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Quaternary Geology of Osaka with Special Reference to Land Subsidence*

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(with 2 Tables, 42 Figures and 1 Plate)

Contents

Introduction

The main part of this paper is originally prepared as Chapter IV "Geologic structure of Osaka Basin" written by IKEBE & TAKENAKA, in the "*Report on Land Subsidence in Osaka*" (September 1969) edited by the Editorial Committee for Technical Report on Osaka Land Subsidence,** for the Symposium on Land Sub-

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* Contribution from the Department of Geosciences, No. 215.

** The Committee consists of the following members:
S. HAYAMI (Chairman), N. IKEBE, J. IWATSU, S. MATSUSHITA, S. MUFAYAMA, and J. TAKENAKA.
A summarized paper has been presented at the Symposium, held in Tokyo in September 1969, by S. MURAYAMA, (MURAYAMA, 1969 MS.).

sidence organized jointly by the International Association of Scientific Hydrology and the Japanese National Commission for UNESCO, to introduce the outline of the present knowledge on the land subsidence in Osaka obtained through various fields and by many investigators. As the Report is of limited distribution, and as it contains many results of investigations since the establishment of the Department of Geosciences (1950) but have not yet been published, the writers think better to publish in this journal in the form of general report, with some additions, corrections and modifications. Particulars on paleontology and geology will be published in near future by each author responsible for respective part.

Outline of the land subsidence in Osaka*

The area including Osaka and its suburban cities is the second largest industrial and commercial area in Japan (Fig. 1). Most part of this fully urbanized

Fig. 1 Index map of the Osaka area.

* Thanks are due to the Osaka Prefectural Government and the Osaka Municipal Office for preparing the data and figures used in this chapter.

area are on an alluvial delta plain formed compositely by such four rivers flowing into Osaka Bay as the Muko, the Ina, the Yodo and the Yamato. The average thickness of the Alluvial formation is about fifteen meters, becoming thicker as it approaches nearer to Osaka Bay (maximum thickness is about 35 m). Below the Alluvium, there exist fairly thick Pleistocene-Pliocene formations, consisting of alternations of sands, clays and gravels.

The groundwater level in the city was high until about fifty years ago and it is reported that even some artesian wells could be seen in the city of Osaka, As shown in Fig. 2, before 1928, the subsidence in the city was very slight, being an average rate of 6-9 mm/y. This slight subsidence is considered to be the result of the natural earth movement and the natural consolidation of the alluvial clay (tectonical and diagenetical subsidence). After that time, however. a remarkable increase of the use of groundwater for industrial purpose caused the increase of the rate of subsidence. The rate of subsidence is acceleratedly increased as indus-

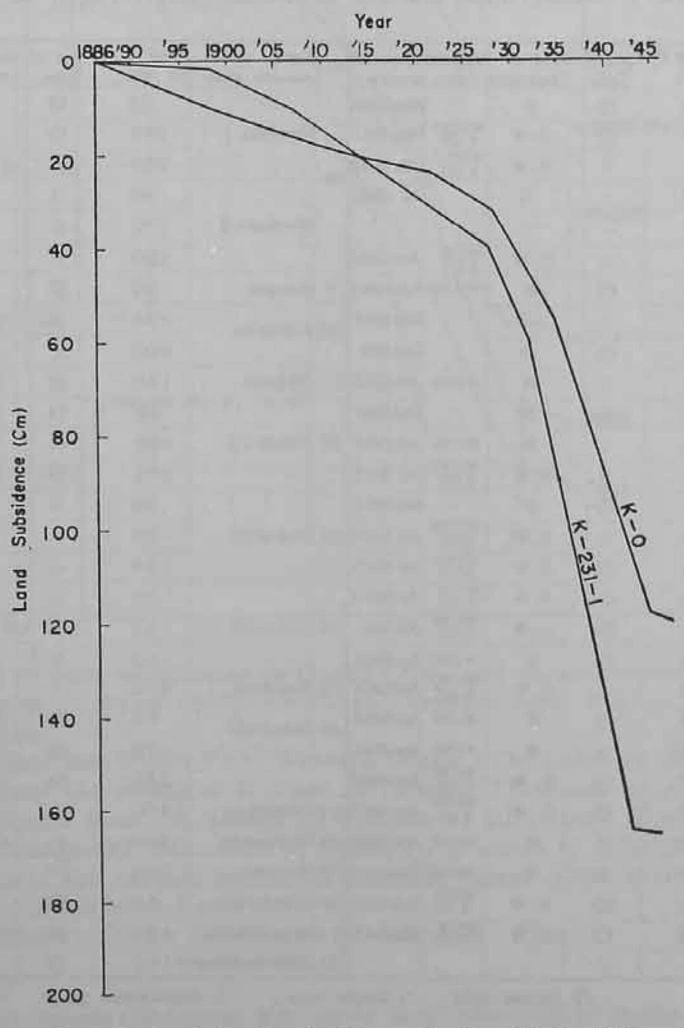


Fig. 2 Variation of amount of land subsidence during 1886—1945, measured at two bench marks (K-0 and K-231-1) near the Osaka Port in Western Osaka. For location of bench marks refer Fig. 7. Thickness of Alluvium : *ca.* 30m.

tries developed.

Since 1934, precise leveling for the wider part in the city area has been carried out every year by or under the supervision of the Geographical Survey Institute of Japan. Besides leveling, the continuous observation using self-recording apparatus* on the amount of compaction of sub-soil layer and the variation of level of artesian heads of various aquifers at Kujoh Park and Tempohzan Pier in the city set about in 1938–1939. Till 1969, 700 bench marks (of which 239 in Osaka City and 124 in Amagasaki City; total length of leveling is 838 km), and 32 observation stations (of which 15 in Osaka City) have been established in the Osaka area, to realize continuously the amount of phenomena relating to the land subsidence (Table 1 and Figs. 7 & 9). A national bench mark at Kema (O. P. 4.697 m) on the bank of the R. Yodo had been used as the standard of leveling till 1962. After the Kema mark, however, was found subsiding noticeably, the standard bench mark

Table 1 Observation stations in Osaka (Refer Figs.7 & 9).

No	Name of Observation Station	Depth of Pipe (m)	Type of Tube	Kind of Observation	Magnification	Open Observation in	No	Name of Observation Station	Depth of Pipe (m)	Type of Tube	Kind of Observation	Magnification	Open Observation in
1	Tempohzan	33	◎	S		May 1938	18	Niwakubo I	50	◎	S, W	W 1/25 S 20	Sep. 1965
		104	◎	S, W	W1/30 S 20	May 1961			100	◎	S, W	W 1/25 S 20	Sep. 1965
2	Kujoh	176	○	S, W	W1/31 S 20	Jan 1939			250	◎	S, W	W1/10 S 20	Sep 1965
		33	○	S		Jul 1960		Niwakubo II	50	○	W	W1/25	Sep 1965
		62	○	—					100	○	W	W1/25	Sep 1965
3	Torishima	93	○	S, W	W1/31 S 20	Jun 1947			250	○	W	W1/10	Sep 1965
		40	◎	W	W1/30	Feb 1960	19	Nangoh	50	◎	S, W	W1/5 S 20	Sep 1965
		35	○	S		Sep 1957	20	Kohnoike	100	○	W	W1/25	Apr 1968
4	Turumachi	30	◎	S		Dec 1951			200	○	W	W1/10	Apr 1968
		30	○	W	W1/30	Jan 1953	21	Nagase	150	◎	S, W	W1/25 S 20	Sep 1965
5	Shimayacho	30	◎	S		Dec. 1951	22	Rinkai (1)	48	◎	S, W	W1/5 S 100	Sep 1961
		30	○	W	W1/32	Jul. 1953			150	◎	S, W	W1/25 S 100	Sep 1961
6	Himejima	68	○	S, W	W1/30 S 20	Jul 1953			245	◎	S, W	W1/25 S 100	Sep 1961
7	Tanakacho	104	◎	S		Mar 1954	23	Rinkai (2)	50	○	W	W1/25	
8	Juso	100	○	S, W	W1/30 S 20	Jul 1960			150	○	W	W1/25	
9	Nakanoshima	96	◎	S, W	W1/63 S 20	Jul 1960			254	○	W	W1/25	
		186	◎	S, W	W1/31 S 20	Jul 1960	24	Rinkai (3)	50	○	W	W1/25	Mar 1963
10	Gamoh	96	◎	S, W	W1/38 S 20	Jul 1960			150	○	W	W1/25	Mar 1963
11	Minato	354	◎	W	W1/60	Apr 1964			250	○	W	W1/25	Mar 1963
		606	○	S, W	W1/30 S 20	Apr 1964	25	Rinkai (4)	300	○	W	W1/5 S 50	Mar 1964
		185	◎	W	W1/30	Apr 1964	26	Rinkai (5)	50	◎	S, W	W1/25 S 50	Mar 1965
12	Miyakojima	300	○	W	W1/60	Apr 1966			150	◎	S, W	W1/25 S 50	Mar 1965
13	Ikuno	17	◎	S, W	W1/30 S 20	Apr 1967			300	◎	S, W	W1/25 S 50	Mar 1965
		200	◎	S, W	W1/30 S 20	Apr 1967	27	Izumiotsu	400	○	W	W1/10	
14	Kunijima	200	○	W	W1/30	Apr 1968	28	Kishiwada	300	○	S, W	W1/10 S 20	
15	Hoenzaka	180	○	W	W1/30	Apr 1969	29	Sennan	200	○	W	W1/10	
16	Toyonaka	47	◎	S, W	W1/25 S 20	Sep 1965	30	Nishikaigan	57	◎	S	1/20	Nov 1952
17	Suita	68	◎	S, W	W1/5 S 20	Sep 1965	31	Higashihama	184	◎	S, W	1/20	Jan 1953
							32	Shinkohnakahama	140	◎	W	1/20	Jun 1961

Annotation ◎ Double tube ○ Single tube S displacement gauge W water gauge

* For details of the self-recording apparatus, refer HAYAMI *et al.*, 1969, p. 38–41.

at Fukui, Ibaragi City (National bench mark F. 21 : 64.1235 m T. P.=65.4235 m O. P.*) has been used as a fixed bench mark for the leveling of the Osaka area since 1963.

Fig. 3 shows the cumulative amount of land subsidence of various bench mark in Osaka City and the secular variation of the level of artesian head at the Kujoh

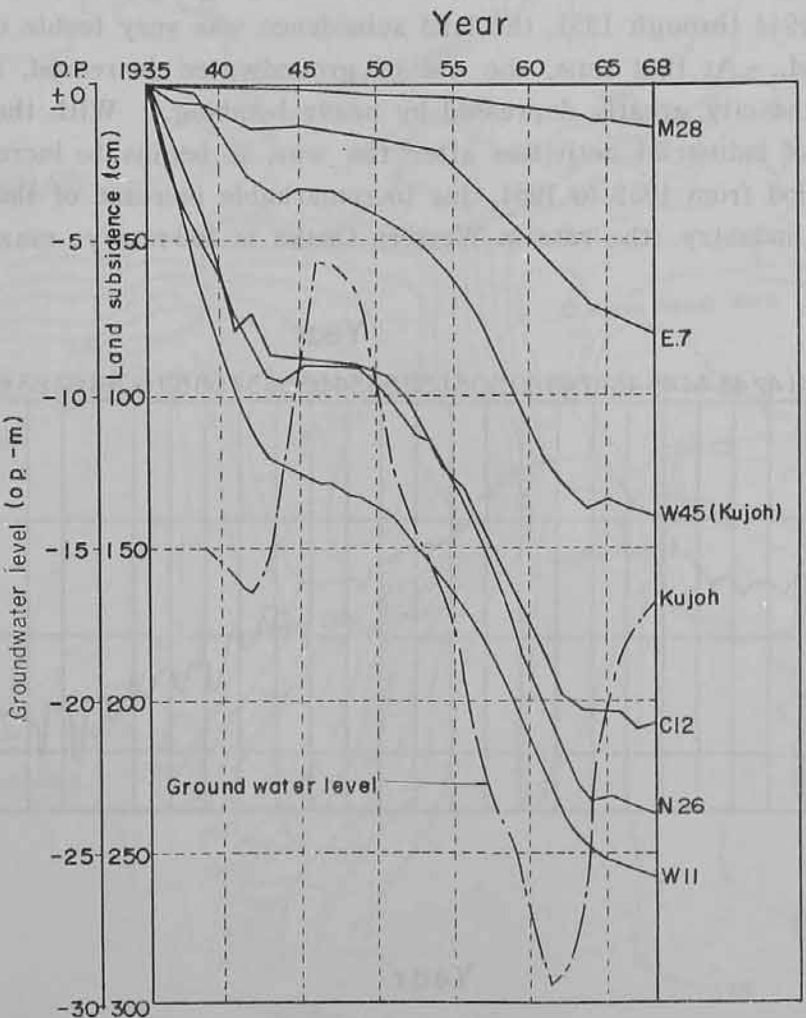


Fig. 3 Amount of land subsidence in Osaka City, and secular variation of groundwater level at Kujoh (1935—1968). For location refer Fig. 7.
Annotations
W11 : near the Osaka Port, Western Osaka (Thickness of Alluvium : 30 m),
N 26 : near the mouth of R. Yodo, W. Osaka (Thickness of Alluvium : 25 m),
W45 : Kujoh Park, W. Osaka (Thickness of Alluvium : 25 m),
C 12 : Amagasaki City, west of Osaka (Thickness of Alluvium : 25 m),
M28 : near the eastern border of Uemachi upland, Central Osaka (Thickness of Alluvium : 5 m),
E 7 : Eastern Osaka (Thickness of Alluvium : 15 m).

* O. P. (Osaka Peil) means the lowest low water level observed in Osaka Port in 1885, and this level is used as the standard datum in Osaka area. T. P. (Tokyo Peil), the mean sea level in Tokyo Bay, is used officially by the Geographical Survey Institute as the standard datum in Japan. 0 m O. P. corresponds to −1.3 m T. P.

well with 176 m depth below O.P. As shown in this figure, the amount of subsidence is closely related to the thickness of the Alluvial formation. Moreover, these curves show that the history of land subsidence in Osaka seems to be classified into four periods from the standpoint of the rate of subsidence. During the period from 1935 through 1943 the land subsidence was very remarkable (the rate in Western Osaka was 140-150 mm/y.), as the developing industries. In the second period from 1944 through 1951, the land subsidence was very feeble or sometimes nearly stopped. At that time, the use of groundwater decreased, as industrial activities of the city greatly depressed by heavy bombing. With the revival and development of industrial activities after the war, it begins to increase again in the third period from 1952 to 1964, due to remarkable increase of the use of groundwater for industry (the rate in Western Osaka is 100 mm/y., maximum is 201

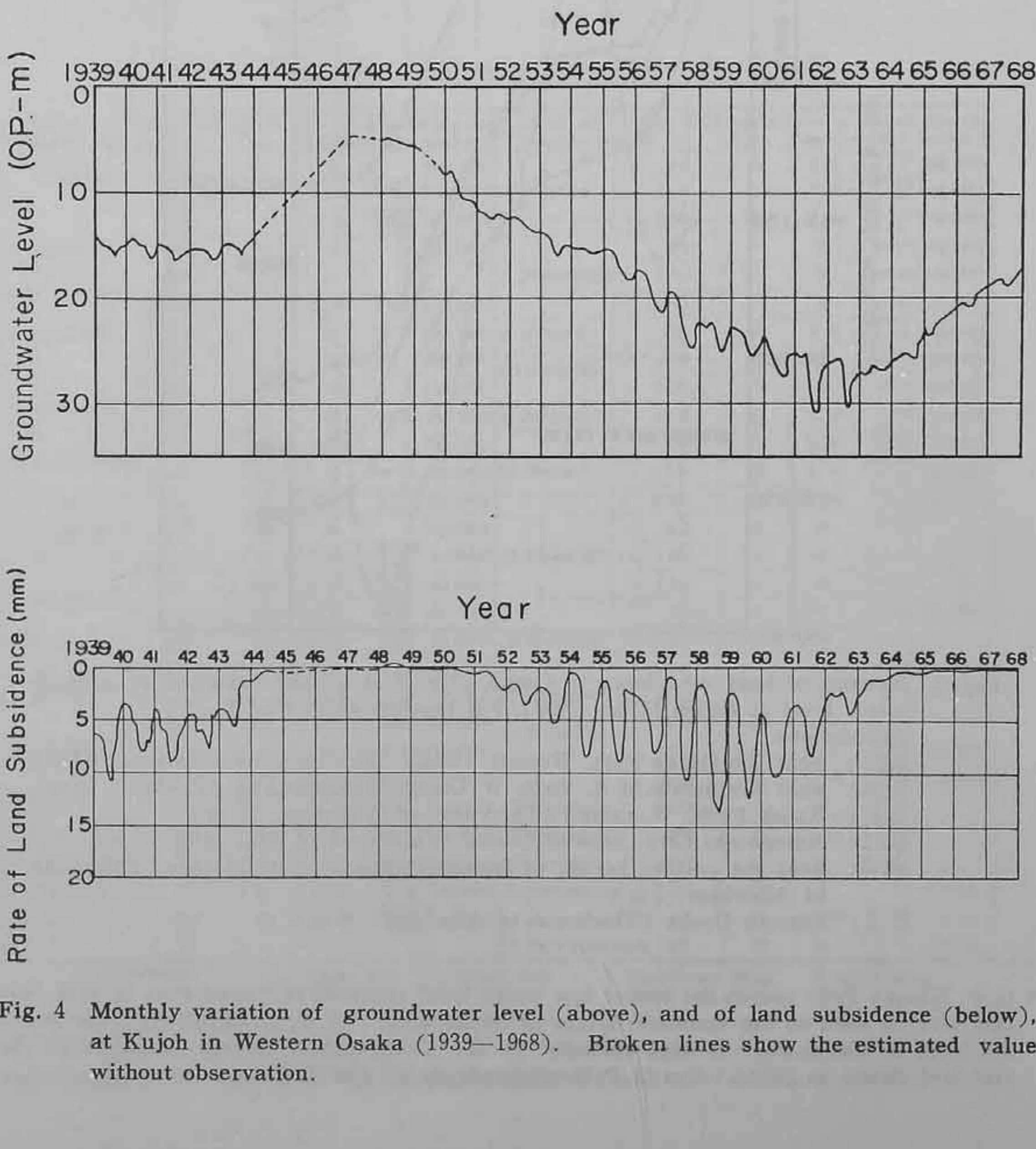


Fig. 4 Monthly variation of groundwater level (above), and of land subsidence (below), at Kujoh in Western Osaka (1939—1968). Broken lines show the estimated value without observation.

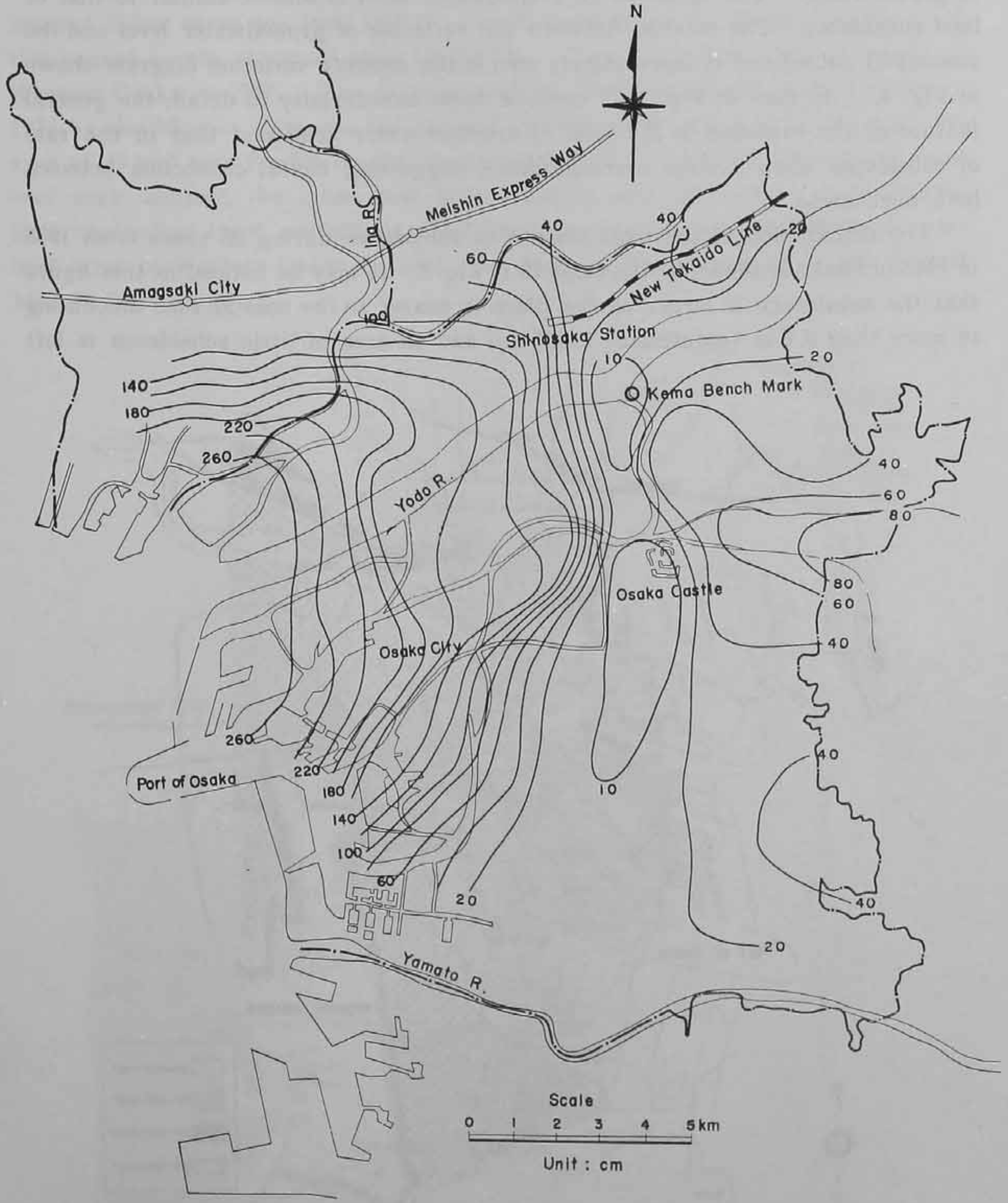


Fig. 5 Isopleth of total amount of land subsidence in Osaka City during 28 years from 1935 to 1963, drawn by TAKENAKA (1965) based on the precise leveling. During this period, Kema bench mark on the bank of the R. Yodo had been used as the fixed bench mark for leveling. This map shows the state of the land subsidence before the severe regulation against use of groundwater.

mm/y.). It is decreasing since 1964 as a result of the regulation against the use of groundwater. The variation of groundwater level is almost similar to that of land subsidence. The relation between the variation of groundwater level and the amount of subsidence is more clearly seen in the monthly variation diagram shown in Fig. 4. As seen in Fig. 4, in spite of some inconformity in detail, the general feature of the variation in the level of artesian water head and that in the rate of subsidence show a close correspondence suggesting causal connection between both phenomena.

The distribution of the total amount of subsidence during 28 years from 1935 to 1963 in Osaka is shown by the isopleth in Fig. 5. It may be noticed in this figure that the subsidence is larger as the place is nearer to the coastal zone amounting to more than 2.6 m (maximum: 2.837 m), and an area of little subsidence is left

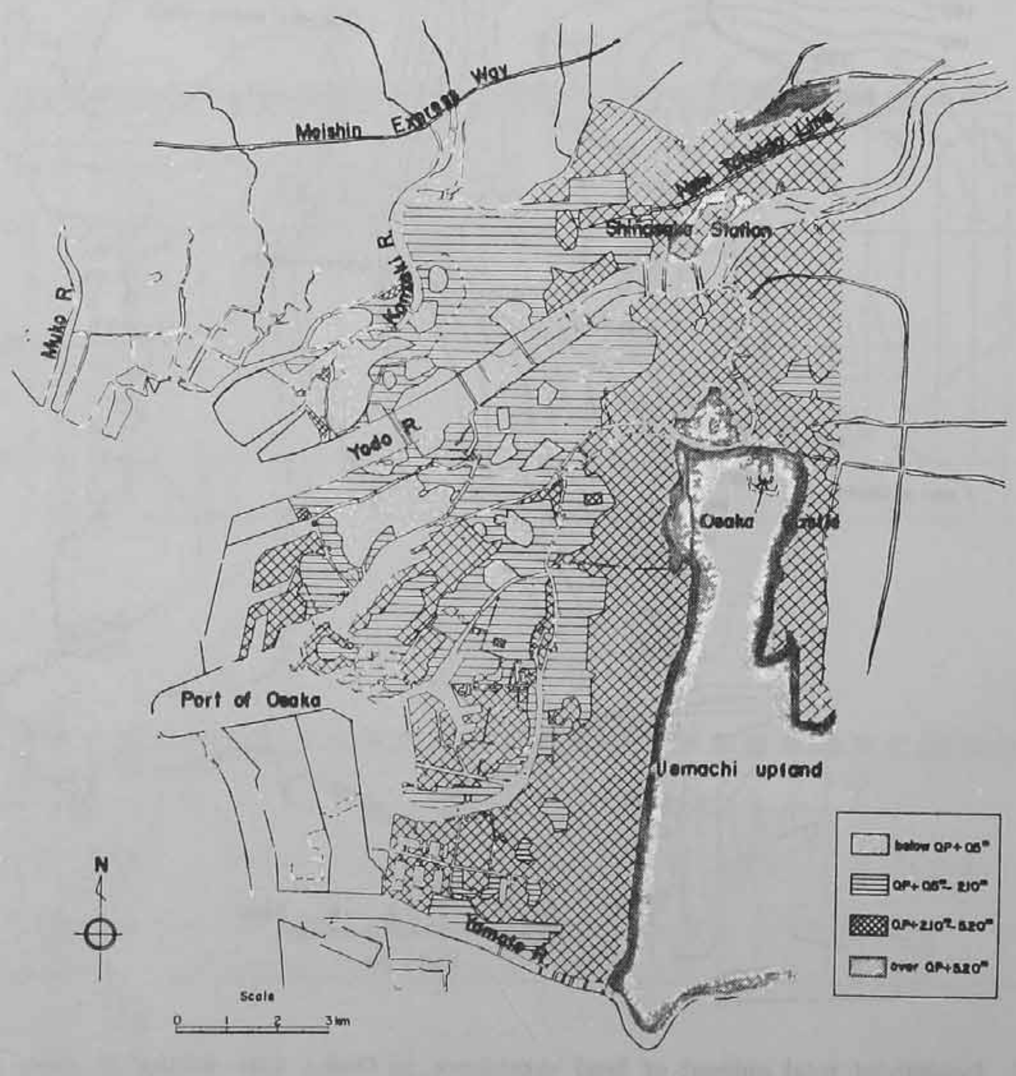


Fig. 6 Ground level in Osaka City in 1967.
Annotation : O.P.+0.50m··················Mean low water level.
O.P.+2.10m··················Mean high water level.
O.P.+5.20m··················Estimated highest high water level.

in the upland of the middle Osaka (Uemachi upland) where no Alluvial covering exists. Due to land subsidence the ground height of a part of Western Osaka has lowered below mean sea level and the city is exposed to the danger of the flood tide caused by the storm surge in Osaka Bay. Fig. 6 shows the ground height of Western Osaka in 1967. The disaster of flood tide was unfortunately realized in 1934 by the Muroto Typhoon, the biggest typhoon ever attacked Osaka, and the area of 49 km^2 was flooded by the storm surge of O.P.+4.20 m. In order to prevent such disaster, the dikes have been repaired and built more satisfactorily. Notwithstanding these preventions, flood disasters of storm surge attacked the lowland areas of Western Osaka in 1950 (the Jane Typhoon) and 1961 (the Second Muroto Typhoon).

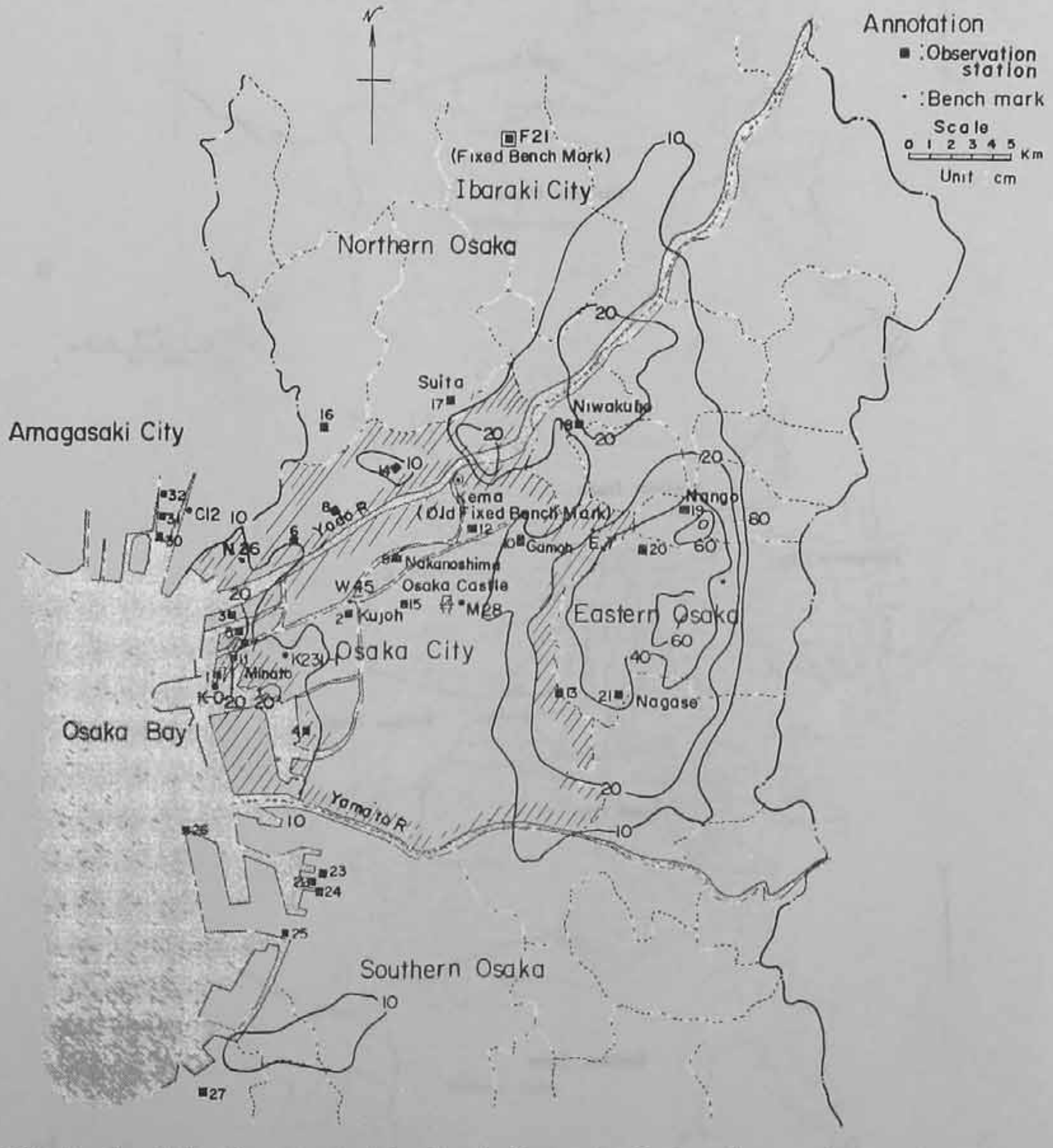
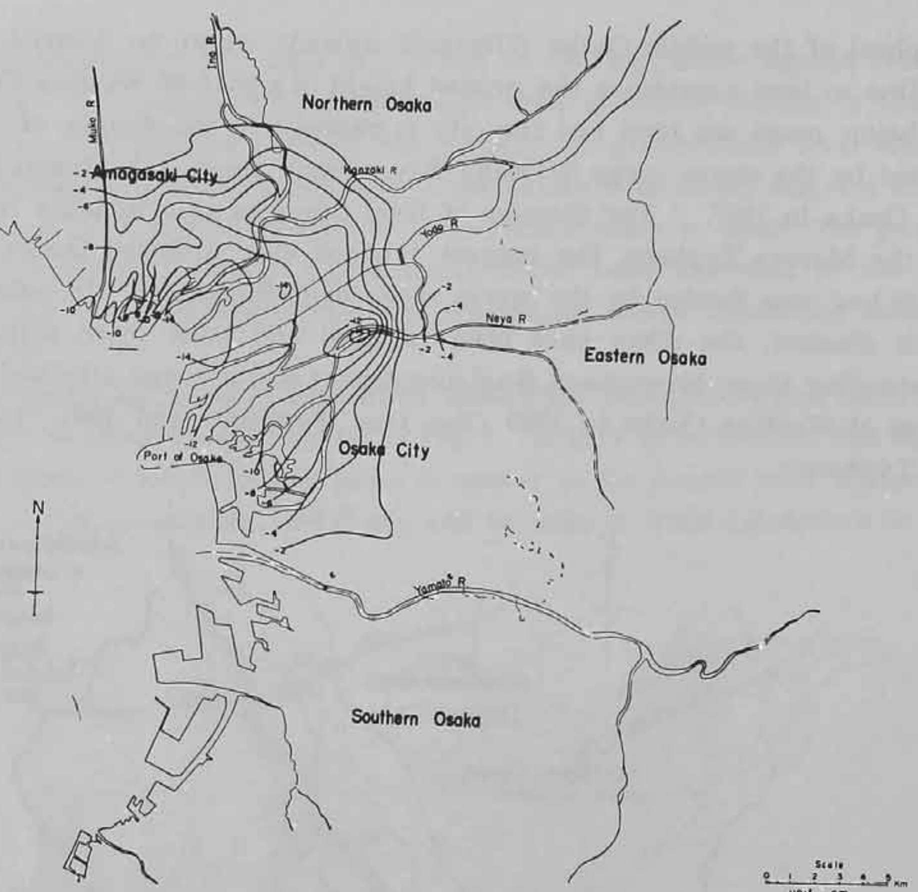


Fig. 7 Isopleth of amount of land subsidence in Osaka City and the suburban area from 1963 to 1968. Unit in cm. Location of observation stations (Table 1) and important bench marks is mentioned. Area of Osaka City is shaded.


Northern Osaka
Amagasaki City
Eastern Osaka
Osaka City
Port of Osaka
Southern Osaka
Muko R.
Ina R.
Kanzaki R.
Yodo R.
Neya R.
Yamato R.
N
a
Scale
0 1 2 3 4 5 Km
unit . cm


Northern Osaka
Amagasaki City
Eastern Osaka
Osaka City
Port of Osaka
Southern Osaka
Muko R.
Ina R.
Yodo R.
Neya R.
Yamato R.
N
b
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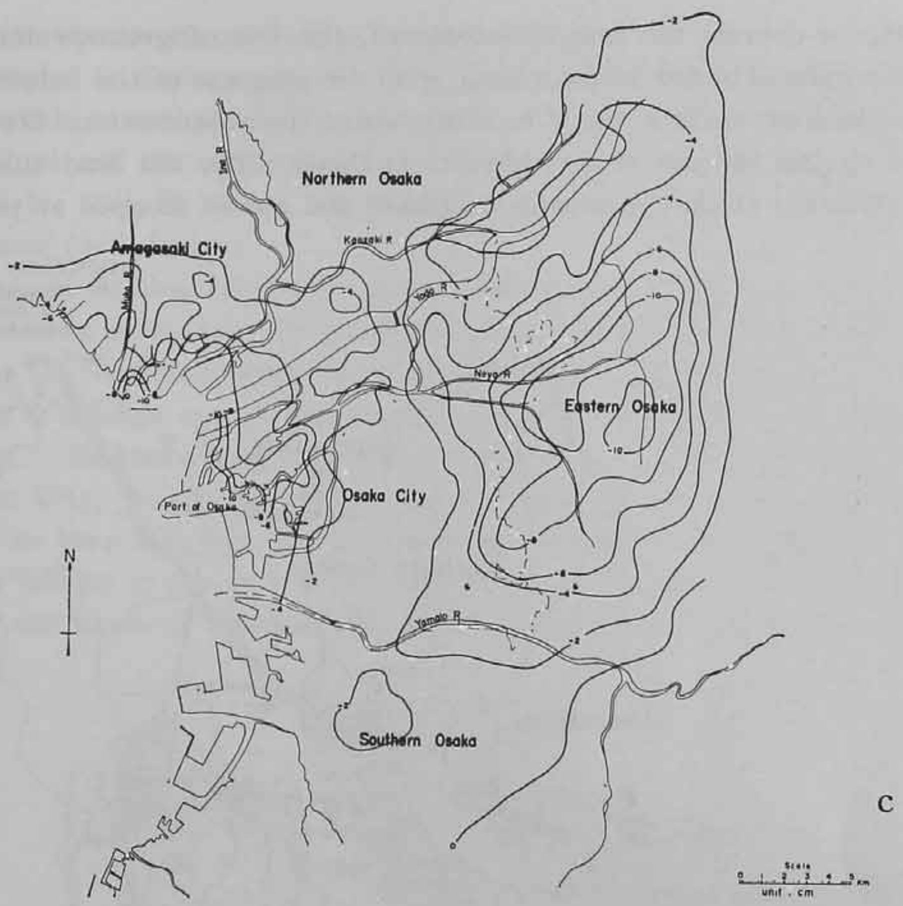


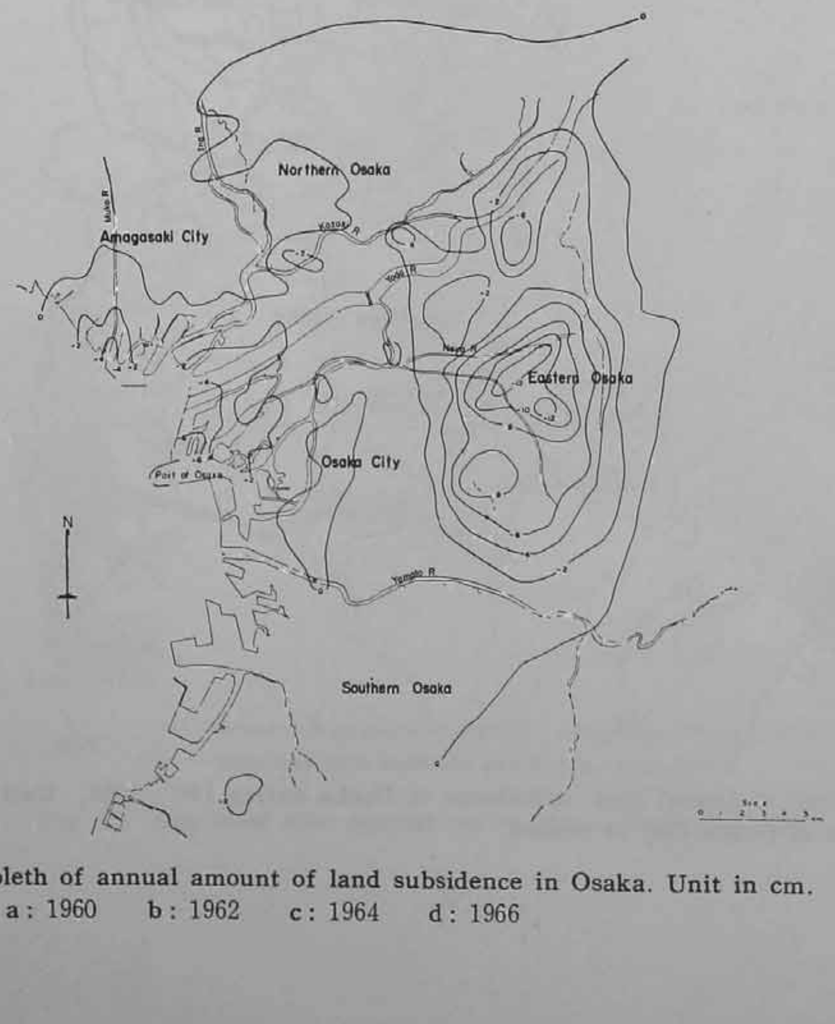


Fig. 8 Isopleth of annual amount of land subsidence in Osaka. Unit in cm.
a : 1960 b : 1962 c : 1964 d : 1966

To stop or depress the rate of subsidence, the use of groundwater has been gradually regulated by law in accordance with the progress of the industrial water supply works from surface water to substitute of the groundwater. Owing to the regulation against the use of groundwater in Osaka City, the land subsidence in the city (Western Osaka) gradually decreased and almost stopped at present. In

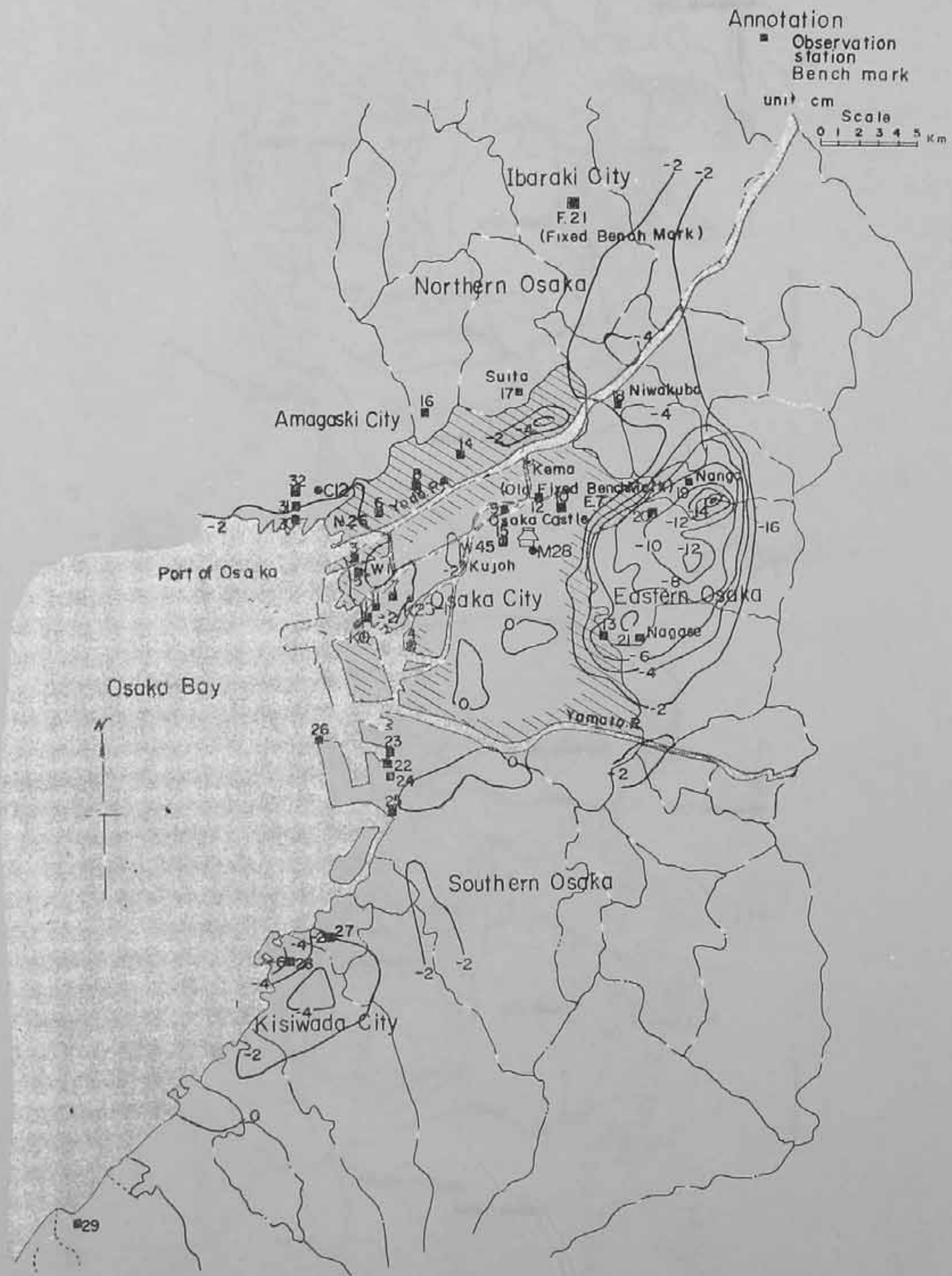


Fig. 9 Isopleth of annual land subsidence in Osaka during 1967—1968. Unit in cm. Area of Osaka City is shaded.

spite of the success in preventing the land subsidence in Western Osaka, however, the subsidence in Eastern and Northern Osaka, lately developed industrial areas, has remarkably increased during few years. Details of these decrease of amounts of subsidence and the shifting of areas of significant land subsidence will be seen in Figs. 7–9. Fig. 10 shows, for reference, the regulated areas against use of groundwater for industry.

In Fig. 9, showing the recent annual subsidence, it may be noticed that the land subsidence in Western Osaka nearly stops except the very coastal area around the port. On the other hand, the land subsidence in Eastern Osaka is still active and there is a large eye of the isopleth of subsidence whose maximum amount is 160 mm. Besides above, a new eye of subsidence is found developing around Kishiwada City, Southern Osaka. In this area, not only the Alluvial covering seems to be very thin, but the relation to the variation of groundwater level seems to be not similar to the case in Western Osaka. So that, a new investigation into the state and cause of the land subsidence of this area is very urgent at present.

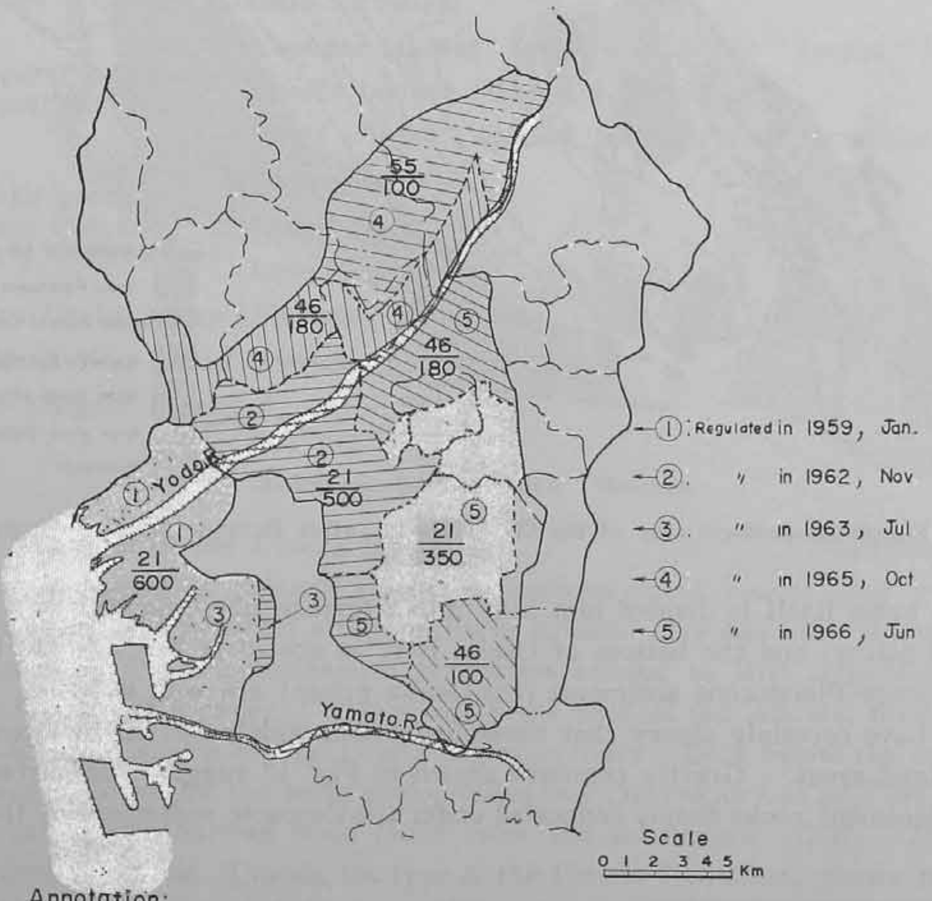


Fig. 10 Regulated area against use of groundwater for industry.

Geologic setting and geomorphic features

The Osaka basin embracing Osaka Bay in its western half, occupies the eastern end of Setonaikai (Setouchi Inland Sea), and geologically is situated at the middle of the Setouchi depressional zone of Southwest Japan (HUZITA, 1962 & 1966; IKEBE & ICHIKAWA, 1967). The basin is oval in shape, filled with late Cenozoic sediments, and surrounded by such mountainous areas composed of Pre-Cenozoic rocks, as the Awaji-Rokko range, the Hokusetsu mountains (southeastern end of the Tamba mountainland), the Ikoma range and the Izumi range (Figs. 11 & 12).

Fig. 11 Simplified geologic map of the Osaka Basin (after HUZITA, IKEBE & HUZITA 1966).

The basin itself is divided into hilly areas, terrace-like uplands, lowland areas (alluvial plains) and the bottom of Osaka Bay, as shown in Fig. 12. In the hilly area Pliocene-Pleistocene sediments (the Osaka group) are well exposed. Drilling surveys have certainly shown that these formations widely and thickly exist below the lowland areas. Gravity contours shown in Fig. 12 suggest the surface relief of the basement rocks deeply concealed under the Cenozoic sediments of the Osaka basin.*

* The gravity contours here used are results of three separately performed surveys during these twenty years: by E. ABE, K. KATSURA & S. NISHIMURA for the northern part (HUZITA, 1966), by the Geological Survey of Japan for the Osaka city area, and by the Teikoku Oil Co., Ltd. for the eastern and southern parts.

S. YAMANE (1930) is the first describing the subsurface geology of Osaka City through the investigation of the drilling cores. His division of the subsurface geology was as follows (in descending order):

1) Umeda formation
2) Tenma formation
3) Uemachi formation
4) Basement formation of Osaka (corresponding to the Osaka group at present)

Detailed stratigraphical surveys of the hilly areas, compilation of a lot of shallow boring data and underground survey by carefully treated core borings (OD-1 to OD-9) drilled in the lowland areas, together with the sonic geological survey of Osaka bay and the investigations in the structure of Rokko mountains, worked out since 1950, have made clear the underground stratigraphy and structure of the Osaka basin.

Geology of the Osaka basin and the surroundings (Fig. 13) is summarized as the following table (in descending order):

Recent Alluvium (Umeda formation)	
Upper Pleistocene formations	Younger (Lower) terrace (Itami or "Tenma" formation)
	Middle terrace (Uemachi formation)
	Older (Higher) terrace (Shinodayama formation)
Osaka group (Late Pliocene–Early Pleistocene)	Upper part
	Lower part
	Lowest part
Infra-Osaka group (Pliocene)	
Kobe & Nijo group (Miocene)	
Pre-Neogene basement	

Geologic bodies since Pliocene

Recent Alluvium or the Umeda formation. Thickness: 0–35 m

Alluvial formation consists chiefly of unconsolidated marine clay with sands and gravels. Mineralogical study on these Alluvial clay has been worked out by KAKITANI (1958). Soil-mechanical properties related to land subsidence will be treated later in this paper. The relief of the base of the Alluvial formation and its isopachs are shown in Fig. 14 and 11 respectively. Data below the sea bottom have been obtained by the sonic geological survey (HAYAKAWA *et al.*, 1964). Radiocarbon dating of a burried wood found from the subsurface (O.P. −24.9 m) at Osaka central station (Umeda, the type of the Umeda formation) shows the age of 9,360±190 y.B.P. (ITIHARA & KIGOSHI, 1962). Judging from the distribution, bottom relief and lithofacies (Fig. 15), these Alluvial sediments are composite delta deposits of R. Muko, R. Ina, R. Yodo and R. Yamato, deposited in drowned estuaries resulted by the Postglacial sea-level rise. Two cycles of development of the Al-

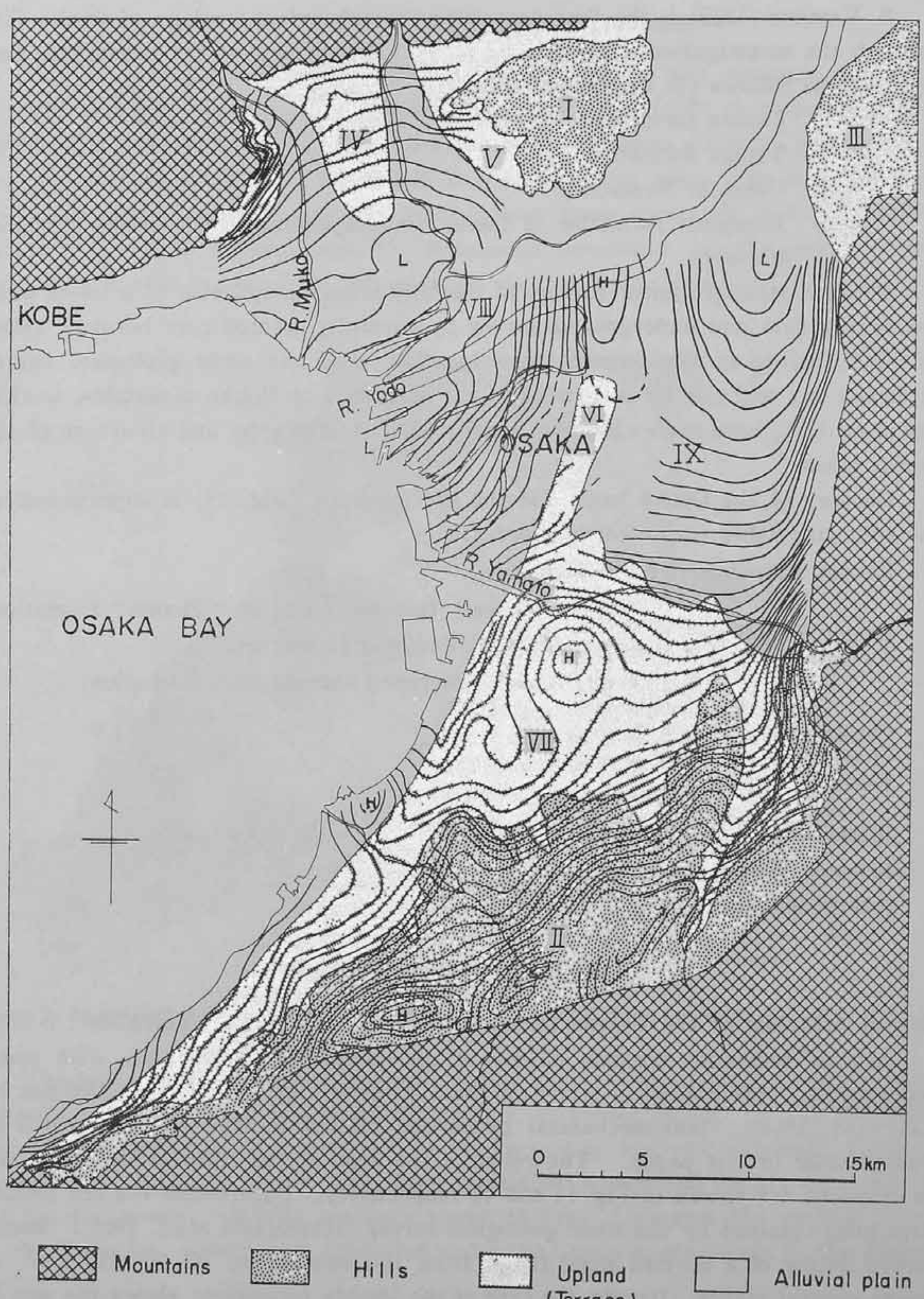


Fig. 12 Geomorphic divisions and gravity contours of the Osaka area. The interval of gravity contour is 1 milligal. As for the gravity survey, see the foot-note.

I Senri(-yama) Hills	II Izumi Hills	III Hirakata Hills
IV Itami Upland	V Toyonaka Upland	VI Uemachi Upland
VII Izumi Upland	VIII Osaka Lowland	IX Kawachi Lowland

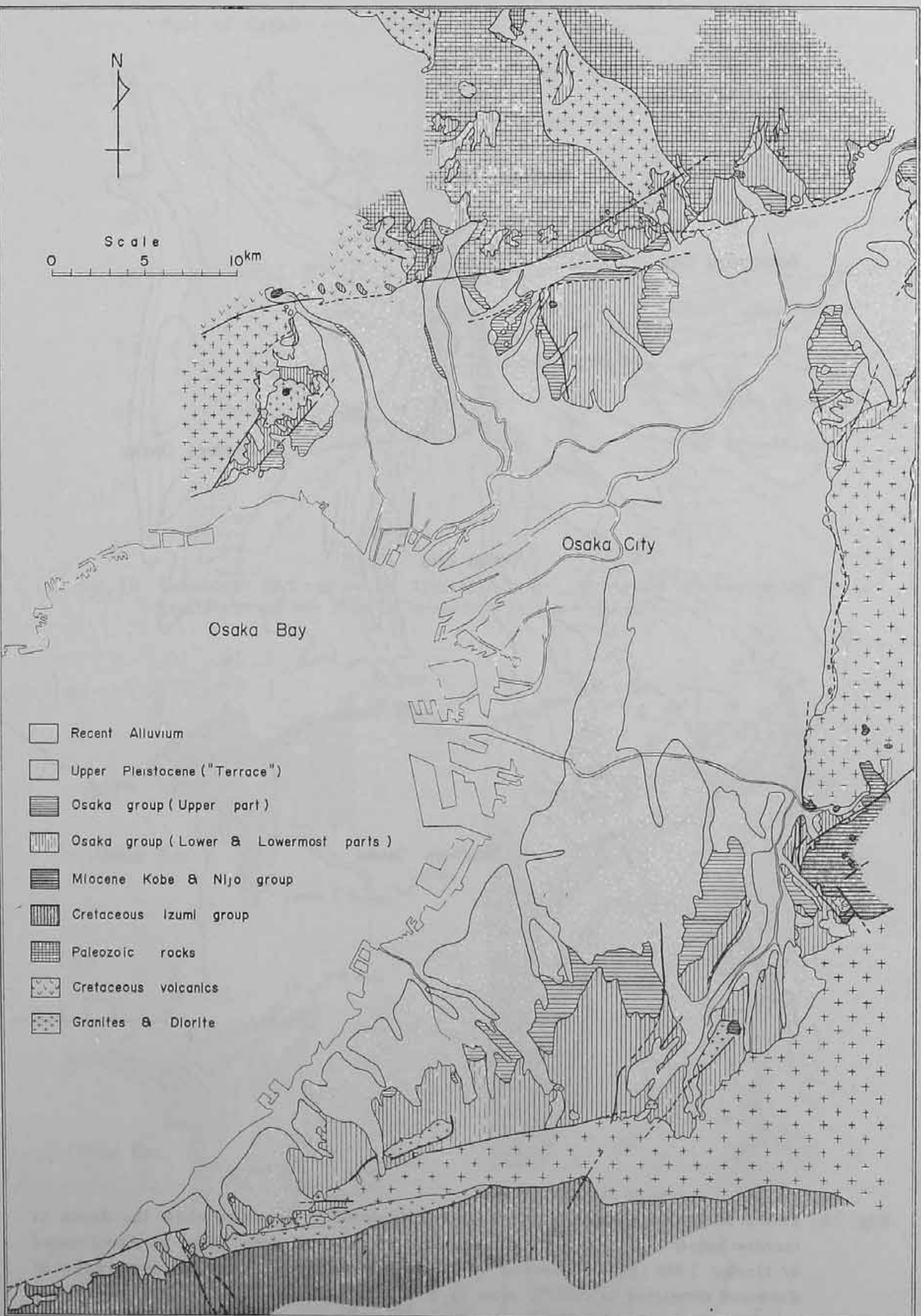


Fig. 13 General geologic map of the Osaka area (after *"Ground of Osaka"*, modified TAKENAKA & IKEBE).

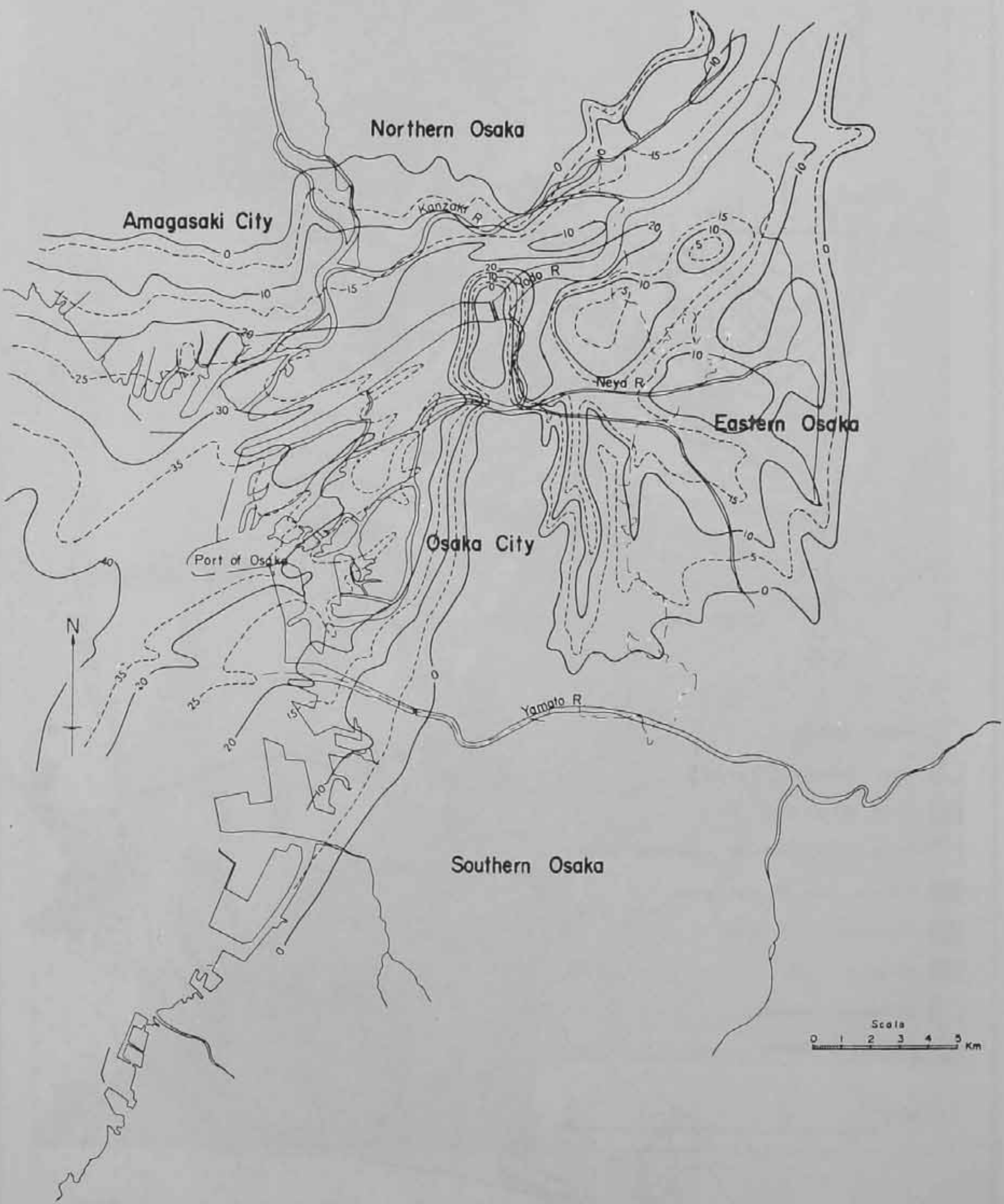


Fig. 14 Relief map of the base of the Recent Alluvium. Contours show the depth in meters below O.P., drawn from the data of shallow wells listed in *The Ground of Osaka*, 1966 (after "*Ground of Osaka*", simplified). Ancient topography of drowned estuaries is clearly seen in this map.

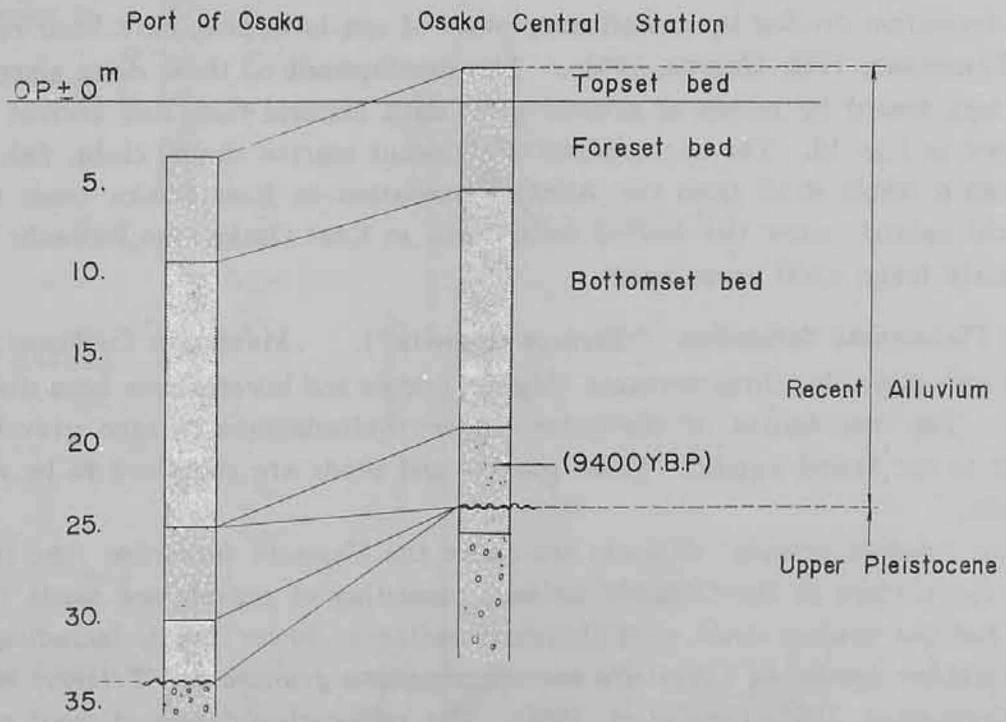
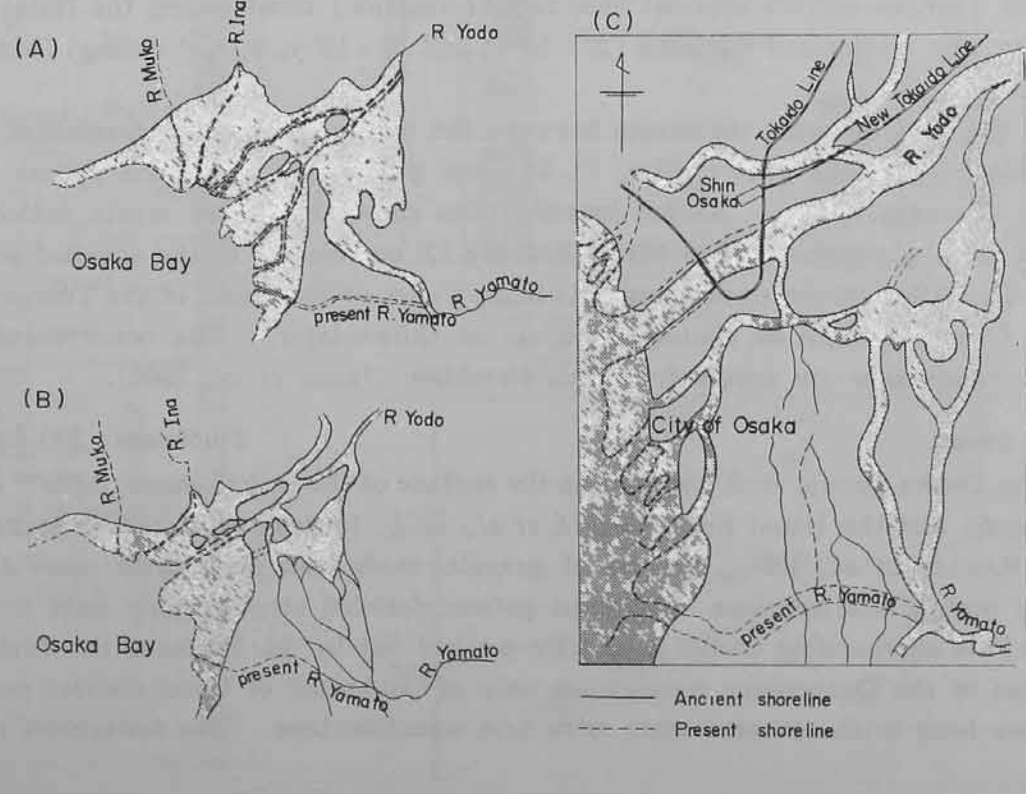


Fig. 15 Columnar sections of the typical Alluvial formation, including the stratotype of the Umeda formation (right) (TAKENAKA).



(A) Osaka about 2000 years ago (after K. Tanaka, 1960)
(B) Osaka about 1200 years ago (after K. Tanaka, 1960)
(C) Osaka about 250 years ago (after ancient map of R. Yodo)

Fig. 16 Development of the Osaka delta plain since 2,000 years ago.

luvial formation divided by a stationary state of sea-level rise, have been recognized (TAKENAKA, 1954, HUZITA, 1966). The development of these delta since 2,000 years ago, traced by means of archeological data, historic facts and ancient maps, is shown in Fig. 16. The occurrences of abundant marine shells, crabs, fish bones and even a whale skull from the Alluvial formation in East Osaka (east to the Uemachi upland) show the marine embayment in East Osaka (the Kawachi basin) was fairly large 5,000 years ago.*

Upper Pleistocene formation ("Terrace deposits"). Maximum thickness: 85 m

Morphologically, three terraces (higher, middle and lower) have been discriminated. The distribution of the older (higer) Shinodayama terrace gravels are limited to the Izumi upland. These gravels and sands are considerd to be mainly fluviatile.

The "middle terrace" deposits are called the Uemachi formation (the type is below the surface of the Uemachi upland) consisting of gravels and sands (upper part) and the marine sands with abundant mollusca (lower part), including such characteristic species as *Turritella kurosio, Anadara granosa* and *Trisidos kiyonoi, etc.* (CHIJI *et al.*, 1962; CHIJI *et al.*, 1966). The radiocarbon dating of wood sample from Nagai, Osaka City, shows its age as$>38\times10^3$ y. (ITIHARA & KIGOSHI, 1962). Another sample from Ebaradera, Sakai City, is dated as *ca.* 24×10^3 y.

The younger terrace deposits (the Itami formation) constructing the Itami upland are also marine and fluviatile (29×10^3 y. and 32×10^3 y. by C^{14} dating) (MAEDA & HUZITA, 1970).

In the lowland area, the strata between the overlying Alluvial formation and the underlying Osaka group (Figs. 32, 34), are practically called the Tenma formation (YAMANE, 1930). Recent investigations show that these strata including marine clays sometimes called Ma 11 and Ma 12, correspond to the socalled younger and middle terrace formations. At least, a part of the Itami, of the Tenma and of the Uemachi might be contemporaneous as shown later. The occurrences of *Elephas naumanni* are surely from this formation (IKEBE *et al.*, 1966).

Osaka group. Thickness: 300-600 m

The Osaka group, well exposed on the surface of the Senri(-yama) hills** (the type area) and the Izumi hills (HUZITA *et al.*, 1951; ITIHARA *et al.*, 1955; ITIHARA, 1955; HARATA *et al.*, 1963), consists of gravels, sands and clays with more than twenty tephra intercalations. Without patient detailed stratigraphic field works in the hills surrounding Osaka especially worked out by M. ITIHARA, the further progress of the Quaternary geology not only of Osaka but of Kinki district would not have been in the present state with firm scientific base. The lowermost part

* By radiocarbon dating. Two wood samlpes have been dated by KIGOSHI, measured dates are 4,500±80 y.B.P. and 6,650±140 y.B.P.

** The site of the World Exposition of 1970.

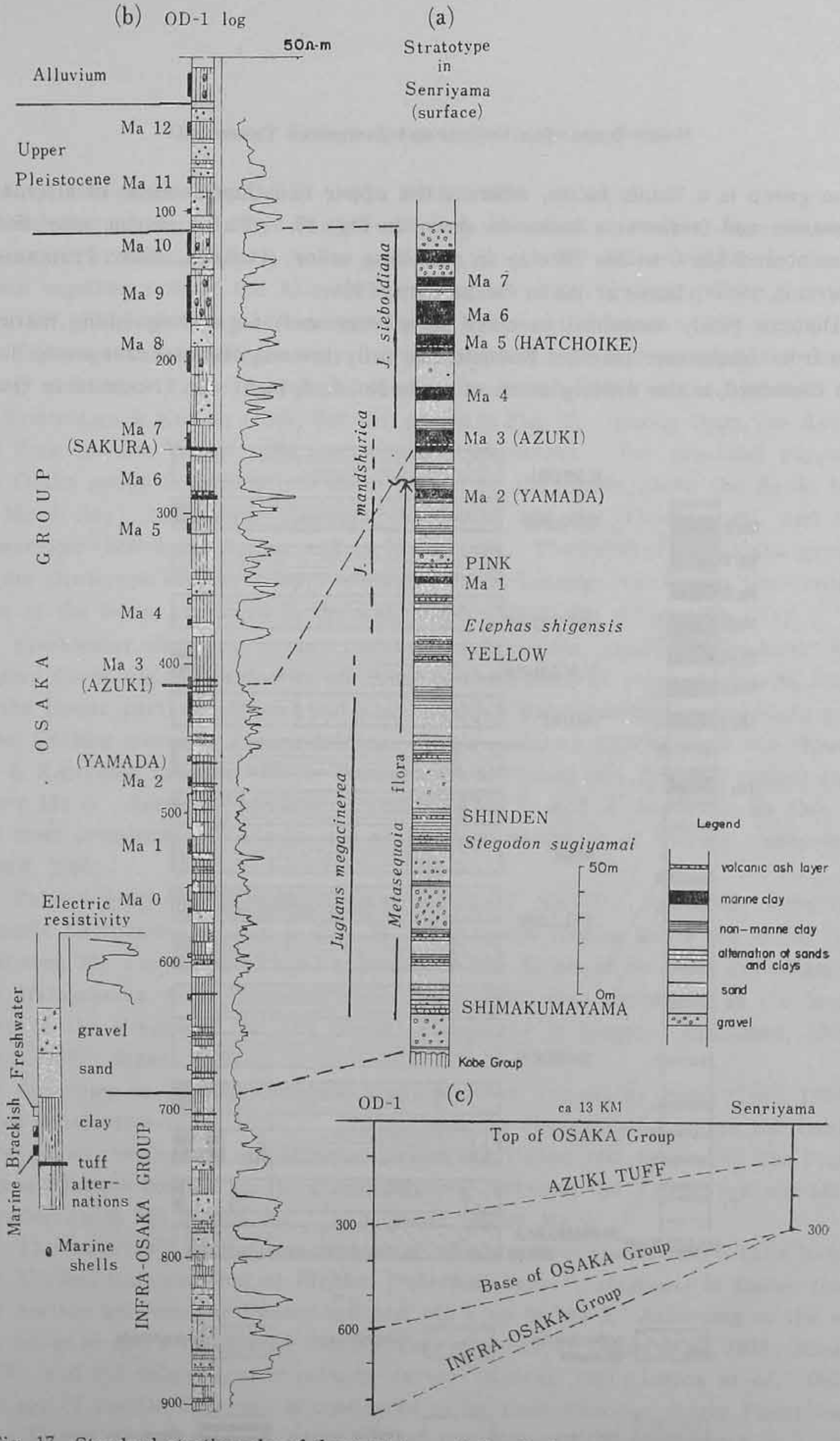


Fig. 17 Standard stratigraphy of the stratotype of the Osaka group at Senri Hills (columnar section after ITIHARA 1961 and ITIHARA & TAKETSUJI 1967) (right), and the columnar section below the Alluvial delta at well No. 6 (OD-1), a standard of strata below the plain (Osaka City, 1964—1966). Lithologic legends and the scales of both columnar sections are different as shown in the figure. The actual situation of both column is shown in Fig. c. Names in capital letters show key tephras. Non-marine clay intercalated by the Yellow tuff in the stratotype section corresponds to the Ma 0 marine clay below the lowland area of Osaka City.

of the group is a limnic facies, whereas the upper two thirds consist of alternating marine and freshwater facies as shown in Fig. 17. These marine clay beds are numbered Ma 0 to Ma 10 clay in ascending order (ITIHARA, 1961: ITIHARA & TAKETSUJI, 1967 ; IKEBE *et al.* in Osaka City, 1964).

Diatoms richly contained in clays serve very well for distinguishing marine clays from freshwater clays. NOGUCHI has fully investigated assemblages of diatoms contained in the drilling cores of wells No. 6, 9, 14, 17 *etc*, (NOGUCHI in Osa-

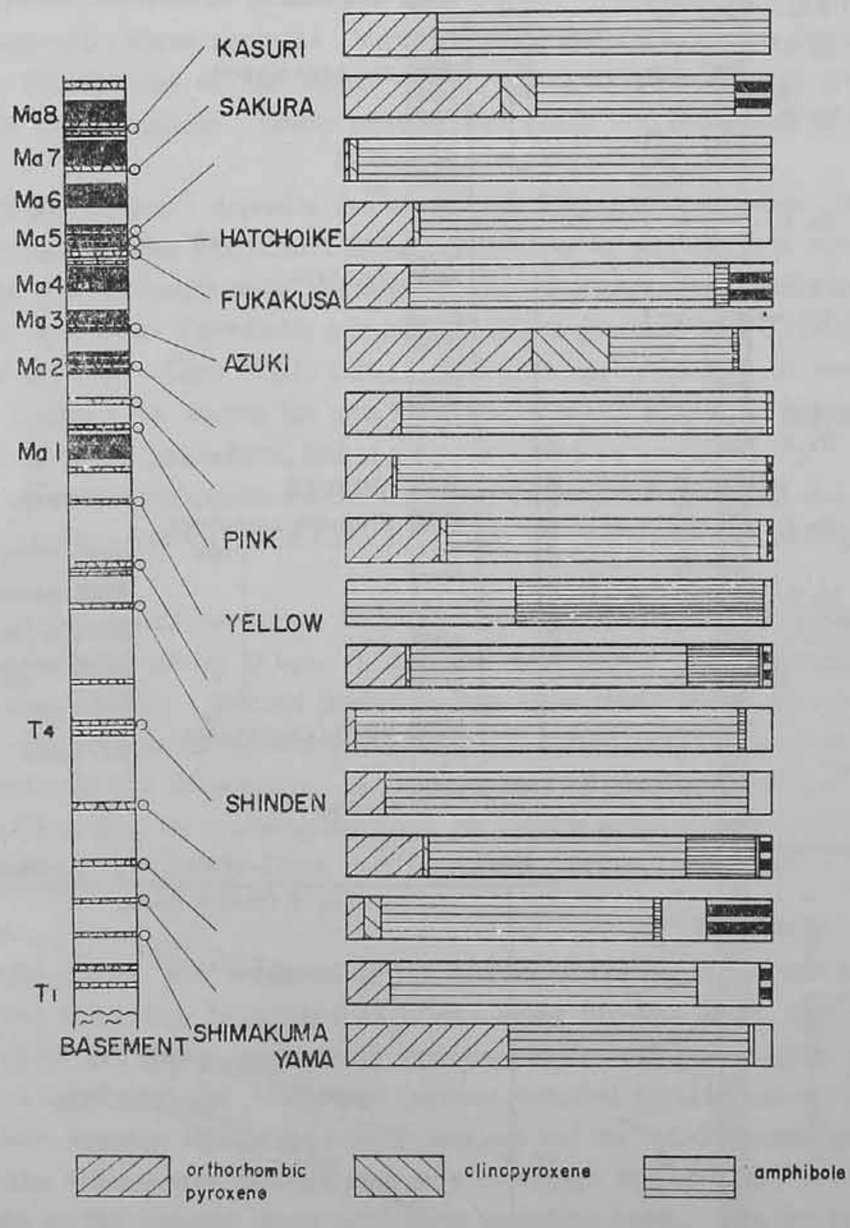


Fig. 18 Proportion of colored minerals included in the key-tephras of the Osaka group (YOKOYAMA & KUSUKI, 1967, 1969).

ka City, 1964-1966 ; NOGUCHI in Osaka Pref., 1967).

Sulphur content of clays is also useful to discriminate marine clays in some extent (Y. ITIHARA, 1960). Amino acids in the muddy sediments of the Osaka group together with of the Alluvial formation have been investigated by Y. ITIHARA (1967, '68) ; other organic matters by N. KAGEMORI (KURODA, 1966).

Tephra intercalations are very useful keybeds in both field mapping and correlating well-logs. The properties of these volcanic ash layers (tephra) worked out by YOKOYAMA & KUSUKI (1967, '69) are shown in Fig. 18. Among them the Azuki, the Pink and the Yellow tuffs are especially important. For practical purpose, the Osaka group is divided into three parts, *i. e.*, the Upper (above the Azuki tuff in Ma 3 clay), the Lower (between the Azuki and the Yellow tuffs) and the Lowermost (below the Yellow tuff in Ma 0 clay). Thickness of the Osaka group, at the stratotype section is approximately 300 m, becomes thicker in the central part of the basin, as shown in the well No. 6 (OD-1) for 600 m (Fig. 17c).

Freshwater clays contain such mollusca as *Lymnium, Anodonta, Cristaria, Hyriopsis, Corbicula* and *Viviparus*, all living in Lake Biwa at present. Marine clays of the Upper part sometimes yield such brackish water mollusca as *Anadara granosa, Cyclina sinensis, Theora lubrica, Paphia undulata, Ostrea gigas, etc.* (KANEKO & KAJIYAMA in CHIJI, 1962). Foraminifera are found only from the marine clay above Ma 8. *Ammonia beccarii* "forma A" (Ma 8) and *A. kawachiensis* (Ma 9) are most prominent ; all species are of brackish water or of marine embayment (CHIJI, 1968).

Palynological studies of the core of the No. 7 (OD-1) (TAI, 1966) show the climatic fluctuations as seen in Fig. 19. The severe cooling below the Azuki tuff (between Ma 2 and Ma 3 clays) indicated by the datum of complete extinction of the *Metasequoia* flora (ITIHARA, 1961 ; NIREI, 1968) may correspond to the boundary of the Preglacial and the Glacial Pleistocene in Europe (BERGGREN, 1968 ; SELLI, 1967 ; IKEBE, 1969).

According to the morphological study of fossil walnuts by NIREI (1968, 1969), three consecutive-range zones of *Juglans* may be discriminated within the Osaka group, *i. e.*, the *Juglans megacinerea* (below the Yellow tuff, overriding the Pleistocene/Pliocene boundary), the *J. mandshurica* (between the Yellow tuff and Ma 2 possibly up to Ma 3) and the *J. sieboldiana* (above Ma 3).

The occurrence of *Stegodon sugiyamai* is known from the horizon a little below the Shinden tuff, and that of *Elephas* ("*Archidiskodon*") *shigensis* is known from the horizon between the Yellow tuff and Ma 1 up to Ma 5. According to the occurrences of the Proboscidean fossils (IKEBE *et al.*, 1966 ; ISHIDA *et al.*, 1966 ; KAMEI 1966), and the paleomagnetic polarity survey (KAWAI, 1951 ; ISHIDA *et al.*, 1969), the age of the Osaka group is considered to be Late Pliocene—Early Pleistocene (the GAUSS normal through early age of the BRUNNHES normal epoch, *i. e., ca.* 2.7-0.4 million years), as shown in Fig. 20 (IKEBE, 1969). The radiometric age of the Azuki tuff dated by fission track method is 0.87 million years, that of the

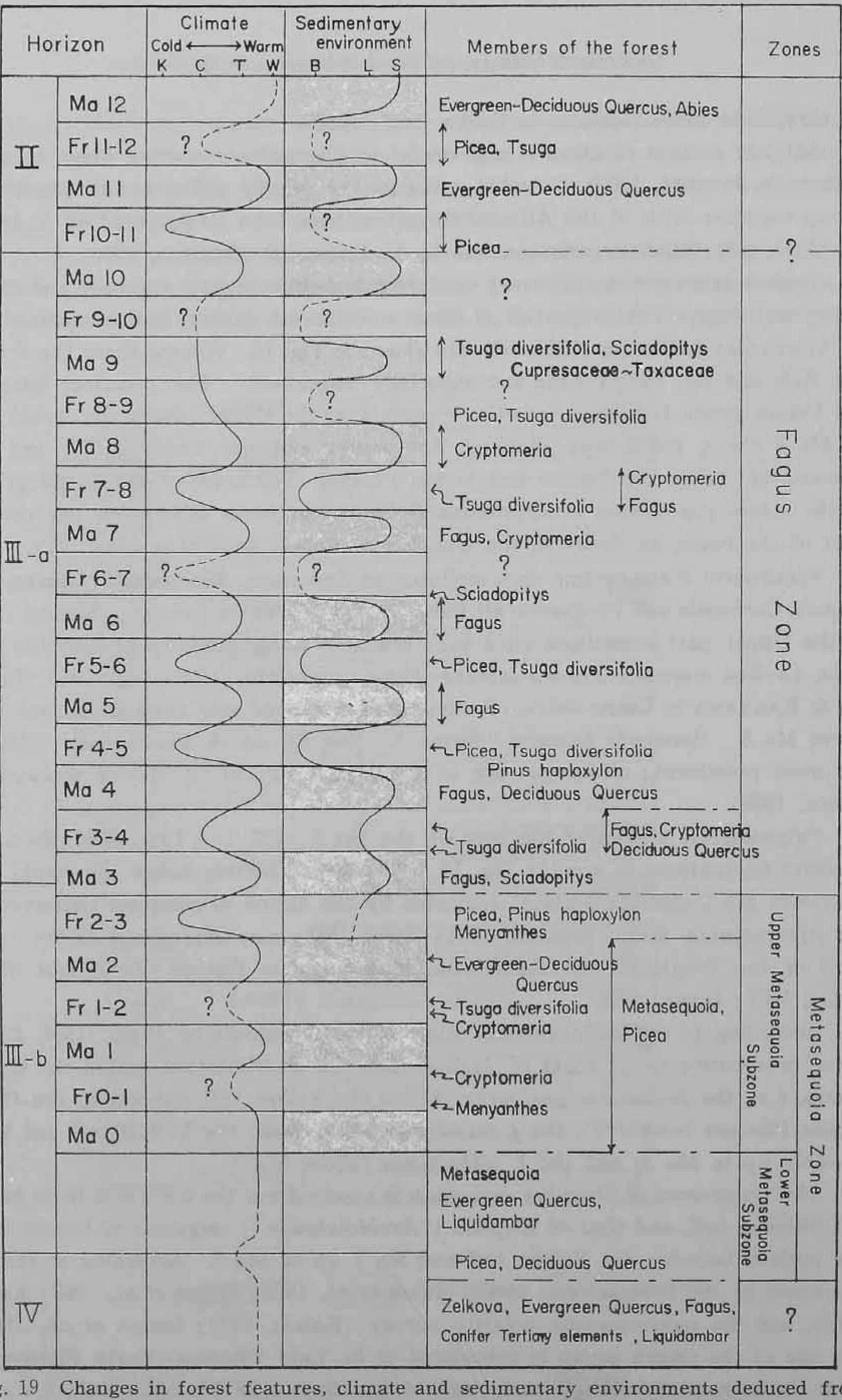


Fig. 19 Changes in forest features, climate and sedimentary environments deduced from the palynological study of the cores of well No. 6 (OD-1) (TAI, 1966).
Annotations: Climate K: cold, C: cool, T: temperate, W: warm.
Sedimentary environments B: bog, L: lake, S: sea.
Horizon II: Upper Pleistocene formation. III-a: Upper part of the Osaka group, III-b: Lower and Lowest parts of the Osaka group, IV: Infra-Osaka group. Ma: marine, Fr: freshwater.

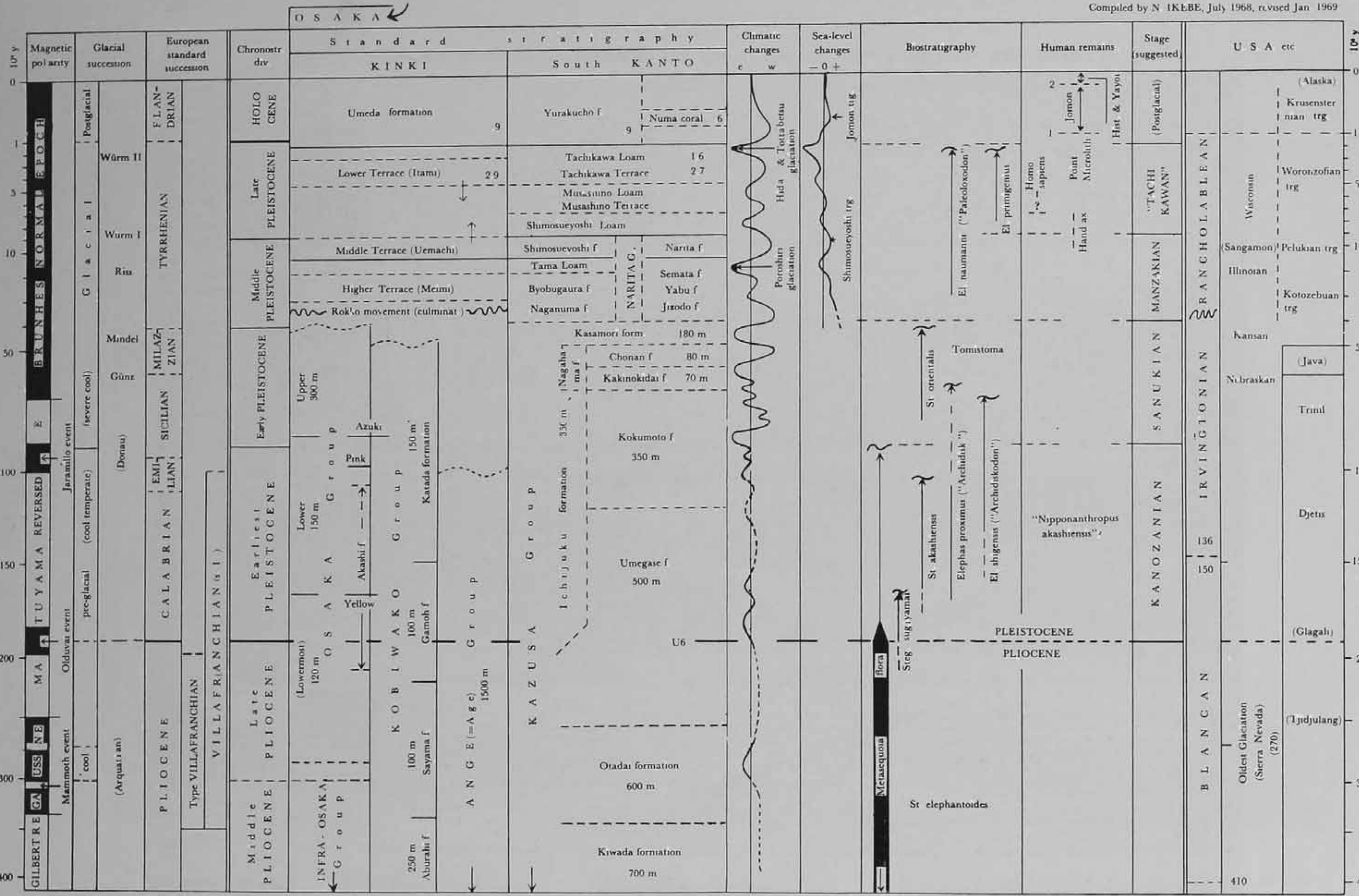


Fig. 20 Synoptical table on the Quaternary of Japan, showing the stratigraphic position and radiometric age of the strata in Osaka (after IKEBE, 1969, modified in 1969 and revised in 1970).

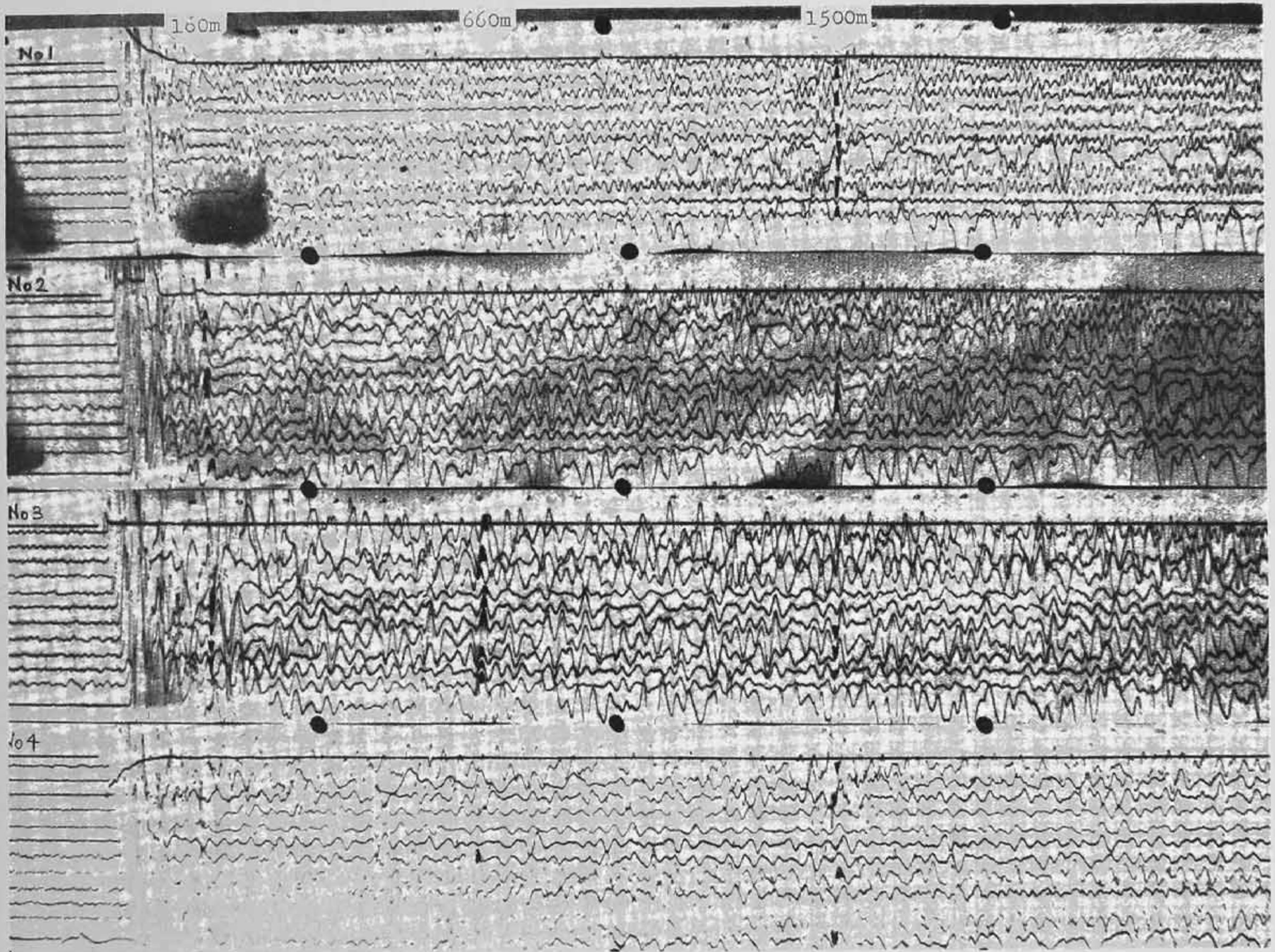


Fig. 21 Reflection seismograph record at the site of the well No. 6 (OD-1) (Hayashida).

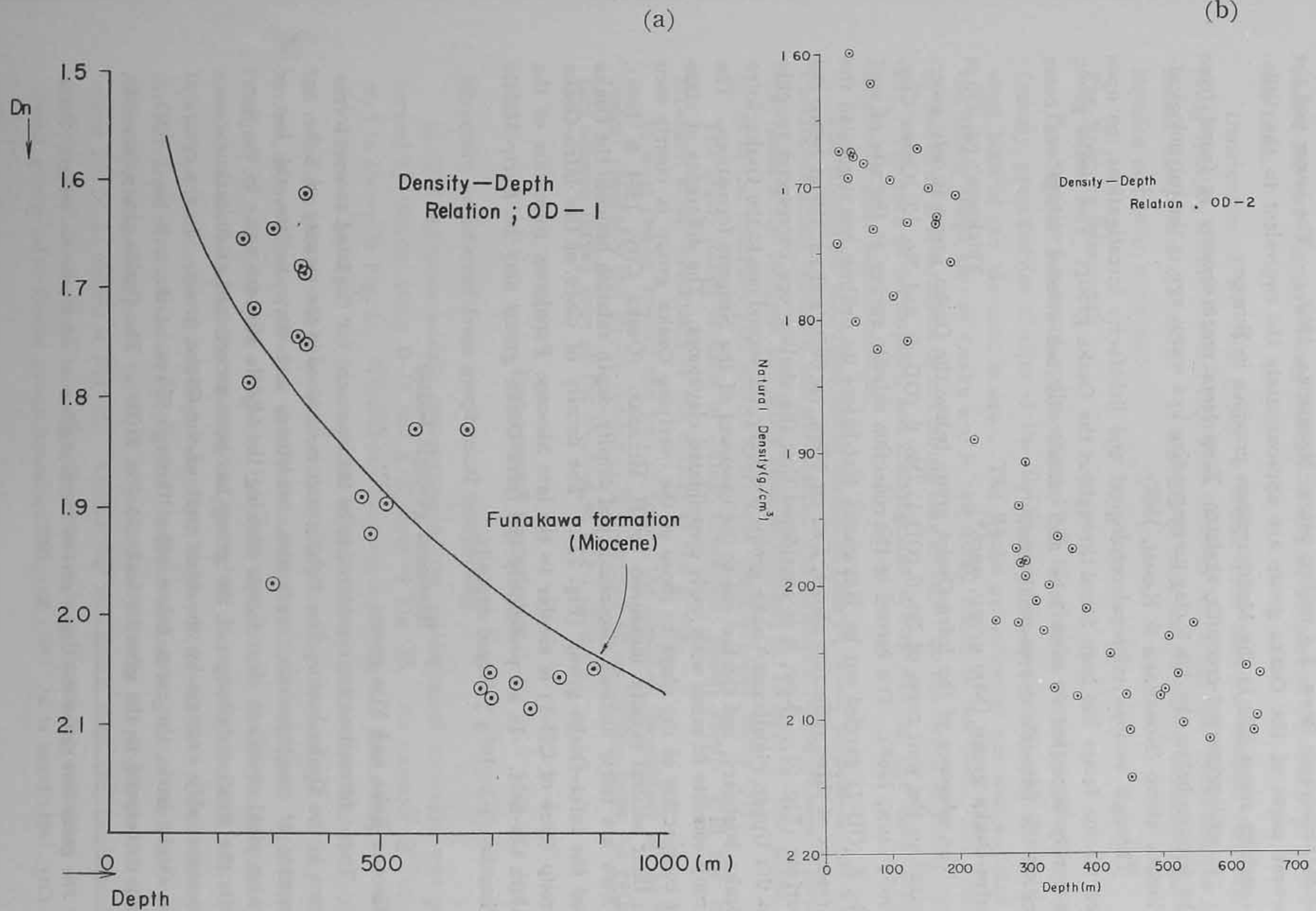


Fig. 22 Density-depth relation of fine sediments of the core-samples (MIYAZAKI). a) Cores of No. 6 well (OD-1). The curve in the figure shows, for comparison, the density-depth relation obtained from the Pliocene-Miocene sediments of the Akita oil-field (MIYAZAKI, 1966). b) Cores of No. 9 well (OD-2).

Shimakumayama is *ca.* 2.4 million years (NISHIMURA, 1969). The lower and the lowest parts of the Osaka group are approximately the equivalent to the Villafranchian *sensu lato* in the Mediterranean province in Europe.

A well-preserved crocodile skeleton *Tomistoma machikanense* is found from the horizon below the Ma 8 clay corresponding to a warm age in the palynological-climatic curve (KOBATAKE & KAMEI, 1966).

Through various micropaleontological and lithofacies investigations, no open sea marine facies has been found throughout the Osaka group. The Osaka group is surely deposited in some lake and occasionally sea-invaded inland sea basin within the Setouchi depressional zone.

Infra-Osaka group (Nijo group, *auct.**). Thickness: *ca.* 230 m

The presence of the Infra-Osaka group below the Osaka group is only ascertained in the well cores of No. 6 (OD-1), No. 9 (OD-2) and No. 10 (Osaka City, 1966; CHIJI, 1968). The record of the reflection seismic survey at the site of well No. 6 (OD-1) carried out by HAYASHIDA just before its drilling, has suggested the presence of three reflection planes, *i.e.*, *ca.* 160m, *ca.* 660m and *ca.* 1500m below the surface (Fig. 21). Now, it is considered that the shallow one correspond roughly to the Upper Pleistocene/Osaka group boundary, the second one to the Osaka/Infra Osaka boundary, and the last one to the basement of the Neogene formations. The group consists of sands with fairly consolidated claystones. The difference of state of compaction of the clays to those of the overlying Osaka group is clearly seen in their natural density measured by H. MIYAZAKI (Osaka City, 1964 & 1966). There are fairly distinct discontinuity of density-depth relation between the Osaka and the Infra-Osaka group (Fig. 22). The density of clays of the Infra-Osaka group (core of OD-1) is similar to the late Miocene Funakawa formation of the Akita Oil-field. In all probability the Infra-Osaka group may be Early-Middle Pliocene ($5\text{-}3\times10^6$ y.) limnic deposits.

Basement geologic bodies

Miocene Kobe and Nijo group.

These formations are considered to be the basement for the late Cenozoic formations in the Osaka basin. The Kobe group is exposed in the vicinity of Kobe, and consists of conglomerates, sandstones, mudstones and vitric tuffites, the last of which yield abundant plant fossils showing the Middle Miocene age. In the Senri hills the small distribution of the group has been ascertained at Shimakumayama unconformably overlain by the basal part of the Osaka group. In the centre of the Osaka basin, the cores below 440 m through 656 m, of the well No. 9 (OD-2) may correspond to the group (thickness: *ca.* 210 m). The Osaka group, however,

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* The group was called the Upper part of the Nijo group in some previous reports (Osaka City, 1964; IKEBE *et al.*, 1965; TAI, 1966).

covers the pre-Tertiary rocks directly in almost all part of the marginal areas of the basin.

Distribution of the Nijo group, a Middle-Late Miocene volcanic complex, is fairly limited, within the Mt. Nijo area between Mt. Shigi and Mt. Kongo in the Ikoma Range east of Osaka. It consists of andesite (including sanukite), dacite, rhyolite and their pyroclasts.

Pre-Neogene basements.

Pre-Neogene basement bodies (Figs. 11 & 13) chiefly consist of granitic rocks (mainly granodiorites-diorites of the Ryoke complex and partly the Rokko granites, both of the Mesozoic in age). The Ryoke granodiorites are well exposed in the Ikoma range east of Osaka and in the Awaji Island to the west. The bottom of the basin is ascertained by the boring core of OD-2 at the depth of 656 m (Fig. 28). The rock is decomposed and disintegrated diorite looking like loose arkose sand with more basic xenoliths.

The Hokusetsu mountains chiefly consist of Late Paleozoic formations and Late Cretaceous acidic volcanics and pyroclasts. The existence of the Paleozoic formation beneath the Neogene has lately been ascertained by IWATSU at the depth of 620 m in the southern part of the Senri hills (Senrioka-cho, Suita City).

The Izumi Range is made of Latest Cretaceous Izumi group, with the late Mesozoic acidic pyroclasts at the bottom of the group.

In west Osaka, toward the port of Osaka, the depth of the surface of the basement (probably the Ryoke complex) is estimated at *ca.* 1500m, from the reflection seismic survey done at the location of OD-1 (Fig. 21).

Underground neotectonics

Structure as inferred from geophysical prospecting.

In 1953 reflection seismic prospecting of the underground structure was performed by IWATSU along D-D′ and E-E′ lines of Fig. 23. An example of the record is shown in Fig. 24. Without any previous knowledge of the average velocity and depth of geologic horizons, reliable information as to the direction of dipping of reflection strata could not be obtained. By assuming the average velocity 1800 m/sec, however, the reflection profile shown in Fig. 25 is obtained. The results suggest an anticlinal rise along the Uemachi upland and its northern extention, similar to the relief of the basement suggested by the gravity contour map (Fig. 12). The correlation of well-logs mentioned below, however, shows the amount of relative rise of the basement along the Uemachi upland is greater than expected. The reflection strata below ca 300 m of S-17, show different dipping from the strata above 250 m, as shown in Fig. 25. Comparing this result with the neighbouring drilling (well No. 9 or OD-2), this discordance is inferred to correspond to the Osaka group/Infra-Osaka group boundary (Fig. 28).

Fig. 26 shows the underground structures made from the data of electric resistivity logs of some wells along the lines A–A′, B–B′ and C–C′ (IWATSU in Osaka Pref., 1967; HAYASHIDA, 1963).

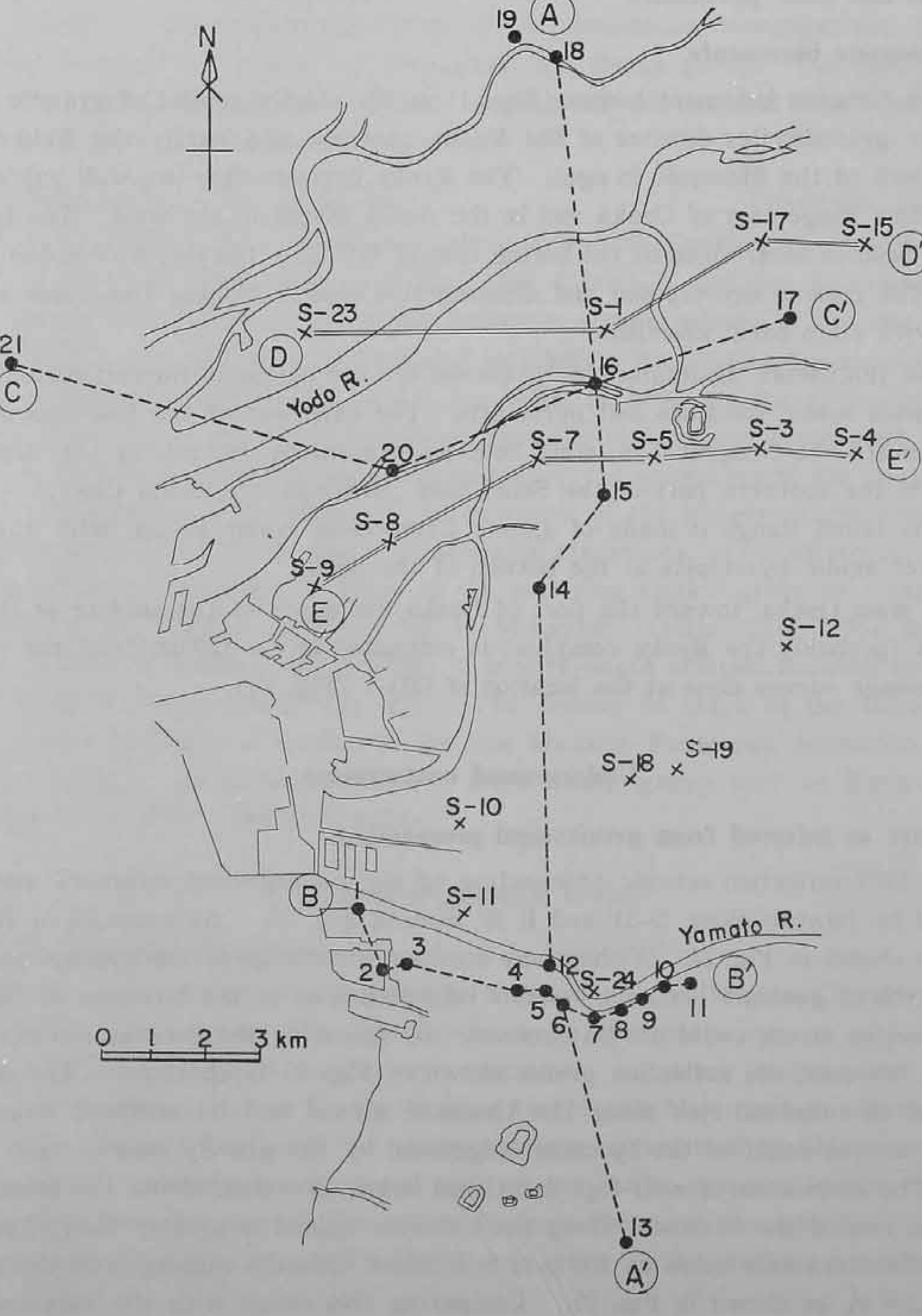

Fig. 23 Location of geophysically surveyed profiles.

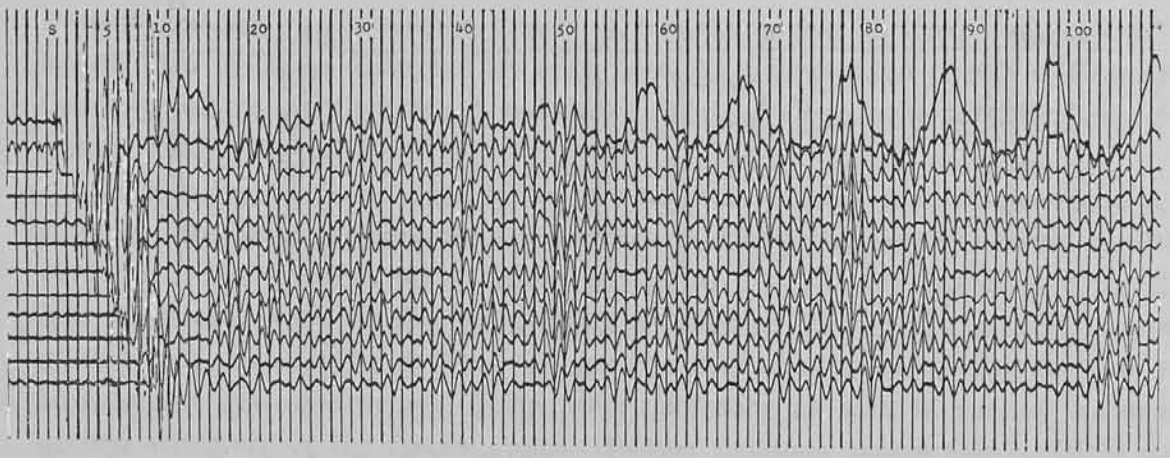

Fig. 24 Reflection seismograph record at S-17 of Fig. 23 (IWATSU & HAYASHIDA). Time interval: 1/100 second.

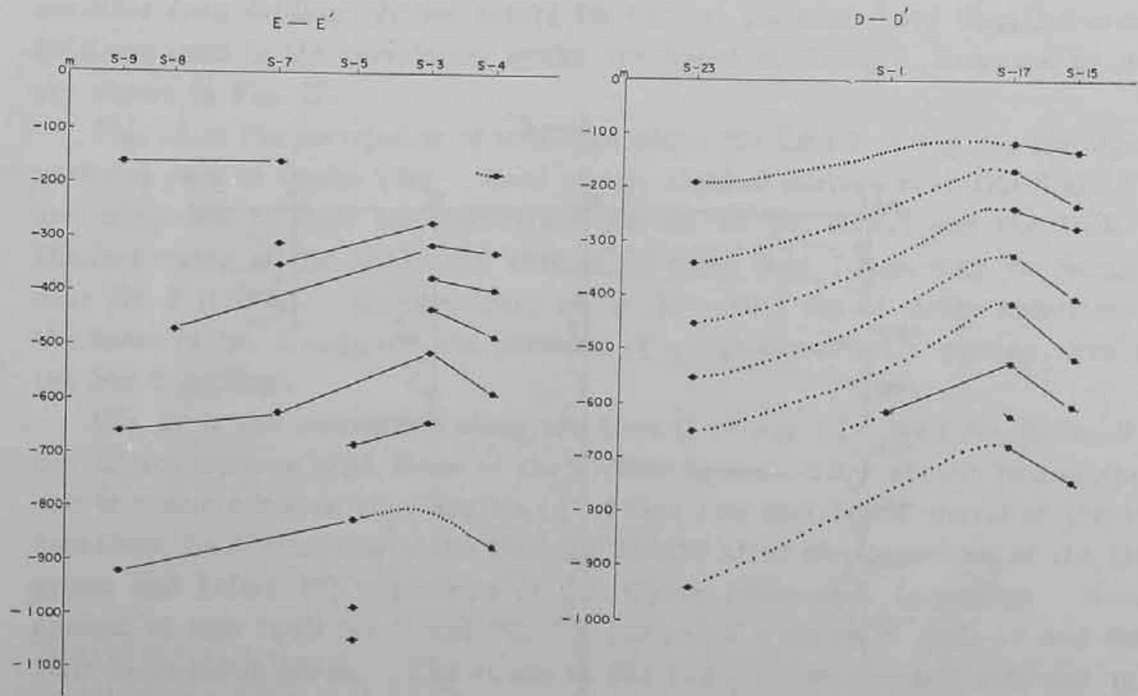

Fig. 25 Profiles obtained from the results of reflection seismic prospecting along the lines D-D′ and E-E′ in Fig. 23 (IWATSU).

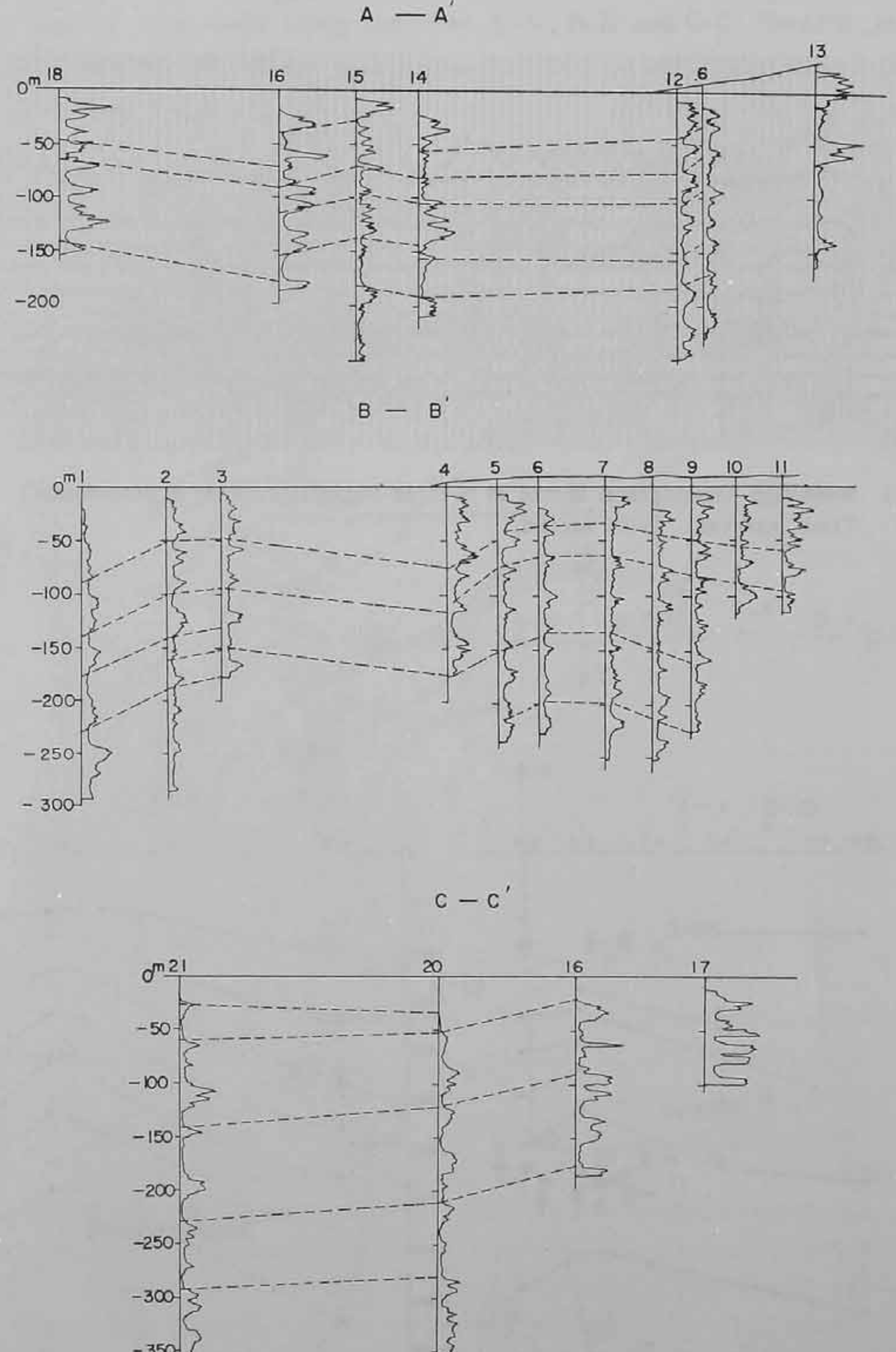

Fig. 26 Profiles obtained from the results of electric resistivity logs in Osaka and Sakai (IWATSU *et al.*, IWATSU in Osaka Pref., 1967). No. 21, 20 & 16 are the same to the well No. 5, No. 7 and No. 8 of Table 2 respectively.

Structure as inferred from correlation of well-logs.

There are a lot of shallow drillings and several tens of deeper drillings in the lowland and less in the upland areas. About thirty five hundred well-logs drilled before 1965 in Osaka City and its near suburbs are recorded in "*The Ground of Osaka*" (edited and published by the Publishing Committee for the Ground of Osaka, 1966).

Considering the land subsidences are not only related to the subsurface Alluvium but to the underlying thick Pleistocene formations in some extent, carefully performed core-drillings with various geological and soil-mechanical investigations into the deeper part of the basin-filling Pleistocene (the Osaka group) had been planned and successfully drilled. To get the fundamental knowledge for the problem of the groundwater regulation, it is necessary as well to realize the underground structure of the Osaka group. Deeper drillings named OD-1—OD-9 were thus performed for these purposes. These cores have beed treated with in detail geologically and micropaleontologically (diatoms, foraminifers, radiolaria and pollens). Some of tuff-samples have been investigated by the method of heavy mineral analysis. From these results worked out by many specialists, the horizons in Ma symbols of each well-log have been identified (Osaka City, 1964-1966; Osaka Pref., 1967; IKEBE *et al.*, 1965; NOGUCHI in Osaka City, 1964-1966; CHIJI, 1968; NAKASEKO & CHIJI, 1964; TAI, 1966). Especially the underground depth of the Azuki tuff has been carefully determined. By comparing the OD-logs, well-logs of other available deep drillings drilled before for various purposes have been reexamined. Drillings used in the correlation works are listed in Table 2, locations of which are shown in Fig. 27.

Fig. 28 is the correlation of well-logs along the Line I of Fig. 27, through the northern part of Osaka City. Data of two shallow borings near OD-8 and OD-2 are mentioned, to show the subsurface position of the Azuki and the Pink tuff. Distinct rising of the Azuki tuff surface, of more than 200 m may be recognized near No. 2 (OD-8). Extraordinary steep (50°—60°) dip of strata ascertained by the cores of No. 2 suggests the presence of a significant fault passing very near the No. 2 drilling.

Fig. 29 is the correlation along the Line II of Fig. 27. Well No. 5, No. 9 and No. 12 are common with those of the former figure. Very abrupt rise of the strata is shown between No. 8 and No. 14. These two correlation charts of the well-logs show the distinct rise of the Uemachi upland after the deposition of the Osaka group and before the deposition of the Upper Pleistocene formation. Relative amount of rise (well No. 9 and No. 14) compared with No. 6 (OD-1) and No. 16 (OD-3) is about 400 m. The strata at the top of this elevated anticline might have been denuded off before the deposition of the Upper Pleistocene. It may be more probable, however, to consider that the rising movement had begun earlier, and thus the upper part of the Osaka group had originally not completely been deposited on the elevated area. Similar consideration is inferred from the research

Table 2 List of deep drillings in Osaka (Refer Fig. 27).

No.	Name of Well	Location	Depth
No. 1	OD-5	Kanzakigawa, Amagasaki-shi	700 m
No. 2	OD-8	Kunishima, Higashiyodogawa-ku	200
No. 3	OD-4	Niwakubo, Moriguchi-shi	250
No. 4		Torigai, Settsu-shi	350
No. 5		Ohama, Amagasaki-shi	420
No. 6	OD-1	Tanaka-motomachi, Minato-ku	907
No. 7		Kasugade, Konohana-ku	430
No. 8		Nakanoshima, Kita-ku	186
No. 9	OD-2	Miyakojima, Miyakojima-ku	667
No.10		Shigino, Higashinari-ku	500
No.11	OD-6	Shinden, Daito-shi	500
No.12		Suminodo, Daito-shi	500
No.13	Kawati ST-1	Haizuka, Daito-shi	501
No.14	OD-9	Hoenzaka, Higashi-ku	200
No.15	OD-7	Tatsumi, Ikuno-ku	200
No.16	OD-3	Mikuriya, Higashi-Osaka-shi	700
No.17		Zone 6, Sakai-shi	300
No.18		Zone 7, Sakai-shi	500
No.19		Zone 5, Sakai-shi	300
No.20		Zone 5, Sakai-shi	300
No.21		Zone 3, Sakai-shi	300
No.22		Zone 4, Sakai-shi, No.3	250
No.23		Zone 4, Sakai-shi, No.1	250
No.24		Zone 4, Sakai-shi, No.2	250
No.25		Izumi-Otsu-shi	400
No.26		Kishiwada-shi	300
No.27		Izumi-Sano-shi	200
No.28		Izumi-Sano-shi	100
No.29		Sennan-cho	200

Annotation *-shi* : city, *-ku* : ward in Osaka City, *-cho* : town.

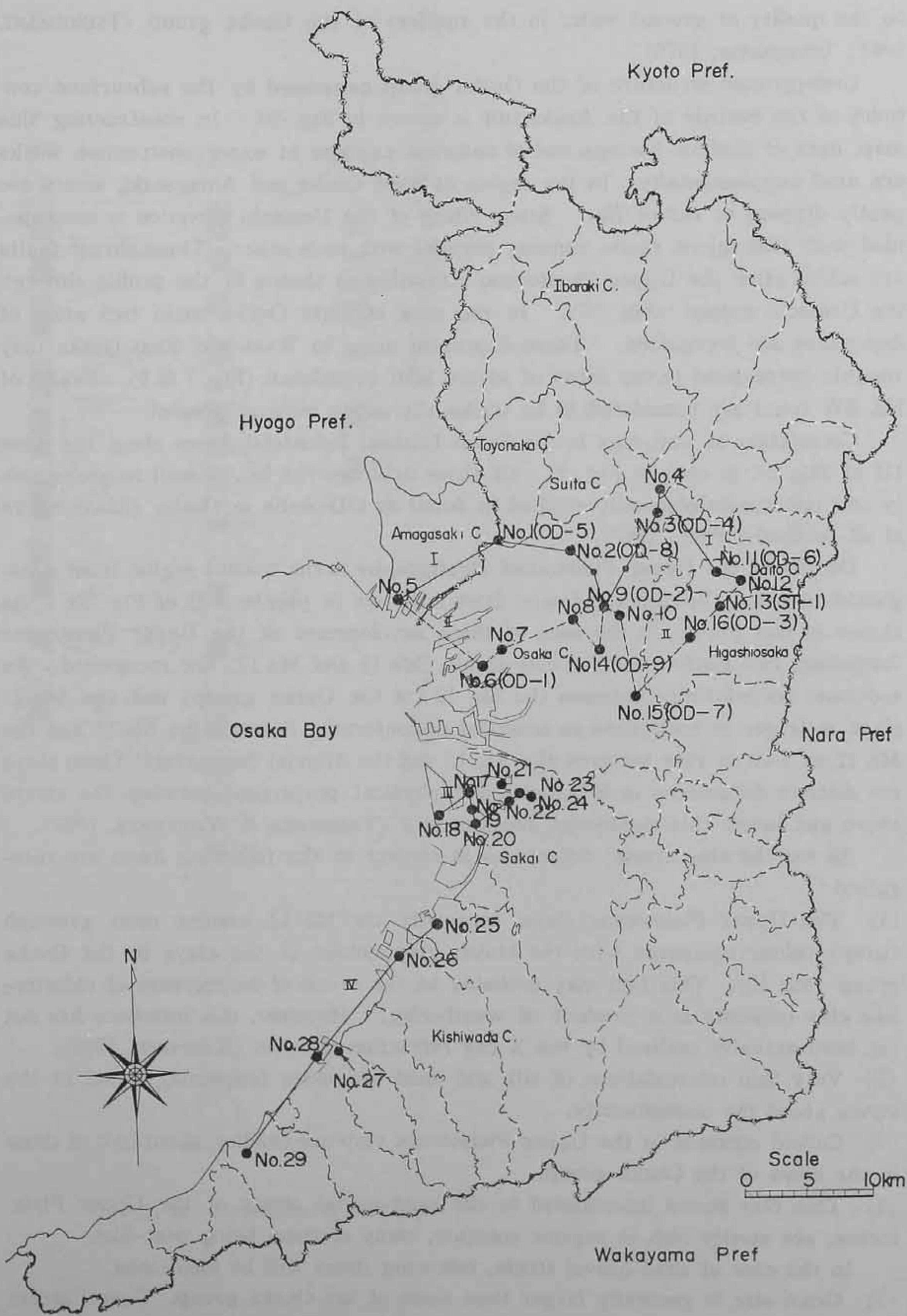

Fig. 27 Location map of deep drillings listed on Table 2.

on the quality of ground water in the aquifers of the Osaka group (TSURUMAKI, 1962; TSURUMAKI, 1970).

Underground structure of the Osaka group expressed by the subsurface contours of the horizon of the Azuki tuff is shown in Fig. 30. In constructing this map, data of shallow borings, and of outcrops exposed at some construction works are used supplementally. In the region of West Osaka and Amagasaki, strata are gently dipping or rather flat. Steep rising of the Uemachi elevation is accompanied with two thrust faults running parallel with each other. These thrust faults are active after the Upper Pleistocene formation as shown in the profile through the Uemachi upland (Fig. 35). In the area of East Osaka basin two areas of depression are recognized. These depressed areas in West and East Osaka may roughly correspond to the areas of severe land subsidence (Fig. 7 & 9). Faults of NE-SW trend are considered to be strike-slip active even at present.

Correlation of well-logs in the Sakai Littoral Industrial Zones along the Line III of Fig. 27, is seen in Fig. 31. Of these drillings the No. 17 well is geologically and micropalentologically studied in detail as OD-wells in Osaka (MATSUSHITA *et al.* in Osaka Pref., 1967).

Details of the Upper Pleistocene stratigraphy in the coastal region from Amagasaki to Sakai through the Osaka Port is shown in profile A-B of Fig. 32. As shown in this profile, in the area of thick development of the Upper Pleistocene formation, two distinct marine clay strata (Ma 11 and Ma 12) are recognized. An erosional unconformity between the Ma 10 (of the Osaka group) and the Ma 11 clays is larger in scale than an erosional disconformity between the Ma 11 and the Ma 12 as well as that between the Ma 12 and the Alluvial formation. Thus, there are distinct differences in lithofacies and physical properties, between the strata above and below this significant unconformity (TAKENAKA & WATANABE, 1966).

As for the clay strata, differences in respect to the following items are recognized:

(1) The Upper Pleistocene clays, especially the Ma 12, assume more greenish (grey) colour compared with the bluish grey colour of the clays in the Osaka group (Ma 10). This fact may probably be the result of the increase of chlorite-like clay minerals as a product of weathering. However, this inference has not yet been actually realized by the X-ray refraction analysis (KAKITANI, 1958).

(2) Very thin intercalations of silt and sand are more frequently found in the strata above the unconformity.

(3) Colloid contents in the Upper Pleistocene clay are smaller, about half of those in the clays of the Osaka group.

(4) Thin clay seams intercalated in the sand-gravel strata of the Upper Pleistocene, are mostly rich in organic contents, many of them being peat-like.

In the case of sand-gravel strata, following items will be mentioned.

(1) Grain-size is generally larger than those of the Osaka group. Gravel strata of 50—100 mm in maximum grain size, are found in the Upper Pleistocene.

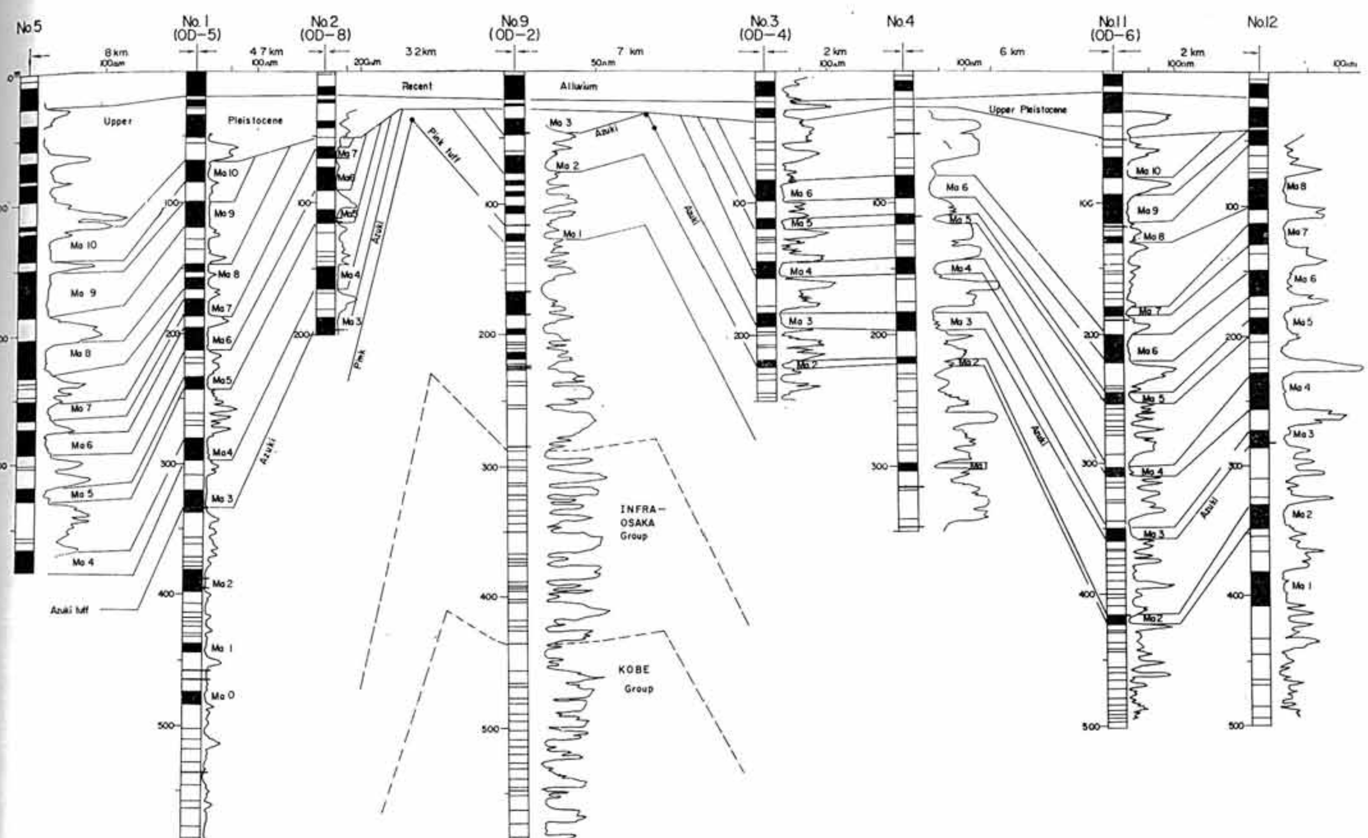

Fig. 28 Correlation of well-logs (I). No. 5—No. 1—No. 2—No. 9—No. 3—No. 4—No. 11—No. 12 (IKEBE & TAKENAKA).

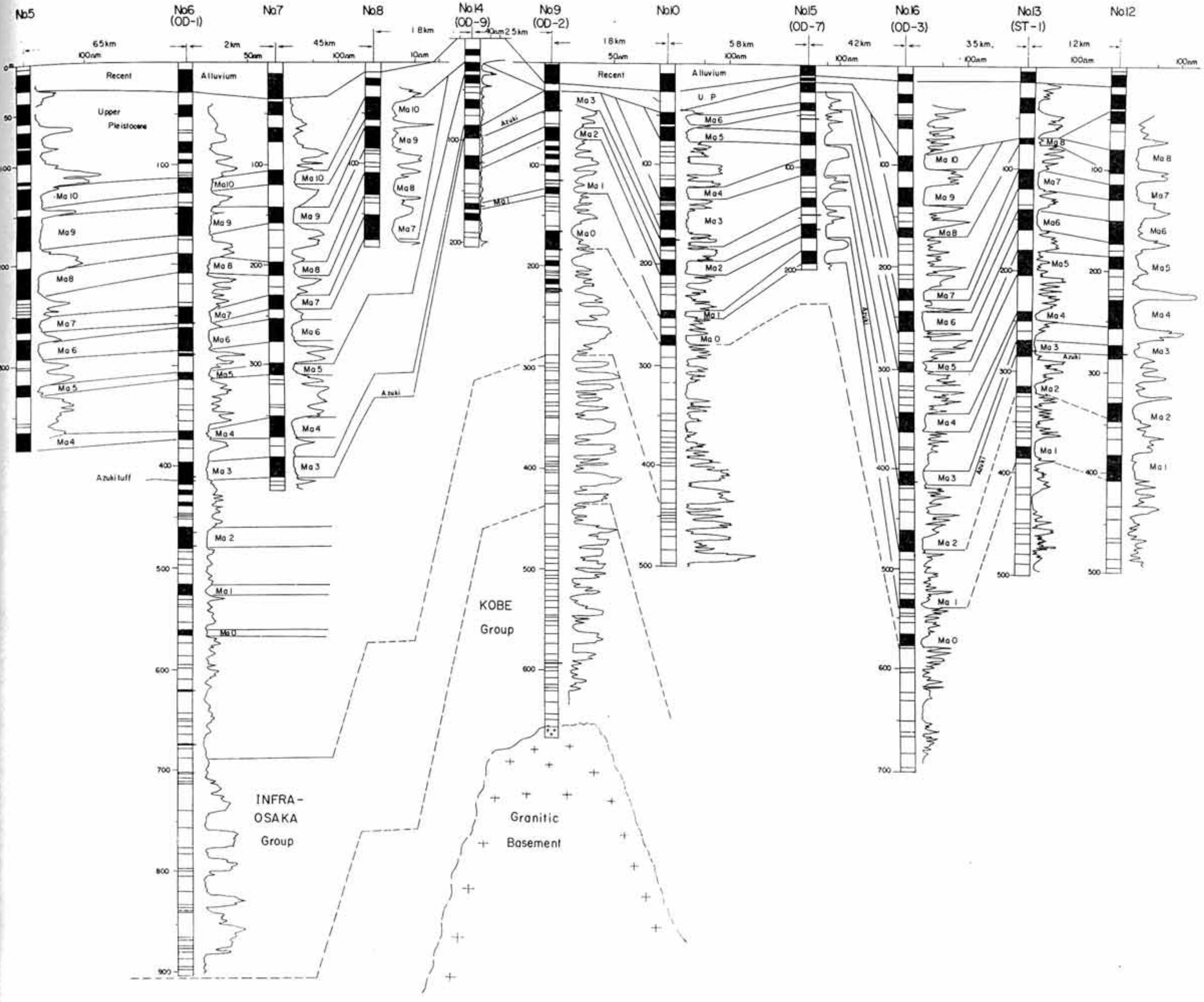

Fig. 29 Correlation of well-logs (II). No. 5—No. 6—No. 7—No. 8—No. 14—No. 9—No. 10—No. 15—No. 16—No. 13—No. 12 (IKEBE & TAKENAKA).

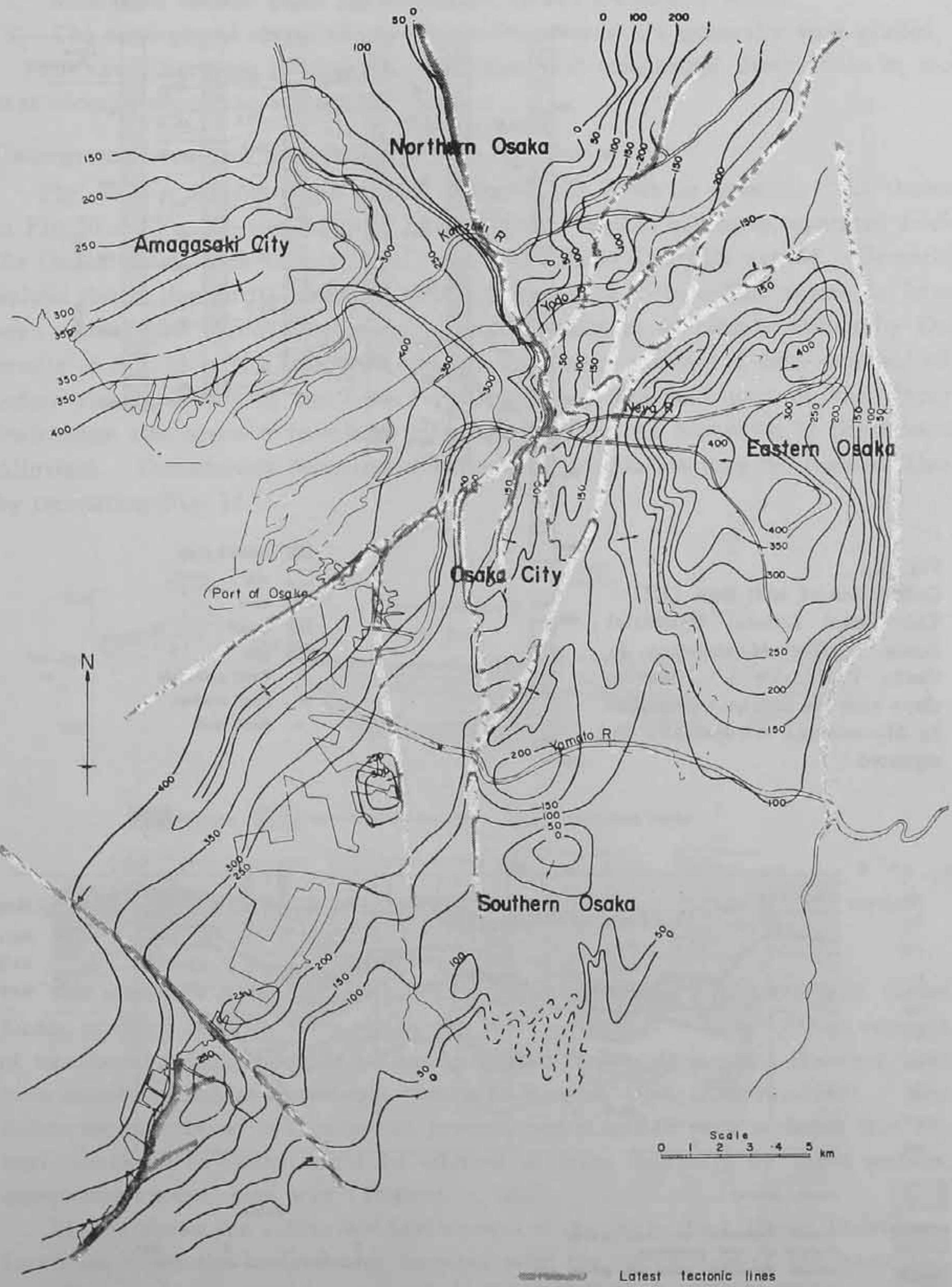

Fig. 30 Subsurface structure of the Osaka group (TAKENAKA & IKEBE). Contour lines show the depth of the Azuki tuff below sea-level. Contour interval : 50 m.

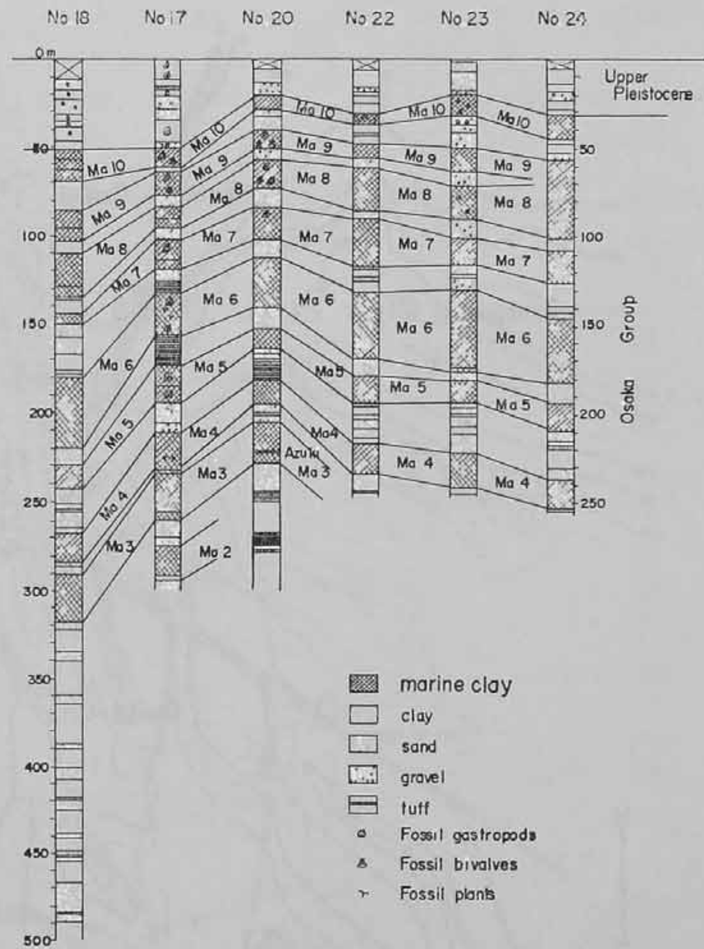

Fig. 31
Correlation of well-logs (III) — The Sakai Littoral Industrial Zones. (after MATSUSHITA in Osaka Pref., 1967). Marine clays with Ma numbers identified by MATSUSHITA are specially designated.

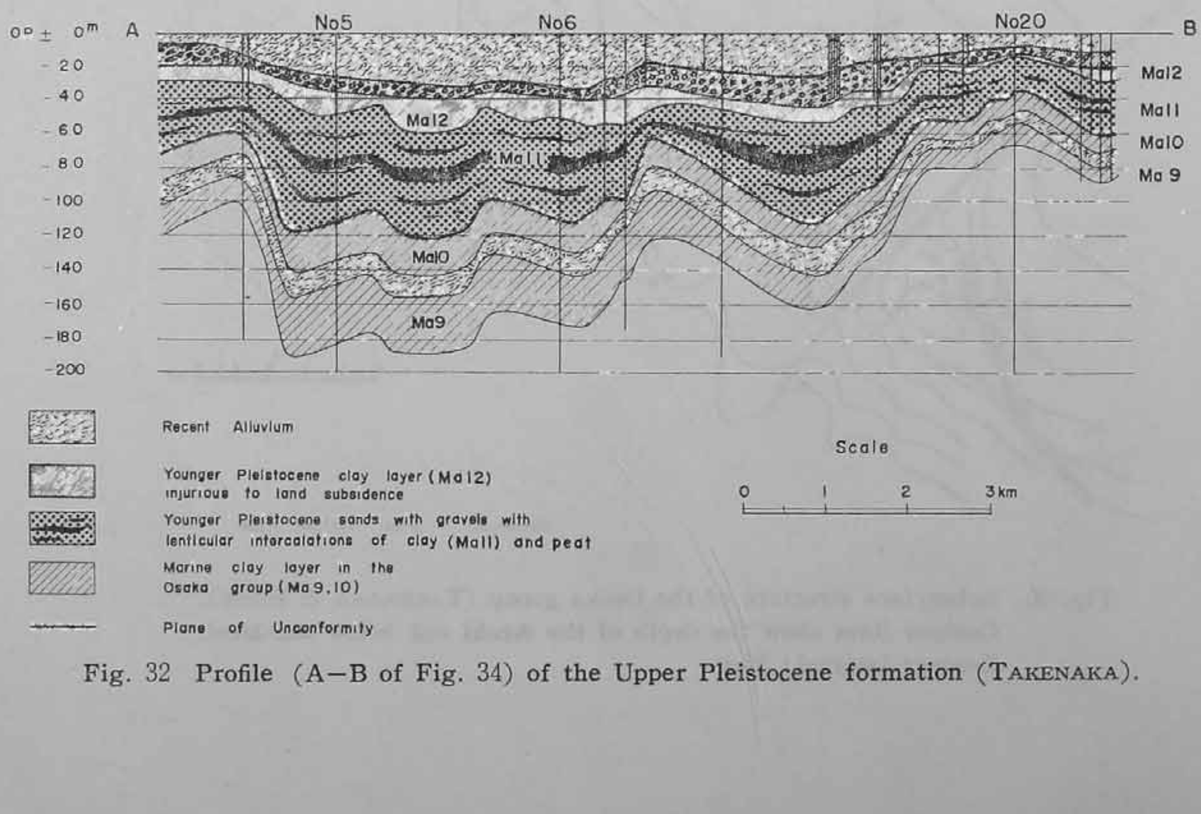

Fig. 32 Profile (A—B of Fig. 34) of the Upper Pleistocene formation (TAKENAKA).

(2) Mud-balls derived from the Osaka group are frequently found.
(3) The sand-gravel strata of the Upper Pleistocene are generally well-graded.

For the differences in physical properties, soil-mechanical descriptions in the next chapter should be referred.

Underground structure in relation to land subsidence.

Fig. 33 is a diagrammatic profile of the Osaka basin in general. As shown in Fig. 30 and Fig. 33, the Kawachi basin (Eastern Osaka) is clearly separated from the Osaka basin *sensu stricto* by a structural rise of Uemachi upland. Uemachi upland itself, though its morphological appearence is terrace-like, seems to have been constructed through some complicated geohistory as clearly shown by the profile of Fig. 35. The anticlinal crest of the Osaka group had been denuded off before the deposition of the Upper Pleistocene. Elevated part of the Upper Pleistocene also seems to have been denuded off before the deposition of the Recent Alluvium. Successively occurred elevation and denudation may be realized also, by comparing Fig. 14.

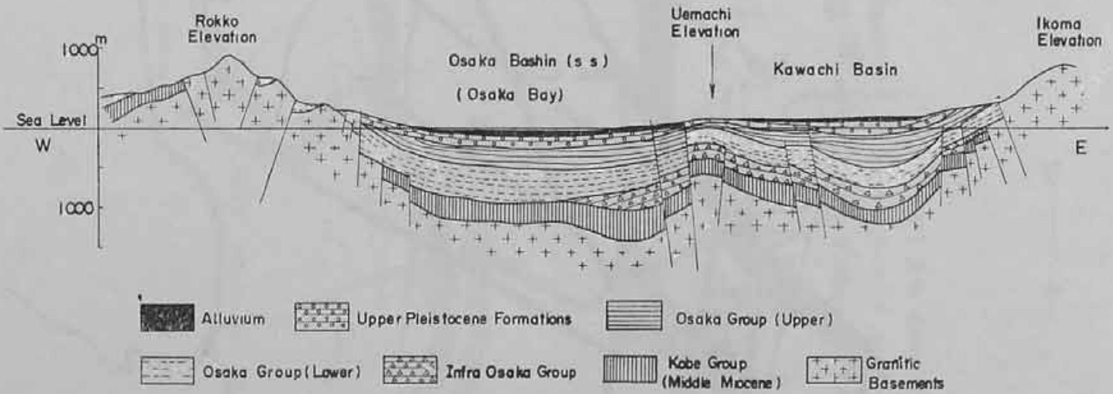

Fig. 33 Diagrammatic profile of the Osaka basin (after IKEBE & HUZITA 1966, revised IKEBE).

The structure is mainly controlled by a kind of foundation folding with thrust faults, modified later by some strike-slip movements. These tectonic movements of meridional-submeridional trend during Middle Pleistocene and the Holocene have been called the Rokko movements (IKEBE & HUZITA, 1966; HUZITA, 1969). The Rokko movements are still active at present, and it will be very probable that the land subsidence in Osaka might be effected at least indirectly by these tectonic movements except some area (TAKENAKA, 1967).

Fig. 34 shows the subsurface development of the fairly thick Upper Pleistocene formation below the lowland area together with the distribution of the latest tectonic lines. As previously mentioned, almost all of these faults are active during and after the deposition of the Upper Pleistocene as shown in the profile through the Uemachi upland (Fig. 35), and some of them are ascertained by TAKENAKA to be active even at present from some surface phenomena observed along the tecto-

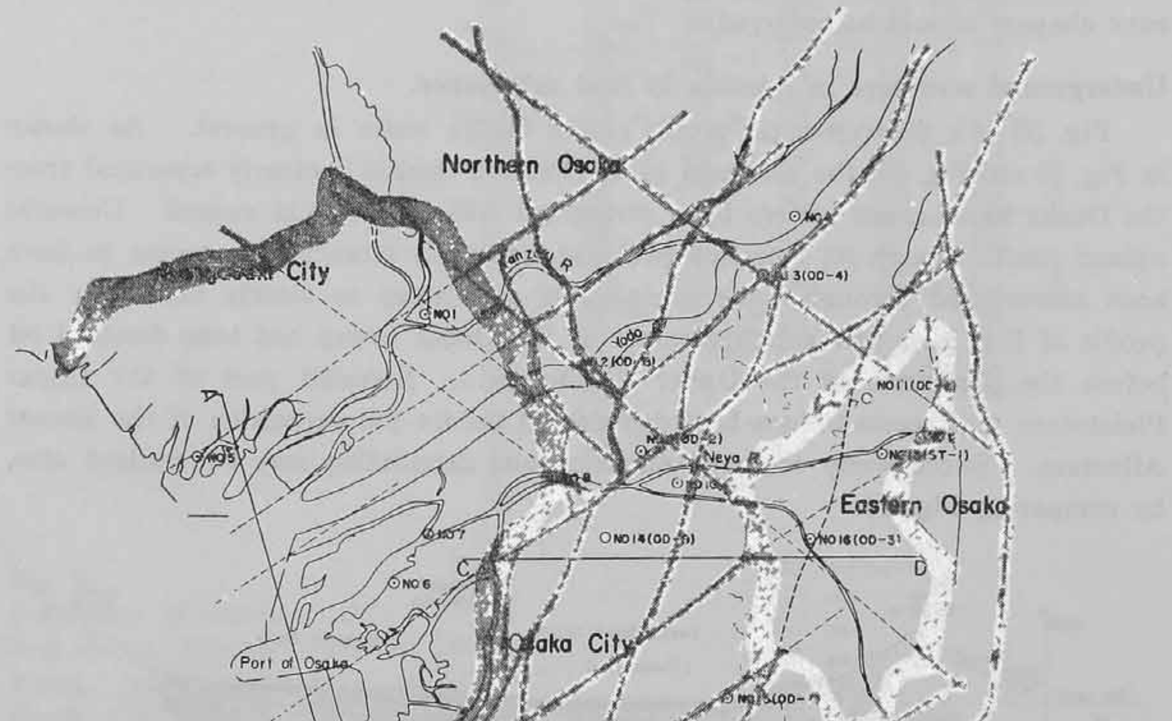

Fig. 34 Distribution of the Upper Pleistocene below the lowland area, and of the latest tectonic lines (TAKENAKA & IKEBE).

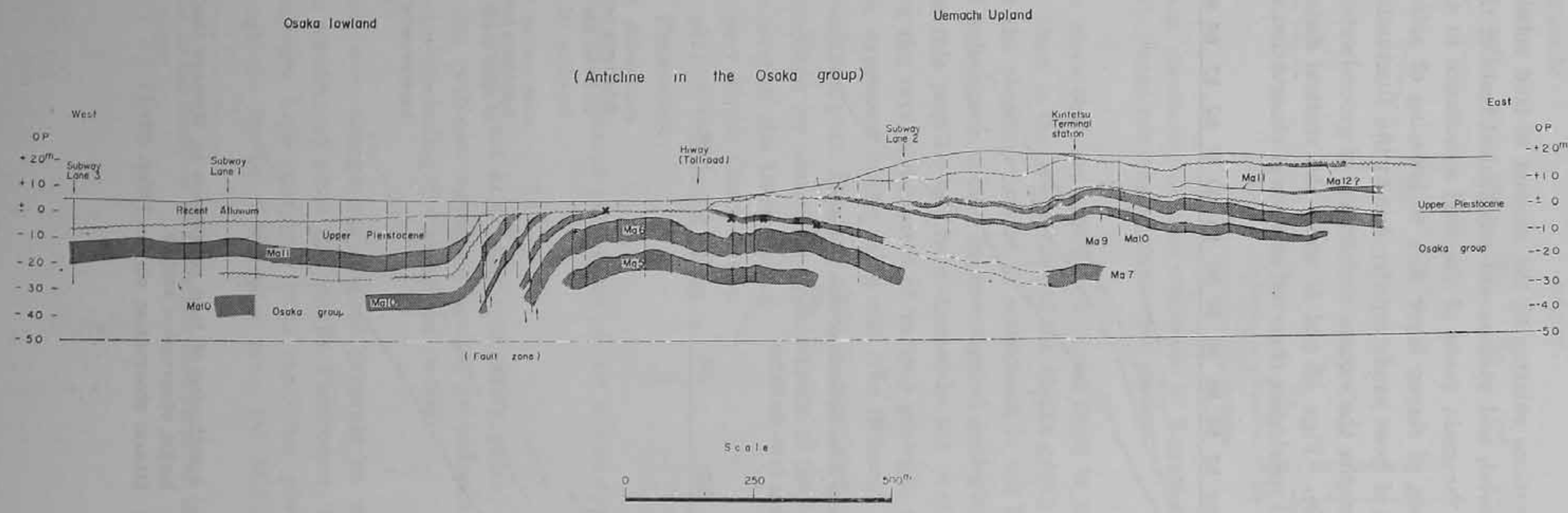

Fig. 35 Subsurface profile of the central part of Osaka City, crossing the Uemachi upland (TAKENAKA & HUZITA). Wavy lines show disconformity of various order. Cross signs show the ascertained location of the Sakura tuff (Ma 7 clay).

nic lines (Plate I).

Through many observations relating to the amount of land subsidence and the changes of groundwater level, and various soil-mechanical tests of the clay layers, it is now confirmed that the main cause of the land subsidence in Osaka is attributable to the consolidation of clayey layer due to lowering of artesian head and the repetitive compaction of loose sandy aquifer due to the fluctuation of the level of artesian head. That means the excess withdrawal of groundwater (MURAYAMA, 1969; HAYAMI *et al.*, 1969). Figs. 36 and 37 show the vertical distribution of the cumulative amount of land subsidence observed at several observation stations (Table

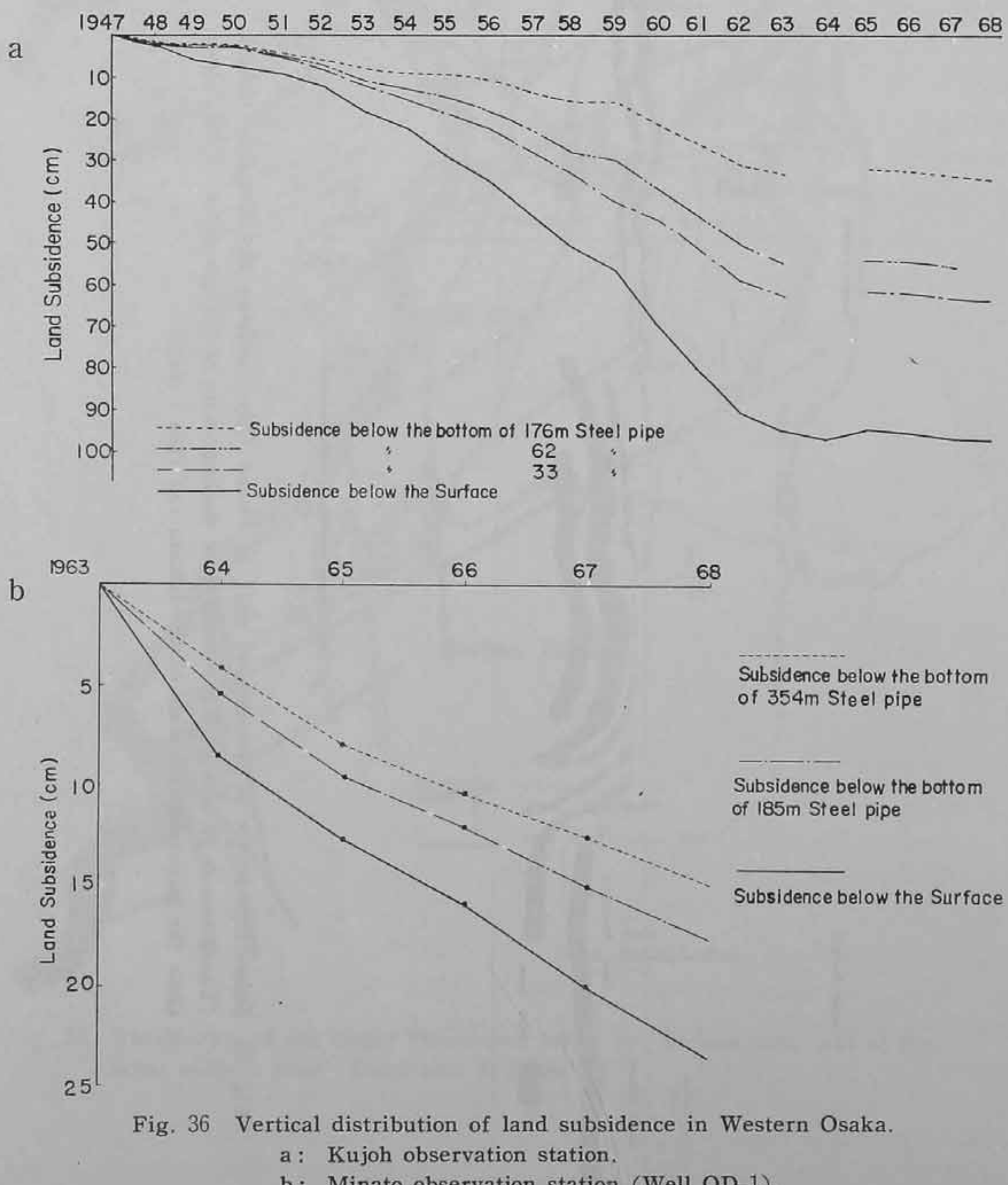

Fig. 36 Vertical distribution of land subsidence in Western Osaka.
a: Kujoh observation station.
b: Minato observation station (Well OD-1).

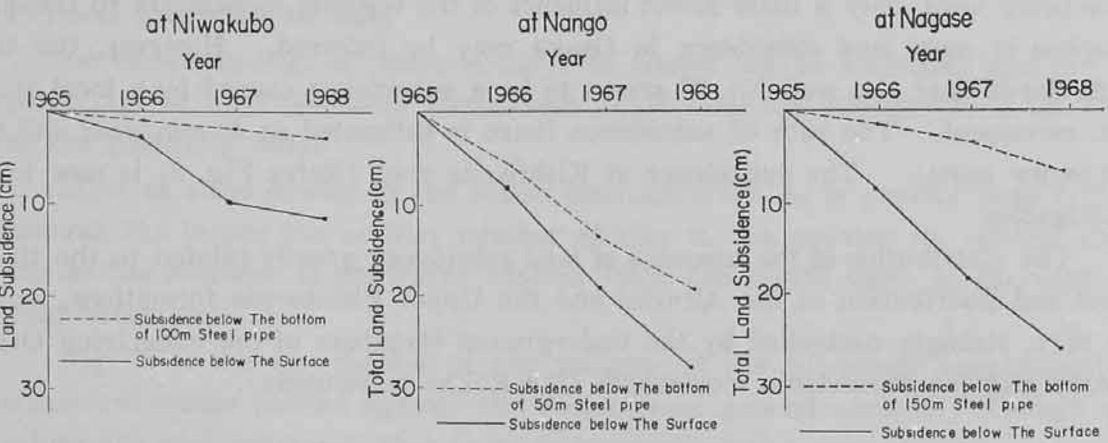

Fig. 37 Vertical distribution of land subsidence in Eastern Osaka. Niwakubo (Well OD-4), Nango and Nagase observation stations.

1). The curves show that the subsidence of one third or more of the total amount is seen to take place in the lower part of the Osaka group with fairly consolidated clays. Though the absolute amount of subsidence is not large, the cause of such deep-originated subsidence should be investigated geologically. A soil-mechanical consideration on this problem will be discussed in the next chapter.

To compare the rate of progress of various geologic phenomena in the Osaka basin, each rate expressed in the same unit (the Bubnoff unit=meter/10^6 years=mm/10^3 years=micron/year. Fischer, 1969) is calculated roughly as follows:

	Bubnoff unit
Rate of deposition (or preferably, of depression of the basin)	
Lowest part of the Osaka group	200*
Lower part of the Osaka group	220*
Upper part of the Osaka group	1,300*
Upper Pleistocene	600–1,000
Recent Alluvium	3,000
Rate of relative upheaval (tectonism of the Rokko movements)	
Uemachi upland	3,000
Rokko mountains	7,000
Rate of land subsidence at present (for thirty years)	
maximum (without regulation against groundwater use)	130,000
maximum (including the regulated period)	90,000
average	30,000

As shown above, even though the rate of progress of various geological phenomena has been accelerated since the Middle Pleistocene, the value of land subsidence is exceedingly high compared with the other phenomena. These values show that though the degree of tectonism since the Middle Pleistocene might be

* Effect of burial to the thickness of strata has been corrected according to the chart made by Miyazaki (1966)

preceding ages, only a little direct influence of the tectonic movements to the phenomena of most land subsidence in Osaka may be inferred. However, the land subsidence near the well No. 26 seems to be a subsidence caused by a local tectonic movement. The rate of subsidence there is estimated at 40 mm/year (40, 000 BUBNOFF units). The subsidence at Kishiwada area (Refer Fig. 9) is now in investigation.

The distribution of the amounts of land subsidence greatly related to the thickness and distribution of the Alluvial and the Upper Pleistocene formations, which, in turn, strongly controlled by the underground structure of the underlying Osaka group and the neotectonic movements (the Rokko movements).

Soil-mechanical properties*

The compressibility of Osaka clays was mainly investigated on the undisturbed samples obtained from deep borings; Boring No. 1 of 700 m deep in Northern Osaka, No. 6 of 900 m deep in Western Osaka, No. 11 of 500 m deep and No. 16 of 700 m deep in Eastern Osaka, No. 19 of 300 m deep in Southern Osaka (Table 2).

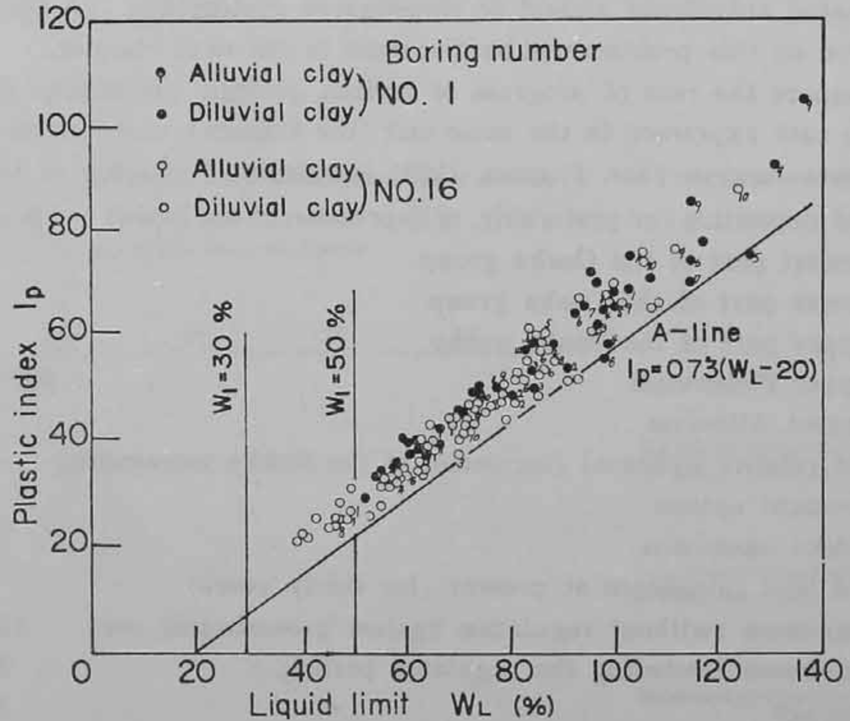

Fig. 38 Liquid limit and plasticity index of Osaka clays plotted on plasticity chart** (MURAYAMA & YAGI).

* Soil-mechanical investigations have been worked out in cooperation of the Department of Geosciences, Osaka City University and the Disaster Prevention Research Institute of the Kyoto University.

** The Dilluvial clays here used correspond to the clays in the Upper Pleistocene down to the Ma 1 clay of the Osaka group.

Physical properties of soils.

As shown in Fig. 38, most of clays in Osaka can be classified into the inorganic clay of high plasticity when their liquid limit and plastic index are plotted on the plasticity chart.

Most of clays belong to the active clay, since the A_c is greater than 1.25. In general, the larger the activity number of clay is, the greater its volume change due to the decrease in its water content from the liquid limit to the shrinkage limit becomes.

Fig. 39 is the distribution of the velocity of the ultrasonic longitudinal and transverse waves plotted against the depth from ground surface. Though these values are very scattered, they seem to increase with depth.

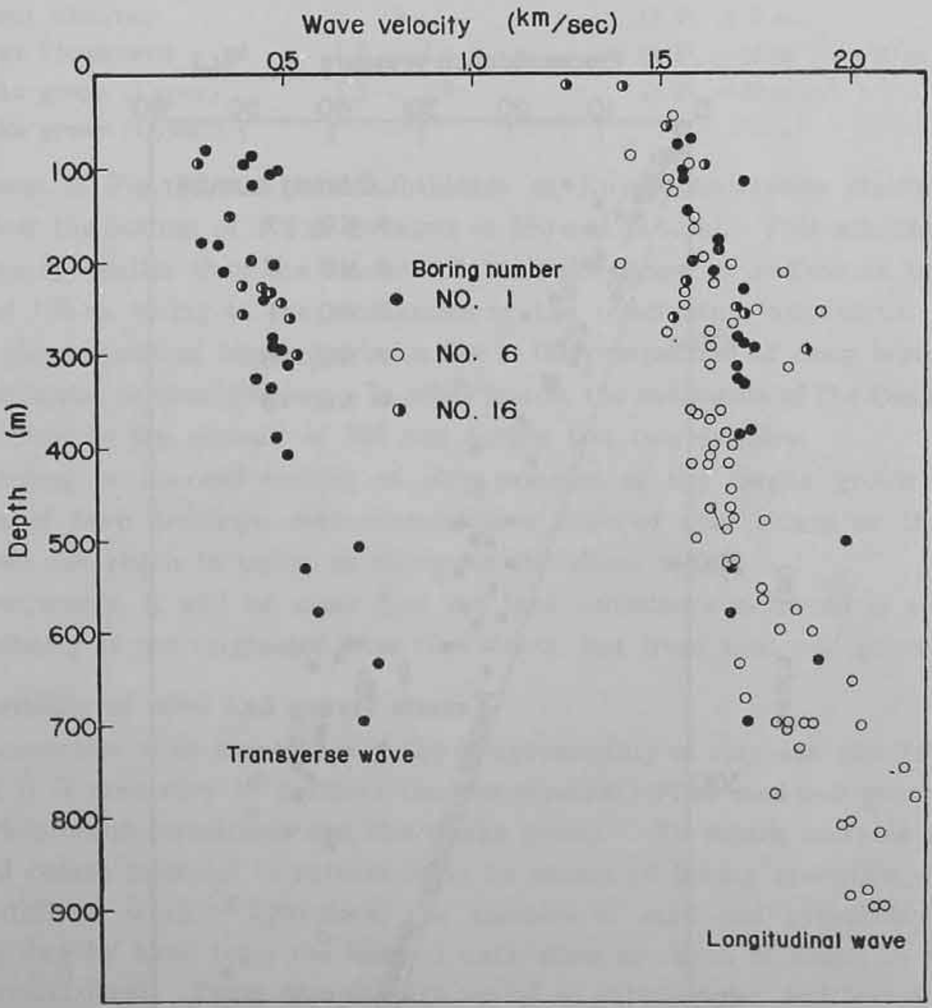

Fig. 39 Distribution of ultrasonic longitudinal and transverse wave velocity (TAKENAKA & YAGI).

Compressibility of clay strata.

The consolidated volume $\Delta V/V$ of the normally consolidated clay due to the stress $P_c+\Delta P$ can be represented by the following equation

$$\frac{\Delta V}{V}=\frac{C_c}{1+e}\cdot\log\frac{P_c+\Delta P}{P_c}$$

where, P_c : the preconsolidation stress of the clay, e: the void ratio of the clay before consolidation, and C_c: the compression index. Therefore, the compressibility of clay depends on C_c and P_c.

Fig. 40 is the distribution of preconsolidation stress P_c plotted against the depth from the ground surface. In this figure, P_c seems to increase in proportion to the depth and is generally larger than the present effective overburden pressure. However, the plots of P_c of the Alluvial clays existing shallower than about 20 m

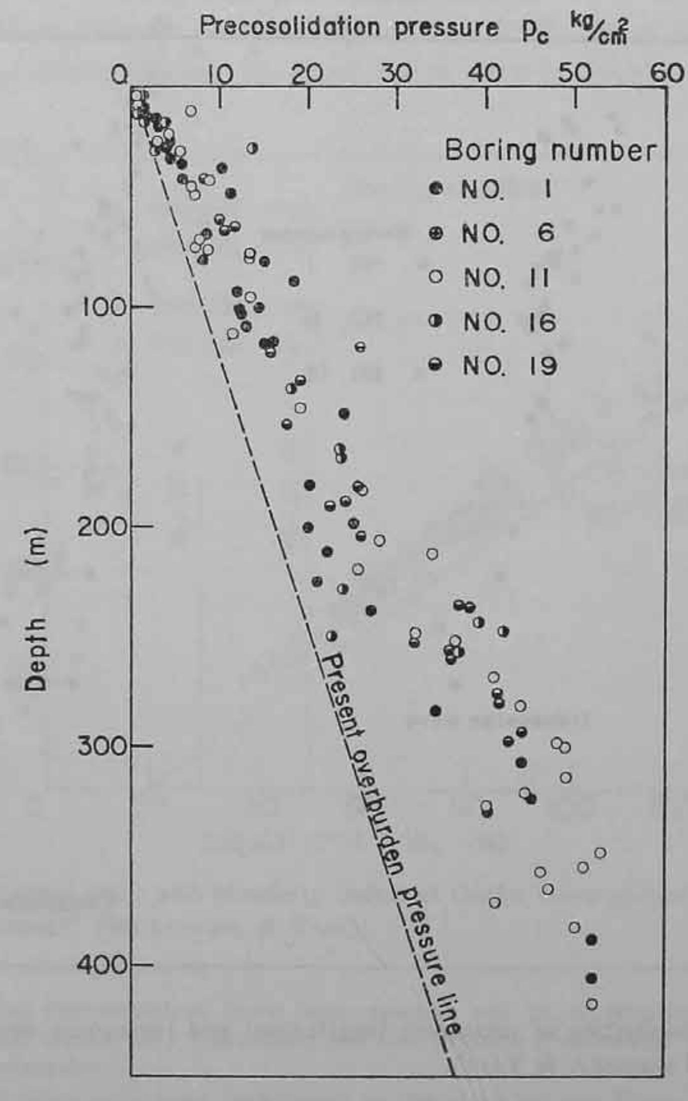

Fig. 40 Distribution of preconsolidation stress measured by oedometer test (MURAYAMA & TAKENAKA).

lie on the overburden pressure line. Therefore, it can be said that these clays shallower than about 20 m belong to the normally consolidated clay and those deeper than about 20 m to the over-consolidated clay.

The degree of over-consolidation are represented in term of over-consolidation ratio. The over-consolidation ratio is determined by the following three quantities : the preconsolidation pressure of clay strata, depth of clay strata and the groundwater level. As the groundwater level is lowering, over-consolidation ratio gradually approaches to unity and land subsidence due to deep layer occurs. The over-consolidation ratio of Quaternary marine clays and the limiting groundwater level concerning the land subsidence in Osaka is summarized as follows :

	Over-consolidation ratio	Limiting groundwater level : over-consolidation ratio approaches to 1
Recent Alluvium	1	O. P. ± 0 m
Upper Pleistocene	1.3 — 2.0	O. P. −10 m — −30 m
Osaka group (Upper)	1.5 — 1.8	O. P. −40 m
Osaka group (Lower)	——	——

As seen in Fig. 36, the land subsidence at Kujoh observation station, 1947—1968, below the bottom of 176 m amounts to 350 mm in total. This amount of land subsidence is smaller than the amount of real shrinkage of sediments below the bottom of 176 m, owing to the mechanism of the observation apparatus. Consequently, the amount of land subsidence due to the compaction of deep layer, at the lowest estimate, is over 500 mm. In other words, the sediments of the Osaka group have shrinked to the amount of 500 mm during last two decades.

According to the soil testing of clay samples of the Osaka group obtained by means of deep drillings, over-consolidation ratio of clay strata of the Osaka group does not reach to unity, as shown in the above table.

Consequently, it will be clear that the land subsidence occurred in such deep layer probably is not originated from clay strata, but from sand and gravel layers.

Compressibility of sand and gravel strata.

In connection with researches in the compressibility of clay samples from deep drillings, it is necessary to perform the compression test of sand and gravel of the Upper Pleistocene formations and the Osaka group. To obtain samples of these indurated coarse material in natural state by means of boring operation, however, is very difficult work. Therefore, the samples of sand and gravel layer were carefully dug by hand from the base of excavation at depth of about 20 m — 30 m below ground level. These samples are sealed in rubber tube, and tested in laboratory.

In Fig. 41 the decreasing of volume of sand and gravel are plotted against the compression pressure at $K_o=0.3$*. From the result of these tests shown in Fig. 41,

* K_o represents the coefficient of earth pressure at rest.

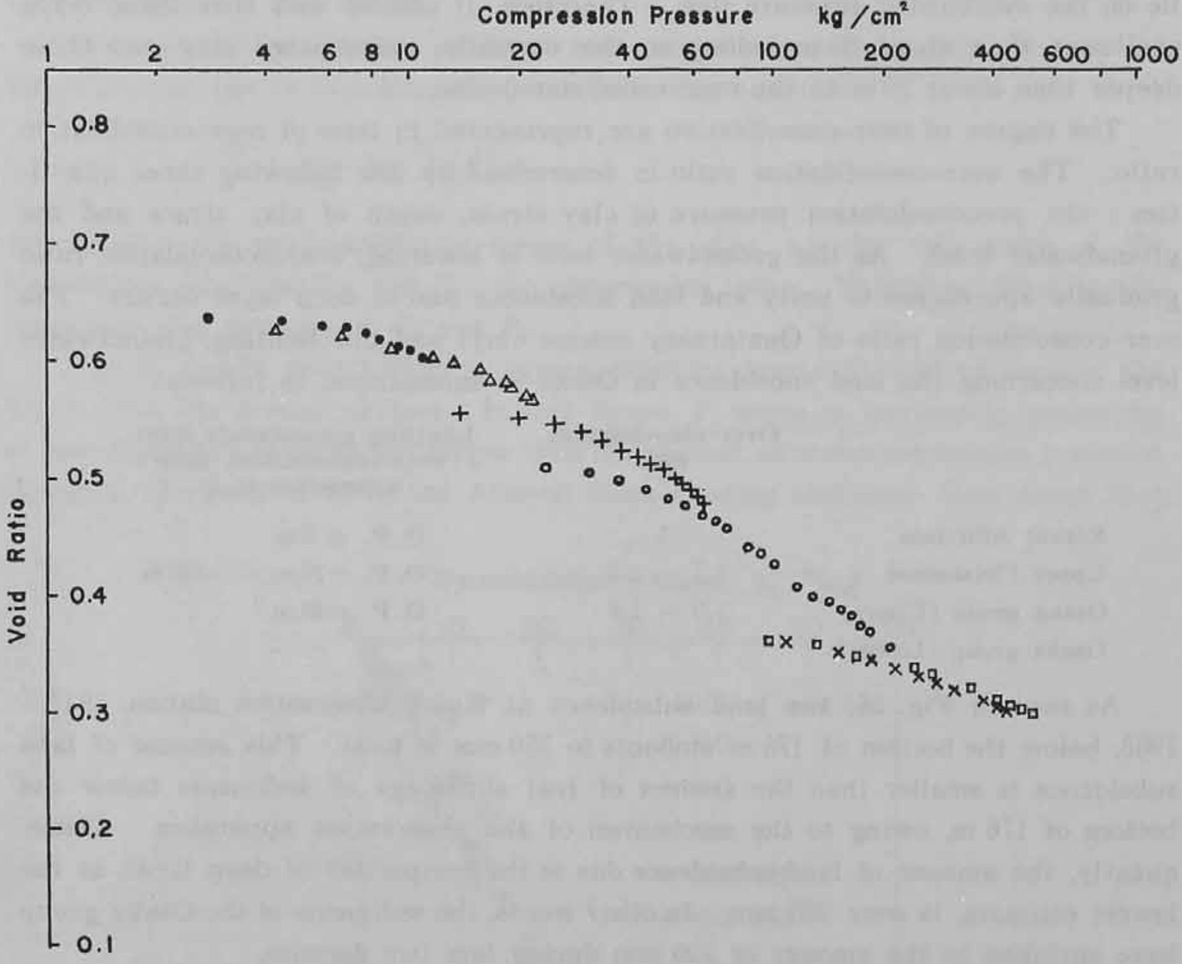

Fig. 41 10 cm dia. × 20 cm high compression tests; Upper Pleistocene sand with gravel (TAKENAKA & YANAGI). Different marks show the different samples tested, under the various initial pressure, all from the same layer and the same location.

it is suggested that near the ground surface, sand and gravel layers of the Upper Pleistocene and the Osaka group are very compressible. This high compressibility may be caused from the crushing of decomposed feldspar grains (TAKENAKA & YANAGI, 1970).

According to the field observation together with the test of core samples from deep drillings, sands and gravels of the Osaka group contain more or less decomposed feldspar grains. Such layers may be shrinked in a considerable amount.

If the mineral composition and degree of decomposition of the Osaka group is assumed to be similar to those of the tested samples obtained near the ground surface, the total amount of ground subsidence due to the shrinkage of sand and gravel layer may be estimated at least 3 m. The quantitative analyses regarding to the shrinkage of sand and gravel layers now in investigation, are expected to produce useful data concerning the mechanism of land subsidence.

Problems on land subsidence to be solved in near future, geologically considered

During last three decades, much empirical knowledge concerning the land subsidence in Osaka has been obtained. Researches on the land subsidence are closely related to the fields of Soil Mechanics, Geology or Hydrogeology and Hydrology. Many investigators have the vision to recognize the great need for a rational approach to these problems from their own professional fields. However, many questions are still left unsolved. Chiefly considered geologically, problems to be solved in near future may be simply summarized as follows.

Mechanism of consolidation of clay.

The shrinkage process of clay is divided into two stages; *i. e.* elastic stage and plastic stage. The pressure corresponding transition between two stages is named preconsolidation pressure. This pressure varies with rate of stress-increasing. The preconsolidation pressure obtained by soil testing indicates the larger value than the one of natural consolidation process of clay stratum, and this behaviour of clay is conventionally called in terms of time effect.

At present, there is no way to estimate this pressure of such weakly over-consolidated clay as of the young Quaternary sediments, in process of natural consolidation.

During a long period the degree of order (orientation) of the molecular structure of absorbed water gradually develops on the surface of clay particles, while some cations are bonding clay particles together. Some contact between particles may be mineral-mineral contact, but it is more probable that the stress between mineral grains is acting via a few molecules of highly ordered, virtually solid absorbed water.

These bonds and contacts in clay structure are viscous and rigid, and such a bonding strength is very relevant property relating to the preconsolidation pressure.

The conception about the development of clay structure is widely accepted. Model of clay-microstructure, however, will have limited application and provides no real insight into behaviour of the materials.

The knowledges of preconsolidation pressure of clay in the young Quaternary sediments is essential to the fundamental understanding of nature of land subsidence or Soil Mechanics. However, to clear up the soil-mechanical properties relating to the time effect, more intimate cooperation of soilmechanists, geologists and as the case chemists or physicists, are necessary.

Compressibility of sand and gravel layer.

Most sand and gravel layers of the Osaka basin are of granitic origin, containing more or less decomposed feldspar grains. Consequently, these sand and gravel layers are very compressible compared with layers of quartzose sand.

According to observations of sand samples from borehole, the Upper Pleistocene sediments are much more decomposed than sediments of the Osaka group.

Results of both field and laboratory tests for compressibility of sand layer show nearly same value of compressibility, and the value may not be disregarded for the land subsidence.

Up to the present, it is considered that land subsidence has been caused by consolidation of clay stratum. However this fundamental conception should be reconsidered in this connection.

Distribution and tectonics of the Upper Pleistocene formation.

It is probably true that the dominant amount of land subsidence in Osaka is due to compaction of sediments ranging from the Upper Pleisthcene to the Recent.

As for the Recent Alluvium in Osaka, its distribution is known precisely from a lot of data obtained by soil surveys for the foundation engineerings as represented in Fig. 14. The information about the Upper Pleistocene formation is not enough yet for the further research in land subsidence. Consequently, in near future the most important geological problems are the detailed investigation in the Upper Pleistocene formation, the analytical studies in their lithofacies, sedimentary environment, primary and secondary tectonics, *etc.*

There are two ways for a purpose to approach to these problems, *i. e.*, stratigraphical method and application of recent tectonics, named "Rokko movements"

In the stratigraphical method, it is required to identify Ma 11 clay and Ma 12 clay in the course of subsurface exploration. Though the methods of this identification are pretty troublesome works, carefully treated soil testing and various micropaleontological analysis will give some effective data for these problems. The other side of investigation for this aim are more extensive and microstructural researches in connection with the nature of the "Rokko movements" around the Osaka basin, because the results of such researches may offer profitable information on the nature and development of the Upper Pleistocene formation.

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Plate I

Explanation of Plate I

Examples of surface folding probably due to the Recent strike-slip movement along some latest tectonic lines.

A. Left above:
Behind Sumiyoshi Shrine, Sumiyoshi-ku, Osaka City
(October, 1969)

B. Left below:
Example 1 at Sayama-cho, Sakai City
(September, 1968)

C. Right above:
Kumatori-cho, Southern Osaka
(January, 1970)

D. Right below:
Example 2 at Sayama-cho, Sakai City
(September, 1968)

Photo by N. IKEBE (A, B, D) & J. TAKENAKA (C)