figure 1) have produced cores of near-surface rocks, providing information about the uppermost caldera fill (data from Sorey et al. [1978]). Grain density, porosity, calculated wet bulk density values, and lithologies encountered for the test holes are given in Table 1 (modified from Sorey et al. [1978]).

Preliminary data are also available from three deep drill holes in Long Valley. These are labeled on Figures 1 and 8 as 66-29 for the hole drilled by Republic Geothermal, Inc. [Smith and Rex, 1977], and as Mammoth 1 and Clay Pit 1 for the holes drilled by the Union Oil Company [Gambill, 1981; Heiken et al., 1982]. Clay Pit 1 corresponds closely to the Antelope shot point on both seismic profiles, while 66-29 is in the same geologic setting as the eastern end of profile A-A′ within the caldera. Lithologies and depths encountered in these three holes are shown in Figure 8; no density information is available. In all three holes, the Bishop tuff is about 1000-1500 m thick with a base at 1400-2100 m depth and is overlain by early postcollapse rhyolitic tuffs or flows, and at 66-29 in the east, 330 m of sediments. In only one of the deep holes, Mammoth 1, was basement rock certainly reached; the granite porphyry unit in Clay Pit 1 may not be the basement [R.A. Bailey, personal communication, 1983].

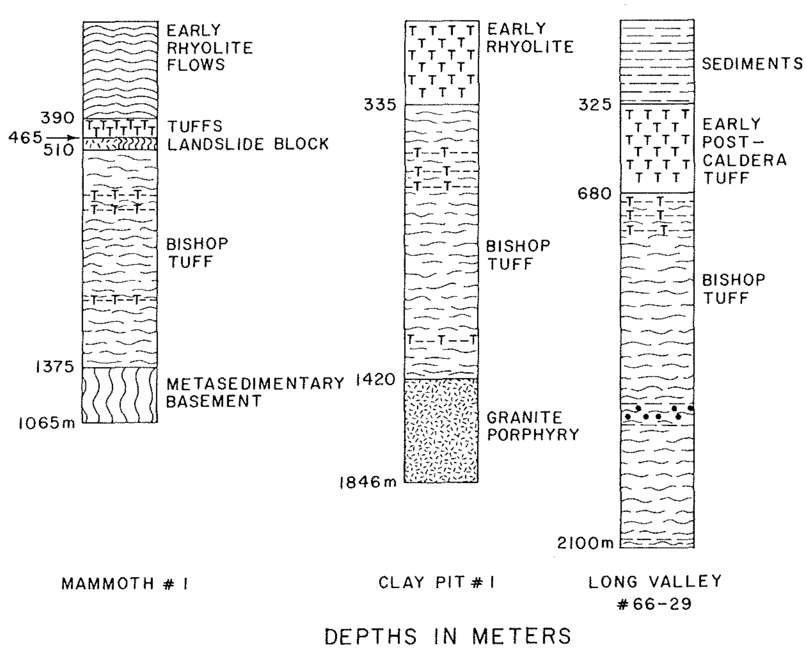

Fig. 8. Lithologies and depths from deep holes located in Figure 1. Columns labeled Clay Pit 1 and Mammoth 1 are from R. Dondanville (personal communication, 1983), and were drilled by Union Oil Company; drill hole Long Valley 66-29 was drilled by Republic Geothermal, Inc. (modified after Smith and Rex [1977].

TABLE 1. Analyses of Test Drill Hole Cores

Site	Test Hole and Location	Depth, m	Lithologic Description	Grain Density, g/cm^3	Porosity, %	Calculated Wet Bulk Density, g/cm^3
CH-1	near Cashbaugh ranch 3S/29E-19C	84	tuffaceous (ashy) sediments	2.34	59.8	1.54
		120	tuffaceous (ashy) sediments	2.40	35.0	1.91
		133	sand	2.33	63.1	1.66
		146	sand	2.33	63.1	1.49
		157	silty ash	2.37	56.9	1.59
		172	tuffaceous sediments	2.60	39.6	1.97
		185	ashy sediments	2.72	45.2	1.94
		209	pumiceous sand	2.37	62.4	1.52
		229	pumiceous tuffaceous sediments	2.69	62.3	1.64
		251	pumiceous	2.67	52.1	1.80
		305	ash	2.69	56.5	1.74
CH-3	W of Lake Crowley 3S/29E-27L	29	rhyolite flow	2.39	31.0	1.96
CH-4	E Rim 3S/30E-19M	58	ash	2.36	66.1	1.46
CH-5	E of Whitmore Hot Springs 4S/29E-5B	122	pumiceous tuff	2.32	46.6	1.70
CH-6	Long Antelope Valley 3S/28E-22F	76	clay-altered tuff	2.64	37.1	2.03
		209	silicified tuff	2.59	6.0	2.49
CH-8	Smokey Bear Flat 3S/28E-18D	57	rhyolite flow	2.52	7.1	2.41
		122	rhyolite tuff	2.33	35.2	1.86
		183	rhyolite tuff	2.28	38.6	1.79
		213	rhyolite tuff	2.30	46.1	1.70
		305	rhyolite tuff	2.35	46.8	1.72
CH-9	U. Dry Creek 3S/27E-20H	42	basalt flow	2.87	13.9	2.61
		54	andesite flow	2.66	10.2	2.49

Sites of the holes are located on Figure 1. Wet bulk density is calculated; all other data from Sorey et al., [1978, Table 5].

Modeling Parameters

Density Constraints

Density values used in modeling the gravity anomaly of the caldera are derived from three sources: the shallow drill hole data, analysis of exposed rocks of equivalent composition to those suspected to exist at depth (i.e., Bishop tuff and Sierra batholith rocks), and empirical velocity-density relationships. From the drill hole data given in Table 1, the average wet bulk density from the eastern caldera holes, CH-1, CH-3, CH-4, and CH-5, is 1.7 ± 0.2 g/cm^3. This is a reasonable density estimate for the 1.5-1.7 km/s layer, which is thickest in the eastern caldera. Bishop tuff is encountered at depth in the caldera in deep drill holes and also appears as inclusions in intracaldera rhyolitic eruptives. I therefore identify the thick 4.0-4.44 km/s layer as densely welded Bishop tuff [Smith and Rex, 1977; Bailey et al., 1976], and assign it a density of 2.4 g/cm^3. The deepest 6.0 km/s layer is most likely typical, largely granitic, Sierra Nevada basement, as indicated by outcrops outside the caldera (Figure 1), and as such would have a density of about 2.7 g/cm^3. This value is assumed in many gravity models of the region [e.g., Kane et al., 1976], although the frequent outcrops of pre-Tertiary metamorphic rocks surrounding the caldera suggests a rather variable and complex basement composition. The Nafe-Drake velocity-density relation was used [from Grant and West, 1965] with observed velocity ranges to constrain densities further. As shown by the hatched areas in Figure 9, density ranges are determined for the four units as 2.6-2.8, 2.33-2.5, 2.1-2.33, and 1.3-1.9 g/cm^3 corresponding to the velocity ranges of 5.6-6.4, 4.0-4.4, 2.7-3.4, and 1.5-1.7 km/s, respectively. The densities determined for the bottom two layers strongly support their identification with the Sierra Nevada basement complex and Bishop tuff, and the top layer's density range agrees with the test hole results. Initial density contrasts for modeling are then 0, -0.3, -0.5, and -1.0 g/cm^3 from bottom to top, relative to a 2.7 g/cm^3 basement.

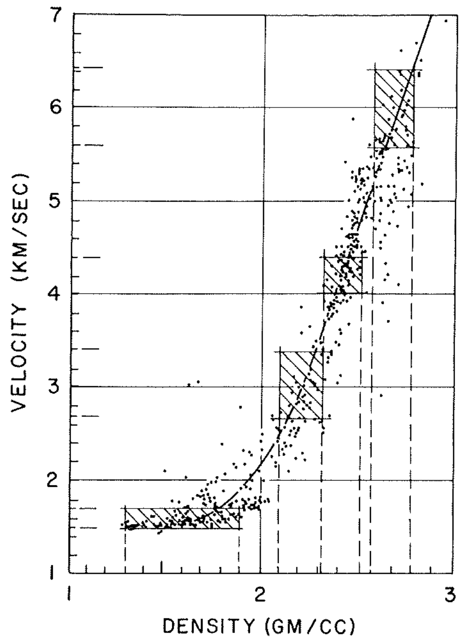

Fig. 9. Observed correlation between velocity and density [after Grant and West, 1965]. Included are blocks showing seismic P wave velocity ranges from units defined on seismic sections (Figure 5 and 6) and the corresponding density ranges, as discussed in the text.

Gravity Modeling

Methodology

Regional gradients were removed from the Bouger gravity data prior to modeling, as linear trends along each profile. A regional trend for A-A′ is established by connecting two areas of relatively "flat" gravity gradients (middle panel, Figure 5), while only a constant factor was considered in reducing profile B-B′. There is some a priori validity in considering a regional gradient along B-B′ negligible, as the profile runs roughly parallel to strike of most major geologic features in the region. The local gravity profiles used are shown in Figures 5 and 6 (bottom panels).

A caldera model was made by taking each seismic section to be a two-dimensional body and calculating the gravity anomaly produced along the profiles. The two-dimensional modeling algorithm of Talwani [1973] was used, in which each body is approximated by a polygonal shape. Long Valley Caldera is clearly a three-dimensional structure and should be modeled using three-dimensional methods; however, the subsurface structure is unconstrained away from the seismic lines except at deep drill holes, and subsurface extrapolation is difficult. In all models, the attitudes of the horizontal boundaries of the layers on the seismic sections are treated as fixed constraints; only the vertical boundaries were changed and then only in places where the seismic horizons were based on late arrivals or were extrapolated, as indicated by dashed lines in the top panels of Figures 5 and 6. Thus the models are an attempt to show that the derived seismic structure can produce the observed gravity anomaly.

As a crude test of the validity of two dimensionality along the profiles, the attraction along similarly placed profiles over a three-dimensional rectangular prism is calculated. The prism has approximately the same aspect ratio at the surface as the inferred caldera margin on the maps and is 3 km deep (Figure 10). The attraction of the box is

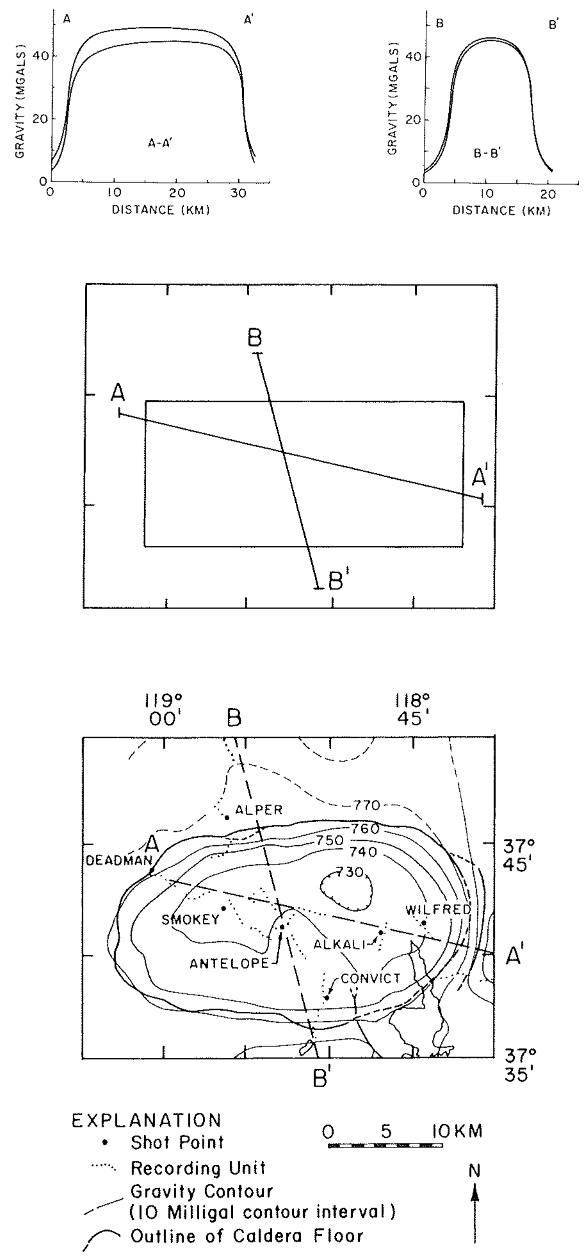

Fig. 10. Parallelopiped used to model effects of two-dimensional approximation in interpreting seismic sections A-A′ and B-B′. (Bottom) From Hill [1976, Figure 1], shows location of profiles, caldera rim, and gravity anomaly contours. (Middle) Rectangular approximation of the caldera, with profiles. (Top) Gravity calculated along profiles, comparing two-dimensional and three-dimensional models.

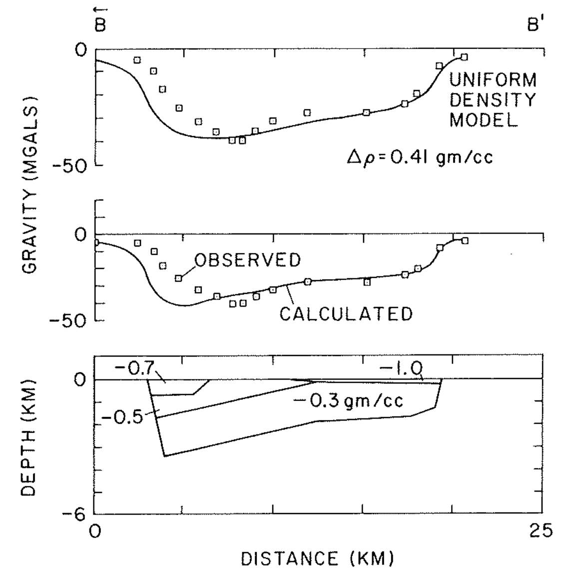

Fig. 11. First and second model for profile B-B′. (Top) First model gravity anomaly; all units have density of -0.41 g/cm^3. (Middle) Second model anomaly. (Bottom) Shape of bodies whose attractions were calculated for second model with density contrasts used, traced from seismic section (Figure 6, top).

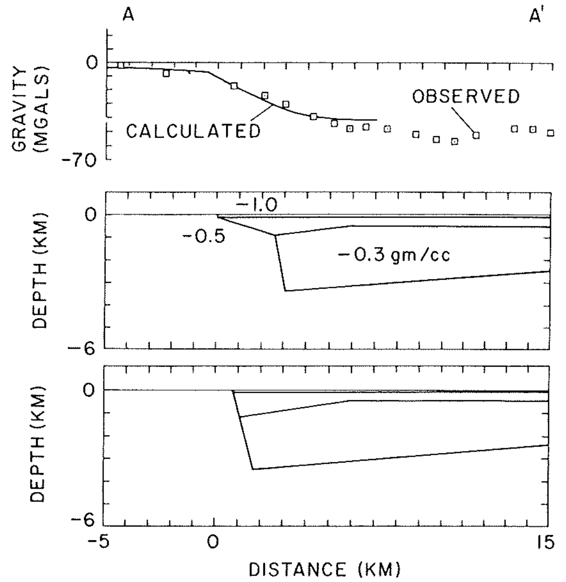

Fig. 13. Model for east caldera margin, along profile A-A′. (Top) Gravity, observed and calculated. (Middle) Model with densities; bodies extend 7 km farther to west. (Bottom) Shape of seismic model, traced from Figure 5, top.

obtained using a formula given by Talwani [1973, p. 354] and is compared with the 2-dimensional attraction of the box calculated along the same profiles. For both profiles, the 2-dimensional model generates larger anomalies than the 3-dimensional model. Results of this test, however (Figure 10, top), show the 2-dimensional approximation along B-B′ deviates only by about 1 mGal of a 50-mGal total anomaly field, while along A-A′ the deviation is closer to 5 mGal.

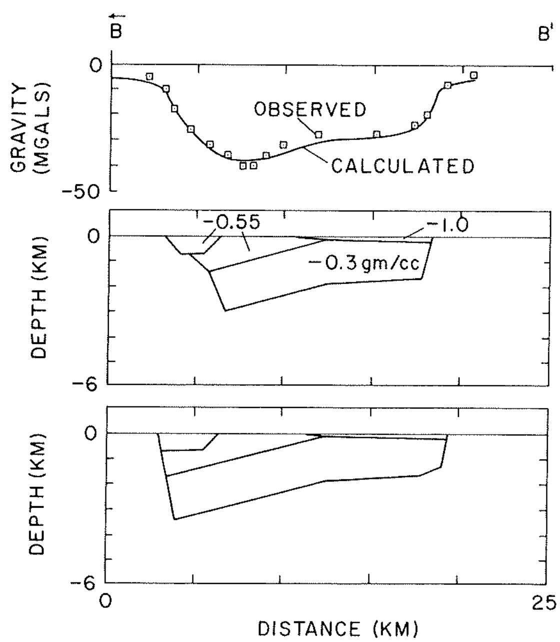

Fig. 12. Final model for profile B-B′. (Top) Calculated and observed anomalies. (Middle) The model, with densities for units shown in grams per cubic centimeter. (Bottom) Original model traced from seismic section.

Profile B-B′

Three gravity models were tested for the north-south profile. The first (Figure 11, top) assumed a uniform density for the entire caldera fill, based on the cross section implied by the seismic data and a density contrast of -0.41 g/cm^3 from a calculation of caldera fill mass

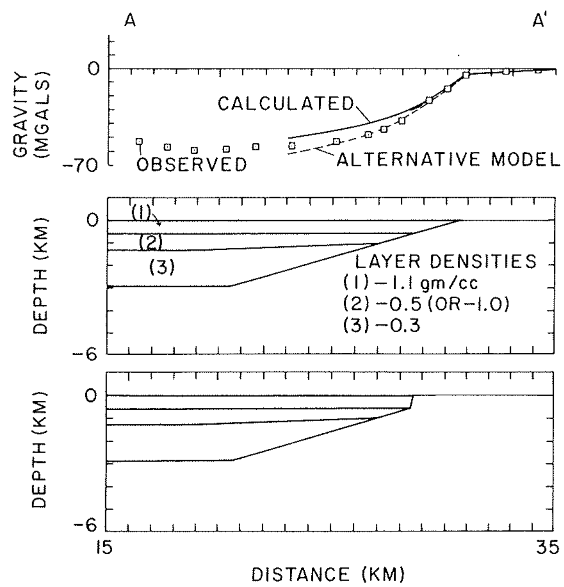

Fig. 14. Model for west caldera margin, along profile A-A′. (Top) Gravity observed and calculated. (Middle) Model and densities; bodies extend 10 km to east. (Bottom) Shape of seismic model, traced from Figure 5, top.

and volume [Muffler and Williams, 1976]. A second model (Figure 11, middle and bottom) strictly interprets the lithological contacts defined by the seismic cross-section and the densities derived from V_p observations, as shown in the bottom panel of Figure 11. The first model cannot generate much of the fine structure in the observed gravity anomaly, while the second model produces a significantly different anomaly in the northern portion of the caldera.

A best fitting model to the gravity data (Figure 12, middle and top panels) was obtained from the second model through a series of "trial and error" iterations, in which only the less certain density contrasts and horizons based on late arrivals and extrapolation were allowed to change. Comparison with the seismic model (Figure 12, bottom) shows that a generally smaller caldera, as well as a more gradual northern (left) boundary, is necessary to match the gravity data.

Profile A-A′

A major concern in the interpretation of Long Valley basin structure is the apparent discrepancy between the seismic E-W model (Figure 5, top) and the observed E-W gravity (Figure 5, middle). The seismic section shows a very shallow depth to basement on the eastern edge (0.5-1 km) and a deep basement on the western margin (>3 km), whereas the observed gravity suggests a structure shallow in the west and deep in the east [Hermance, 1983, Figure 15]. Recognizing that three-dimensional gravitational effects are significant along this profile a complete structure model was not attempted. Only the local structure immediately adjacent to the caldera boundaries was examined in detail. In both models, all 2-dimensional structures were extended as horizontal layers 20 km in a direction perpendicular to the caldera boundary.

The eastern caldera gravity anomaly was modeled with a 0.5-1.0 km thick low-density upper layer (on the seismic profile Figure 5, middle). A fair fit was made to the observed gravity values (Figure 13), while a better fit was achieved by using an anomalously high-density contrast for the middle layer (-1.0 g/cm^3, labeled "alternative model" on Figure 13). It would also be possible to achieve this fit by increasing the thickness of the top layer near the caldera margin.

The western edge of the caldera was modeled using nearly the same densities as in the east (Figure 14), resulting in a model which obeys all the "hard" constraints. The deep western margin of the Bishop tuff (the inferred boundary fault) was moved 2 km to the east, and the shallow upper layers were extended 0.5-1.0 km to the west. These two models indicate that the apparent discrepancy between seismic and gravity interpretations may be largely due to lateral changes in the density structure of the caldera fill.

Conclusions

The best fitting models (Figures 12-14) show that the seismic data are consistent with observed gravity, since all modifications to the seismic model are in areas weakly constrained by the seismic data. The close agreement between the final density values used in the model and the best constraints supplied by drill hole samples and local geology suggest that error in assuming two dimensionality, which should underestimate densities, may not be important, possibly because the layers with high-density contrasts are near the surface where three-dimensional effects are minimal.

The subsurface stratigraphy suggested by others [e.g., Bailey et al., 1976] is supported by this model. Granitic and metamorphic rocks form a basement below a depth of 2-3 km, overlain by 1.0-1.5 km of Bishop tuff everywhere within the caldera, a less dense layer of early rhyolites thickest near the caldera rim, and a thick layer of low-density sediments covering the eastern caldera.

Although the models give a general indication of the shape of the caldera, they should only be considered as preliminary to the development of a complete three-dimensional model. There are considerable difficulties in formulating such a model, such as extrapolating structure away from the seismic profile into the rest of the caldera. More seismic and deep drill hole data are needed to help constrain such modeling. Nevertheless, a three dimensional model would be quite valuable for refining concepts regarding tectonic, geothermal, and hydrologic processes associated with the caldera.

Acknowledgments. This report was prepared as an undergraduate senior thesis at Brown University. I would like to thank H. W. Oliver of the U.S. Geological Survey for providing the Bouguer gravity data and Don Forsyth for providing the two-dimensional modeling program. I am particularly grateful to Jack Hermance, whose comments, suggestions, and careful listening provided much of the motivation and direction for this project. The preparation of this manuscript was funded by Department of Energy Office of Basic Energy Sciences contract DE-AC02-79ER10401.

References

Bailey, R. A., G. B. Dalrymple, and M. A. Lanphere, Volcanism, structure, and geochronology of Long Valley Caldera, Mono County, California, J. Geophys. Res., 81, 725-744, 1976.

Bailey, R. A., and R. P. Koppen, Preliminary geologic map of Long Valley, Mono County, California, U.S. Geol. Surv. Open File Map, 77-468, 1977.

Gambill, D. T., Preliminary hot dry rock geothermal evaluation of Long Valley Caldera, California, Rep. LA-8710-HDR, p. 22, Los Alamos Nat. Lab., Los Alamos, N.M., 1981.

Grant, F. S., and G. F. West, Interpretation Theory in Applied Geophysics, p. 583, McGraw-Hill, New York, 1965.

Heiken, G., F. Goff, and G. Cremer, Hot dry rock geothermal resource - 1980, Rep. LA-9295-HDR, UC-66a, p. 113, Los Alamos Nat. Lab., N.M., 1982.

Hermance, J. F., The Long Valley/Mono Basin volcanic complex in eastern California, Status of present knowledge and future research needs, Rev. Geophys., 21, 1545-1565, 1983.

Hill, D. P., Structure of Long Valley Caldera, California from a seismic refraction experiment, J. Geophys. Res., 81, 745-753, 1976.

Kane, M. F., D. R. Mabey, and R. L. Brace, A gravity and magnetic investigation of the Long Valley Caldera, Mono County, California, J. Geophys. Res., 81, 754-762, 1976.

Miller, C. D., D. R. Mullineaux, D. R. Crandell, and R. A. Bailey, Potential hazards from future volcanic eruptions in the Long Valley-Mono Lake area, east-central California and southwest Nevada - A preliminary assessment, U.S. Geol. Surv. Circ., 877, p. 10, 1982.

Muffler, L. P. J., and D. L. Williams, Geothermal investigations of the U.S. Geological Survey in Long Valley, California, 1972-1973, J. Geophys. Res., 81, 721-724, 1976.

Oliver, H. W., and S. L. Robbins, Bouguer gravity map of California, Mariposa Sheet, scale 1:250,000, Cal. Div. of Mines and Geol., Sacramento, 1978.

Pakiser, L. C., M. F. Kane, and W. H. Jackson, Structural geology and volcanism of Owens Valley Region, California - A geophysical study, U.S. Geol. Surv. Prof. Pap., 438, 1-68, 1964.

Ragan, D. M., and M. F. Sheridan, Compaction of the Bishop tuff, California, Geol. Soc. Am. Bull., 83, 95-106, 1972.

Ryall, F., and A. Ryall, Attenuation of P and S waves in a magma chamber in Long Valley Caldera, California, Geophys. Res. Lett., 8, 557-560, 1981.

Ryall, A., and F. Ryall, Spasmodic tremor and possible magma injection in Long Valley Caldera, Eastern California, Science, 219, 1432-1433, 1983.

Savage, J. C., and M. M. Clark, Magmatic resurgence in Long Valley Caldera, California: Possible cause of the 1980 Mammoth Lakes earthquakes, Science, 217, 531-533, 1982.

Smith, J. L., and R. W. Rex, Drilling results from the Eastern Long Valley Caldera, in: Energy and Mineral Resource Recovery, pp. 529-540, American Nuclear Society, C.A., 1977.

Sorey, M. L., R. E. Lewis, and F. H. Olstead, The hydrothermal system of Long Valley Caldera, California, U.S. Geol. Surv. Prof. Pap., 1044-a, A1-A60, 1978.

Talwani, M., Computer usage in the computation of gravity anomalies, Methods Comput. Phys., 13, 343-389, 1973.

G. Abers, Department of Geological Sciences, Brown University, Providence, RI 02912.

(Received January 3, 1984;
revised December 26, 1984;
accepted January 7, 1985.)