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Gravity Anomaly Map and Inferred Basement Structure in Osaka Plain, Central Kinki, South-west Japan

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(With 8 Figures and 3 Tables)

Abstract

The Bouguer anomaly map of the Osaka Plain was compiled from gravity measurements that have been performed by several groups. The map is expected to be used for the analysis of the basement structure or for urban disaster prevention in the Osaka area. The Bouguer anomaly in the Osaka Plain indicates a somewhat intricate feature which well correspond to the geological structure. Those structures are characterized by a number of major reverse faults bounding between the Osaka Plain and the surrounding mountain ranges. A linear relation between the corrected Bouguer anomaly and the depth of granitic basement rocks is obtained from an analytical study on some field informations such as geological survey, deep drilling and seismic exploration.

The regional Bouguer anomaly is considered to be influenced by the attraction of the subducting slab under Kii Peninsula. On the other hand, the local anomaly seems to be directly reflected to the basement structure in the Osaka sedimentary basin.

The spatial structure of the granitic basement is estimated by comparison with gravity anomalies, and the basement depths determined directly by *in situ* measurement.

Key Words: Gravity map, Bouguer anomaly, Osaka Plain, Subducting slab, Estimation of basement depth, Philippine sea plate, 2-parallel layer model

1. Introduction

Gravity maps in and around the Japanese Islands have been compiled by several investigators (e.g., Tomoda 1973, Segawa and Bowin 1976, Kono and Furuse 1989). However, the detailed gravity map of the Osaka Plain has not been published yet, although the determination of the underground structure by gravity analysis appears to be

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of vital importance, from the engineering standpoint, for the prevention of disaster in the urbanized area.

The first measurement of gravity in the Osaka Plain was performed at about 60 points by IIDA and others in order to investigate a secular variation of the gravity due to the land-subsidence of the urbanized ground in Osaka City (IIDA *et al.*, 1953). From that time to present, more detailed gravity data in and near Osaka Prefecture have been obtained by several groups. Most of this data, however, has not been presented in formal publications. Accordingly, an attempt is made here to compile the gravity anomaly map of the Osaka Plain, based on these data (Fig. 1).
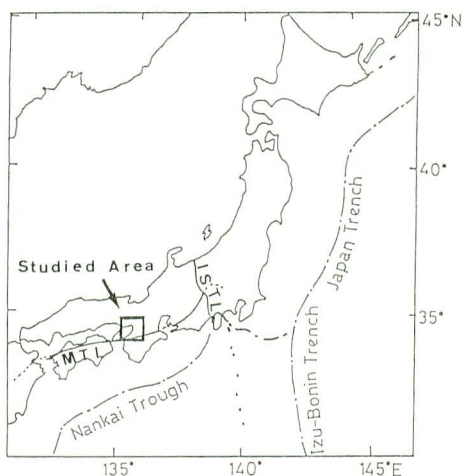

Fig. 1   Map showing location of the area of compilation of gravity data.

It has been difficult to investigate the underground structure in the Osaka Plain based on the gravity analyses, because there has been, until now, scarce information on the underground structure, such as deep well data, to which the geophysical data can be referred. Recently, deep well borings have been made frequently, due to explosive hot-spring boom, and an outline of underground structure of the plain has been gradually revealed. Consequently, it has now become possible to discuss the basement structure by comparing gravity anomalies and well data.

2. Data Sources

The data sources of the present compilation are shown in Table 1. YAGI (1962) and YAMASAKI (1962) are unpublished inside reports of the Teikoku Oil Co. Ltd. RYOKI (1982) and MUTO (1990) are unpublished graduation theses. The contour map of the Amagasaki region was drawn by ABE *et al.* (1964) and was published by HUZITA (1966). ITO *et al.* (1989) reported the gravity anomaly in the vicinity of Arima-Takatsuki Tectonic

Line. We use the original data provided by these observers. Fig. 1 is an index map showing the location of the area described, and the location of measurement points is shown in Fig. 2. Fig. 3 shows schematic geological diagram of studied area and locations of the data related to the depth of granitic basement.
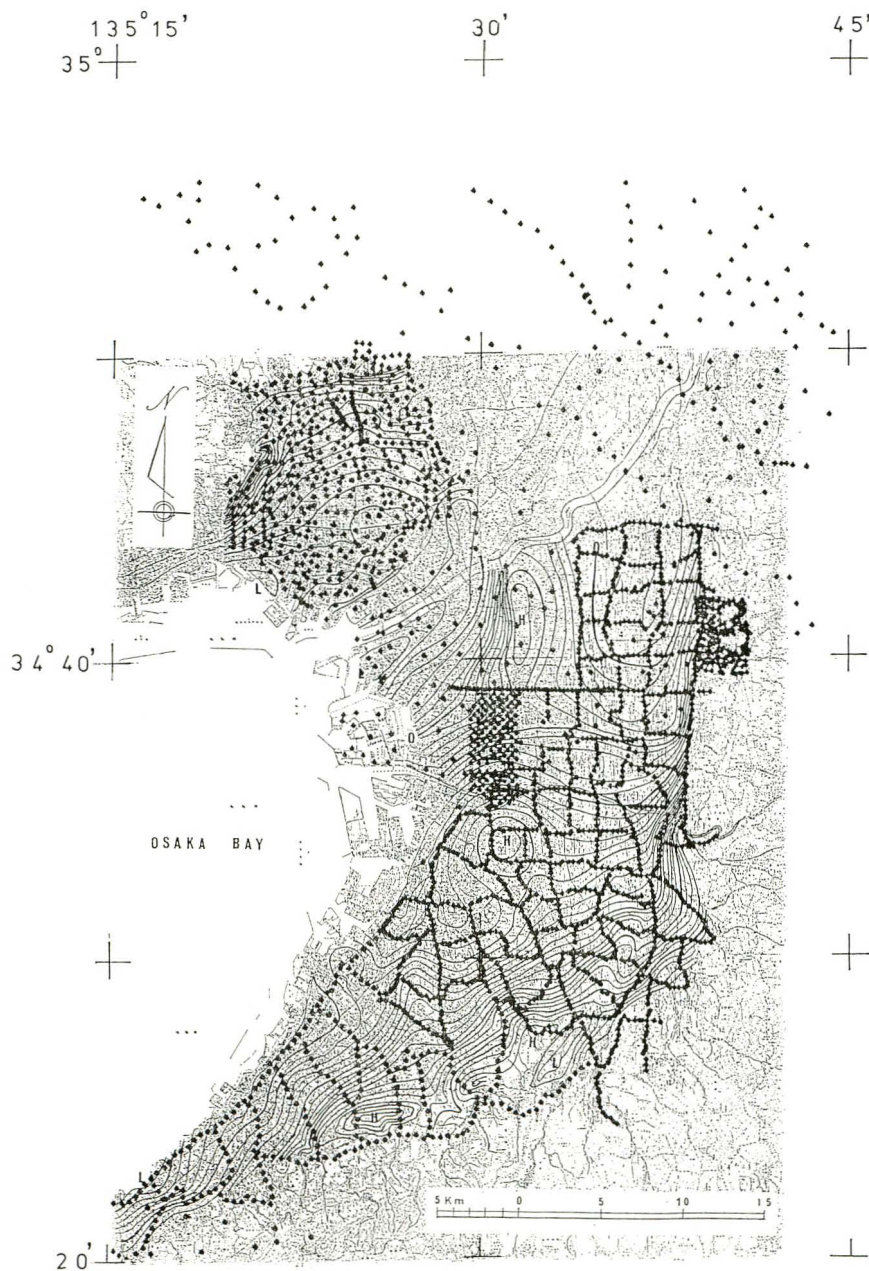

Fig. 2. Map showing location of gravity stations.

Koichi Nakagawa, Kunihiro Ryoki, Naomi Muto, Susumu Nishimura
                                and Kiyoshi Ito

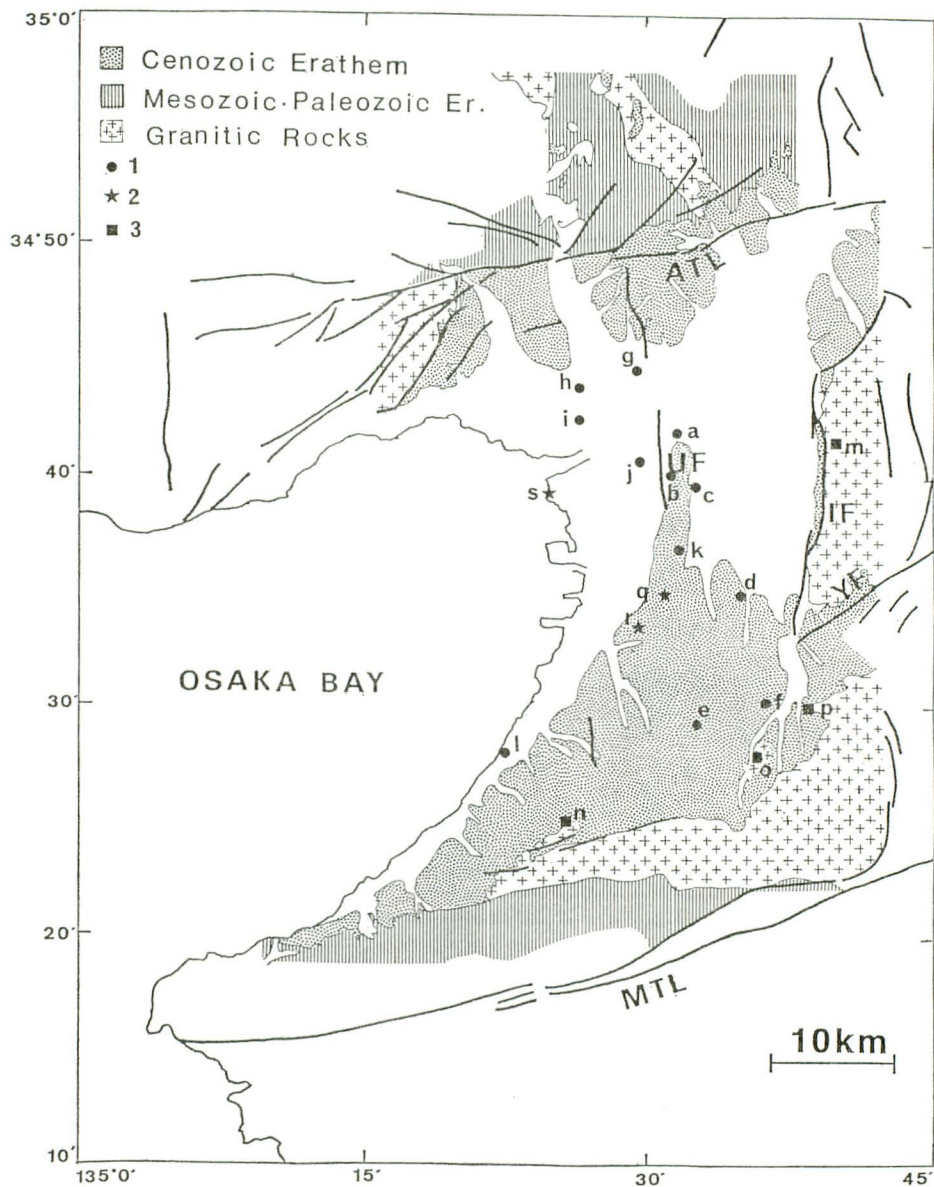

Fig. 3   General geologic map of the Osaka Plain.   Locations of several exploration
         points of the basement rocks are shown.
         1—deep drilling point,
         2—seismic exploration point.
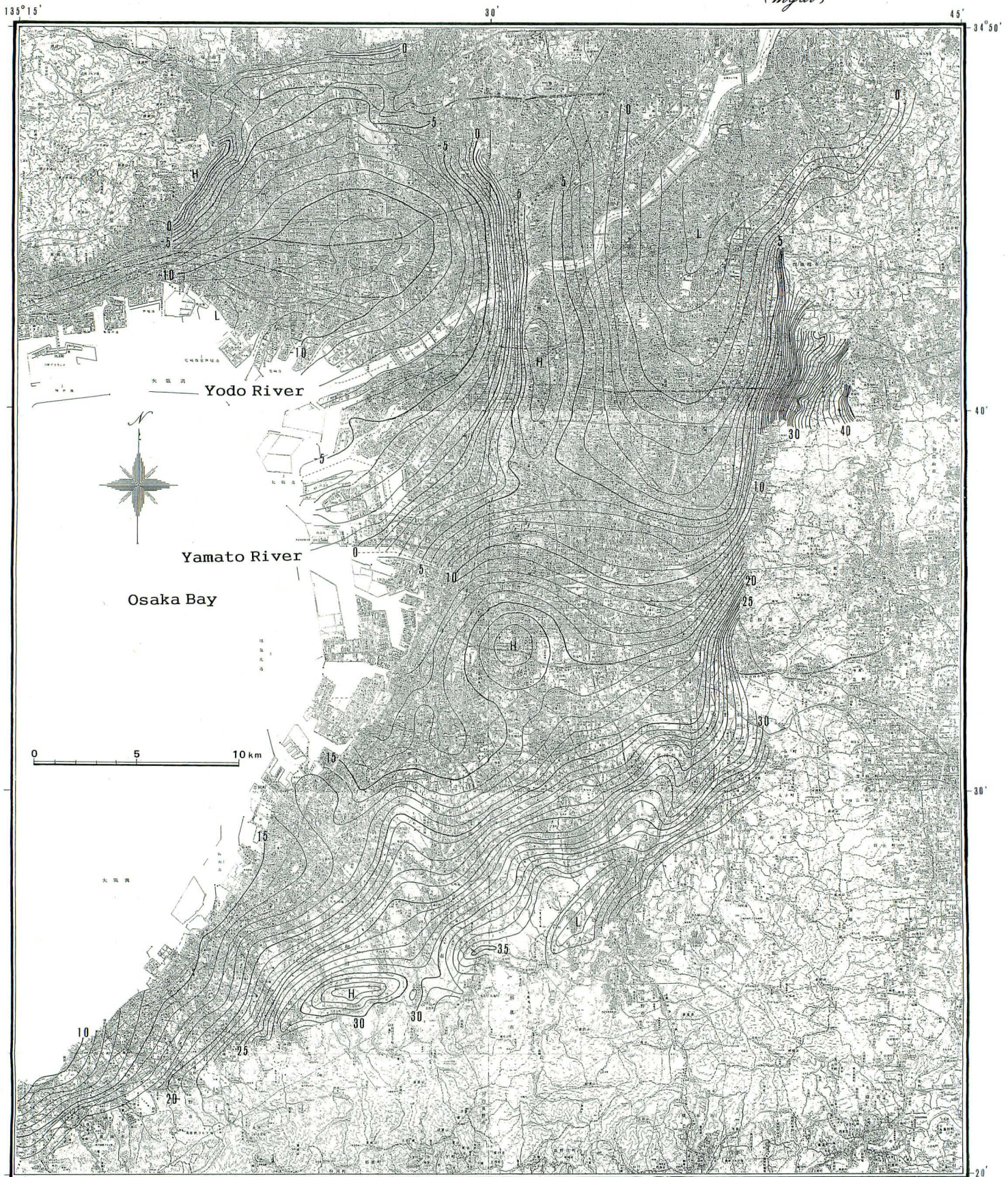   3—outcropping points of basement rocks,
         a~s: data points for relation between the basement depth and the Bouguer
             anomaly (see Fig. 7).
         MTL: Median Tectonic Line,   ATL: Arima-Takatsuki Tectonic Line,
         UF: Uemachi Fault,   IF: Ikoma Fault,   YF: Yamatogawa Fault.

Bouguer Gravity Anomaly in Osaka Plain

(mgal)

Yodo River

Yamato River

Osaka Bay

N

0   5   10 km

Fig. 4   Contour map of Bouguer anolmaly in the Osaka Plain.   Contour interval is 1.0 mgal.

Table 1 Data sources of the present compilation.

Area	Instruments	Observer
Southern area	NA	Teikoku Oil Co. Ltd.: YAGI (1962) and YAMASAKI (1962)
Central area	LaCoste	Osaka City Univ.: RYOKI (1982)
Northwestern area	NA	Kyoto Univ.: ABE et al. (1964)
Northeastern area	LaCoste	Kyoto Univ.: ITO et al. (1989)
Ikoma Mountain Range	LaCoste	Osaka City Univ.: MUTO (1990)

NA: the North American gravity meter.
LaCoste: LaCoste and Romberg gravity meter.

3. Compiled Bouguer Anomaly Map

When we reduce the Bouguer gravity anomaly from an observed value through the free-air, the terrain and the Bouguer corrections, we assume the density of sub-surface rocks. The density used to calculate the correction values are somewhat different among the data of the present compilation. Table 2 shows the assumed values of the density in the original reports. It is advisable to reduce the gravity anomalies through the recalculation of gravity corrections for the original data, based on the common standard density. However, we use the Bouguer anomalies given in the original reports except for a slight adjustment to reduce a contradiction of gravity anomalies in boundary zones between surveyed areas.

In the southern and the northwestern areas of the Osaka Plain, the International Gravity Formula γ_{1930}:

Table 2 Gravitational correction.

Area	(km²)	C.S. (g/cm³)	S.D.S. (g/cm³)	D.B. (g/cm³)	D.T.N. (mgal/m)	D.T.F.	C.F.A.
Eastern area	250	818	3.3	1.80	1.50	2.00	0.3086
Southern area	305	640	2.1	1.80	1.50	2.00	0.3086
N-W area	125	400	3.2	****	****	****	0.3086
N-E area	120	235	2.0	2.67	2.60	2.60	0.3086
Central area	170	303	1.8	1.45–1.94(1)	—(2)	—(2)	(3)
Ikoma Mt. Range	12.7	166	13.1	2.70	2.70	2.70	0.3086

C.S.: count of survey.
S.D.S.: surface density of survey.
D.B.: density for Bouguer correction.
D.T.N.: density for terrain correction at near-field.
D.T.F.: density for terrain correction at far-field.
C.F.A.: coefficient for free-air correction.
Notes
(1) Attributed to the drilling core, from surface to sea level, near the observation point.
(2) Abbreviated because observation in the plain area.
(3) $d\gamma/dh = 0.30855 + 0.00622 \cos^2\phi - 0.000144h$

$$\gamma_{1930} = 978.049(1+0.0052884 \sin^2 \phi - 0.0000059 \sin^4 \phi)(\text{gal}) \qquad (1)$$

was used as the standard gravity, where ϕ is the geocentric latitude. On the other hand, the Normal Gravity Formula γ_{1967}:

$$\gamma_{1967} = 978.0318(1+0.0053024 \sin^2 \phi - 0.0000059 \sin^4 \phi)(\text{gal}) \qquad (2)$$

was used in other areas. As we use γ_{1967} in the present compilation, we add the difference $\Delta\gamma$ between equations (1) and (2)

$$\Delta\gamma = 0.0171 - 0.0136 \sin^2 \phi \; (\text{gal}) \qquad (3)$$

to data in the southern and the northeastern areas.

Fig. 4 is a contour diagram of the Bouguer anomalies obtained by the adjustments among the data sets. The contour lines are drawn at an interval of 1 mgal. The Bouguer anomaly in the Osaka Plain indicates a somewhat intricate feature striking roughly northeast-southwest. It also reflects well the geological structure which consist of number of major reverse faults between the Osaka Plain and the surrounding mountain ranges.

As is shown in the contour map, there are two areas of positive high anomalies near the center of the plain, corresponding to north-south upland belt called Uemachi Daichi which is known as a Late Pleistocene uplift zone. The Bay area and the lowland between the Uemachi Daichi and the Ikoma mountain range show a high negative anomaly and suggest that the underlying basement rocks exist at considerably great depths.

4. Discussion

4.1 Basement Rocks

Most of the basement rocks under the Osaka sedimentary basin, which forms the Osaka Plain, are thought to be Ryoke granitic rocks; they are commonly exposed at various locations in the surrounding mountain ranges. The Ryoke granitic rocks consist mainly of granite, as well as some diorite, gabbro, tonalite and other types.

Gabbro similar to that outcropping in the Ikoma mountain range was sampled from the bottom of the deep well OD-2, drilled in the central part of the Osaka Plain (Osaka City 1964–1966). Therefore, the mean density of the basement rocks seems to be slightly higher than that of normal granite and may be estimated to be 2.70 g/cm³. This value is also supported by the gravity anlaysis in Ikoma mountain range as shown below.

If the subsurface materials are uniform over a wide area, a linear relationship should be seen between the gravity anomaly $g-\gamma$ and the altitude H as follows:

$$g-\gamma = a - H(\beta - 2\pi G\rho) \qquad (4)$$

where a is the Bouguer anomaly, β is a constant for the free-air correction and G is Newton's universal constant of attraction (HAGIWARA 1978). If we have a linear relationship between $g-\gamma$ and H, we can calculate the density of the subsurface material from the
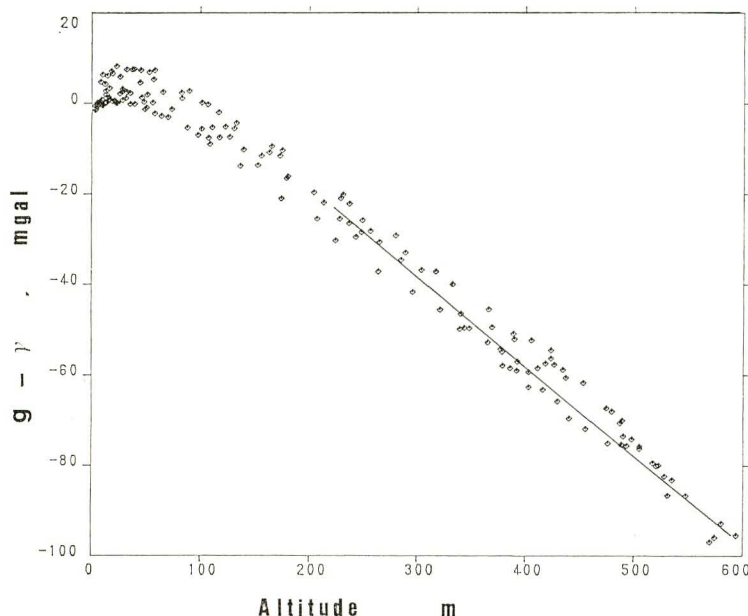
Fig. 5   G-H relation in the vicinity of the Ikoma Fault.

slope $(\beta - 2\pi G\rho)$.

Fig. 5 shows the correlation between the gravity anomaly and the altitude, the so-called $g-H$ correlation for observations carried out in the Ikoma mountain range. It is clear that the linear correlation exists between $g-\gamma$ and H, except at altitudes lower than 150 m. We determine the linear trend by the least square method and have $\rho =$ 2.71 g/cm^3 as the density of subsurface material; that is, as the density of the basement rocks under the Osaka Plain. The reason why the linear relationship does not hold at low altitudes is because young sediments exist near the low altitude region as the result of large-scale thrusting along the west side of the mountain range.

4.2   Density Profile based on the Bouguer Anomalies

The deep wells provide the reference data to determine the underground structure from gravity anomalies. We have one well penetrating into the basement in the central part of the Osaka Plain; OD-2 mentioned above. The data of OD-2 can be used as the standard section to infer the density profile based on the Bouguer anomalies. Fig. 6 shows a density profile in an E-W direction across the Uemachi Daichi, obtained by the two-dimensional Talwani method (TALWANI *et al.* 1959). The figure suggests that there is a local variation in the depth of the basement. It should be noted, however, that the profile does not take into account the regional trend of the Bouguer gravity anomaly discussed below.
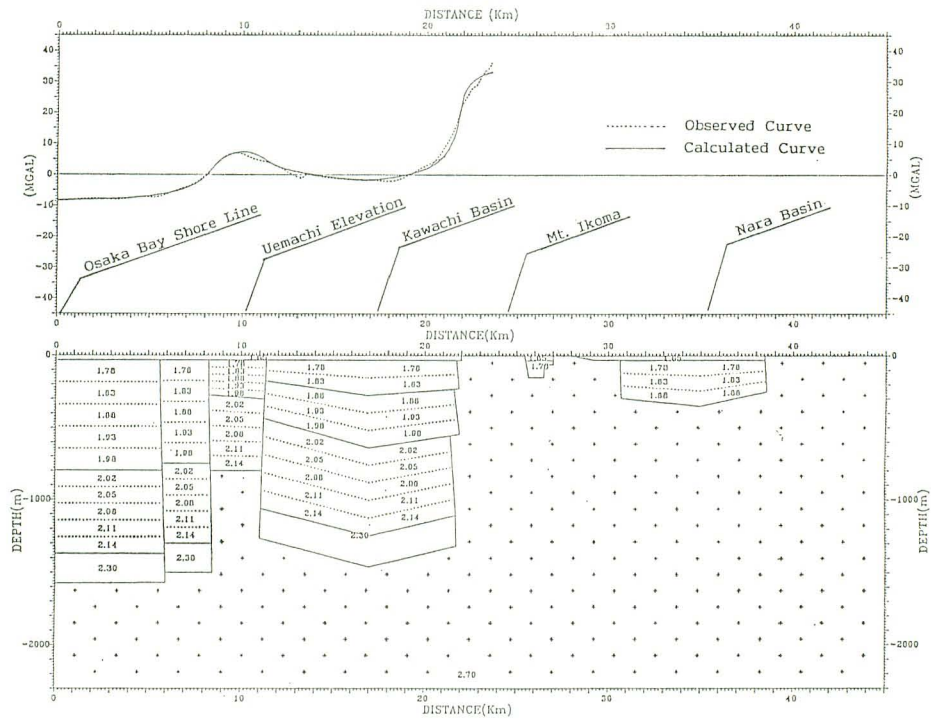
Fig. 6. Possible underground structure along E-W section of the Osaka Plain, based on the gravity anomalies. Values shown are density of sedimentary layer or basement rock (after RYOKI and NAKAGAWA 1984, NAKAGAWA *et al.* 1990).

4.3 Relationship between the Bouguer Anomaly and the Depth of the Basement

Most recently, many hot-spring wells have been drilled through the sedimentary layers into the basement rocks. Furthermore, the depths of the basement rocks have been obtained seismologically by means of reflection and refraction methods at several places (NAKAGAWA *et al.* 1989, NAKAGAWA 1990). Using these data, we can compare the Bouguer anomalies with the depths of basement rocks.

Fig. 7(a) shows the relationship between the Bouguer anomalies and the depths of basement rocks underlying the post-Miocene soft sediments at 18 points listed in Table 3. However, three data points at the northern part of the Osaka Plain, north of Yodo River, are excepted from the figure. The reason is that the Miocene or pre-Miocene sedimentary strata with a larger density may very possibly be distributed over the granitic basement in the region.

The data plots in the figure show a large scattering and the relationship is not clear. We interpret the scattering as the regional effect of the attraction of the subducting slab under the Kii Peninsula. Based on this interpretation, we expect that the linear rela-
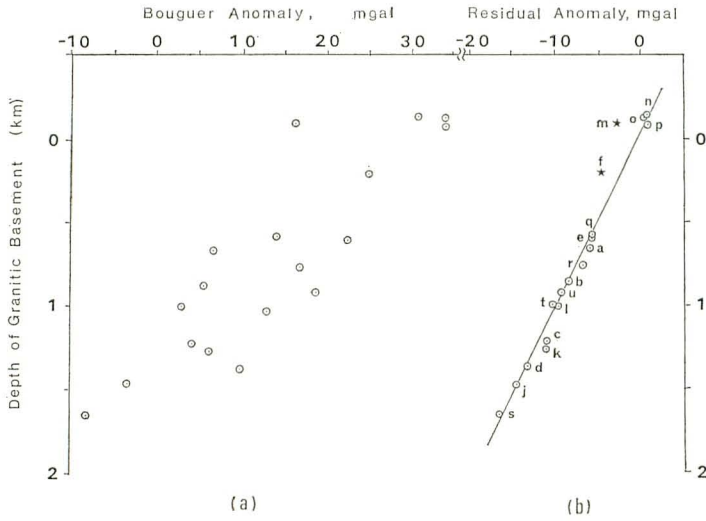
Fig. 7   Relation between the basement depth and the Bouguer anomaly.   Location
of points are as shown in Fig. 3.
Before (a) and after (b) reduction of the regional garavity anomaly.

tionship appears between the Bouguer anomalies $\Delta g''$ and the depths of the basement
rocks Z if we remove the regional effect of the attraction, using the formula

$$\Delta g'' - (\text{attraction of the slab}) = CZ + E \qquad\qquad (5)$$

Because the slab is planar and somewhat far from the Osaka Plain, let us assume that
the effect of the slab is expressed by a linear function of horizontal coordinates X and
Y:

$$(\text{attraction of the slab}) = AX + BY + E'$$

where X and Y are distances from the origin (135°30′E, 34°40′N) measured eastwards
and southwards, respectively.   Then we can expect the following relationship:

$$\Delta g'' = AX + BY + CZ + E$$

The constants A, B, C and E were determined by the least square method using the
data at 16 points (Table 3),
giving the results shown bellow,

$$A = 0.549 \text{ mgal/km} \qquad\qquad B = 0.730 \text{ mgal/km}$$
$$C = -0.00935 \text{ mgal/m} \qquad E = 12.55 \text{ mgal}$$

The correlation coefficient equals 0.999, and the standard deviation equals 0.70 mgal.

Fig. 7(b) shows the relationship between the depth of the granitic basement and
the residual Bouguer anomaly ($\Delta g'' - AX - BY - E$) for 18 points listed in Table 3.   It

Table 3   Bouguer anomalies and depth of granitic basement rock at each location.

No.	Location	$\Delta g''$ (mgal)	Depth (m)	X (km)	Y (km)
	Deep Well				
a	Osaka C., Miyakojima	7.5	655	2.52	−3.20
b	Osaka C., Tanimachi 6	6.3	858	1.76	−0.53
c	Osaka C., Momodani	5.2	1,215	3.67	0.92
d	Matsubara C., Bessho	11.0	1,350	7.11	9.02
e	Osakasayama C., Iwamuro	23.7	580	3.59	19.02
f	Tondabayasi C., Shindo	26.3	203	8.48	17.26
g	Suita C., Enoki	−5.8	1,374	−0.42	−9.63
h	Amagasaki C., Tsugiya	−11.7	1,201	−4.58	−7.82
i	Amagasaki C., Kuise	−10.7	1.353	−4.92	−5.35
j	Osaka C., Edobori	−3.0	1.474	−0.38	−2.18
k	Osaka C., Nishitanabe	7.2	1,254	1.60	4.58
l	Kishiwada C., Namimatsu	15.0	1,050	−11.38	22.30
t	Osaka C., Kouzu	4.0	996	0.84	0.15
u	Sakai C., Minaminoda	19.5	920	4.40	16.70
	Observation at Outcrop				
m	Higashiosaka C., Kamiishikiri	18.0	−100	14.44	−1.27
n	Kishiwada C., Konoyama	31.0	−140	−7.11	27.96
o	Tondabayashi C., Yokoyama	35.0	−130	7.95	22.60
p	Tondabayashi C., Taishicho	35.0	−80	12.38	19.18
	Seismic Exploration				
q	Osaka C., Sugimoto	15.0	580	0.69	9.09
r	Sakai C., Nagasone	16.5	760	0.69	12.76
s	Osaka C., Hokko	−6.5	1,650	−9.17	0.61

is clear that most of the data distribute near a straight line.

However, the two points f and m are not close to the straight line. These points are in Shindo (Tondabayashi City) and Ishikiri at the foot of Mt. Ikoma, respectively. Both are situated on well-known major thrust faults; they indicate low gravity because the sedimentary layers with a low density exist under the basement rock, and the faulting makes the density of rock bodies lower by the crushing.

From the good correlation between the depth of basement and the residual Bouguer anomaly, we conclude that for the local gravity structure in the Osaka Plain, the residual gravity anomaly at each point can be explained by a simple two-layer model, except for the area near the fault zone. Further, the estimated values of the constants A and B indicate that the attraction of the subducting slab decreases toward the direction of N37° W at a rate of 0.91 mgal/km. The attraction has the same value along the line parallel to the long axis of the Osaka sedimentary basin but not to the general direction of the large scale geologic structure such as the Arima-Takatsuki Tectonic Line, the Median Tectonic Line or the Nankai Trough.

4.4 Basement Structure in the Osaka Plain

The relationship shown in Fig. 7 indicates that the depth of the basement can be directly estimated from the residual gravity anomalies, except for the area near the fault, without complex calculations of gravity inversion. Fig. 8 shows the approximate depth
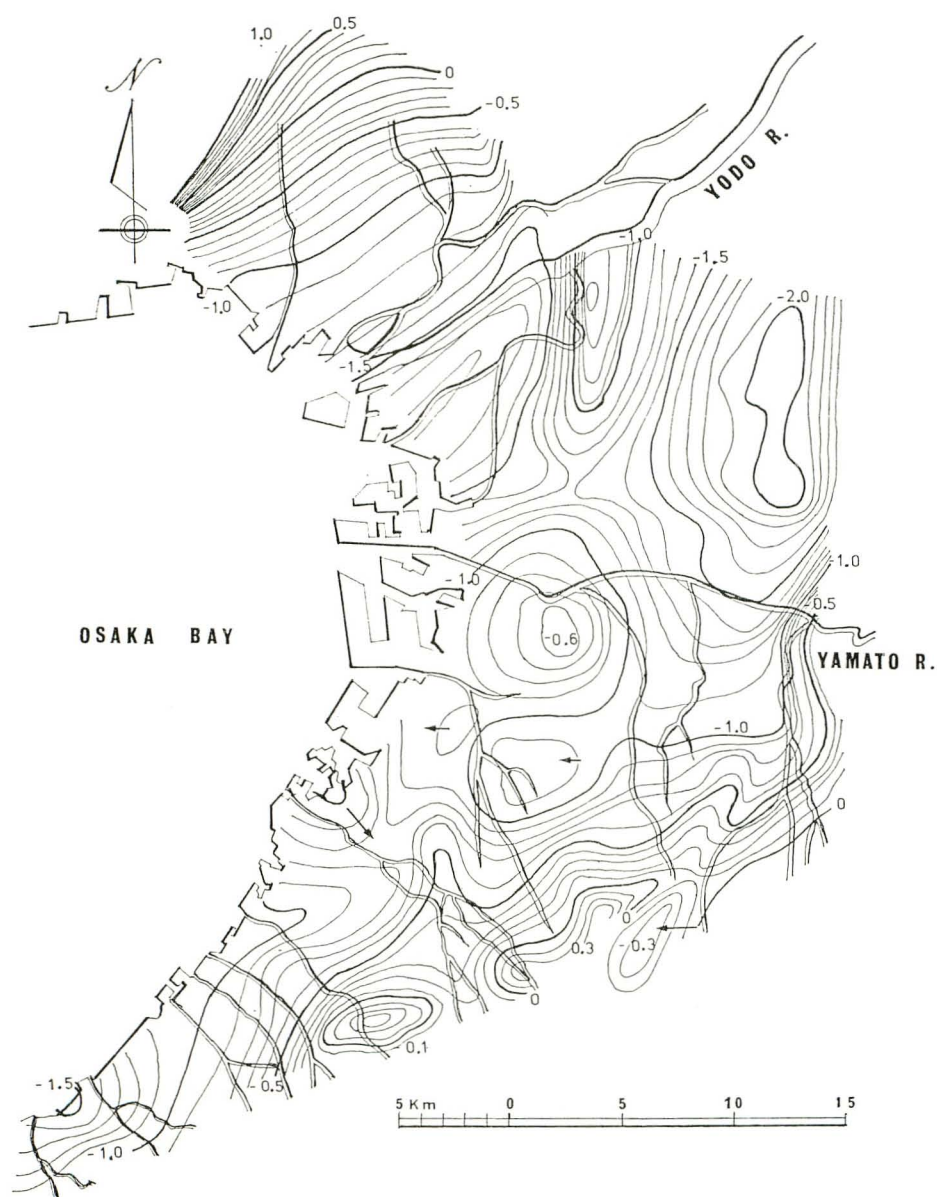

Fig. 8. Bottom surface featur of the Osaka sedimentary basin. The contour lines (0.1 km interval) represent depth (km) from sea level.

of the basement estimated from the residual gravity anomalies.   The structural features of the underlying basement are summarized below;

(1)   The maximum depth of the basement in the land part is over 2,000 m in the Higashi-Osaka region.   As the region is situated adjacent to the Ikoma mountain range which has a maximum height of 642 m, the difference between them may exceed about 3,000 m, which considered to be the amount of the vertical displacement by the Ikoma fault system which runs along the boundary between them.

(2)   At the estuary of Aji River (2.5 km south of the estuary of Shin-Yodo River), the basement is deepest in the area.   The region seems to be just on the active fault which characterizes the Yodo River Seismic Zone.

(3)   Under the Asakayama region in Sakai City, south of Yamato River, there is a subsurface hill which is comparable to the Uemachi Upland.

(4)   The structural trend of the basement is nearly NE-SW or N-S.   Those directions are concordant with long axis of Osaka Bay or the direction of Ikoma mountain range.

(5)   Basement structure is closely related to the surface geology or topography.   There is a high possibility that the structure strongly reflects the influence of Quaternary diastrophism.

Acknowledgments

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