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Gravitational Compaction of the Neogene Muddy Sediments in Akita Oil Fields, Northeast Japan*

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(With 3 Tables and 12 Figures)

CONTENTS

Introduction

Sedimentological studies in the oil fields of Japan have been made mainly from the viewpoint of geochemistry of bituminous sediments. When the migration of petroleum is examined and the isopach map is investigated from the sedimentological standpoint, compaction of sediments must be considered. According to T. MITSUCHI, petroleum is generated quite early after the deposition of its source sediments (protopetroleum) and begins to move along with water as the sedimentary compaction current. With regard to the subjects mentioned above, the

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quantitative estimation of the compaction ratio of beds and the liquid volume squeezed out from them after burial are necessary in order to restore the buried beds to initial state in thickness. A construction of the chart that can be of use in restoring the actual beds to initial state in thickness, is one of the purposes of this work.

The writer has been interested in the fact that there seems to be a fairly regular relationship between the compaction ratio (porosity or density) of the muddy core samples from wells and the depth at which they were, as expressed by ATHY and others. Then an attempt has been made to find out the standard relation between them on the basis of the data from the wells in Akita oil fields, which consist of the Neogene sediments widely developed and distributed in the so-called green tuff region of the Uetsu Geosyncline in Northeast Honshu, Japan.

Most of the data, perhaps all, that have been utilized by many sedimentologists to examine the compaction of sediments, seem to be derived from core samples from wells. Recently core drilling has hardly been done in the oil fields where a large quantity of core samples was already collected and they cannot be expected to increase in quantity. The studies which have been made on the basis of core samples, therefore, may tend to be made on outcrop samples in the future. Considering that the organic content of sediments and the number of foraminifera in the unconsolidated core samples are different from these in the outcrop samples, it is alike guessed that the relationship between the depth of burial and the compaction ratio of muds on the former samples, might differ from that on the latter. In the latter part of this work, an examination has been made to point out some differences in the two kinds of density-overburden relation. This examination has been carried out on the horizontal distribution of the mudstone densities at the basal part of the Funakawa formation and the accumulated overburden map of the Funakawa-Sasaoka formations.

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I. Compaction of Muddy Sediments

It is well known that the compaction of sediments is, in general, due to increasing overburden (ATHY, 1930 ; HEDBERG, 1936). Compaction is a phenomenon that the rock volume reduces with outer pressure. Each sediment is compacted according to the depth of burial in the manner peculiar to itself. Among the sediments, muddy sediments in particular take the effect of overburden sensitively, and the compaction of mud is expressed by ATHY to be an exponential function of the depth of burial. According to the laboratory experiments, mud has about 80 per cent initial porosity at the sedimentary surface, and compaction begins to occur 5 to 10 centimeters below the surface of deposition.

The porosity and density are known as the indicators of the compaction of sediments. Although the former seems to be convenient in estimating the compaction ratio quantitatively, all the data applied in this work is density, especially natural density, because the measurement of the porosity of fine-grained sediments is very difficult.

The porosity and density are theoretically related, and if the grain density is known, the porosity is calculated from density by use of an equation as shown later.

1) Definitions of Rock Density

According to the nomenclature of HEDBERG, the definitions of rock density are as follows ;

Bulk Density (rock density, lump density) is the density of the thoroughly dry rock, that is, the rock with pore space free of liquids.

Natural Density (wet density) is the density of the rock with all pore space filled with water which is assumed to be the usual condition found in nature.

Grain Density (mineral density, absolute density) is the density of the constituent paticles of a rock, that is, the rock substance free from pore space.

Dry Density is a term commonly applied to naturally dried rock samples.

It is perhaps too difficult to determine the true density of natural sediments under the natural state as they are buried because of the differences in the physical conditions between surface and subsurface. In most cases, all pore space of the sediments which are buried is filled with water and the natural density shown above seems to be most nearly similar in value to the density of the sediments under natural state. The natural density was accordingly adopted in this work to deal with all samples.

2) Stratigraphical Successions in Akita Oil Fields

Akita oil fields are composed of the Neogene sediments, under which the Pre-Tertiary basement rocks such as the granitic rocks and Paleozoic sediments are presumed to lie. In the Middle Miocene age, this region began to sink and the transgression occurred accompanied by severe volcanism. After various volcanic activities, several sedimentary basins grew up all over this region where the thick geosynclinal sediments were produced.

Y. IKEBE (1962) defined standard stratigraphical succession of the Tertiary rocks in Akita oil fields, and recognized nine stages as shown in Table 1. Characteristics of the rock facies on each formation are summarized as follows ;

I-Stage (Monzen Stage), mainly altered andesites and brackish water sediments.

Table 1

Stratigraphical sequence in Akita oil fields

Geologic Age		Stage	Standard Stratigraphy				
			Oga Peninsula		Akita City		
Quaternary		Katanishi	Katanishi F.		Terauchi F.		
Tertiary	Miocene——Pliocene	Shibikawa	Shibikawa F.		Shibikawa F.		
		Sasaoka	Wakimoto F.	Upper F.	Sasaoka F.		
		Tentokuji		Middle -Lower F.		Tentokuji F.	Upper F.
			Kitaura F.		Katsurane F.		Lower F.
		Funakawa	Funakawa F.		Funakawa F.		Upper F.
							Lower F.
		Onnagawa	Onnagawa F.		Onnagawa F.		
		Nishikurosawa	Nishikurosawa F.		Uyashinai F.		
					Sunakobuchi F.		
		Daijima	Daijima F.		Okurayama F.		
		Monzen	Monzen F.		Haginari F.		
			Akashima F.		Omata F.		
Pre-Tertiary		Basement	Granites		Granites		

(After Y. IKEBE, 1962)

II-Stage (Daijima Stage), mainly dacite and its tuffs, and brackish water sediments.

III-Stage (Nishikurosawa Stage), mainly characterised by marine molluscs and foraminiferas in warm current. Volcanic rocks are rhyolitic, dacitic and basaltic.

IV-Stage (Onnagawa Stage), mainly banded hard shale or siliceous hard shale with fossil fishes and fish-scales, having the uniform rock facies throughout all fields. Volcanics are also active ; effusive basalts, intrusive dolerites and widespread acidic tuffs.

V-Stage (Funakawa Stage), mainly dark grey mudstone or siltstone with acidic tuffs at its upper part.

VI-Stage (Tentokuji Stage), mainly grey mudstone or siltstone which is locally represented by the alternation of sandstone and mudstone (so-called Katsurane Alternation).

VII-Stage (Sasaoka Stage), mainly bluish grey siltstone and sandy siltstone.

VIII-Stage (Shibikawa Stage), mainly sand with clay, gravel and lignites.

IX-Stage (Katanishi Stage), mainly soft clay, sand and gravel which deposited in brackish or fresh water condition.

3) Data and Determination of Densities

Akita oil fields are the most productive oil fields in Japan, along with the Niigata oil fields. The core samples, used in this work, are obtained from 16 test wells in Akita oil fields in Akita prefecture. Only fine-grained sediments (claystone to siltstone) were picked up to determine their densities. They range from the mudstone of the Sasaoka formation to the so-called black shale of the Funakawa formation. The black shale mentioned above and the so-called hard shale of the underlying Onnagawa formation are recognized as the source rocks of petroleum in this region.

In determining of the density of the core samples, it may be more significant to deal with as many samples as possible and obtain their average value than to determine each of them strictly taking much time. Then, the natural densities of the samples were measured within a few hours just after taken from wells as follows. The apparatus used for determining the natural density of the samples is shown Fig. 1. On each sample saturated with water, the water attached on its surface was wiped off by a piece of cloth. First the weight of each sample in the air was measured on the scale A and second its weight in the water on the scale B. Then the apparent natural density of each sample (D) was calculated by the following equation.

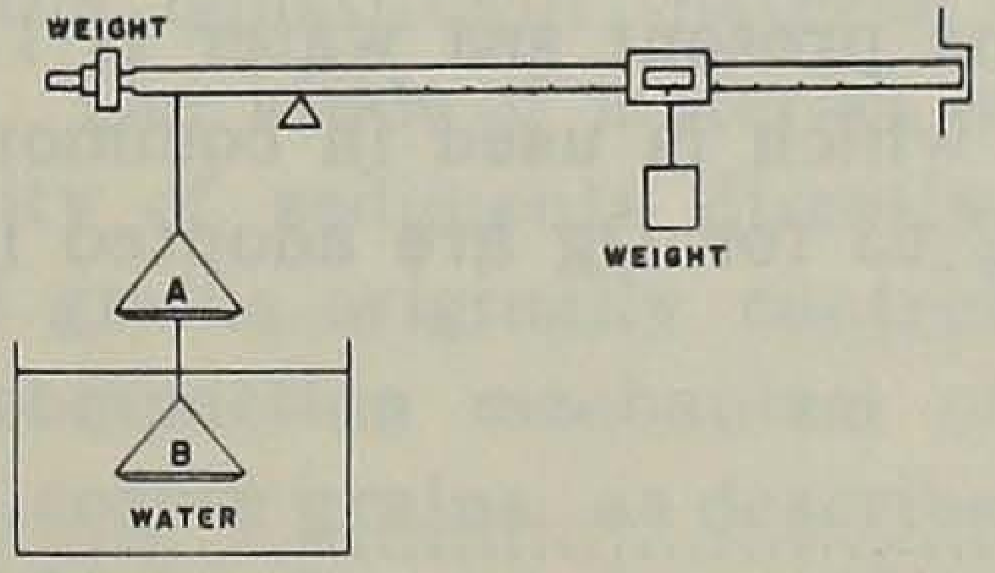

Fig. 1 Apparatus for determining the natural densities of mudstones

$$D=\frac{W}{W-W'}dt+\left(1-\frac{W}{W-W'}\right)a \cdots\cdots(1)$$

Where W is the weight of sample in the air,
W′ is the weight of sample in the water,
dt is the density of the water under t°C of temperature,
a is the density of the air.

In this equation, the last term $\left(1-\frac{W}{W-W'}\right)a$ and the dt-correction could be neglected because each of them has no influence on the numerical value of the two places of decimals in D, when the temperature of the water is 10 to 25°C and the numerical value of $\frac{W}{W-W'}$ is 1.50 to 2.50.

As to the surface tension of the thin lines keeping the scale B with water, it may be also neglected when the weight of a sample is more than 200g (after A. MATSUZAWA). W and W′ were read down to the places of decimals and D was calculated by use of the equation and were adopted to the two places of decimals also.

4) Relationship between Density and Porosity

The sediments consist of grain and pore, and the latter is classified into the open pore and closed pore. The closed pore of the muddy sediments occupies a larger percentage of the whole pore than that of the sandstone and coarse tuff, and the permeability of the muddy sediments is accordingly very low. This fact makes it very difficult to determine the porosity of muds directly. The natural density is related to the porosity as a following linear equation ;

$$D=(1-\phi)Dg+\phi Dl \cdots\cdots (2)$$

therefore,

$$\phi=\frac{Dg-D}{Dg-Dl} \cdots\cdots (3)$$

Where D is the natural density of mud,
ϕ is the porosity of mud,
Dg is the grain density,
Dl is the density of pore water.

The specific gravity of the present sea water is 1.025 or so and the average specific gravity of the grain, which is used in common, is 2.65. When the numerical values 1.00 for Dl and 2.65 for Dg are adopted in the above equation (3), it is shown as follows ;

$$\phi=\frac{2.65-D}{1.65} \cdots\cdots (4)$$

As to the method for determining the grain density, samples are commonly dried by heating at 110°C for 24 hours or more to drive off pore water. As WELLER and others have pointed out, there are some suspicions about this method, for instance, that all adsorbed water may be not always driven off and on the other hand some crystal water may be driven off. Consequently, the equation (4) is, to the last end, an apparent relation between natural density and porosity.

5) Processes of Compaction

HEDBERG (1936) classified the processes of the compaction of fine-grained sediments into the following four stages.

(1) Mechanical rearrangement stage
(2) Dewatering stage
(3) Mechanical deformation stage
(4) Recrystallization stage

Muds are compacted with increase of overburden pressure through the above stages after deposition, but it is suggested that there is no clear boundary among these stages and they overlap each other. The initial porosity of fine-grained sediments is 80 per cent or so at the surface of deposition where the adsorbed water of each grain is in contact one with another.

With overburden increase, first, grains rearrange towards more stable state, free water occupying pore space begins to escape to the surface, followed by the adsorbed water. When grains come into contact (2nd stage), jarring occurs toward the dense system of packing, and the expulsion of adsorbed water continues. According to WELLER, a reduction of porosity from 45 to 35 per cent belongs to the second stage.

Judging from the facts that porosity ranges from 47.64 to 25.90 per cent in the case that the spheres of the same size contact each other, and that the perticles of natural sediments are various in shape and size, the porosity of sediments at the lowest limit of this stage may be below 30 per cent. Under still more overburden pressure, compaction is accompanied by a change in shape of grains by the mechanical deformations such as crushing and granulation. The 4th stage is the final. Reduction of porosity below 10 per cent is caused chiefly recrystallization and a porosity gradually approaches zero per cent.

6) Factors Controlling Density Variations

Although the fine-grained sediments are compacted mainly with overburden increase, causing increase in density, there are many factors causing their density variations.

The characteristics of the constituent material of the sediments are most fundamental for the factors. The kinds of material, namely the density variations of material, control the density of sediments directly, and the uniformity of the size, shape and roundness of grains originally control the degree of compaction. As to the size of grain, the compaction mechanism of the very fine grains must be different from that of the coarse grains, as described by WELLER. Nevertheless, a little knowledge has been obtained not only on the characteristics of the very fine-grained sediments like clays but also on their compaction mechanism. Each feature of grains is characterized by the natures of material source, the distance from the source area, and the depositional environment.

Cementation (very common in sand), degeneration of minerals, recrystallization, and the other phenomena caused by the pressure change, the temperature increase and so on, are important as factors controlling the density variations in sediments.

In the density distribution of muddy core samples, in most cases, there can be found the abnormally scattered zones in density value in the neighbourhood of the fault plane and beneath the unconformity. These disturbances in density value must be causes by the secondary pressure without overburden pressure and the effects of the weathering suffered on the surface.

Also the occurance of muddy sediments seems to have some effects on the degree of compaction. When a mud bed is relatively thin, the pore water is more easily squeezed out into the adjoining beds having higher permeability. It is suggested that the thinner the mud bed is and the higher the permeability of the beds next to muddy bed is, the more easily the mud is subjected to compaction. This suggestion has been given by R. NISHIZAWA as a result of the examinations on the sonic logging data.

Time factor plays important roles in controlling rock density. In fact, the various processes of diagenesis in sediments including the foregoing cementation etc., must require much time and the sediments must finally achieve their settled state in compaction under each overburden.

The curves (1), (2) and (3) in Fig. 5, even though the sedimentary environment of each basin might have been more or less different from the others, seem to suggest that the sediments may require much time in achieving equilibrium with respect to overburden pressure through the various processes of lithification.

7) Assumptions

In addition to the foregoing factors causing density variation, there may be many other factors controlling compaction and all of them are serious. In order to examine quantitatively the overburden-compaction relation on the muddy core samples taken from subsurface, it is necessary to simplify many complex elements. The writer, therefore, has set up the following three items as assumptions in carring out this work.

(i) Compaction of muds is exclusively due to overburden pressure.

(ii) Compaction of muds is an unreversible phenomenon, that is, the muds being buried under the surface have achieved equiliblium with respect to overburden pressure, which they suffered already.

(iii) The natural density and porosity of muddy sediments are in a fixed linear relation as shown as by the equation (4).

8) Relationship between Density and Depth

Overburden pressure means the thickness of overburden namely the depth of burial*. Under the foregoing assumptions (i) and (ii), the degree of compaction of each muddy core sample signifies its maximum depth of burial suffered. The natural density variations of the core samples taken from the test wells in Akita oil fields with respect to present depth, are given in Fig. 2. It gives a general idea on the compaction-depth relation. In other words, the curve connecting the maximum density values at each depth on the Figure, it becomes clear that each sample of the points distributed below the assumed curve must have been at the deeper position in geologic age than the present depth. Consequently, it is possible to slide these points to the right in parallel with the depth axis on the graph and to estimate to some extent their maximum depth of burial.

The data plotted in Fig. 2 were obtained through the above mentioned method on the siltstones to claystones. The data on the samples which seemed to be tuffaceous even slightly were excluded, because tuffs generally make the rock density abnormally lighter.

Natural Density-Maximum Depth of Burial : In order to know the standard relation between the natural density and the maximum depth of burial in the region around the Akita oil fields, the density data from four wells (Tsuchizaki

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* The term 'depth of burial' used in this paper means the depth from the surface of deposition to the concerned point, and the similar term 'depth of burial of a stratum' means the depth from the surface of deposition down to its top.

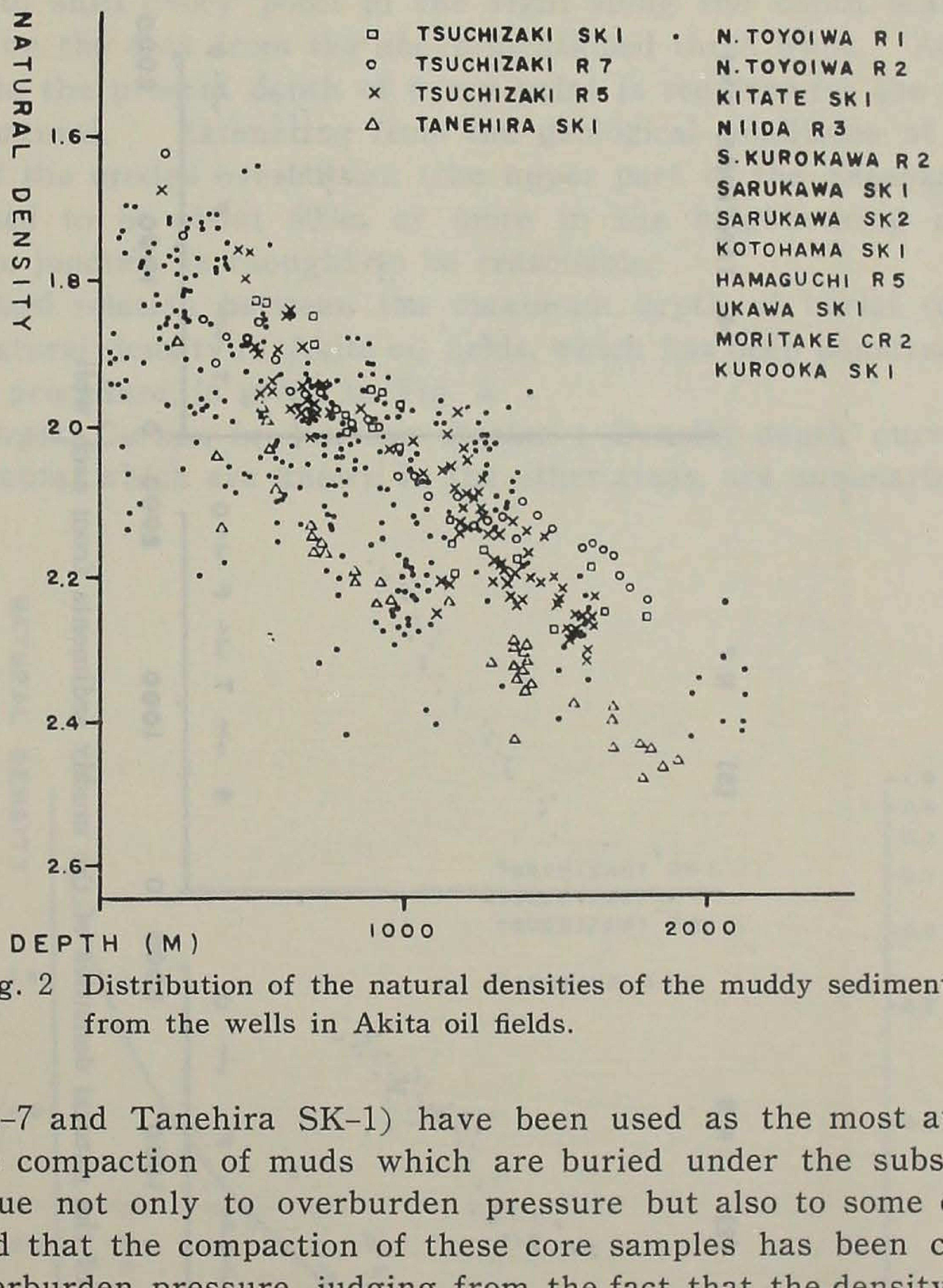


Fig. 2 Distribution of the natural densities of the muddy sediments from the wells in Akita oil fields.

SK-1, R-5, R-7 and Tanehira SK-1) have been used as the most available data. Although the compaction of muds which are buried under the subsurface might have been due not only to overburden pressure but also to some other effects, it can be said that the compaction of these core samples has been caused exclusively by overburden pressure, judging from the fact that the density distribution on each well seems to be quite normal. As to the Tsuchizaki SK-1, R-5 and R-7 wells, they are situated about 2km apart from each other at the mouth of the Omonogawa River near Akita City as shown in Fig. 8. As the area around these wells corresponds to the low gravity zone where little erosion caused by uplift is known, it is said, broadly speaking, that this area has still kept on sinking since the Onnagawa age (Upper Miocene).

Each well is situated near the crest of gentle anticline, where there can be recognized no structural disturbances in sediments without the local scattered zone in density value caused by a fault at the depth of 1100m in the well R-5 (Fig. 3). In Fig. 2, the data from three Tsuchizaki wells are distributed in the deeper part with respect to their density values than the other data. The facts said above show that these data are the most satisfactory as the standard relation ranging from 200m to 2000m in depth.

The data from the well Tanehira SK-1 have been utilized to extent this relation downward to still greater depth. As they are distributed in the shallower domain of the present depth against the data from the Tsuchizaki wells in Fig. 2,

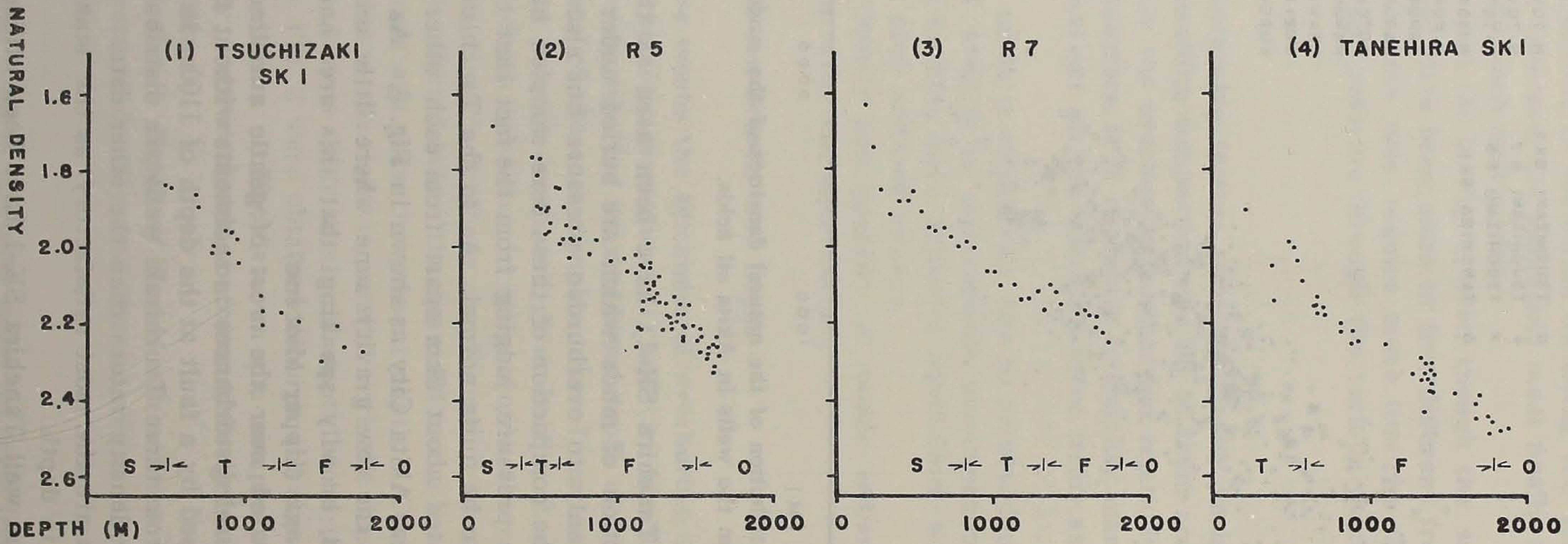


Fig. 3 Distribution of the natural densities of the muddy sediments from each well

it is possible to shift every point to the right along the depth scale and make them overlap on the data from the above-mentioned three wells. Actually, addition of 600m to the present depth of every point is required for the junction that seems to be natural. Estimating from the geological conditions at the surface, the amount of the eroded overburden (the upper part of the Sasaoka formation) can be assumed to be about 500m or more in the neighbouring of this well. Therefore, this junction is thought to be reasonable.

The standard relation between the maximum depth of burial (downward to 2600m) and natural density in Akita oil fields, which has been constructed through the foregoing procedure, is given in Fig. 4.

Density-Depth Curves in Various Basins : Density-depth curves on fine-grained sediments, which are known in the other areas, are summarized in Fig. 5.

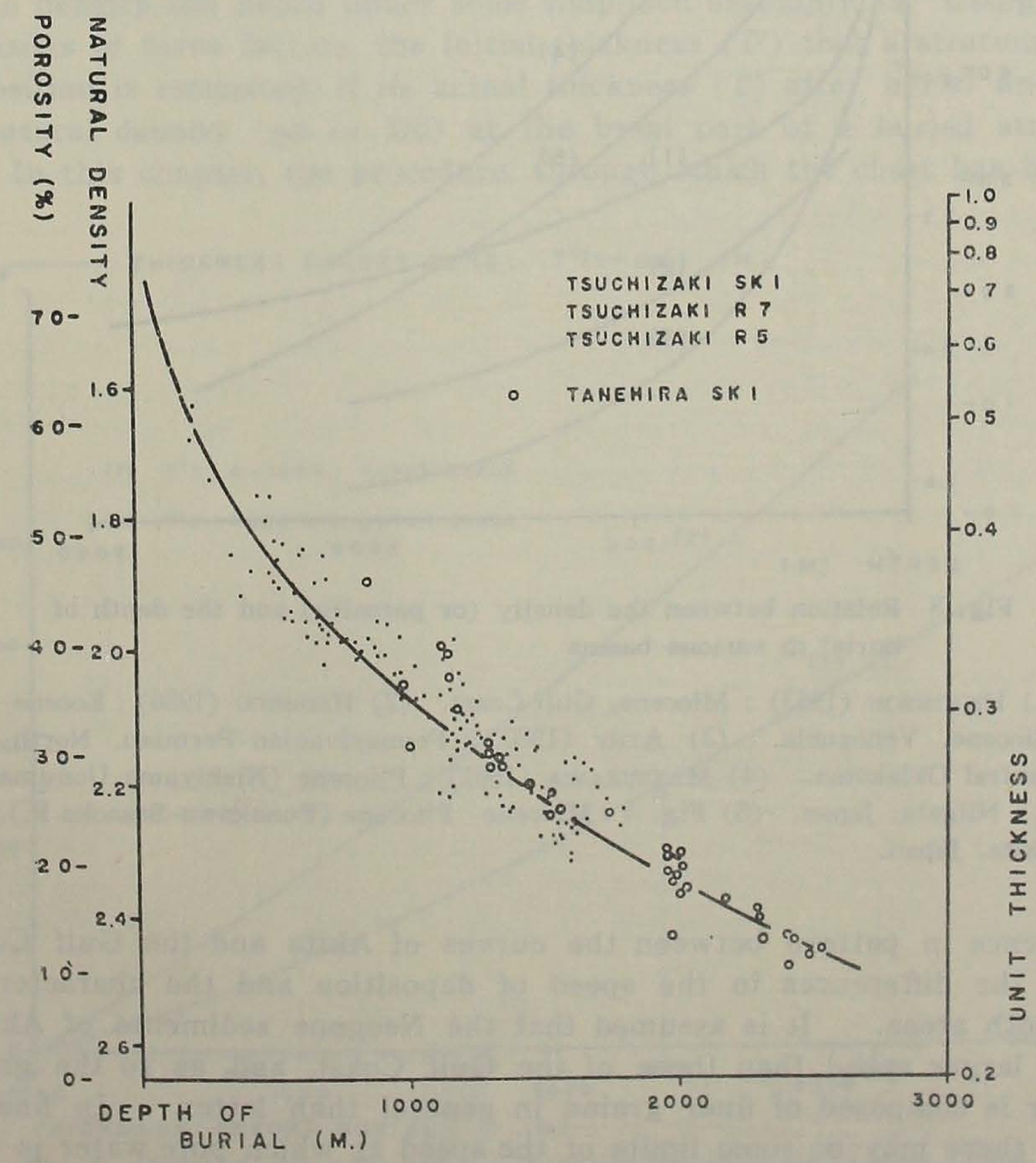


Fig. 4 Standard relation between the natural density and the depth of burial for the muddy sediments in Akita oil fields.

Data from the well Tanehira SK-1 are plotted after adding 600m to the actual depth under the assumptions (i) and (ii). Unit thickness is given by 1/5(1-P). P : porosity

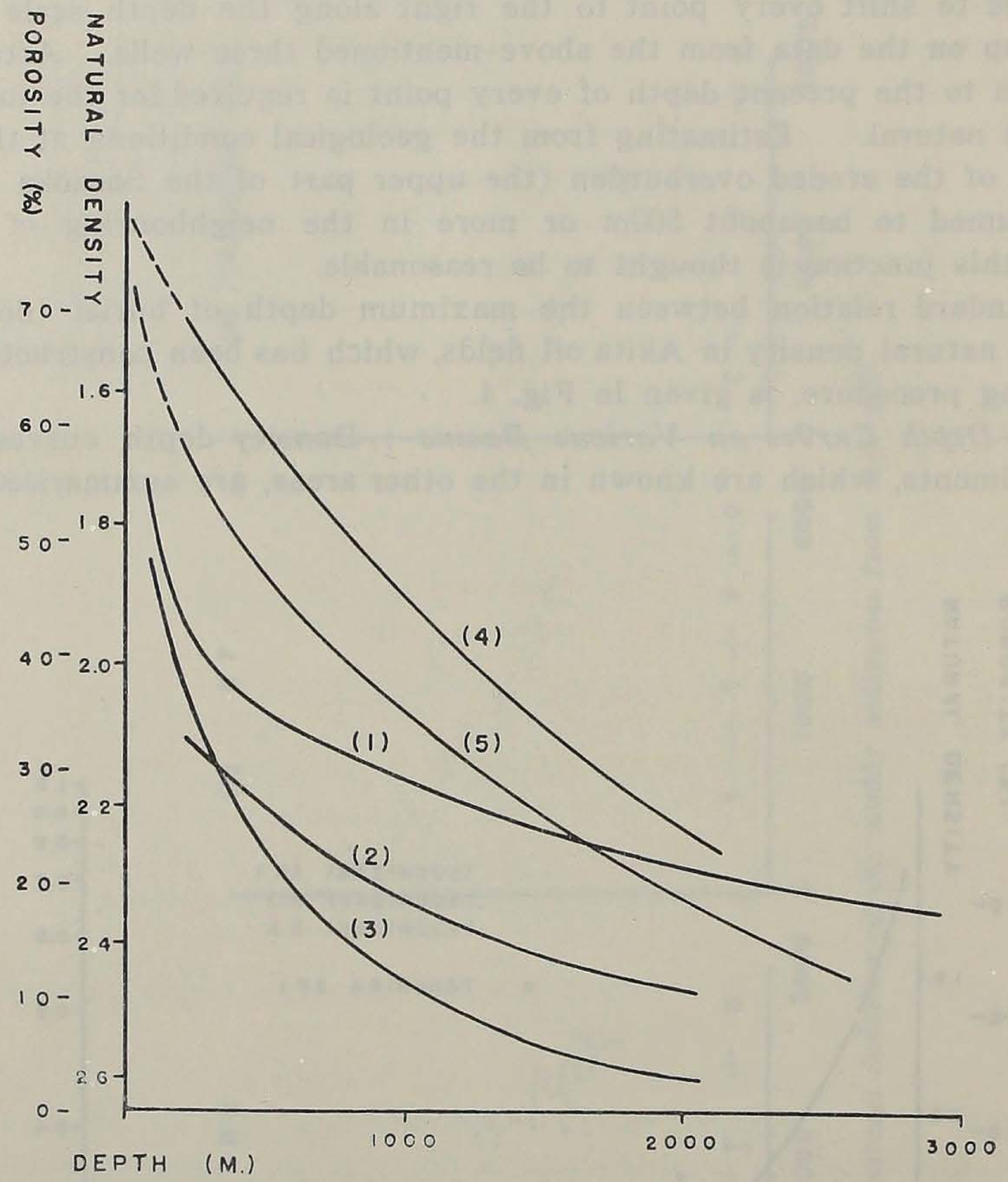


Fig. 5 Relation between the density (or porosity) and the depth of burial in various basins

(1) DICKINSON (1953) : Miocene, Gulf Coast. (2) HEDBERG (1936) : Eocene-Miocene, Venezuela. (3) ATHY (1930) : Pennsylvanian-Permian, North-Central Oklahoma. (4) MATSUZAWA (1961) : Pliocene (Nishiyama-Uonuma F.), Niigata, Japan. (5) Fig. 4 : Miocene- Pliocene (Funakawa-Sasaoka F.), Akita, Japan.

The difference in pattern between the curves of Akita and the Gulf Coast may be due to the differences in the speed of deposition and the characteristics of grain in both areas. It is assumed that the Neogene sediments of Akita were yielded at larger speed than those of the Gulf Coast, and, as to the grain size, the former is composed of finer grains in general than latter. In fine-grained sediments there may be some limits of the speed at which pore water is squeezed out and consequently it is speculated that the compaction (of foregoing stage (1) and (2)) of muds do not proceed simply in proportion to the increase of overburden pressure, when the speed of sedimentary accumulation is larger or when the strata are dominantly composed of fine-grained sediments.

Considering the fact that the Neogene sediments of Akita and Niigata are composed of very fine grains on the whole, these sediments may have gone through the case of process of compaction, just mentioned. The discrepancy between the two curves, in the other words, must be due to the difference in the speed of deposition, that is, the sediments of Niigata might have been produced more rapidly than those of Akita.

The sediments of the Gulf Coast are fairly coarse and more variable in grain size than those of Akita and Niigata. Therefore, they must have reached the jarring stage earlier after deposition.

II. Restoration of Buried Muddy Strata

In order to calculate the degree of compaction of actual muddy strata, a chart to restore the buried strata to initial state in thickness has been constructed. This attempt has been made on the basis of the foregoing standard relation (Fig. 4) between density and depth under some simplified assumptions. Using the chart which consists of three factors, the initial thickness (T′) that a stratum had just after deposition is estimated, if its actual thickness (T) after burial and a porosity or natural density (ϕb or Db) at the basal part of a buried stratum are known. In this chapter, the procedure, through which the chart has been cons-

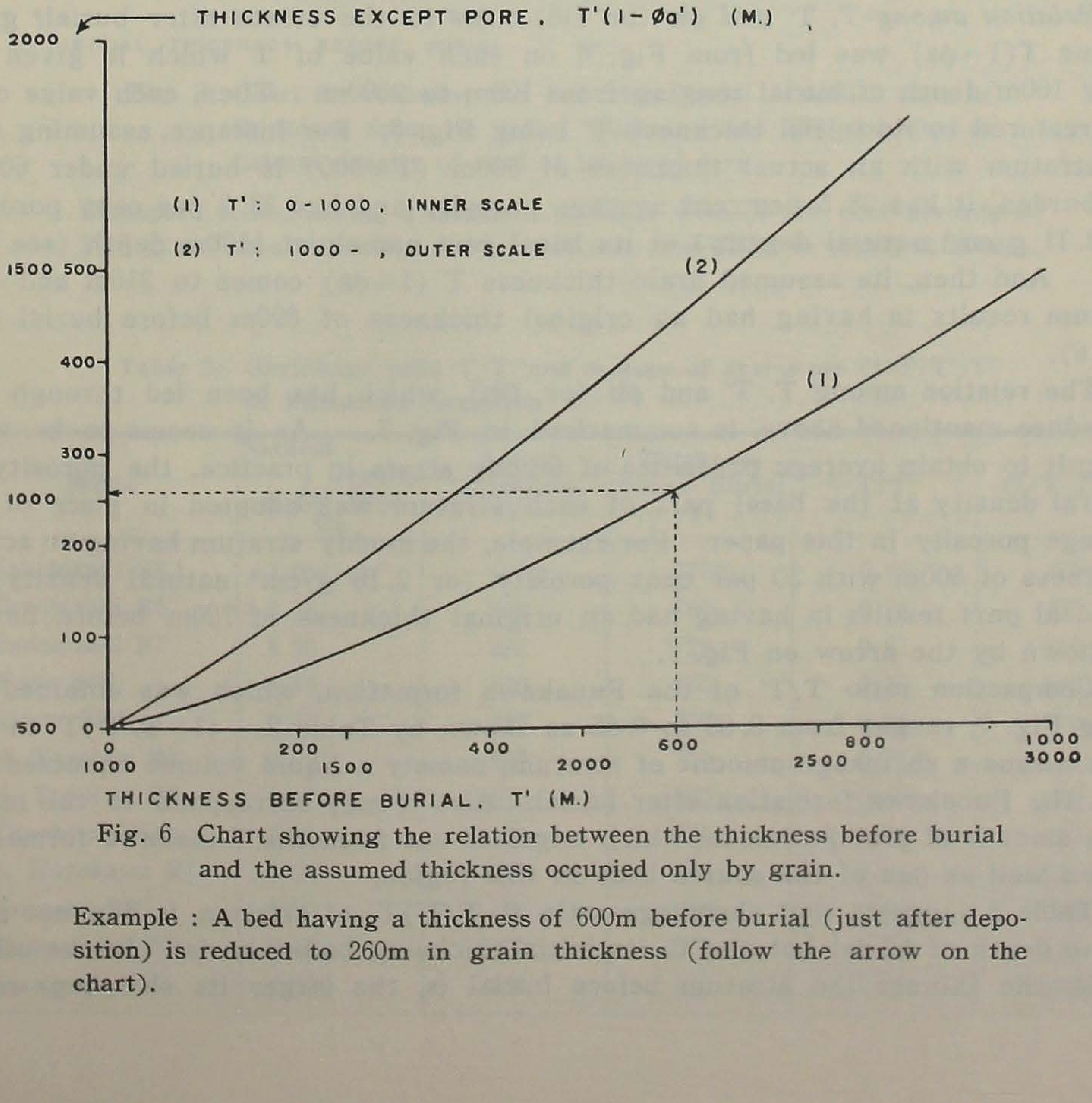


Fig. 6 Chart showing the relation between the thickness before burial and the assumed thickness occupied only by grain.

Example : A bed having a thickness of 600m before burial (just after deposition) is reduced to 260m in grain thickness (follow the arrow on the chart).

tructed, is given and its practical applications to calculate the degree of compaction of the buried muddy strata, are made.

Assuming that grain volume (except pore space) of homogeneous muddy strata is the same before and after burial, the following equation is given ;

$$T'(1-\phi a')=T(1-\phi a) \cdots\cdots \tag{5}$$

where T' is the thickness of stratum before burial,
T is the thickness of stratum after burial,
$\phi a'$ is the average porosity of stratum before burial,
ϕa is the average porosity of stratum after burial.

Relation between T' *and* $T'(1-\phi a')$: $T'(1-\phi a')$ means the thickness of muddy column under the assumed state that all pore space is occupied by grains. As to the stratum before burial, the thickness of stratum before burial T' and its average porosity $\phi a'$ are obtained from the curve in Fig. 4. $\phi a'$ is an average value of porosity at every 100m depth as shown in the following formula.

$$\phi a'=\phi n/n \cdots\cdots \tag{6}$$

T', $T'(1-\phi a')$ relation is shown in Fig. 6. For example, the muddy stratum having a thickness of 600m before burial (just after deposition) is reduced to a grain-thickness of 260m as guided by the arrow on Fig. 6.

Relation among T, T' *and* ϕb (or Db) : As to the strata after burial, grain volume $T(1-\phi a)$ was led from Fig. 4 on each value of T which is given for every 100m depth of burial ranging from 100m to 2000m. Then, each value of T was restored to its initial thickness T' using Fig. 6. For instance, assuming that the stratum with an actual thickness of 500m ($T=500$) is buried under 600m-overburden, it has 38.5 per cent average porosity and has 33.0 per cent porosity (or 2.11 g/cm^3 natural density) at its basal part namely at 1100m depth (see Fig. 4). And then, its assumed grain-thickness $T(1-\phi a)$ comes to 310m and this stratum results in having had an original thickness of 690m before burial (see Fig. 6).

The relation among T, T' and ϕb (or Db), which has been led through the procedure mentioned above, is summarized in Fig. 7. As it seems to be very defficult to obtain average porosities of muddy strata in practice, the porosity or natural density at the basal part of each stratum was adopted in place of its average porosity in this paper. For example, the muddy stratum having an actual thickness of 500m with 30 per cent porosity (or 2.16 g/cm^3 natural density) at its basal part results in having had an original thickness of 720m before burial, as shown by the arrow on Fig. 7.

Compaction ratio T/T' of the Funakawa formation, which was obtained by using Fig. 7, ranges from 0.63 to 0.85 as shown by Table 2. $(1-T/T')T'$ in the table means a shrinkage amount of stratum, namely a liquid volume squeezed out form the Funakawa formation after burial. Also it may correspond to the maximum amount of protopetroleum which migrated out from the Funakawa formation known well as one of the source beds in this region.

Table 3 suggests that shrinkage-ratio $(1-T/T')T'$ of stratum is due not only to the depth of burial but also to its initial thickness before burial. In the other words, the thinner the stratum before burial is, the larger its shrinkage-ratio

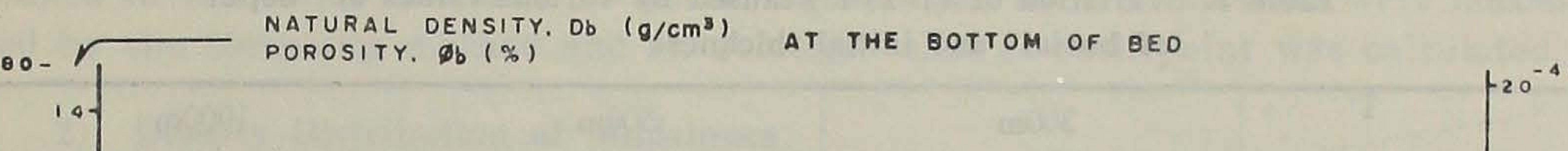


Fig. 7 Chart for restoring the bed after burial to initial state in thickness from its actual thickness and the porosity or natural density of mud at its basal part.

Example : A bed having a thickness of 500m with 30 per cent porosity or 2.16 g/cm³ natural density at its basal part, was 720m in initial thickness.

Table 2. Shrinkage ratio T/T′ and amount of shrinkage (1-T/T′)T′ of Funakawa formation

Wells	Natural Density at the Base Dn	Actual Thickness T	Thickness before Burial T′	T/T′	(1-T/T′)T′
Tsuchizaki SK1	2.25g/cm³	500m	770m	0.65	270m
Tsuchizaki R5	2.18	560	790	0.71	230
Tsuchizaki R7	2.20	480	720	0.67	240
Wada SK1	2.10	570	760	0.75	190
Kitate SK1	2.08	400	570	0.70	170
N. Toyoiwa R1	2.02	600	710	0.85	110
N. Toyoiwa R2	2.02	530	660	0.80	130
Tanehira SK1	2.41	1180	1580	0.75	400
S. Kurokawa R1	2.02	240	370	0.65	130
Kurooka SK1	2.30	490	780	0.63	290
Hamaguchi R5	2.02	430	570	0.76	140
Sarukawa SK1	2.25	550	830	0.66	280

Table 3. Variation of (1-T/T′) caused by various values of 'depth of burial' and initial thickness

T′ / Depth of Burial	300m		500m		1000m	
	T	1-T/T′	T	1-T/T′	T	1-T/T′
100m	250m	0.17	450m	0.10	940m	0.06
500	190	0.37	350	0.30	800	0.20
1000	160	0.47	300	0.40	700	0.30
1500	140	0.53	270	0.46	630	0.37

(This table has been constructed during the procedure through which Fig. 7 was made out.)

becomes under a fixed overburden.

Therefore, the isopach map after burial must be, in general, different in contour pattern from that before burial. This fact shows that some attentions are required when an isopach map is used as a datum on the sedimentological examinations at the time of deposition.

III. Density of Mudstones from Outcrop

1) Data

Stratigraphical horizon of the samples taken and sampling method : In order to examine the horizontal density-distribution of the mudstones exposed on the surface, mudstones at the base of the Funakawa formation (so-called black shale) were collected, and their natural densities were measured. The Neogene sediments are widely distributed in Akita prefecture and the stratigraphical studies on them have made progress because of economical necessity. As to the geological structure, in general, uplift has more extensively developed in Akita than in Niigata since the Later Funakawa stage. Therefore, it is possible to take many control points for the map of density-distribution and this region seems to be the most suitable for the purpose above mentioned. The reasons why the basal part of the Funakawa formation was selected as a stratigraphic horizon for this attempt are as follows.

(1) The Funakawa formation (black shale) overlies the Onnagawa formation (hard shale) with the thin alternation of black and hard shales and they can easily be distinguished from each other.

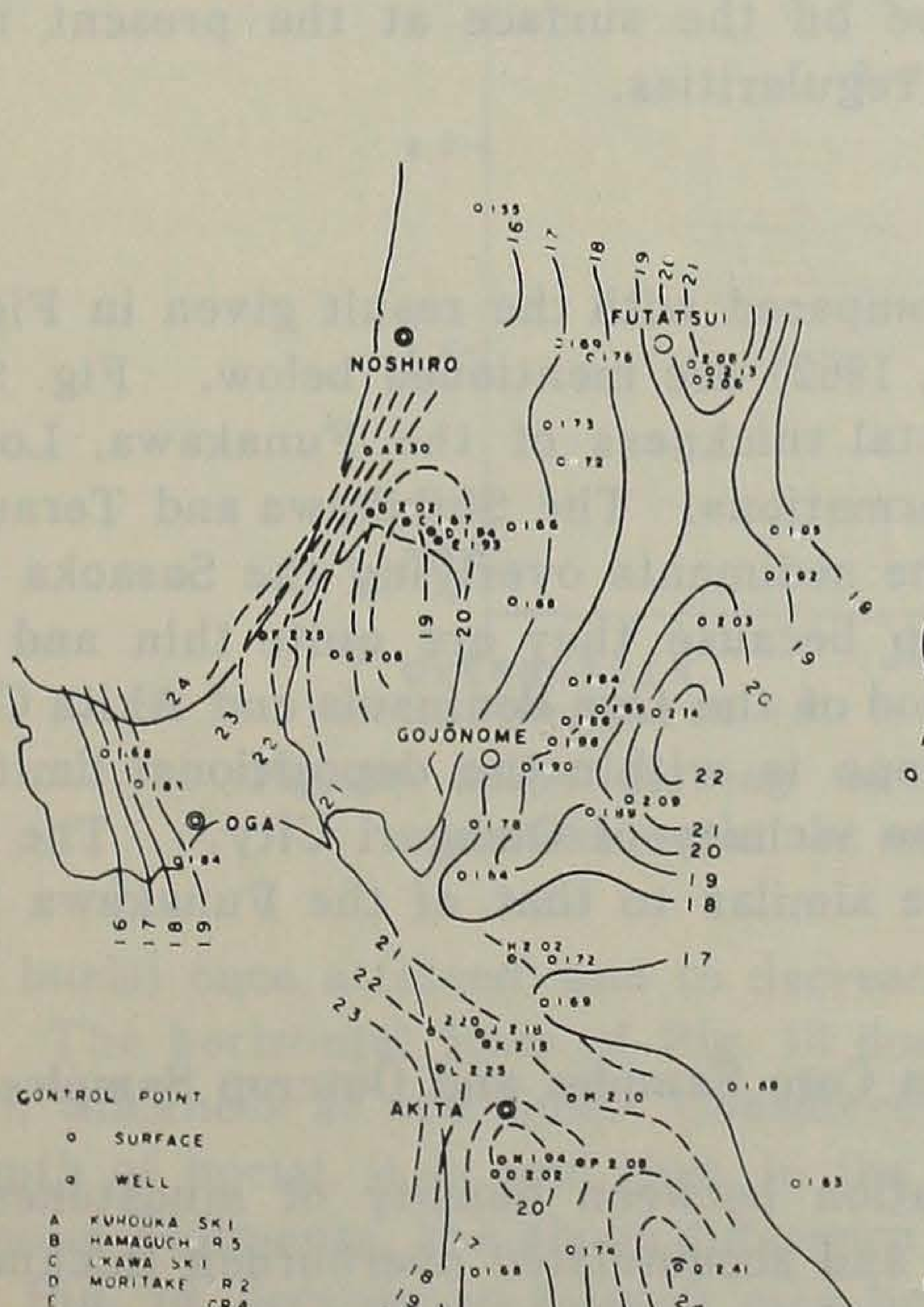
(2) The Funakawa formation having the thickness of 300-1500m consists mainly of dark grey massive mudstone and it is widely distributed on the surface all over Akita prefecture.

To avoid the density variation caused by the tuff-blend and other disturbances during deposition, sampling was done at the parts 20m above the top-horizon of the alternation of hard and black shales. Also, to reduce some errors caused by sampling, the writer tried to cut off the dry surface-part of outcrop and to take 6 to 10 samples along a line vertical to bedding planes at each control point.

The samples taken from outcrops were cut into about 200g-blocks and were soaked in the water for 15 to 20 hours. Then their natural densities were measured by the foregoing method and an average value at each point was calculated.

2) Density-Distribution of Mudstones

Fig. 8 shows the horizontal density-distribution of the mudstones at the base of the Funakawa formation. The isodensity lines for core samples and outcrop samples are drawn separately. Both contour patterns of isodensity lines seem to coincide each other naturally but there is a remarkable difference in density value between them. In the vicinity of the well S. Kurokawa SK-1, to which some



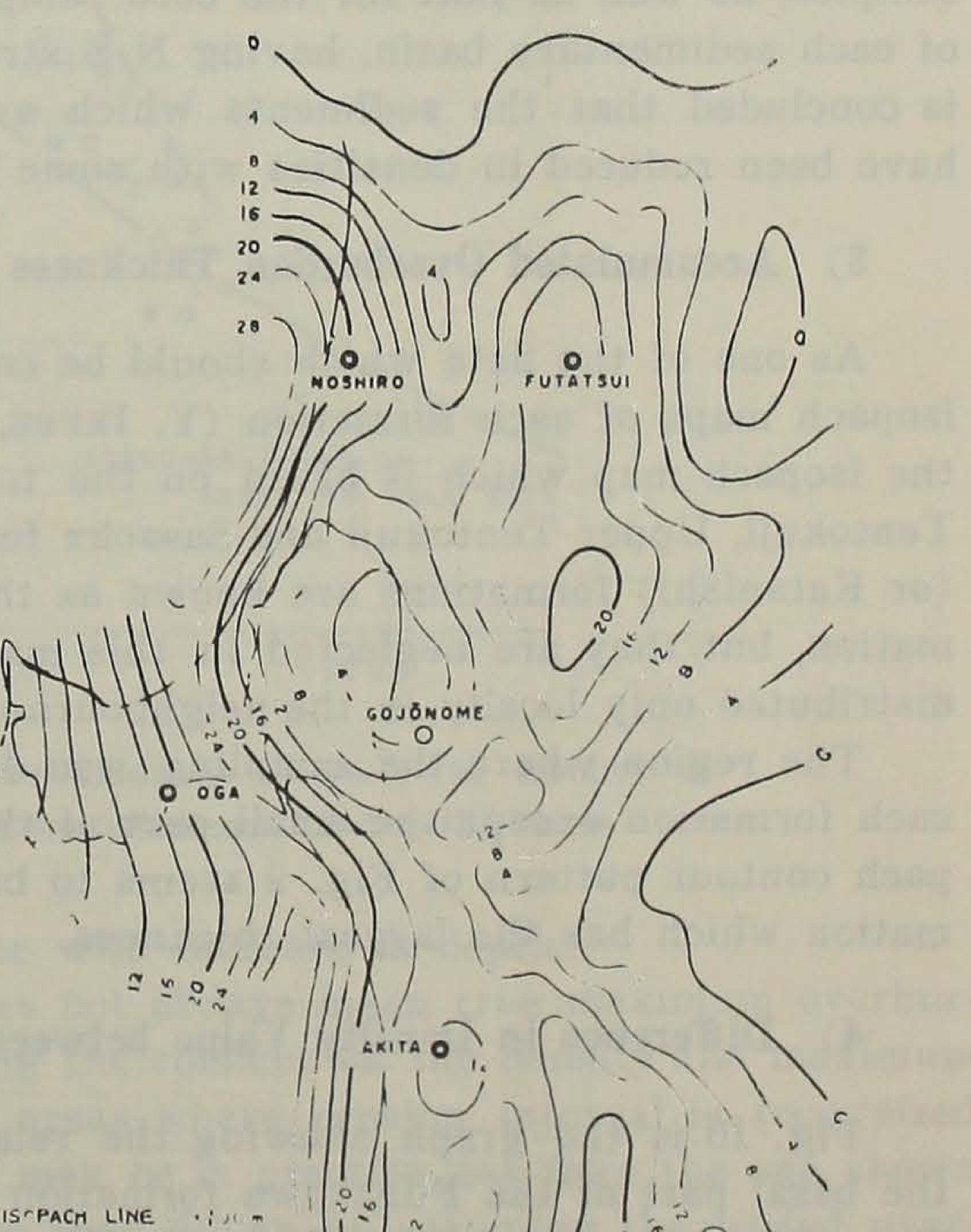


Fig. 8 Map showing the density distribution of mudstones at the basal part of the Funakawa formation in Akita oil fields.

Fig. 9 Map showing the accumulated overburden thickness ranging from the Funakawa formation to the Sasaoka formation.

control points of outcrop samples are adjacent, the numerical difference between both data from the well (2.02 g/cm^3) and the outcrops (1.72, 1.69 g/cm^3) is about 0.3 g/cm^3. Judging from the geological conditions on the surface, the overburden thickness of this area is nearly the same. Likewise, in the vicinity of Gojonome, it can be presumed from both kinds of density line that a numerical gap between them is about 0.4 g/cm^3.

These facts may show that the compacted sedimentary rocks, which exposed then on the surface and have suffered the weathering in broad sense, result in weakening of their packing or in alternation of their mineral constituent, and then the density of sediments decreases. However the contour pattern for the outcrop samples, as well as that for the core samples, is, as a whole, similar to the form of each sedimentary basin, having N-S structural trend, in this region. Then, it is concluded that the sediments which are on the surface at the present time have been reduced in densities with some regularities.

3) Accumulated Overburden Thickness

As one of the data which should be compared with the result given in Fig. 8, isopach maps of each formation (Y. IKEBE, 1962) are mentioned below. Fig. 9 is the isopach map which is based on the total thickness of the Funakawa, Lower Tentokuji, Upper Tentokuji and Sasaoka formations. The Shibikawa and Terauchi (or Katanishi) formations are known as the sediments overlying the Sasaoka formation, but they are neglected in this map because they are quite thin and are distributed only locally in the neighbourhood of the Oga Peninsula and Akita City.

The region where the sampling was done is within the depositional limit of each formation except the small part of the vicinity of Omagari City. The isopach contour pattern of Fig. 9 seems to be similar to that of the Funakawa formation which has the largest thickness.

4) Difference in Density Value between Core Samples and Outcrop Samples

Fig. 10 is the graph showing the relation between density of mudstones at the basal part of the Funakawa formation and accumulated overburden thickness. It was made out from Fig. 8 and 9. Each point plotted in the graph is classified into two groups (core samples and outcrop samples) and the samples from outcrop are grouped into four. In Fig. 10, the points of core samples are distributed in the neighbourhood of the solid line which corresponds to the standard curve based on the data from wells (Fig. 4), while those of outcrop samples are plotted entirely in the upper domain of the line. At the northern and eastern area of Gojonome and the Yuri area (from Akita to Honjo), as a whole, there is known little erosion among the sediments since the Funakawa age. Therefore, each isopach map must be comparatively reliable and the thickness of overburden in Fig. 9 may show almost maximum depth of burial in these areas. Average value of all points in these areas are shown by the broken line.

The difference in density scale between two lines is about 0.35 g/cm^3 at the depth of 1000m and the broken line tends to approach the solid line with depth increase. In the other words, the numerical difference in mudstone density between two kinds of samples is concluded to be a function of the maximum depth

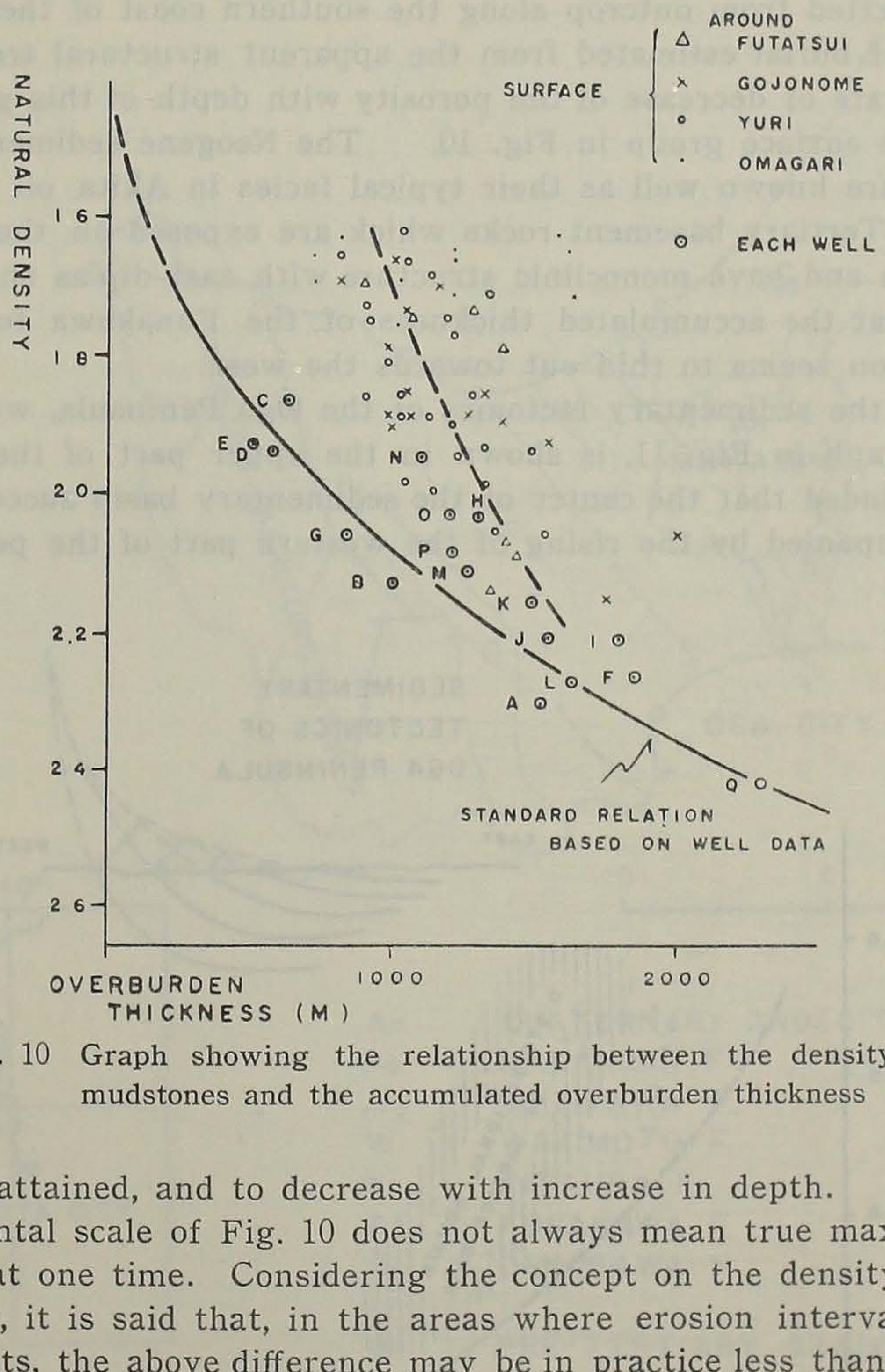


Fig. 10 Graph showing the relationship between the density of mudstones and the accumulated overburden thickness

of burial once attained, and to decrease with increase in depth.

The horizontal scale of Fig. 10 does not always mean true maximum overburden thickness at one time. Considering the concept on the density and maximum depth of burial, it is said that, in the areas where erosion interval is recognized among sediments, the above difference may be in practice less than the one shown in Fig. 10, because an isopach map has been drawn by assuming the eroded overburden thickness. The fact that the data from the vicinity of Omagari are irregularly scattered in the graph, suggests that the maximum depth of burial, which the basal part of the Funakawa formation suffered at one time, might have been abnormally less than the assumed overburden thickness in this area, because the area must have been the marginal part of basin.

Muds are said to have the tendency of increasing their volume in two earlier compaction stages ; (1) mechanical rearrangement stage and (2) dewatering stage. In the stage (2), jarring makes porosity reduce to about 30 per cent (natural density ; 2. 10-2. 20 g/cm^3). The muddy sediments, which have suffered the maximum depth of burial less than 1200-1300m, must be under the compaction stage (1) or (2) and the packing of their constituent matter may be unstable.

5) Mudstone Density and Sedimentary Tectonics

Fig. 11 shows the relationship between the vertical density variation of the mudstones collectted from outcrop along the southern coast of the Oga Peninsula and the depth of burial estimated from the apparent structural trend of the formations. The rate of decrease of the porosity with depth of this group is smaller than that of the surface group in Fig. 10. The Neogene sediments forming the Oga Peninsula are known well as their typical facies in Akita oil fields. They overlie the Pre-Tertiary basement rocks whick are exposed on the western front of the peninsula and have monoclinic structure with east-dip as shown in Fig. 12. Fig. 9 shows that the accumulated thickness of the Funakawa formation to the Sasaoka formation seems to thin out towards the west.

An idea on the sedimentary tectonics of the Oga Peninsula, which was deduced from the graph in Fig. 11, is shown in the upper part of the Figure. In brief, it is concluded that the center of the sedimentary basin successively shifted eastwards accompanied by the rising of the western part of the peninsula. The

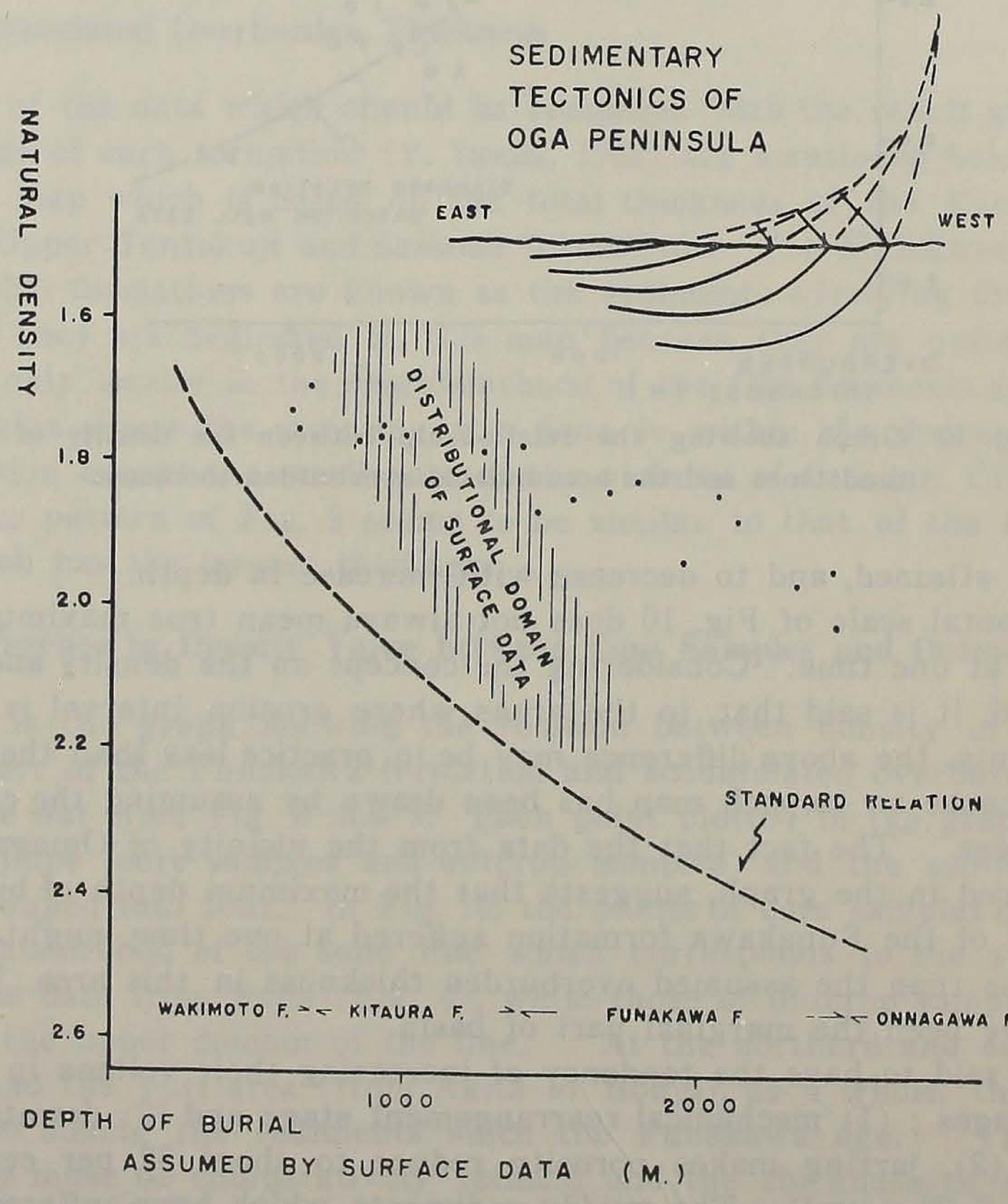


Fig. 11 Schematic section showing an idea of the sedimentary tectonics of the Oga Peninsula deduced from the density variation of mudstones and the structural trend of the formations.

The lower graph showing the relation between the density of outcrop samples from the South-Coast of the Oga Peninsula and the overburden thickness estimated from the structural trend of the formations.

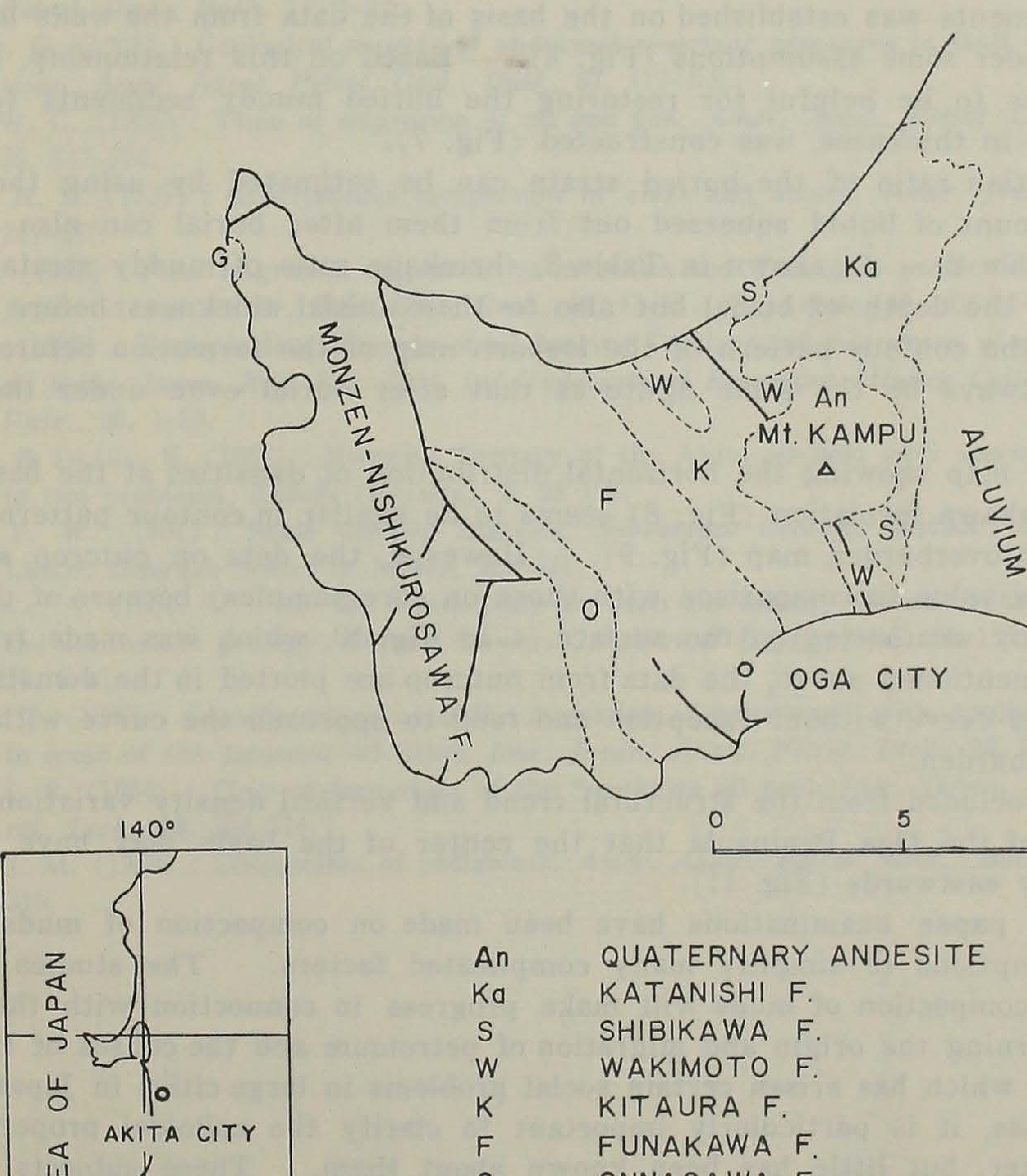


Fig. 12 Geologic map of the Oga Peninsula

fact that the degree of the density increase is lower as compared with that of the apparent overburden increase, means that the actual overburden must have been less than the amount estimated from the apparent structural trend of the formations on the surface.

Estimating the actual depth of burial at the basal part (sampling point) of the Funakawa formation from the average curve for density values of outcrop samples (broken line in Fig. 10), it is about 1300m and corresponds more or less to the half of the apparent overburden.

Summary

The results obtained through this paper are summarized as follows.

1. The standard relationship between compaction and depth of burial on

muddy sediments was established on the basis of the data from the wells in Akita oil fields under some assumptions (Fig. 4). Based on this relationship, a chart which seems to be helpful for restoring the buried muddy sediments to their initial state in thickness, was constructed (Fig. 7).

Compaction ratio of the buried strata can be estimated by using the chart and the amount of liquid squeezed out from them after burial can also be calculated (Table 2). As shown in Table 3, shrinkage ratio of muddy strata is due not only to the depth of burial but also to their initial thickness before burial. Therefore, the contour pattern of the isopach map of the formation before burial, may not always be the same figure as that after burial even under the same overburden.

2. The map showing the horizontal distribution of densities at the basal part of the Funakawa formation (Fig. 8) seems to be similar in contour pattern to the accumulated overburden map (Fig. 9). However, the data on outcrop samples (show lower value in comparison with those on core samples) because of the effects caused by weathering on the surface. In Fig. 10, which was made from the two maps mentioned above, the data from outcrop are plotted in the domain above the standard curve without exception and tend to approach the curve with increase in overburden.

It is concluded from the structural trend and vertical density variation of the sediments of the Oga Peninsula that the center of the basin may have shifted successively eastwards (Fig. 11).

In this paper, examinations have been made on compaction of muds using some assumptions to simplify many complicated factors. The studies on the process of compaction of muds will make progress in connection with the questions concerning the origin and migration of petroleum and the causes of the land subsidence, which has arisen certain social problems in large cities in Japan. For these studies, it is particularly important to clarify the colloidal properties of clayey matter, but little has been known about them. These subjects should be investigated by experimental methods from the viewpoints of soil mechanics and sedimentology. The effects of the chemical cementation, hydraulic uplift, hydraulic pressure and secondary pressure caused by structural movements are also important for the compaction of sediments.

The core samples, on which compaction of muddy sediments has been discussed by many investigators so far, may hardly be collected in the future because of economical reason. The densities of the mudstones taken from outcrop are fairly regularly distributed as shown in Fig. 11. Therefore the writer believes that studies of outcrop samples will be alike of use in speculating on sedimentary tectonics and will offer some useful data to construct isopach map, if sufficient considerations on the overburden- compaction relation and other factors are made on outcrop samples.

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