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Quaternary Stratigraphy Subsurface of the Kochi Plain, Kochi Prefecture, southwest Japan

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Abstract

A re-examined stratigraphical division of subsurface geology in the central part of the Kochi Plain is as follows: the Ogura Formation (the lower and the upper parts), the Kawauchi Formation (the lowermost, the lower and the upper parts), and the Holocene Urado Formation (the lower and the upper parts). Two volcanic ashes, which are found in the lower part of Kawauchi Formation, and Harimaya-bashi Volcanic Ash Layer in the bottom of the upper part of Urado Formation, are correlated with Hiwaki and Kikai-Akahoya tephras, respectively.

The Ogura Formation was deposited before 580ka. The lower part was formed as a lacustrine deposit, and then the upper part was formed by debris flows. The Pleistocene sediments, the lowermost part of Kawauchi Formation, were deposited before 580ka as a fluvial plain. Then, the lower part was formed between 580ka and 38ka. The upper part had begun to form the muddy beds in shallow seawater around 38ka, and then the gravelly beds of this part were deposited between 32ka and 8.3ka as a fluvial deposit. The lowermost layer of the lower part of Urado Formation had begun to form in the incised valley before 8.3ka. The following layers were deposited until at least 4.2ka at the inner-bay prodelta as bottomset then at the delta front as foreset beds and at the subaqueous delta as topset beds. Sedimentation of the sands intercalated the lower part between 8.3ka and 7.3ka as a distributary mouth bar deposit and as a channel deposit of the Paleo-Kagami River. Along the Kokubu River, a set of sands and sandy gravels found in the upper part of Urado Formation has been deposited by the Kokubugawa delta system since 7.3ka. Another set of sands and gravels found along the Kagami River has been deposited by the Kagamigawa delta system since 4.2ka. Both of the sets of sands and gravels had formed at the delta front and the delta plain as topset beds, since delta mass had been progradating to the Urado Bay. Finally, in the area between the Kagamigawa and the Kokubugawa Deltas, an interdistributary bay had been left where the upper part of the Urado Formation had developed.

Key-words : Pleistocene, Holocene, Kochi Plain, volcanic ash, radiocarbon dating

I. Introduction

The Kochi Plain occupies the central part of the southern coastal plain of Shikoku Island facing the Pacific Ocean (Fig. 1 (a)). The plain is an example of a tectonic basin (Katto and Nishi, 1971) and is a suitable area for studying the standard stratigraphy of the Quaternary in the southern area of Shikoku Island because of the availability of many drill data. Detailed research of subsurface geology based on drilling-core observation has not been carried out since the early 1980s.

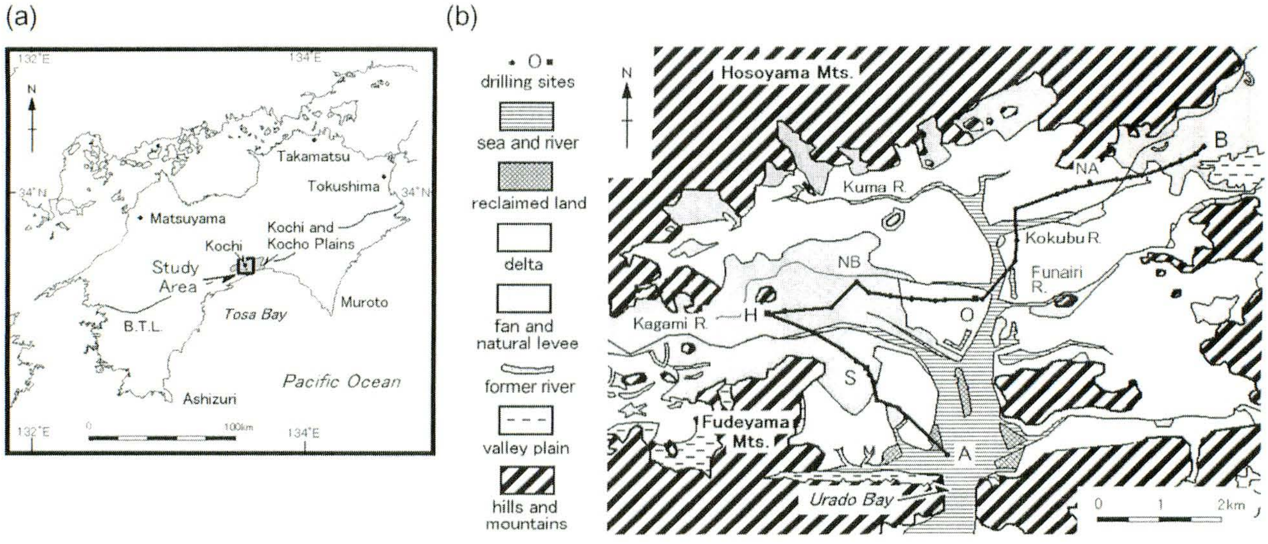

Fig. 1 Study area and geomorphological division
Panels (a) and (b) show location of study area and drilling sites.
Distribution of fault is after Katto et al. (1968), and geomorphological division and distribution of the terrace deposits are after Hosoi (1966) and Mitsushio and Katto (1996) respectively.
Abbreviations O, H, and S indicate the location of drilling-cores at Ogura, Honmachi, and Sanbashi used in this study and "NA" and "NB" indicate Locs. A and B in Nakao and Mimoto (2003).

Prior to beginning the current discussion, it is useful to review the existing research. The pioneering study of the Quaternary stratigraphy in the plain is Mitsushio and Katto (1966). The group of papers by Nakamura (1969), Nakamura et al. (1972) and Yamanaka (1983) show the palynological zonation of the formation. Nakamura (1969) reports the results of radiocarbon dating of the Pleistocene peaty sediment from the eastern part of the plain. The observed lithostratigraphy of several drilling-cores is explored by Katto and Nishi (1971, 1972) and Katto et al. (1984). Katto and Nishi (1971) report one result of radiocarbon dating beneath the plain. Katto et al. (1984) additionally discussed the geomorphological development of the plain during the Holocene.

Some modern radiocarbon dating results have recently emerged from Nakao (2000) and Nakao and Mimoto (2003). Thus we have been able to discuss the Holocene formation ages in the plain. On the other hand, just one dating result of the Pleistocene was obtained by Katto et al. (1984). Compared with the significant progress on the study of neotectonics in the upheaval region of southern Shikoku (e.g.; review by Mitsushio and Kagami, 1992), such as Muroto and Ashizuri areas, we have less data on the chronostratigraphy of the Pleistocene in Kochi plain's subsidence region. So neotectonics in the central part of southern Shikoku has still not been discussed in detail with enough stratigraphic proofs such as many radiocarbon dating and common wide spread tephra.

The objectives of the present study are a re-examination and a discussion of the age of the Quaternary sediments, through the detailed observation of three new drilling-cores from the central area in the plain, particularly on the basis of both the recognition of volcanic ashes and radiocarbon dating.

II. Outline of geomorphology and geology in the study area

The plain is elongated from east to west, and the Butsuzo Tectonic Line (B.T.L.) lies at the southern rim of the plain (Fig. 1 (a), Hosoi et al., 1966; Katto et al., 1984) and along the Niyodo Thrust that is the boundary between the Kurosegawa Tectonic Zone and the Sambosan Terrane of the Chichibu Belt (Hosoi et al.1966; Hada, 1993). The plain is divided into western and eastern parts: the Kochi and Kocho Plains (Katto, 1969). The Kochi Plain has been formed by the river and/or delta systems of the Kagami, the Kuma, and the Kokubu Rivers. On the other hand, the Kocho Plain has been formed by alluvial sedimentation by the Monobe River (Katto and Nishi, 1971).

The Kagami and the Kuma Rivers, two major rivers in the Kochi Plain, run south and then east from the Kuishi Mountains to the Urado Bay. The Kokubu River, another major river, is running south and then west to the Urado

Bay. As for geomorphological division, the Kochi Plain is classified as fan, delta, and reclaimed land (Hosoi, 1966, Fig. 1 (b)).

Immediately to the north and west of the Kochi Plain lie the Hosoyama Mountains, which are underlain by the Mesozoic Chichibu Terrane (Katto and Nishi, 1971, 1972 etc.). The plains' southern neighbor, the Fudeyama Mountains, is made up of the Mesozoic to Palaeogene Chichibu and Shimanto Terranes (Katto and Suyari, 1966).

No active fault system has been found in the plain (e.g.; Tsukuda et al., 1982). Katto et al. (1984), however, have inferred two possible active faults. One of the faults, the Harami Fault may lie beneath the lower reaches of the Kuma River along the central part of the plain from north to south. Another unnamed fault has also been estimated along the Butsuzo Tectonic Line, but the distribution of the two possible faults has not been clarified.

III. Methods

Three drilling-cores (Ogura, Honmachi, and Sanbashi sites, Fig.1b) were used for the discernment of lithofacies and precise analyses of faunal fossils and several intercalated volcanic ashes.

The Ogura drilling-core (133° 33′ 59″E, 33° 33′ 39″N, Tokyo Peil: T.P. +0.53 meters) was drilled 104 meters deep at Ogura, Kochi city for the purpose of geotechnical research by the Shikoku Technical and Engineering Office, Ministry of Land Infrastructure and Transport in 2006.

The Honmachi drilling-core, 38.0 meters long, was sampled at Honmachi 5-chome (133° 31′ 54″ E, 33° 33′ 27″ N, T.P. +2.56 meters) in 2006. Sanbashi drilling-core, 69.0 meters long, was drilled at Sanbashi-street (133° 32′ 50″E, 33° 32′ 5.8″N, T.P. +0.94 meters) in 2002. Both of the cores were drilled for the purpose of geotechnical research by the Kochi City Office.

The authors referenced the drill database compiled by Shikoku Ground Information Utilizing Association (2007) and collected by Shikoku Technical and Engineering Office of Ministry of Land Infrastructure and Transport for the purpose of determining the lithological division of the formation.

The lithology of the samples, such as grain-size distribution, fossils, and sedimentary structure, were described by inspection with macroscopic and microscopic observations. Volcanic ash samples are picked up after core observation.

Large-size mollusk fossils were directly picked up from drilling-core samples. Ten- to twenty- gram sample blocks were collected and washed with water on a 1/8-millimeter mesh sieve, and the fossils were separated with the aid of a stereoscopic microscope. The ecological data of mollusk, e.g. vertical distribution, follow Higo and Goto (1993) and Higo et al. (1999).

The intercalated volcanic ashes and mineral compositions were defined with the shape and refractive index of glass shards in terms of petrography. Classification of glass shards' shapes (H, C, T and other types) is after Yoshikawa (1976). The refractive index was measured by the temperature change method using the refractometer "MAIOT" (Furusawa, 1995). The accuracy of measurements by this method is approximately ± 0.0001. The refractive index of glass shards from each volcanic ash sample was determined by the measurements of twenty glass shards.

AMS radiocarbon dating of marine shell fragments in the sediments of the drilling-core samples was undergone for the purpose of inferring age of the sediments. Basic data about the materials were obtained from Beta Analytic Radiocarbon Dating Lab, which performed the radiocarbon analysis. Conventional radiocarbon ages were obtained after $\delta^{13}C$ calibration. ^{14}C half life adopted in this dating is 5,568 yrs as suggested by Libby (Godwin, 1962).

IV. Lithological units

On the basis of lithofacies, the authors divide study drilling-cores into 18 lithological units. These lithological units are summarized in Table 1.

Unit Mm-s: This unit is comprised of dark gray well sorted silt. The silt was characterized as bearing the shell of the upper shallow sea mollusk, *Kurosioia cingulifera*. The unit also yields shell fragments and land plant debris. Occasionally, this unit is disturbed with burrows of benthic animals.

Unit Mm-st: This unit is dark gray well sorted massive clay or clayey silt. The unit yields land plant debris, occasional burrows by animals, and fragments of shells correlated with *Theora fragilis*, inner-bay living species. Gypsum crystallizes on the dried out core surface.

Unit Mm-is: This unit is comprised of dark gray well sorted fine sandy silt. The silt bears land plant debris and some intertidal zone to upper shallow seashell fragments. Burrows by animals are found occasionally.

Unit MSm: This unit consists of dark gray well sorted alternating beds of silt and silty very fine sand. Land plant debris and shell fragments are found occasionally in the unit. Gypsum crystallizes on the dried out core surface.

Unit Mb: This unit is comprised of dark brownish-gray, well sorted massive clay beds with intercalated sand layers, which is underlain by unit SGm. The unit contains land plant debris and occasional shell fragments. Burrows are

Table 1 Lithological units and interpretation of their sedimentary environments

Code	Lithology					Occurence of fossil	secondary formed materials	Sedimentary environment
	Grain size and fabric etc.	Color	Sort-ing	B.T.*	Roundness of gravel			
Mm-s	massive silt	dark gray	well	rare		upper shallow sea mollusc; e.g. *Kurosioida cingulifera*; and plant debris	gypsum	shallow sea
Mm-st	massive clay or silt	dark gray	well	rare		sparse shell fragments; e.g. *Theora fragilis*; land plant debris	gypsum	mid-inner bay
Mm-is	massive fine sandy silt	dark gray	mod-erate	com-mon		intertidal zone to upper shallow sea mollusc; land plant debris	none	interdistributary bay
MSm	alternating beds of silt and silty very fine sand	dark gray	well	rare		sparse shell fragments; land plant debris	gypsum	delta front
Mb	massive clay beds intercalated sand layer underlain by unit SGm	dark brown-ish gray	well	com-mon		sparse shell fragments land plant debris	gypsum	brackish or salt marsh
Mf	clay to silt	dark gray	well	none		none	none	back marsh
MSf	tens of meters thick fine sand to mud	light brownish-gray to gray	well	none		none	none	lake
If	inverse grading from silt to sand or silt to pebble upward	brownish-gray	well	none	subrounded to rounded	none	none	natural levee or back marsh
SMm	grading sand to clay upward; partly laminated clayey silt	dark gray	well	none		none	gypsum	delta front
Sm	meium to coarse sand	dark gray	well	none		shell fragments; land plant debris	none	delta front
SOm	massive sand intercalated silt bearing organic materials layer	dark gray	well	none		sparse shell fragments; plant debris in common	none	subaqueous levee
SGm	fine or medium sand contain-ing pebble	gray to dark gray	poor	rare	subrounded to rounded	sparse shell fragments; intertidal zone mollusc	none	estuary
GMm	pebbly silt to silty pebble	dark brownish -gray	poor	none	subrounded	sparse shell fragments	gypsum	estuary
GSf	massive silty or sandy gravels with coarse sand as matrix	grayish or brownish-gray	poor	none	subrounded to subangular	none	none	braided river
Gf	stratified gravels; pebble or cobble in unit GSf	brownish-gray	mod-erate	none	subrounded to subangular	none	none	channel or bar in braided river
B	silt matrix breccia with fine or medium sand	miscellan-eous	poor	none	anguler to subrounded	none	none	debris flow
V	massive silt to fine sand grained volcanic ash	light gray	well	none		sparse shell fragments	none	(volcanic ash fall)
A	gravelly sand including blocks of concrete and wood	miscellan-eous	poor	none		none	none	reclaimed land

*B.T.: bioturbation

found commonly. Gypsum crystallizes on the dried out core surface.

Unit Mb: This unit is comprised of dark gray well sorted massive clay or silts, which is underlain by unit GSf.

Unit MSf: This unit consists of light brownish-gray to gray well sorted accumulation of fine sand to mud dozens of meters thick.

Unit If: This unit is the brownish-gray well sorted inverse grading bed, in which silt beds grade into sand or silt beds grade into pebbles upward. The roundness of pebbles is subrounded to rounded.

Unit SMm: This unit is comprised of dark gray well sorted grading sand upward to clay and partly planer lamina clayey silt. Gypsum crystallizes on the dried out core surface.

Unit Sm: This unit is well sorted medium or coarse sand of a dark gray color. This sand silt yields land plant debris and shell fragments.

Unit SOm: This unit consists of dark gray well sorted massive sand, intercalated silt, and organic materials layers derived from land plants. This unit occasionally bears shell fragments.

Unit SGm: This unit is made of gray to dark gray poorly sorted fine or medium sand containing subrounded to rounded pebble. Intertidal zone molluskan shell fragments are contained sparsely in the unit. Burrows from animals are also found occasionally.

Unit GMm: This unit is comprised of dark brownish-gray poorly sorted pebbly silt to silty subrounded pebbles. The unit bears occasional shell fragments. Secondary formed gypsum crystals are found.

Unit GSf: This unit is comprised of grayish to brownish-gray poorly sorted massive silty or sandy gravels with coarse sand as a matrix. The roundness of main clast in gravels is subrounded to subangular.

Unit Gf: This unit is an accumulation of brownish-gray moderately sorted gravels, stratified by subrounded to subangular pebbles or cobbles.

Unit B: This unit is mainly comprised of an unsorted breccia with silt matrix supported by boulder to pebble and intercalated fine or medium sand layers.

Unit V: This unit is made of light gray volcanic ash that is well sorted massive silt to fine sand grained. This unit yields occasional shell fragments.

Unit A: This unit bears a gravely sand frequently with blocks of concrete and wood.

V. Quaternary stratigraphy

In this section, we will briefly describe Quaternary stratigraphy in the central part of Kochi Plain in ascending order (Figs. 2, 3, and 4).

Ogura Formation (new usage)

The formation, overlaying the Mesozoic Chichibu Terrane and underlying the lowermost part of Kawauchi Formation, is distributed beneath the Kochi plain. The authors define the type locality as between T.P. -99.2 and -72.2 meters of the Ogura drilling-core, Ogura-cho, Kochi city (Fig. 4). The formation is characterized with moderately consolidated sand, silt, and breccia. The thickness of this formation may be up to 30 meters thick.

The formation is divided into two parts: the lower and the upper parts. The lower part is intercalated between T.P. -99.2 and -85.6 meters of Ogura drilling-core and is comprised of well sorted homogenous silty fine-grained sandstone and siltstone (unit MSf). No sulfur and gypsum crystal are found on the surface of core samples, which

Geological age	Katto (1969)	Nakamura et al.(1972)	Yamanaka(1983)	Katto et al.(1984)	This study				
	Kochi P.	Kochi P.	Maruike-cho, Kochi	central part of Kochi Plain	central part of Kochi Plain				
	stratigraphy	stratigraphy	Pollen Zone(P.Z.)	stratigraphy	stratigraphy			volcanic ash	wide-spread tephras(eruption age)
Holocene	Urado Formation	Up. Alluvium		Top sand and gravel deposits(G I)	Urado Formation	Upper part		Harimaya-bashi(Har)	K-Ah(7.3ka)
		Low.Alluvium	the First P.Z.	Upper Mud deposits (M I)					
			the Second P.Z.						
		Onji	volcanic ash						
		Lowermost Alluvium	the Third P.Z.	Upper Sand deposits(S I)		Lower part			
				Lower Mud					
Pleistocene	Kawauchi Formation	Diluvium	the Forth P.Z.	G II a	Kawauchi Formation	Upper part	Gravelly beds		
			the Fifth P.Z.	M III a			Muddy beds		
			the Sixth P.Z.						
			the Seventh P.Z.	G II b		Lower part	Gravelly beds		
				M III b			Muddy beds	(volvanic ash)	Hiwaki(580～570ka)
				?		Lowermost part			
					Ogura Fm.	Upper part			
						Lower part			

Fig. 2 Correlations of the stratigraphy and pollen zones beneath the Kochi Plain

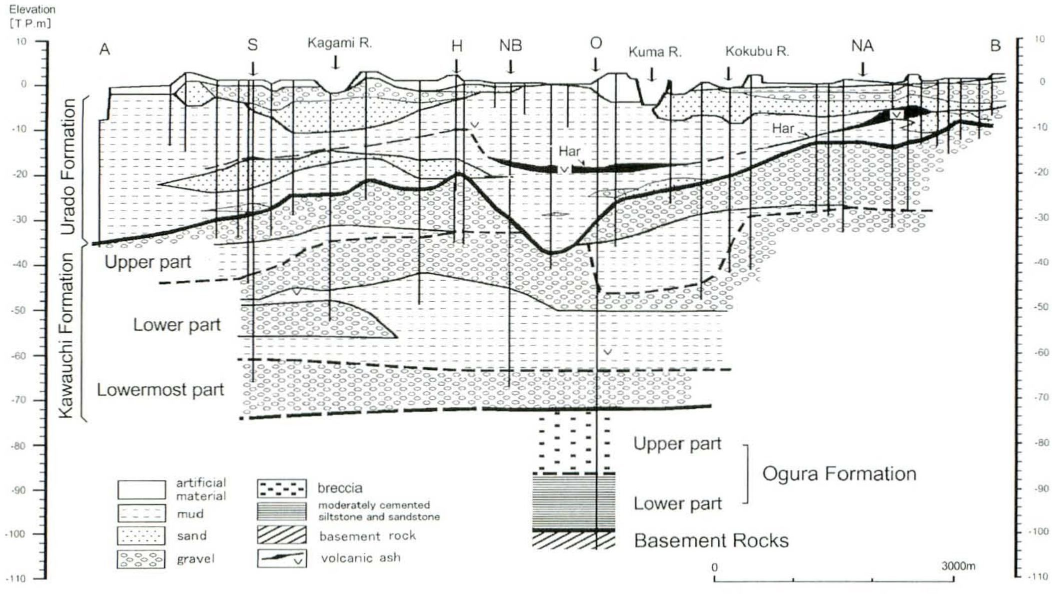

Fig. 3 Geological section in Kochi Plain

Line A-B and abbreviations of drilling sites are shown in Fig. 1. Un-named drilling sites are based on the logs of Shikoku Ground Information Utilizing Association (2007) and the database collected by Shikoku Technical and Engineering Office, Ministry of Land Infrastructure and Transport.

The abbreviation "Har" means Harimaya-bashi Volcanic Ash Layer.

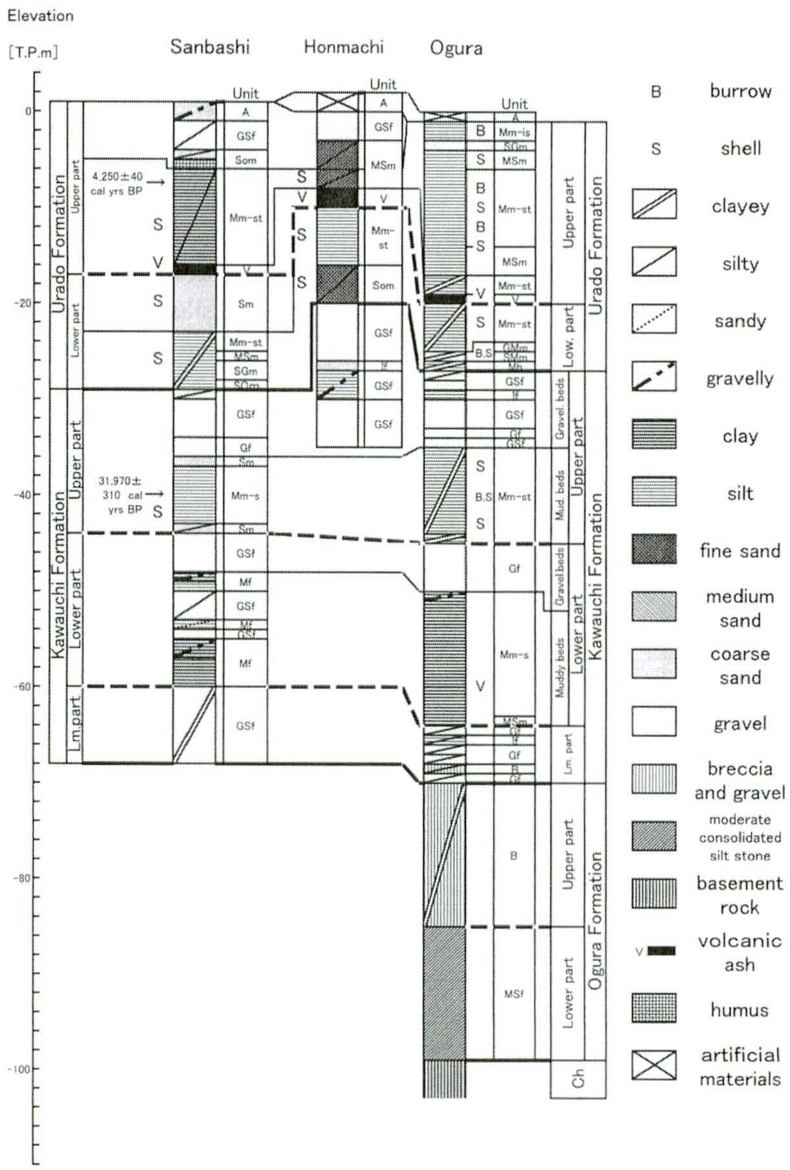

Fig. 4 Geological columnar sections in the Kochi Plain
The abbreviation "Ch" means the formation of Chichibu Terrane.

may indicate low-content sulfate in the samples. The upper is intercalated between -85.6 and -72.2 meters in the Ogura drilling-core and consists of very poorly sorted breccia infilled with sand and gravel. The main clasts are angular to subrounded pebbles to boulders (unit B). Considering referenced drilling-logs, the formation would be found between T.P. -150 and -72 meters beneath the lower reaches of the Kagami and the Kuma Rivers (Fig.3).

Kawauchi Formation (redefinition)

Katto (1969) preliminarily named the Pleistocene sediments in the plain the Kawauchi Formation, but he didn't provide a precise definition. In spite of this proposal, he did not continue to regularly use this name. In the present study, the authors reconfirm that the Kawauchi Formation is composed of the sediment consisting of sandy gravels and muds, unconformably overlaying the Ogura Formation and unconformably underlying the Urado Formation beneath the Kochi Plain. The authors define the type locality as between T.P. -72.2 and -28.1 meters of the Ogura drilling-core, Ogura-cho, Kochi city (Fig. 4). The formation lies approximately between T.P. -74 and -10 meters. According to the referenced drilling-logs, the formation is 25 to 50 meters in thickness. From the lithological viewpoint, each part of the Kawauchi Formation can be correlated with the Pleistocene sediments named by Katto and Nishi (1971) and Katto at al.(1984).

The succession of the sediments of the formation is, in ascending order, the lowermost part (LmK), the lower part

(LK), and the upper part (UK).

Lowermost part: This part is found between -72.2 and -64.3 meters in Ogura drilling-core. It is an accumulation of silt, sand, and sandy gravel beds, which are subrounded to rounded (unit GSf). Inverse grading beds (unit If) are intercalated frequently, such that silt bed grades into sand bed. Occasionally breccia beds (unit B) are superimposed in the sediments.

Lower part: This part is found in the drilling-core between T.P. -64.3 and -50.2 meters in the Ogura drilling-core. The lower part is subdivided into the muddy beds and the gravelly beds in ascending order. The muddy beds are comprised by an accumulation of silt and frequently display gypsum and sulfur (unit Mm-st) on the surface of the drilling cores. The lowermost beds, in ascending order, consist of fine sand, silty very fine sand and silt. The volcanic ash is found between T.P. -59.7 and -59.1 meters in the drilling-core.

The gravelly beds distribute between T.P. -40 and -27 meters beneath the river mouths of the Kagami and the Kuma Rivers (Katto and Nishi, 1971; Katto et al., 1984) and are found in the Ogura drilling-core between T.P. -50.2 and -45.3 meters. These beds consist of gray massive sandy gravel that contain subrounded to rounded pebbles with coarse sand (unit GSf).

The volcanic ash layer is described in the referenced drilling-log at approximately T.P. -47 meters beneath the northeastern side of Mt. Fudeyama. In the present study, however, the authors cannot describe the volcanic ash because no sample has yet been obtained. The lower part is correlated with the Third b Mud deposits (MIIIb) and the Second Gravel b deposits (GIIb) that was described by Katto and Nishi (1971) and Katto et al.(1984).

Upper part: In ascending order, the upper part is subdivided into the muddy beds and the gravelly beds.

The muddy beds are distributed between T.P. -48 and -28 meters and are assumed to be 0 to 14 meters in thickness. The beds are found between T.P. -45.3 and -35.1 meters in the Ogura drilling-core. The muddy beds are mainly comprised of accumulated clayey silt (unit Mm-st). In the lower half of the part, the beds' grading consists of fine sand to silt. The authors found shallow sea mollusk shells from the muddy beds of Ogura and Sanbashi drilling-cores, e.g., *Kurosioia cingulifera* and *Dentalium (Paadentalium) octangulatum* etc. The volcanic ash layer is described in a referenced drilling-log at approximately T.P. -30 meters between JR Kochi station and the Kuma River.

The gravelly beds are distributed between T.P. -40 and -10 meters beneath the plain and are 7 to 15 meters in thickness. The bed is found between T.P. -35.1 and -28.1 meters in Ogura drilling-core. The beds consist of the gray massive gravel which contains subrounded pebbles (unit GSf), sometimes containing inversely graded sand and silt (unit If), and stratified pebble and cobble layers (unit Gf). According to the referenced drilling-log, in the northern part of the plain beneath the area along the Kuma River, between T.P. -12 and -10 meters, a volcanic ash layer lies locally. The upper part is correlated with the Third Mud a deposits (MIIIa) and the Second a Gravel deposits (GIIa) that was described by Katto and Nishi (1971) and Katto et al.(1984).

Urado Formation (redefinition)

Katto (1969) preliminarily named the Holocene sediments in the plain the Urado Formation but he did not provide a precise definition. In spite of this proposal, he did not continue to regularly use this name. In the present study, the authors reconfirm that the formation is characterized by sediments consisting of sandy gravel, sand and mud, unconformably overlaying the Kawauchi Formation beneath the Kochi Plain. The authors define the type locality as between T.P. -28.1 and -0.5 meters of the Ogura drilling-core, Ogura-cho, Kochi city (Fig. 4). In the central area, the formation lies above approximately T.P. -36 meters and below T.P. +3 meters. The sediments are 10 to 38 meters thick (Fig. 3).

The formation is divided into the lower and the upper parts, marked by the base of the Harimaya-bashi Volcanic Ash Layer (new usage, mentioned below).

Lower part: This part is found throughout the basin, between T.P. -38 and -4 meters and with a thickness of between 0 and 15 meters. Thickness in the marginal area of the plain is thinner than the central area. The part lies between T.P. -28.1 and -20.3 meters in the Ogura drilling-core (Fig.4). The lowermost layers are silty gravel including fragments of mollusk shells and echinus (unit GMm), humus-bearing silt with burrows from animals (unit Mb), and normal grading from sand to clay (unit SMm). This part mainly consists of massive clay and clayey silt occasionally bearing shells of *Theora fragilis* and echinus fragments (unit Mm-st). In the southeastern part of the basin, sandy beds underlying gravel beds are intercalated in the muds.

This part intercalates the sand bed in the southern part of the Kochi Plain (Fig. 3). The sand bed can be found locally underneath the lower reaches of the Kagami River. The bed is found between T.P. -23 and -15 meters and is 1 to 6 meters thick at the southwestern rim of the basin (Fig. 3), and between T.P. -28 and -18 meters at a thickness of 2 to 5 meters beneath the southern straits of the Kochi Port. In the Sanbashi drilling-core, this sand bed is found between -22.7 and -16.6 meters, occupying the lower horizon of the Harimaya-bashi Volcanic Ash Layer. The sand bed is dark gray and characterized by massive sands intercalated by silt layers, which has a thin lamination of plant debris and includes mollusk shells (unit SOm). In the area to the west of Mt. Fudeyama, the sand is overlain by gravelly beds. Nakao and Mimoto (2003) report a tidal flat association of mollusks at Harimaya-bashi (see their study site in Fig. 3) overlain by the lowermost of the sand layers. In the lower river regions along the Kokubu and the Funairi Rivers, sands or sandy silt (unit Sm) distribute in the lower part.

Nakao and Mimoto (2003) show the subtidal molluskan association from the lower part of the sands (the site "NA" in Fig. 1). In the eastern part of the study area, the sand is overlain by gravelly beds and grades into a mud member laterally.

Upper part: The sediments lie between T.P. -24 and +3 meters and are found between T.P. -20.3 and -1.0 meters in the Ogura drilling-core (Fig. 4). The thickness of the bed ranges from 3 to 19 meters. This part is composed of an accumulation of massive clay and clayey silt (unit Mm-st), alternations of silt and fine sand (unit MSm), silty sand intercalated by silt layers (unit Sm), and fine sandy silt (unit Mm).

In the clayey beds of this part, a stagnant water-dwelling mollusk, *Theora fragilis*, and a subtidal zone mollusk, *Dentalium* (*Paadentalium*) *octangulatum*, are found in unit Mm-st. Additionally, in the uppermost layer of the part, dark gray, fine-sized massive sand beds containing gravel (unit SGm) are intercalated. The gravelly layer yields marine mollusk fossil like *Batillaria zonalis* and *Batillaria multiformis*, *Crassostrea gigas* as an intertidal zone species, and *Anomia chinensis* and *Anomalocardia* (*An.*) *squamosa* as intertidal-to-subtidal zone mollusks.

In the right bank area of the Kokubu River, gravels and gravelly sands (unit GSf) are intercalated between T.P. -12 and +1 meter (Fig. 3). Thickness of this gravelly layer is less than 2 meters.

Harimaya-bashi Volcanic Ash Layer (Har): (new usage)

Katto and Nishi (1971, 1972) have shown that a distribution of the volcanic ash is intercalated in the Urado Formation. As shown in the geological cross-section (Fig. 3), the layer widely occurs underneath the plain between T.P. -25 and -2 meters at a thickness of 0 to 7 meters, and it is available as a marker bed (Katto and Nishi, 1971; Katto et al., 1984).

The layer is comprised of volcanic glass shards with grained silt to fine sand bearing shell fragments in the upper part (unit V).

VI. Sedimentary environments

Ogura Formation

Lower part: The lower part, that is the fine-grained sand to silt without sulfate minerals (unit MSf), as well as the fact that the beds are dozens of meters in thickness, may suggest that the beds themselves were formed as a lacustrine deposit.

Upper part: The upper part suggests that the sediment of the bed, described as unit B, was formed as a debris flow, evidenced by the matrix of supported large grains and poorly sorted fabric (e.g. Kohashi et al. 1980; Prothero and Schwab, 2004; Bridge and Demicco, 2008).

Kawauchi Formation

Lowermost part: The inverse grading layer of grained silt to sand size (unit If) found in the gravelly bed (unit GSf) shows evidence of flood sediment (Iseya, 1982; Masuda and Iseya, 1985). Thus, the subrounded to rounded gravel bed intercalated by an inverse grading bed is due to a fluvial deposit (e.g.; Miall, 1978; Reineck and Singh, 1980). The unit GSf suggests that the unit was formed at a braided river environment.

Lower part: Precipitated gypsum and sulfur on the weathered surface of the clay shows marine sediments (Itihara, 1960). So the accumulation of clay (unit Mm-st) suggests, for example, inner-bay sediment. The fining upward sequence near the bottom of the silt beds may be due to relative sea-level rising. The beds which mainly consist of massive sandy gravel containing subrounded to rounded pebbles (unit GSf) are a fluvial deposit as suggested by Katto et al. (1984). The unit GSf might form at a braided river as mentioned above.

Upper part: The dominant species of the fossil assemblage found in the silt beds (unit Mm-s) is the shallow sea-living mollusk *Kurosioia cingulifera*. Finally, the authors regard that the unit Mm-s is a shallow marine deposit as Katto et al. (1984) interpreted. The fining upward sequences near the bottom of the silt beds may due to a relative rise in sea level. The massive sandy gravelly beds that contain subrounded to rounded pebbles (unit GSf) as a fluvial deposit is, as mentioned above, formed at a braided river. Likewise, unit If is characterized as flood sediment at alluvial plain. Unit Gf and the intercalated unit GSf are interpreted as the channel or bar deposits of a braided river. Thus, our interpretation resembles the results of Katto et al. (1984).

Urado Formation

Lower part: The lowermost part of Urado Formation consists of pebbly silt (unit GMm), humus-bearing silt with burrows by animals (unit Mb), and grading, sandy clay (unit SMm). Units GMm, Mb, and SMm are interpreted as estuary, marsh, and delta front environments (Table 1). Nakao and Mimoto (2003) report a tidal flat association of mollusks from the silty beds of the lowermost layers of this part. The unit SMm is correlated with this silt. Thus the lowermost layers of the part are interpreted as incised valley fill (Okazaki and Masuda, 1992) during Holocene transgression. Nakao and Mimoto (2003) also report inner-bay muddy bottom associations from around T.P. -20 meters, the lower part of the Urado Formation. Throughout the lower part of the formation, however, sparse fragments of mollusk shells are found (unit Mm-st). Such occurrence of faunal fossil, e.g. *Theora fragilis*, living in the massive clay (unit Mm-st) of the muddy bottom of the inner-bay, suggests that the sedimentary environment is mid-inner bay.

Upper part: Firstly, accumulation of homogenous-looking clay (unit Mm-st) suggests that the beds were deposited as delta bottomset at mid-bay (Reineck and Singh, 1980). A subtidal zone-living molluskan shell, *Theora fragilis*, which was found in the clay, indicates an inner-bay environment. Also, the alternation of silt and very fine sand with occasional plant debris (unit MSm) corresponds with the features of delta front sediment (Reineck and Singh, 1980). Secondly, the uppermost layer of the part, intercalated massive sand beds containing gravel and shell fragments (unit SGm), suggests an estuary deposit such as a distributary mouth bar (Reineck and Singh, 1980). Thirdly, silt bed bearing the shells of mollusks living in intertidal to subtidal zones (unit Mm) may indicate the presence of interdistributary bay sediment. Generally speaking, then, these properties indicate that the upper part was formed during the Holocene high stand sea-level stage.

The sands in the lower part: Katto and Nishi (1971) and Katto et al.(1984) interpret that the sediment is a sand bar deposit, while Nishi(1992) regards the bed as inner-bay sand bar sediment. As described above, this bed is made up of sand and intercalated silt, often with the presence of a thin lamination of plant debris (unit SOm). These features correspond with those of a distributary mouth bar (Reineck and Singh, 1980). Considering the additional tidal flat association of mollusks in the layer, we can conclude that the unit is characterized as a subaqueous topset deposit, at the distributary mouth bar forming the "the Paleo-Kagami River."

The sands and sandy gravels along the Kokubu River: According to the referenced drilling-logs, the lower sands contain a subtidal molluskan association (Nakao and Mimoto, 2003). The sands, overlain alluvial sandy gravel (unit GSf), are an example of delta front sediment and resemble delta front sheet sands that have drifted laterally (e.g. Reineck and Singh, 1980). The clay is composed of non-marine mud overlying the alluvial unit GSf, and it is deposited at back marsh on the delta as topset beds. Thus, we can conclude that the delta front sandy deposit, which the channel deposit incorporated, had been progradated to the Urado Bay by the Kokubu River when "the Kokubugawa Delta" had been formed.

The sands and sandy gravels along the Kagami River: Katto and Nishi (1971) and Katto et al. (1984) interpret that this deposit was formed at a fluvial or distal fan. The sandy gravels have an elongated distribution along Kagami River. Examined minutely, the lower part, sandy sediment, is found throughout the river, hence the middle part, sandy gravel, distributes at the northern and the eastern foot of the Fudeyama Mountain. The lower sands normally bear a few faunal fossils (unit SOm), which are interpreted to be delta front sediment such as a subaqueous levee deposit (Reineck and Singh, 1980). Characteristics of the sandy sediment are similar to those of bar-finger sand (Fisk et al., 1954). For example, channel sediment (the upper part of the sandy gravels) is incorporated, grading laterally into a deltaic plain deposit (Reineck and Singh, 1980).

The upper sandy gravels consisting of subrounded to rounded gravel (unit GSf) are interpreted to be a fluvial deposit, such as a river channel (e.g. Miall, 1978; Reineck and Singh, 1980), as on the delta plain.

VII. Results of analysis and correlation of volcanic ash

AMS radiocarbon age

Table 2 shows results of radiocarbon dating obtained for the Kochi Plain. The radiocarbon ages of the mollusk shells found at T.P. -39.96 and -6.52 meters in the Sanbashi drilling-core dates to approximately 31,970 and 4,250 cal yrs BP, respectively.

Petrographical characteristics of volcanic ashes

Table 3 shows petrographical characteristics of volcanic ashes beneath the plain.

Volcanic ash in the lower part of Kawauchi Formation: Fine sand-sized vitritic volcanic ash is found between T.P. -59.8 and -59.1 meters in the Ogura drilling-core. The volcanic ash is mainly composed of clear glass shards with plagioclase, small amounts of quartz and hornblend crystals. The shapes of the glass shards are mainly classified into H and C types and, occasionally, T type. The refractive index (n) of the glass shards ranges from 1.498 to 1.503 (mode: 1.500～1.501).

On the basis of their similar lithological characteristics and stratigraphical relation, the volcanic ash can be correlated with Hiwaki tephra (Machida and Arai, 1992, 2003). The shape and refractive index of glass

Table 2 Results of AMS radiocarbon dating in the Kochi Plain

Drilling-site (abbr. in Fig.1)	Stratigraphy	Elevation [T.P.m]	Material	$\delta^{13}C$ [‰]	^{14}C date [yrs BP]	Conventional ^{14}C date [cal yrs BP]	Lab. no. Beta-	References
Harimaya-bashi-cho (NB)	up. Urado Fm.	- 5.2	*Paphia undulata*	-1.5	3,840±40	4,230±40	160060	Nakao and Mimoto (2003)
Sanbashi drilling-core (S)	up. Urado Fm.	- 6.5	*Ostrea* sp.	+0.8	3,830±40	4,250±40	228455	Present study
Harimaya-bashi-cho (NB)	up. Urado Fm.	- 9.2	*Paphia undulata*	-0.6	3,950±40	4,350±40	160069	Nakao and Mimoto (2003)
Harimaya-bashi-cho (NB)	up. Urado Fm.	-14.5	*Paphia undulata*	-1.5	5,950±40	6,340±40	160068	Nakao and Mimoto (2003)
Harimaya-bashi-cho (NB)	low. Urado Fm.	-20.5	*Paphia undulata*	-2.0	7,470±40	7,850±40	160067	Nakao and Mimoto (2003)
Harimaya-bashi-cho (NB)	low. Urado Fm.	-24.5	*Cerithidea djadjariensis*	-0.2	7,920±40	8,330±40	160060	Nakao and Mimoto (2003)
Sanbashi drilling-core (S)	up. Kawauchi Fm.	-39.9	*Kurosioida cingulifera*	-0.2	31,560±310	31,970±310	228456	Present study

Table 3 Petrographical characters of the volcanic ashes

Name	drilling-site and T.P.m	Glass shards: Shape (%) H C T Oth	Glass shards: Refractive Index (n) range	Glass shards: Refractive Index (n) mode	Mineral composition
Harimaya-basih Volcanic Ash	Ogura -20.25 Harimaya-bashi° -18～16	61.0 33.0 6.0 0 (H)	1.509-1.515 1.509-1.515	– –	Opx, Cpx ; Pl
K-Ah*		H > T	1.508-1.516	–	Opx>Cpx
Volcanic ash in low. Kawamuchi Fm.	Ogura -59.7～-59.1	H > C > T	1.498-1.503	1.500-1.501	Ho ; Pl, Q
Hiwaki*		H > T	1.498-1.502	–	Ho>Cpx; Q

Shape of glass shards (Yoshikawa, 1976) ; H: H-type shards, C: C-type shards, T: T-type shards, Oth: other, Shape (%) ; *: less than 1%
Minerals; Q: quartz, Pl: plagioclase, Ho: hornblends, Opx: orthopyroxenes, Cpx: clinopyroxenes
References; °: Nakao and Mimoto (2003), *: Machida and Arai (1992, 2003)

shards and mineral composition of Hiwaki resemble those of the volcanic glass (Table 3).

Harimaya-bashi Volcanic Ash Layer: This layer is a light brownish-gray, silt to fine sand-sized vitritic volcanic ash. This volcanic ash is mainly composed of clear glass shards but also includes brown-colored glass shards and some orthopyroxene, clinopyroxene, and plagioclase crystals. The shapes of glass shards are H, C and T types (H>C>T). The refractive index of glass shards ranges from 1.509 to 1.515 as one of the current authors, Kawamura, reports in Nakao and Mimoto (2003).

Petrographical characteristics, such as the refractive indexes and shapes of glass shards, resemble Kikai-Akahoya tephra (K-Ah, n=1.508～1.516; Machida and Arai, 1992, 2003). In addition, the Harimaya-bashi Volcanic Ash Layer is intercalated below and above the fossil-bearing bed. Two ^{14}C ages on the mollusks in the fossil-bearing bed indicates data of 8,330±40 and 7,850±40 cal yrs BP from the lower horizon of the volcanic ash and 6,340±40 cal yrs BP from the upper horizon at the Harimaya-bashi area (Table 2, Nakao and Mimoto, 2003).

Nakamura (1965) reports the volcanic ash layer intercalated in the Holocene deposits in Kochi prefecture. Mitsushio and Katto (1966) describe the mineral composition of the volcanic ash, and they suggest that the volcanic ash would be correlated with one of the Aso tephras. Considering the time of the eruption of K-Ah (7.3ka; Machida and Arai, 1992, 2003) and the radiocarbon ages below and above horizon of Har, the volcanic ash layer and K-Ah are closely correlated as mentioned by Yamanaka (1983).

VIII. Correlation

Radiocarbon ages and the correlation of volcanic ashes can provide a rough estimate of the age of the formations.

Ogura Formation

As we discuss below, the lower part of Kawauchi Formation that overlays the Ogura Formation began to form before 580 to 570 ka, so we estimate that the Ogura Formation had been deposited before 580ka. Thus, this formation corresponds to the Lower-Middle Pleistocene.

Kawauchi Formation

The volcanic ash in the lower silt beds of this part can be correlated with Hiwaki tephra, which erupted between 580 and 570 ka (Machida and Arai, 2003). This suggests that the lower silt beds began to be deposited in the Middle Pleistocene.

Considering the inferred age of the lower silt beds of this part as well as the radiocarbon ages of the upper part of the Kawauchi Formation as mentioned above, the gravelly beds of the lower part were formed between 580 to 570ka and 38ka.

Upper part: As shown in table 2, at T.P. -39.9 meters of the Sanbashi drilling-core, ^{14}C age of the shells is 31,970±310 cal yrs BP. Katto and Nishi (1984) report that the radiocarbon age of humus from the uppermost beds of the upper part of Kawauchi Formation at Yoshida-cho, Kochi city, is >37,800 yrs BP (Nakamura, 1969). Accordingly, the marine silt beds of the upper part of this formation can be MIS 3 (MIS: marine isotope stage, Imbrie et al., 1984). Referring to pollen analysis by Yamanaka (1983), pollen from both the V and the VI pollen zones, can be correlated with the silt beds of the upper part of Kawauchi Formation; so, the silt beds correspond to the Mindel-Riss interglacial stage (around 300ka, Kikuchi, 1996). In another paper, Nakamura and Yamanaka (1992) re-examined the pollen zones, showing that the zone can be correlated with the Riss-Würm interglacial stage (around 150-100ka, Kikuchi, 1996). Thus, the correlation on this horizon differs from palynological study and radiocarbon dating. Further study on the Pleistocene pollen analysis is required, as Yamanaka suggests (Yamanaka, 1983).

Urado Formation

As shown in table 2, radiocarbon ages of the shells are around 8,330 and 7,850 cal yrs BP (Nakao and Mimoto, 2003). The lower part underlies Harimaya-bashi Volcanic Ash Layer that is correlated with K-Ah. According to Machida and Arai (1992, 2003), K-Ah erupted at approximately 7.3ka. This leads us to conclude that the lower part can be correlated to the early Holocene.

Nakao and Mimoto (2003) report that marine mollusks whose radiocarbon age is 6,340±40 cal yrs BP are found at T.P. -14.5 meters from the lower beds of the upper part of Urado Formation (Loc. NB in Figs. 1 and 3). At T.P. -6.51 meters of Sanbashi drilling-core, which is in the upper part of the Urado Formation, the radiocarbon age of the shells is around 4,230±40 cal yrs BP. Considering these radiocarbon ages, the upper part was formed between 6.3ka and 4.2ka in the term of the high stand of the Holocene transgression.

The sands and gravels along the Kokubu River, covering the Harimaya-bashi Volcanic Ash Layer (Fig. 3), had been deposited around 7.3 ka. In the meantime, the sandy gravels along Kagami River overlying mud bed of the upper part (6.3ka to 4.2ka), the Kagami River delta has progradated since 4.2ka.

IX. Conclusions

The stratigraphical division of subsurface geology in the central part of the Kochi Plain is as follows: the Ogura Formation (the lower and the upper parts), the Kawauchi Formation (the lowermost, the lower and the upper parts), and the Holocene Urado Formation (the lower and the upper parts).

Two volcanic ashes, found in the lower part of the Kawauchi Formation and in the Harimaya-bashi Volcanic Ash Layer in the Urado Formation, are described and correlated with the Hiwaki and Kikai-Akahoya tephras, respectively.

The Ogura Formation had been deposited before 580ka. The lower part was formed as lacustrine deposit, and the upper part was formed by debris flows.

The Pleistocene sediments, the lowest part of the Kawauchi Formation, were deposited before 580ka, which occurred at the fluvial plain. Then the lower part was formed between 580ka and 38ka. Relative rises in sea level caused the lower part to be deposited as inner-bay sediment. A sandy gravel fluvial deposit followed.

The upper part of the Kawauchi Formation had begun to form as silt beds in shallow marine water caused by a relative rise in sea level after 38ka. Then, the gravelly beds of the upper part of the formation were deposited between 32ka and 8.3ka as a fluvial deposit.

Concerning the Urado Formation, our conclusions are the following. The lowermost layers of the formation had begun to form in the drowned valley before 8.3ka. The following muds were deposited at least until 4.2ka: at the inner-bay prodelta as bottomset, next at the delta front as foreset beds, and then at the subaqueous delta as topset beds. The sands in the lower part were also formed between 8.3ka and 7.3ka as distributary mouth bar deposits and as channels of the Paleo-Kagami River. The sands and sandy gravels along the Kokubu River have been formed as topset beds of the Kokubugawa delta system since 7.3ka, progradating to the Urado Bay at the delta front and the delta plain as delta mass. The sands and sandy gravels along the Kagami River have been deposited by the Kagamigawa delta system since 4.2ka in the same way as the Kokubu River. Finally, in the area between the Kagamigawa and Kokubugawa Deltas, an interdistributary bay has been left where the muds of the Urado Formation have been deposited.

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