PROCEEDINGS OF THE GEOLOGICAL SOCIETY OF CHINA
NO. 13, PP. 76-89, 10 FIGS., APRIL, 1970

GEOLOGY AND GRAVITY ANOMALIES OF THE PINGTUNG PLAIN, TAIWAN[1]

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(with 10 text-figures)

ABSTRACT

The results of detailed gravity measurements have been analyzed to evaluate the structural configuration underneath and around the Pingtung plain in southern Taiwan. The gravity anomalies indicate the presence of lithologic or structural breaks that correspond with the Chaochou fault and the Chishan fault. The upthrown sides of large faults and the anticlines have positive gravity anomalies and high gravity gradients. This is attributed to a variable density of the rocks involved which were verified by Nettleton's density profiles.

The Pingtung syncline, trending N-S from Likang to Tungkang, is on a series of great negative gravity anomalies. It is a sedimentary trough due to step-faulting of the basement resulting from upthrusting of the eastern block of the Chaochou fault. Local structures such as the Pingtung anticline and the Chaochou structure produce appreciable anomalies on the residual gravity map that are almost obscured by strong regional gradients on the Bouguer gravity map.

There seems to exist a discordance between the surface and the deeper structures of the Fengshan anticline which lies on the southern trend of the Chishan fault.

The Fengshan anticline and the Chaochou structure that are situated at the inner margin of the Pingtung basin should be considered as having suitable conditions for trapping oil and gas, so for as the petroleum geology is concerned.

INTRODUCTION

The Pingtung plain, lying in the southern part of Taiwan, is somewhat rectangular in shape, 50 km long in the north-south direction and 30 km wide in the east-west, its area being approximately 1500 sq km. This plain extends to low hills on the north, which are cut by the Liukwei fault; to the Chishan fault and the Fengshan anticline on the west; to the southwest coast of Taiwan on the south; it is limited by the wall-like southern stretch of the Central Range of Taiwan on the east. The Hsiatanshuichi, the second longest stream on Taiwan flowing throughout the area of the Pingtung plain, has played a very important role in the accumulation of the younger sediments in this area but a trough with especially thick sedimentary fills of Tertiary rocks is considered to be here whcih may be favourable for future oil exploration.

One of the pre-requisites for the formation of an oil-field is the presence of a large sedimentary through with parent and reservoir rocks for hydrocarbons and favourable tectonic structures. Consequently, the Pingtung plain has aroused the interest of petroleum geolcgists for their studying of the subsurface structures of the area. In the fall of 1966 and the spring of 1967, a detailed gravity survey was carried out by the Taiwan Petroleum Exploration Division, Chinese Petroleum Corpo-

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ration, with the thought that such data might possibly contribute to a better structural understanding of the area. A Master Type of the Worden Gravimeter, No. 520, with a sensitivity of approximately 0.1091 milligal per scale division, was used to establish about 4000 stations covering an area up to 1560 sq km. It is hoped that the results of this study will be useful in the study of the petroleum geology as well as in focusing attention on the quantitative interpretation of the subsurface structures.

In order to understand much more accurately the possible geologic structures that caused the gravity anomalies, the surface and the subsurface geological information was studied in detail, particularly the structural cross section based on Pingtung PTG-1 well logs and the density distribution of the surface rocks which are considered to be a very important factor for the Bouguer correction. The "trial and error" method was used to process the data obtained from the gravity measurements. The methods of least squares and the analytical method were introduced to remove both the regional gravity and undesired anomalies. The upward continuation of the gravity data and the line-integral method were also used for calculating the possible subsurface structures and attitudes of the faults.

SURFACE GEOLOGY

The general geology of the Pingtung plain is presented to aid the reader in understanding the geophysical information developed from this study (Fig. 1). The plain is covered by sands and gravels of recent alluvial deposits, while Neogene rocks are distributed around the border of the plain.

A thick sequence of hard black slate intercalated with beds of medium- to fine-grained quartzose sandstone is distributed on the western flank of the Central Range east of the plain. These hard rocks which are probably equivalent to the Suao Group of Eocene-Oligocene age are now considered to be Miocene in age by some geologists.

In the vicinity of Chishan and Liukwei, north of the plain, the alternating beds of sandstone and shale are widespread. Altogether these alternating beds are about 3,000 m thick and may be equivalent to the Mucha Formation of Miocene age in the Chishan oil field. The Pliocene Gutingkeng Formation and the Pleistocene Linkou Conglomerate are exposed widely on the northwest and the west edge of the plain. This thick conglomerate is in an unconformable contact with the underlying Gutingkeng Formation.

SUBSURFACE GEOLOGY

The first stratigraphic test well in this area, the Pingtung PTG-1, was drilled by TPED, CPC in October 1967 at a selected location about 1.5 km east of Pingtung city. The well reached a depth of 3,003 m, which was the limit of the capacity of the well drilling rig used. No oil and gas was found in this well. The rock succession encountered in the PTG-1 well, which has been preliminarily examined by the Paleontological Laboratory of TPED, CPC, is as follows:

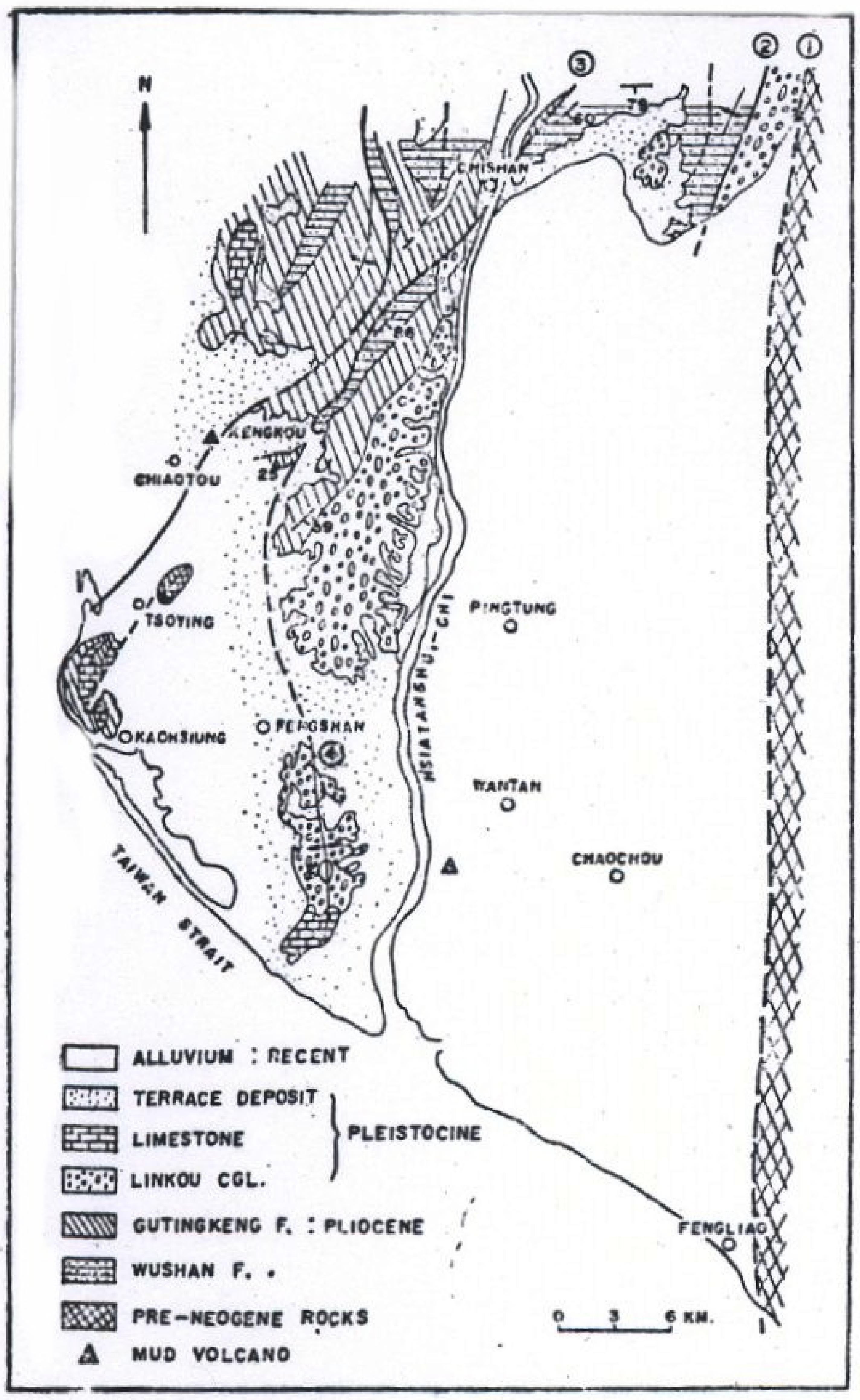

Figure 1. Geologic map of the Pingtung plain, southern Taiwan. (1), Chaochou fault; (2), Liukwei fault; (3) Chishan fault; (4), Fengshan anticline.

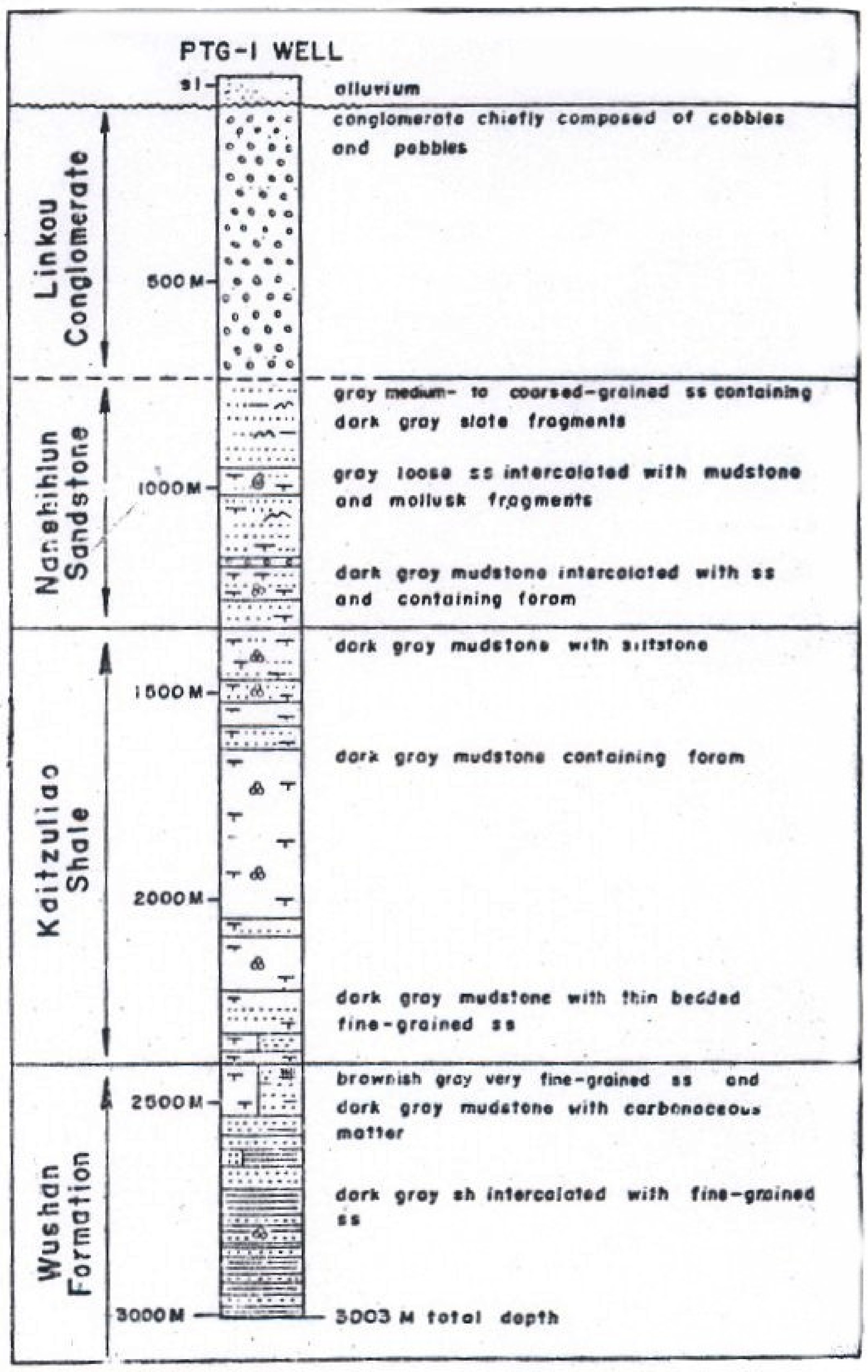

Figure 2. Stratigraphic columnar section of the Pingtung PTG-1 well.

		Depth, m
Recent	Alluvium	0- 73
	- - -Unconformity	
Pleistocene	Linkou Conglomerate	73- 737
	- - -Disconformity	
Plio-Pleistocene......	Nanshihlun sandstone	737-1341
Pliocene..............	Kaitzuliao Shale	1341-2395
	Wushan Formation	2395-3003

The stratigraphic columnar section is presented in Figure 2. The Pleistocene Linkou Conglomerate is a loose deposit, about 660 m thick. It is composed chiefly of cobbles and pebbles of quartzose sandstone, and occassionally intercalated with some thin layers of sandstone. The Linkou Conglomerate may be tentatively correlated to the upper Toukoshan Formation in northern and central Taiwan.

The Nanshihlun Sandstone penetrated in the depth between 737 to 1341 m is very loose medium- to coarse-grained sandstone containing a very high percentage of dark gray slate fragments. The depositional condition of the slate fragments seems similar in many respects to that of the Plio-Pleistocene rocks under the Chiayi coastal plain (1962, Hsieh).

The Kaitzuliao Shale encountered first at the depth of approximately 1341 m is 1010 m in thickness. It contains dark gray soft mudstone intercalated with whitish gray siltstone. Numerous mollusks and foraminifers are found in the upper part of the shale, among which *Operculina ammonoides* is the most abundant. This shale may probably be equivalent to the upper Gutingkeng Formation in the Tainan-Kaohsiung area.

The Wushan Formation, having a thickness more than 550 m, occurs in the deepest part of the well. Its total thickness is not known because the well has not yet penetrated through the formation. It consists of brownish gray, very fine-grained sandstone and dark gray mudstone intercalated with shale and sandy shale. This formation is correlated with the lower Gutingkeng Formation in the Tainan-Kaohsiung area.

According to the geophysical prospecting records, both the gravity and the seismic, the formations mentioned above evidently thin out toward the up-dip direction in the eastern part of the plain.

STRUCTURE

Three striking structural features can be observed in the Pingtung plain. They are named the Chaochou fault, the Chishan fault, and the Fengshan anticline. In general, the predominating trend of strike in these three structures is recognized as N-S to NNE-SSW.

The Chaochou fault is the most significant structural feature of the Pingtung plain. It is a high-angle longitudinal thrust which brings the pre-Neogene rocks in direct contact with the Pleistocene Linkou Conglomerate in the north of the plain. The alluvium and terrace deposits on the plain conceal the southern stretch of the fault but no one would fail to recognize its trace from the topographic expression along the straight eastern edge of the plain.

The Chishan fault, lying in the northwest part of the plain and extending further south from a town called Chishan, from which the locality name of the fault is derived, is one of the major structural lines in the area. This fault is an upthrust fault, approximately 22 km in length and is concealed by the alluvial deposits near the little town of Kengkou, so that the southward extension is still in speculation. The fault plane dips at a high angle toward the east which is the upthrown side. The maximum throw is not less than 2000 m in the vicinity of Chishan and may gradually decrease southward and die out near Fengshan.

The Fengshan anticline, located on the west margin of the area investigated, is a broad gentle fold. It is a nearly asymmetrical elongate anticline trending N-S with a traceable length of about 14 km and a width of 4 km. The rocks exposed on this anticline are predominately Pleistocene reef limestone and the Linkou Conglomerate. They generally dip at 25 degrees on the west flank and at 10 to 12 degrees on the east flank. The anticline axis plunges to the north and is concealed by a rather thick alluvial deposits.

THE GRAVITY SURVEY

With the thought that the gravity data may possibly contribute to a better structural understanding of the Pingtung plain, a rather detailed gravity survey was carried out by the gravity crew of TPED, from September 1966 to March 1967.

The framework of the gravity measurements is a series of subbases which were set out at intervals of around 10 km. Nineteen subbases were distributed over the area of the plain. These subbases were first established by a series of looping observations from the gravity bases at Tsoying and Fengliao, that were derived from the fundamental gravity base at the Taipei Military Air Transport Service Terminal in June 1962. The traverse lines within 2-3 km spacing were mostly along the roads and the station readings were taken at 300 m intervals. About 4000 stations were established to cover the area up to 1560 sq km. Base or subbase checks were made at least once every two hours and numerous tie stations were reoccupied to obtain accurate data. In order to compare with the Bouguer gravity map made in other parts of Taiwan, all gravity values established in the area of the Pingtung plain were referred to the zero gravity base 0-0 located at the gate of the building of the Taiwan Petroleum Exploration Division at Miaoli.

Elevations and locations of stations were run by level and plane table surveys. The limits to which the closures were being held were for level within 7 cm multiplied by the square root of the traverse length in km and for horizontal control 25 m, so that no significant error might be introduced into the final result.

All the area that could be travelled by wheeled vehicles was worked in the conventional manner and the rougher part of the foothills where travel by cars was impossible, was necessarily done by walking on foot.

Latitude corrections were obtained from the well-known International Formula of 1930. Topographical and elevation corrections were made by applying the Bouguer type correction which is proportional to sea-level elevation.

DENSITY MEASUREMENTS

The Bouguer correction made in the reduction of gravity data requires the knowing of the average densities of the rocks near the surface. It is necessary that all reductions should be made to a precision to retain all of the accuracy of the field observations. The rock densities which play a very important role on the correction cannot be obtained on the basis of a few direct determinations from rock samples because of the variations in lithology. Therefore, the Nettleton's profile method, which has been found quite satisfactory for determining density of the surface rocks by use of the gravimeter itself, was introduced in this study. Twenty density profiles were made in the vicinity of the Pingtung plain and the results are as follows:

Stratigraphic unit	*Average density*
Alluvial deposits	1.9 G/cm^3
Linkou Conglomerate	2.0
Upper Gutingkeng Formation	2.1
Lower Gutingkeng Formation	2.2
Wushan Formation	2.3
Pre-Neogene rocks	2.5-2.6

The map of the density distribution of the rocks from surface to the datum plane taken at sea level has been reconstructed with the values obtained from the density profiles (Fig. 3). In addition, map of density distribution may reveal some significant structures caused from the contrasts of the rock densities. The sharp variation of the density as indicated in the eastern part of the Pingtung plain is one of the strong evidences showing the structural or stratigraphic discontinuity there. It is the trace of the Chaochou fault.

CEOLOGIC SIGNIFICANCE OF THE GRAVITY DATA

The gravity data together with surface ond subsurface geologic information have been analyzed to evaluate the structural configuration in the area investigated. In general, gravity maps are obviously not geological in nature, so that other steps such as removing regional effects, calculating derivatives, and other analytical processes are required before these maps can be directly related to geology. For this reason, the Bouguer, regional, and residual maps, and the structural cross section combined with the gravity profile were prepared as shown in Figures 4 through 9. In order that the gravity contours may be more easily compared to geologic data, the structural trends and the surface traces of faults have been sketched on the gravity maps (Figs. 5 and 6). An analysis of these gravity anomaly maps in connection with the geology suggests the following elements in the surveyed area:

1. Pingtung basin; 2. Chaochou fault; 3. Chaochou structure; 4. Liukwei graben
5. Chishan fault; 6. Fengshan anticline; 7. Hsiaoliuchiu anticline.

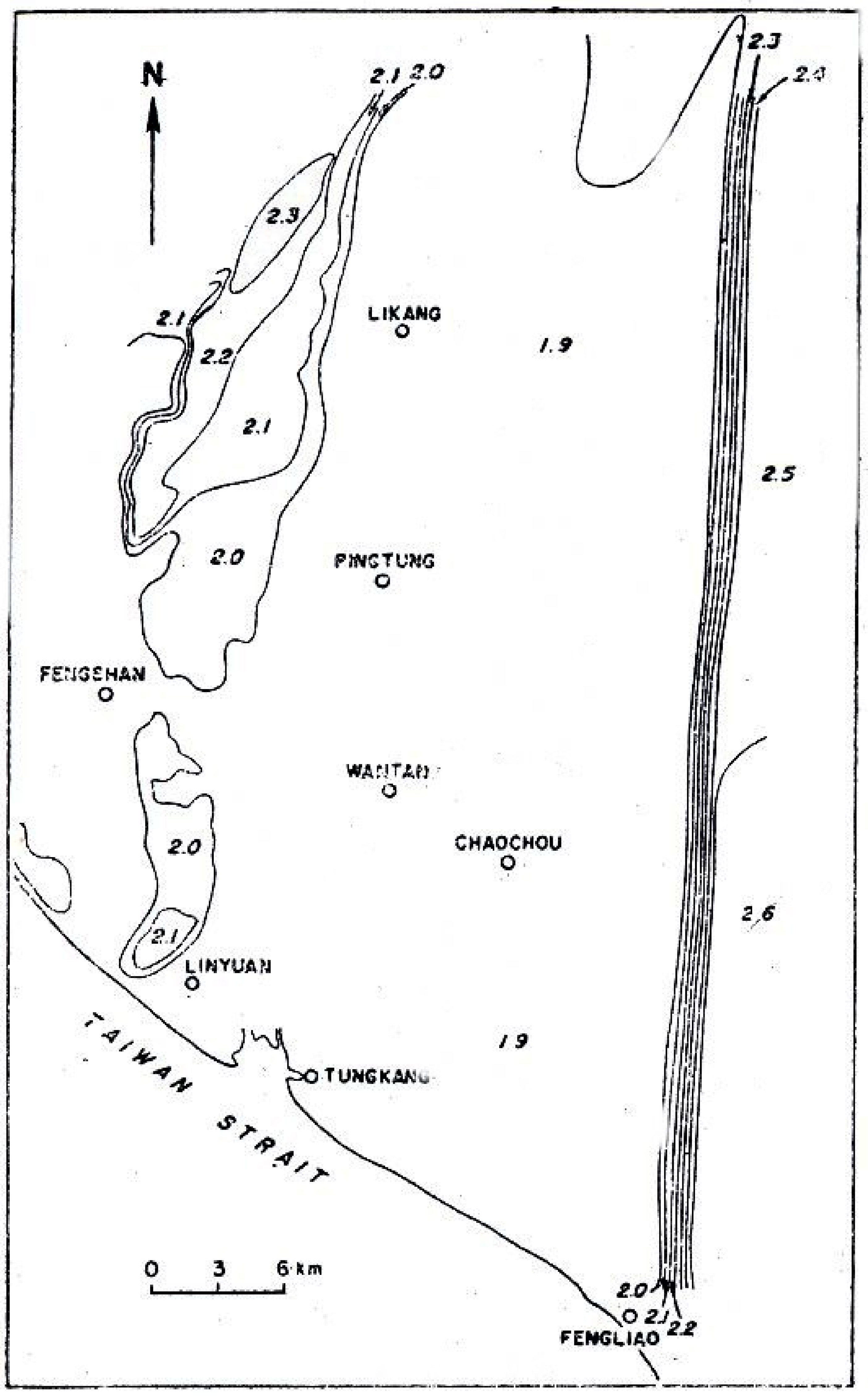

Figure 3. Density distribution of the rocks from surface to sea level around the Pingtung plain, southern Taiwan.

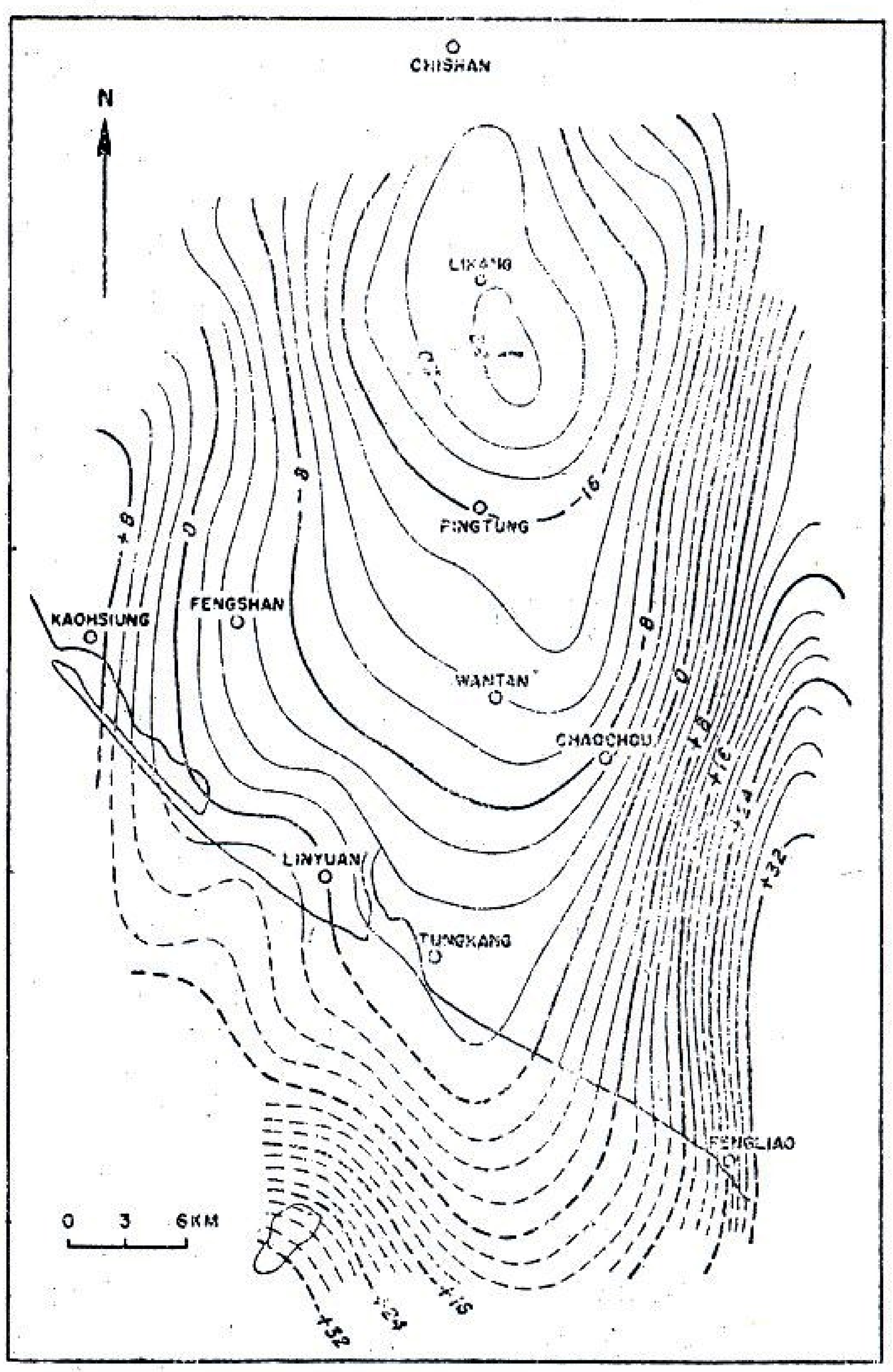

Figure 4. Regional gravity map of the Pingtung plain, calculated by the analytical method with radius $R=\sqrt{5}$ km.

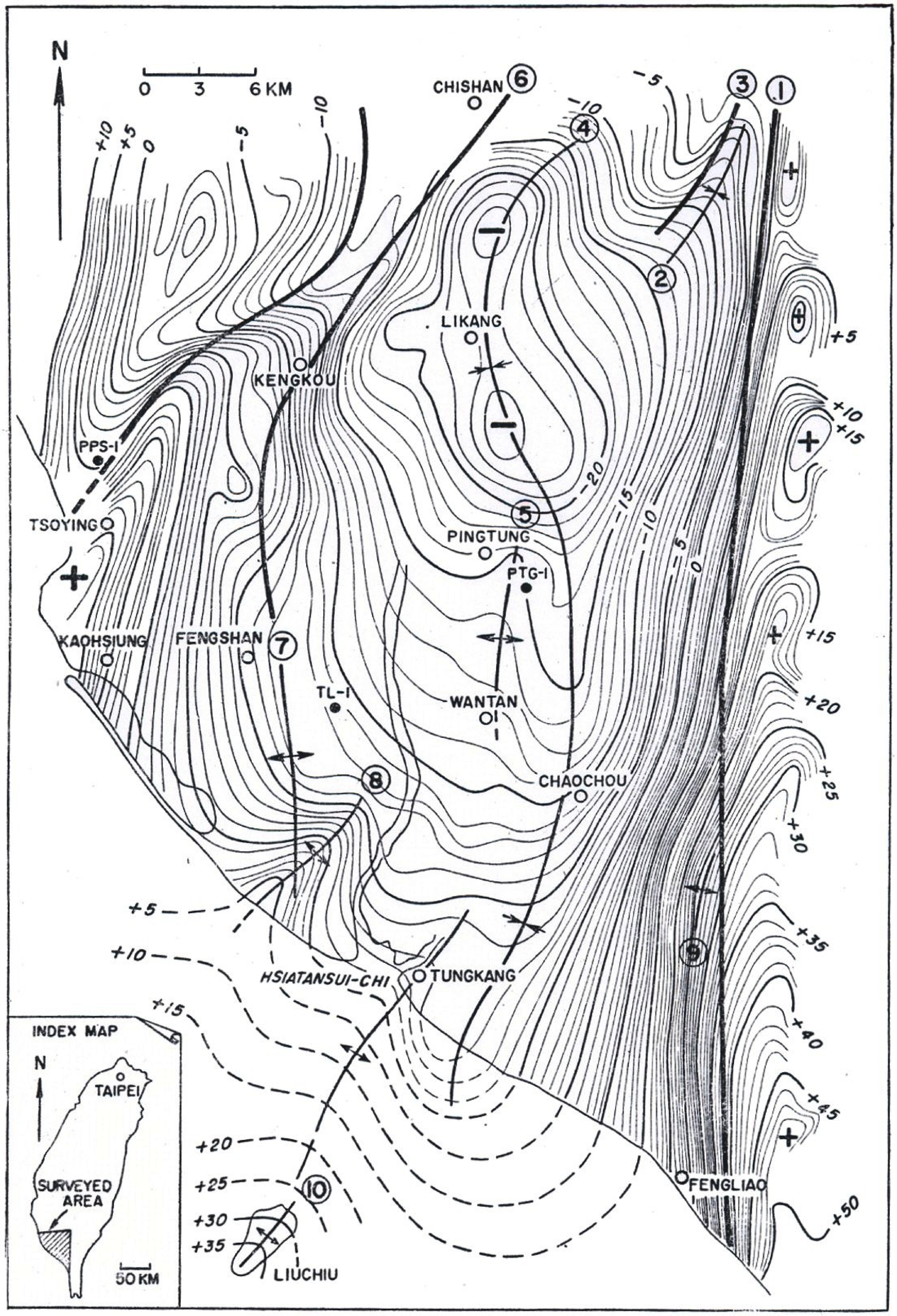

Figure 5. Bouguer gravity map with geological structures of the Pingtung plain. (1), Chaochou fault; (2), Liukwei graben; (3), Liukwei fault; (4), Pingtung syncline; (5), Pingtung anticline; (6), Chishan fault; (7), Fengshan anticline; (8), Deeper trend of the Fengshan anticline; (9), Chaochou structure; (10), Hsiaoliuchiu anticline.

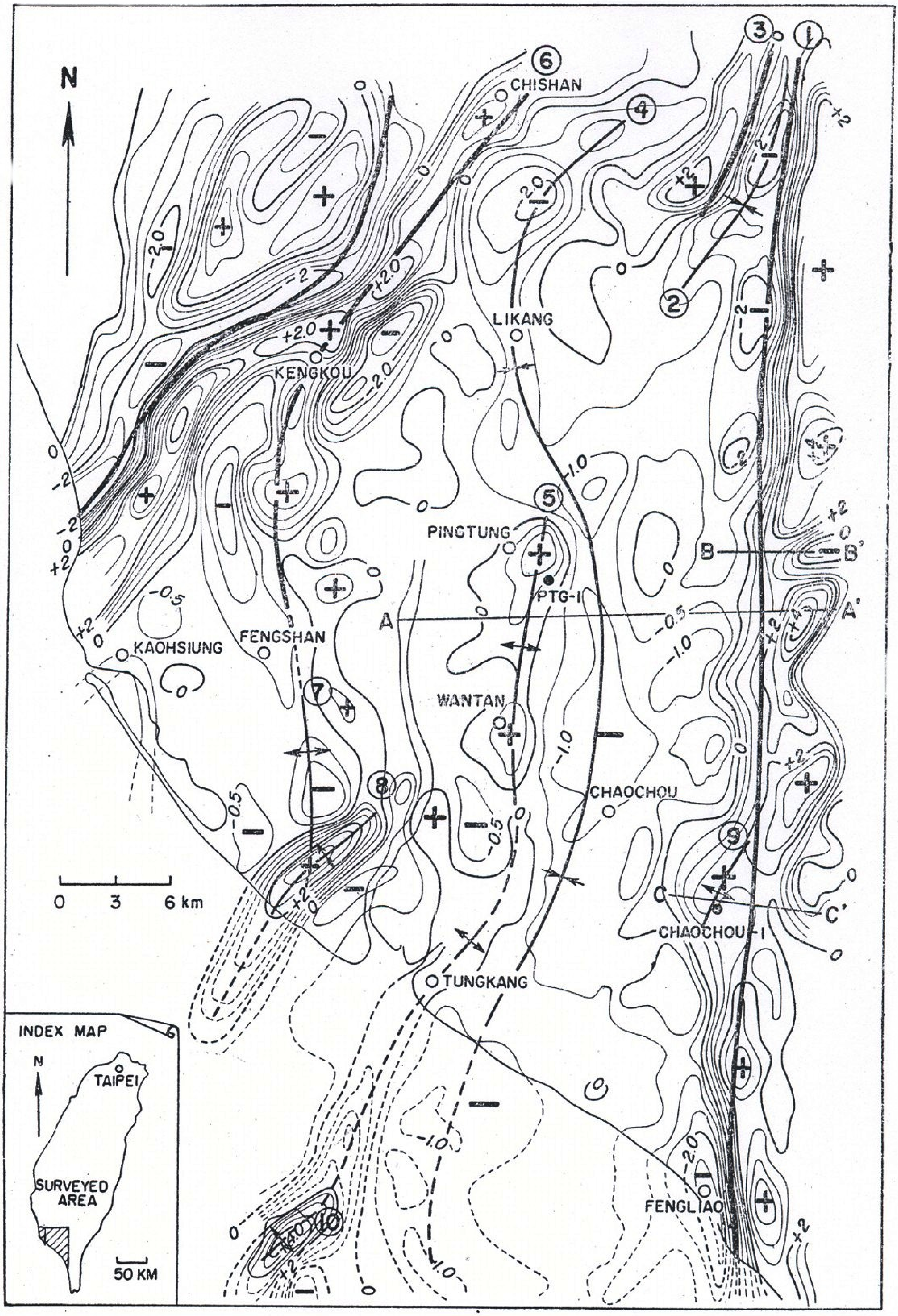

Figure 6. Residual gravity map derived from Fig. 5 by the 8 points analytical method with grid of 1-km spacing and radius $R=\sqrt{5}$ km, showing the correlation of the anomalies and the structures of the Pingtung plain (see Fig. 5 for names of the structures).

Pingtung Basin

The Pingtung basin is located in the central part of the Pingtung plain. It is brought out by oval-shape isogals forming a great minimum of about -23 milligals, the oval trending N-S, between Pingtung and Likang (Fig. 5). This gravity minimum spreads out in all directions with steep gravity gradients, 3.5 mgal/km, 2.2 mgal/km, and 2.0 mgal/km respectively in the east, the north, and the west of the basin, while a rather broad gentle gradient, around 1.0 mgal/km, is recognized in the south. The great minimum may be inferred as a possible sedimentary trough lying under the Pingtung plain with considerable thick sediments deposited in it. The trough is shown in a series of negative gravity anomalies lying in a N-S direction through Likang, Pingtung, Chaochou, the east of Tungkang, and probably continuing into the Taiwan Strait (Fig. 6). The series of the negative gravity anomalies is called the Pingtung syncline by the writer. The regional gravity (Fig. 4) shows smooth curves which are attributed to the effects of the deep and broad sedimentary basement.

Besides these strong minimum anomalies, there is to be observed a subordinate narrow small positive anomaly, also trending N-S, west of the Pingtung syncline. This positive anomaly has been proved to be a fold structure by the seismic reflection surveys. It is the Pingtung anticline. The depth of the mass from which the Pingtung anomaly is produced can be estimated by the graticule method or by the half width on the gravity profile. Although the anomaly of the Pingtung anticline persists from Pingtung to Wantan, 10 km in length (Fig. 6 and 9), it is a rather shallow structure approximately 1000 m below the surface and may be possibly no more existent in the deeper part below 2000 m. In October 1967, the PTG-1 well was drilled down to 3003 m in the Pingtung anticline by CPC. No oil or gas has been found but it yielded very important subsurface geological information. This small anticline in the big basin may be adequately explained as but an anticline in the synclinorium. Therefore, no more attention need be paid on such a structure, as far as the petroleum geology is concerned.

In comparing gravity effects of assumed subsurface structure with actually observed values of gravity, a line-integral method of computing the gravimetric effects of two dimensional masses is used. The computations are somewhat laborious. The preliminary results are graphically presented in Figures 7 and 8.

Figure 7 shows the case in which the subsurface structural configuration of the Pingtung basin is assumed to be a simple one. No fault has been taken into consideration. The computed curve does not differ so much from the observed one and so the sedimentary basement is estimated to be 6000 m deep in the vicinity of Pingtung and becomes shallower in the eastern part of the area because the basement rocks, say pre-Neogene, have been brought near to the surface by the uplift due to the upthrusting of the eastern block of the Chaochou fault. The formations encountered in the PTG-1 well are thinning out in the up-dip direction toward the Chaochou fault.

Figure 8 indicates the down-warping of the sedimentary basement with respect to the several step-faults resulted from the upthrust of the Chaochou fault. Under this assumption, the calculated gravity values are somewhat similar to that of the observed one. The Chaochou-1 well, drilled recently by CPC on the Chaochou structure, supplies certain subsurface data supporting this assumption.

According to the verified conditions, the extension and depth of the Pingtung sedimentary basin can be calculated. Furthermore, structures and faults can be deduced. The gravity measurements can be applied to oil geology problems. There is very high possibility of existence of stratigraphic or faulted traps in the for-

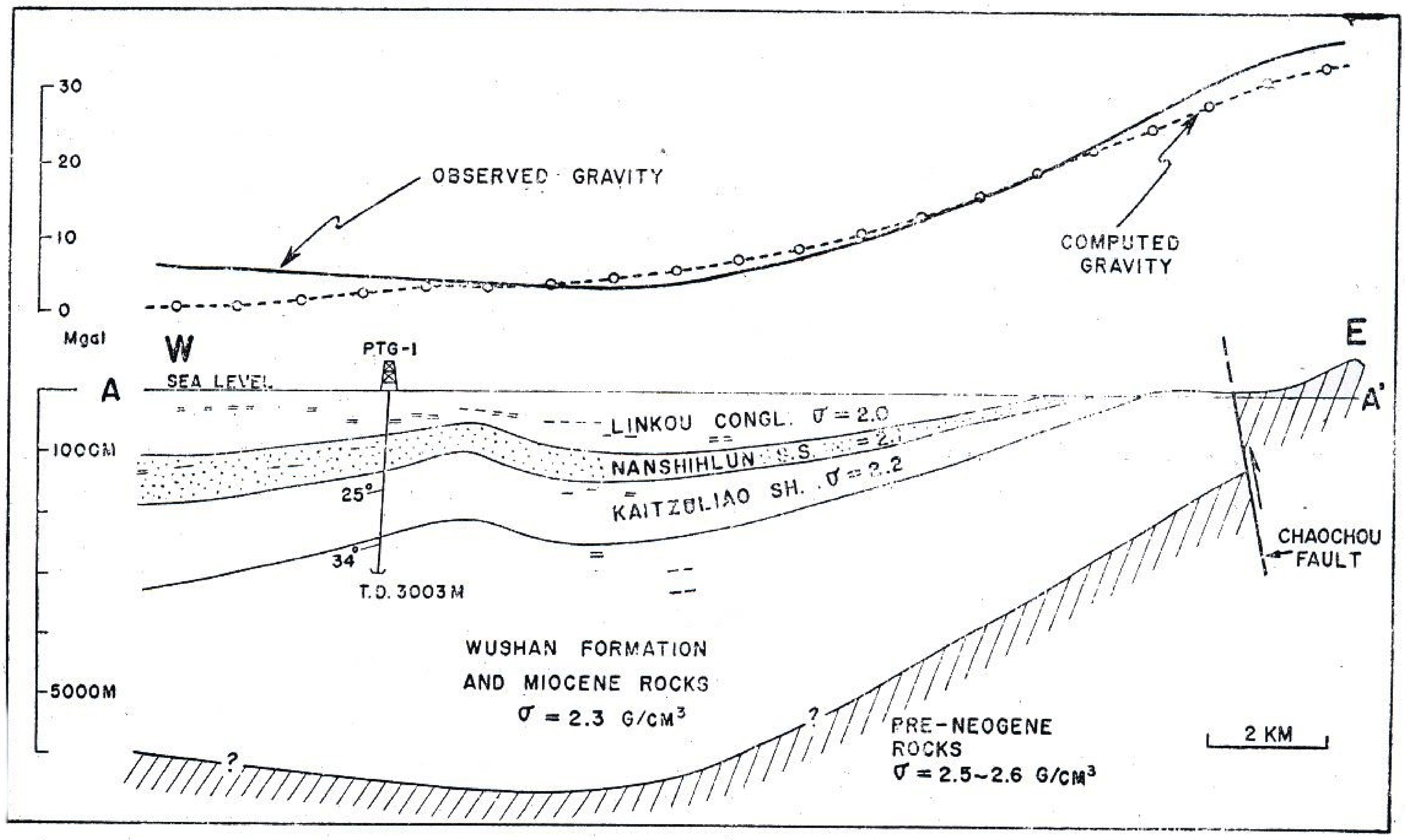

Figure 7. Gravity anomaly curves and east-west structural cross section A-A′ through the PTG-1 well, showing the computed gravity for configuration with a simple down-warping of the sedimentary basin in the Pingtung plain, southern Taiwan.

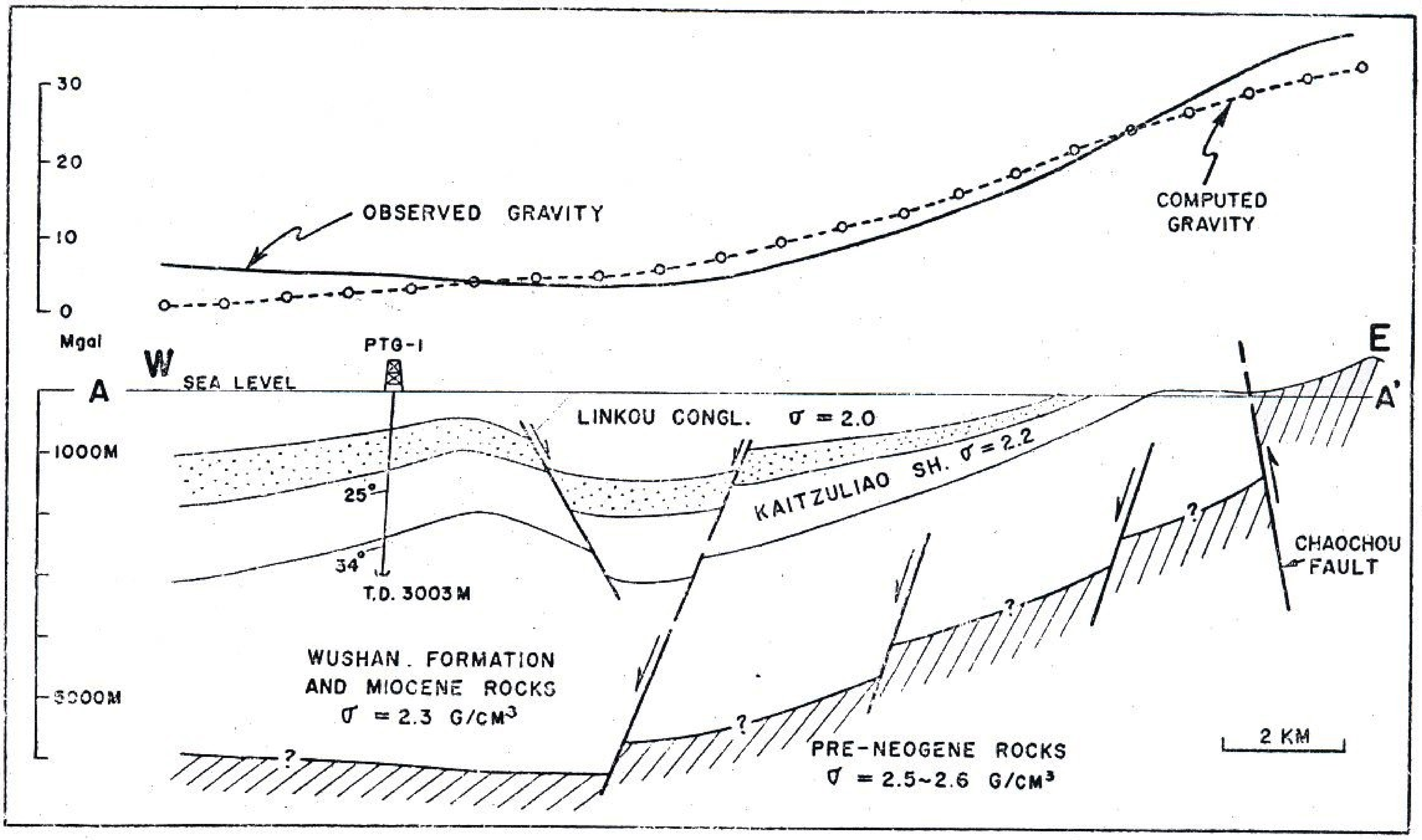

Figure 8. Gravity anomaly curves and east-west structural cross section A-A′ through the PTG-1 well, showing the computed gravity for configuration with several step-faults in the sedimentary basement of the Pingtung plain, southern Taiwan.

mations favourable for hydrocarbon accumulations in the eastern margin of the Pingtung basin, if the structural configuration as shown in Figure 8 is taken into account.

Chaochou Fault

Another striking feature indicated by the anomalies is the very great gravity effect of the Chaochou fault which extends in the N-S direction for more than 60 km in the eastern part of the Pingtung plain. It has a strong effect on the Bouguer gravity curves (Fig. 5) that increase suddenly from 1-2 mgal to 5-7 mgal per kilometer. On the residual gravity map, a series of positive gravity anomalies along the east side of the fault are recognized. It seems that the only reasonable explanation of this large gravity effect is that the densities of the rocks involved on both sides of the fault are quite different, and this effect also indicates that the stratigraphic displacement of the fault is of course very large, not less than 1000 m. With the help of the upward continuation of the observed gravity profile, the position of the Chaochou fault trace and the dip of the fault plane are estimated (Fig. 10). The fault dips toward the east with high angles ranging from 75 to 80 degrees. It is a thrust fault with the upthrown side on the east.

Chaochou Structure

The Chaochou structure located 7 km southeast of Chaochou city can be hardly recognized on the Bouguer gravity map because the anomaly that is believed to be due to a local structure is almost obscured by the strong regional gradients near the Chaochou fault. After elimination of the regional effect, the positive anomaly with a closure of +5 milligals is presented in Figures 6 and 9. It is considered to be an faulted anticlinal structure which seems to be a more favourable structure than the Pingtung anticline for trapping oil and gas.

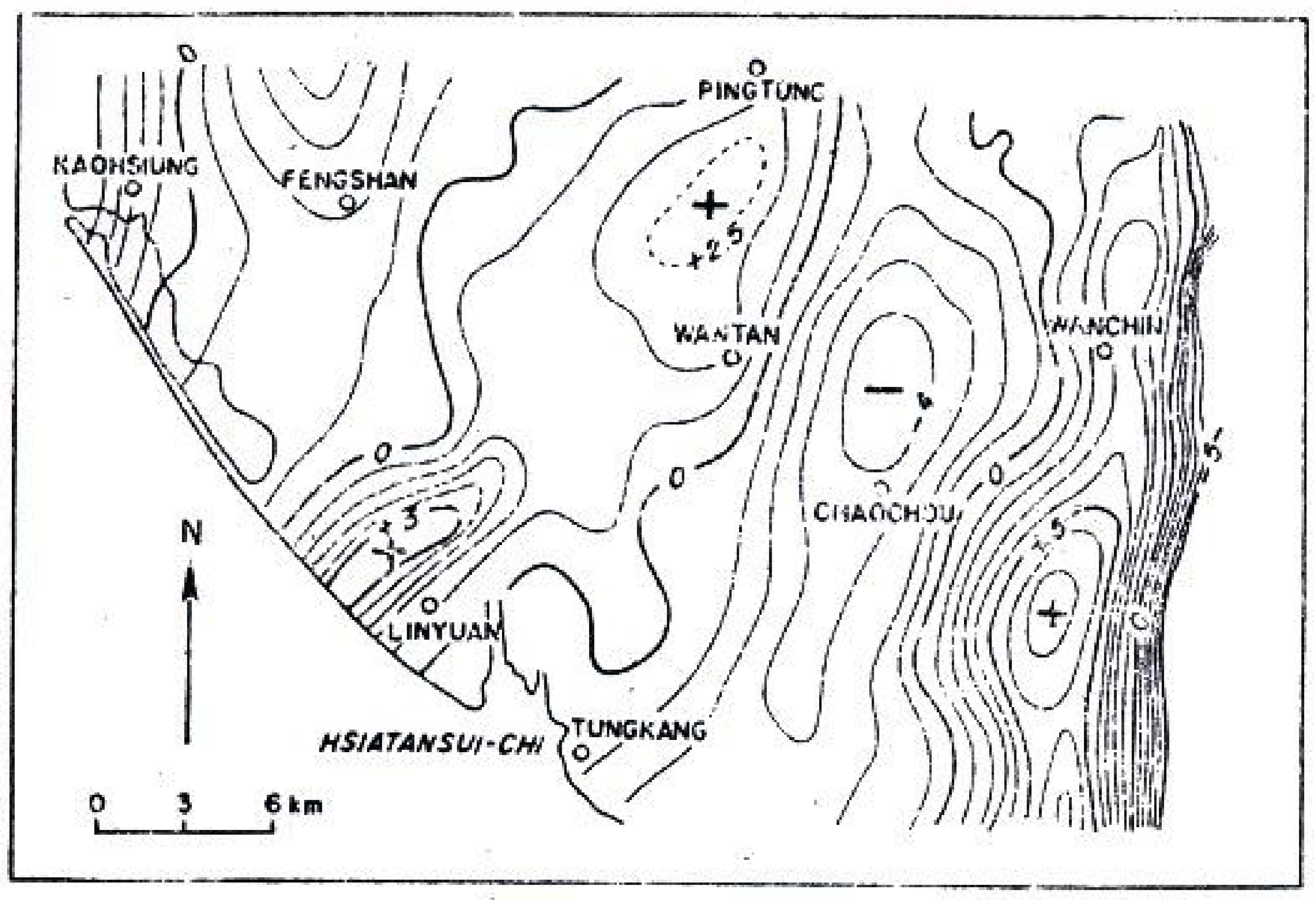

Figure 9. Residual gravity map of the Pingtung plain, calculated by the least squares method and 3rd order polynomials for estimating the regional gravity field.

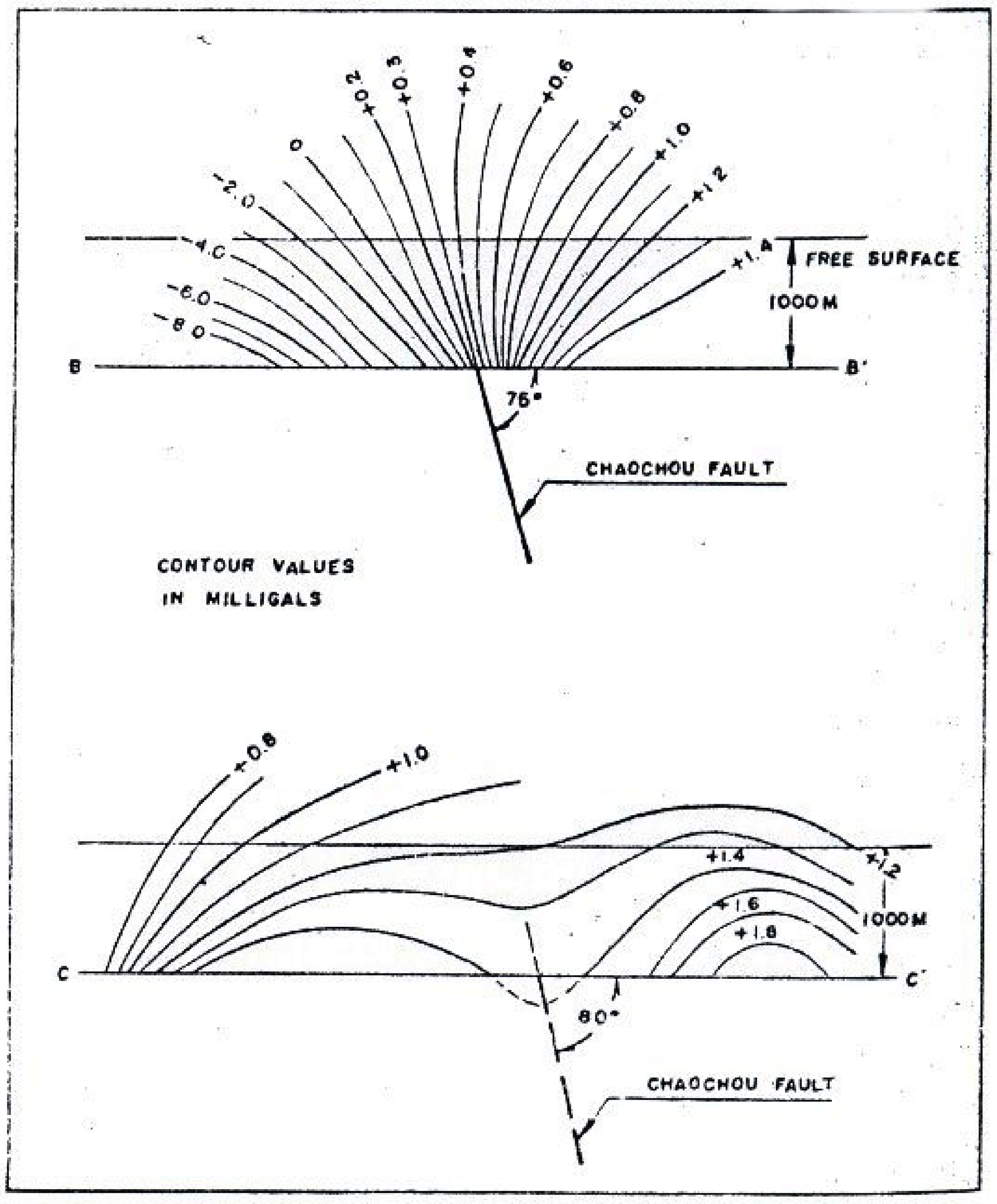

Figure 10. Upward continuation of the observed gravity profiles, B-B′ and C-C′ (see Fig. 6 for location), showing the attitude of the Chaochou fault in the Pingtung plain, southern Taiwan.

Liukwei Graben

The Liukwei graben located at the northeastern corner of the Pingtung plain has long been known as one of the conspicuous structures in southern Taiwan. It is a narrow small negative anomaly of about −2 milligals between the Chaochou and the Liukwei faults. This negative anomaly with high gravity gradients on both sides seems to be a simple expression of lower density of the sediments within the graben as in contrast to adjacent heavier rocks that have been brought up by the faults. On the gravity map, the Liukwei graben is associated with the Pingtung basin.

Chishan Fault

Gravity anomalies indicate the presence of lithologic breaks that correspond with the known geology along the Chishan fault. This is an upthrust fault with the up-throw on the east side. The fault is traceable from Chishan to Kengkou from surface geological feature and is concealed by the alluvial deposits in the vicinity of Kengkou. Therefore, its southward extension is uncertain. According to the gravity survey, the more continuous gravity features corresponding closely with the trends of the Chishan fault indicates that the fault extends further south from Kengkou to the north end of the surface axis of the Fengshan anticline. Though the stratigraphic throw of the fault is so big in the Chishan area, it decreases gradually southward and dies out near Fengshan.

Fengshan Anticline

The particular anticline situated on the west margin of the Pingtung plain may have oil and gas possibilities ascertainable with structural study. It was mapped by W. S. Tu of TPED in 1966. The surface axis striking N-S plunges northward into the trace of southern stretch of the Chishan fault. A very interesting fact is that gravity expression of the Fengshan anticline shows some deviations from the surface trend of the anticline. The positive anomaly produced by the deeper structure of the anticline trends N45°E, quite different as compared with the N-S trending of the surface axis. It seems probable that there is a discordance between the surface and the deeper structures of the anticline. The deeper culmination of the anticline may extend southwestward into the Taiwan Strait. The gravity data may throw light on the study of the structural development of the anticline and also give very important exidences for evaluating the subsurface structure with the structural discontinuity taken into consideration.

Hsiaoliuchiu Anticline

The Hsiaoliuchiu anticline is situated on the islet named Liuchiuhsu in the Taiwan Strait, 13 km south of Tungkang city near the southwest coast of Taiwan. This anticline is a symmetrical fold trending NNE-SSW with a traceable length of about 3 km and a width 1 km. The dip angles on both flanks are about the same, ranging from 30 to 45 degrees.

About 30 gravity stations were distributed over the islet which has an area of approximately 6 sq km. The Bouguer gravity map looks like the surface structure in some extent, but the subsurface culmination may be shifted to the southern part of the islet. Viewed as a whole, the gravity map indicates that the Hsiaoliuchiu anticline is probably a southern extension of the Pingtung anticline, *en échelon* with the Fengshan anticline.

CONCLUSIONS

1. A study of gravity data together with surface and subsurface geology suggests that the Pingtung plain may consist of the following elements: (1) Pingtung basin, (2) Chaochou fault, (3) Chaochou structure, (4) Liukwei graben, (5) Chishan fault, (6) Fengshan anticline, and (7) Hsiaoliuchiu anticline.

2. The major and more continuous gravity features parallel with the general trends of the structures in the area. One big gravity minimum associated with the Pingtung plain reveals that the Pingtung basin is a sedimentary trough filled with considerably thick low density sediments. The Pingtung syncline and the Pingtung anticline are the striking features indicated by the anomalies in the central part of the basin. No more attention need be paid on the Pingtung anticline so far as the petroleum geology is concerned.

3. The Chaochou and the Chishan faults, which are believed to be high-angle thrust faults, have strong effects on the Bouguer gravity curves. The continuous positive gravity anomalies corresponding closely with the trends of these faults are always on the up-thrown side. This is due to density variations of the surface rocks around the fault.

4. The Chishan fault may extend southward to the Fengshan anticline where the stratigraphic displacement of the fault may decrease to a few meters or even be not in existence.

5. The axis of positive gravity anomaly caused by the deeper structure of the Fengshan anticline does not coincide with the surface axis. The only reasonable explanation is that a structural discordance probably exists between the surface and the deeper structures of this anticline.

6. The small structures such as the Pingtung anticline and the Chaochou structure that are concealed beneath the plain have been deduced in this study. It is therefore concluded that the detailed gravity survey may be useful in the quantitative interpretation of the subsurface structures.

ACKNOWLEDGMENTS

The writer is deeply indebted to Mr. C. C. Hu of TPED for his great assistance and valuable suggestions. Thanks are also extended to the National Council on Science Development for a partial research fund for this study.

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Received March 4, 1970

臺灣屏東平原區地質及重力異常之研究

謝 世 雄

節 要

根據地面地質及重力資料分析，臺灣南部屏東平原區之構造可分如下：(1)屏東盆地，(2)潮州斷層，(3)潮州構造，(4)六龜陷谷，(5)旗山斷層，(6)鳳山背斜及(7)小琉球背斜。一般而言，重力異常皆與地面地質構造之形貌相符，同時由重力異常亦可推論地下深處地質構造。

屏東平原中央部份，里港至屏東為一重力異常低區，顯示此平原為斷層所形成的構造陷谷，沉積密度較小厚層岩石。此異常低區向南延展二十餘公里，經潮州、東港進入臺灣海峽。在此重力異常大低區內，屏東至萬丹一帶尚產生局部呈南北走向之重力異常高區，相當於屏東背斜；此局部高區恰如大向斜內之小褶皺，對於油氣集積是不具經濟價值的。

屏東平原與其東側高山地帶交界附近，重力值增加遞度陡急，等重力線變化非常不調和，顯然係表示此兩者間之不連續，產生此重力異常主因，當為南北走向之潮州大斷層，其斷層面向東傾斜七十五至八十度，為一高角度衝上斷層。潮州東南面七公里附近與此斷層間有一異常高區，其地下地層極可能形成斷層封閉，以石油地質而言，此異常高區之地下構造當比屏東背斜利於油氣儲積。

旗山大斷層地層落差在旗山一帶最大，而向南延展落差逐漸減少，至鳳山一帶可能已不復存在，鳳山背斜軸恰位於此斷層的向南延續。由重力證實，鳳山背斜之地表軸向與其深處構造高區之軸向不一致，相差四十五度，在此上下兩構造間可能有不調和或不連續現象。

小琉球等重力線圖與其地表背斜構造相似，但其地下深處之構造高區偏向島嶼南端，小琉球背斜與鳳山背斜呈雁行排列。

總而言之，屏東平原地下構造為一呈南北延長之橢圓形盆地，因此其邊緣的構造應視為油氣游移集積之有利構造。