Quaternary Tectono-sedimentary History of the central Honshu area, Japanese Islands

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Abstract. Quaternary crustal movement of the Japanese islands caused the rapid uplift of mountain ranges and the relative subsidence of coastal and inland basins. Chronostratigraphic and facies analyses of Pliocene to Quaternary sediments of 33 areas in the central Honshu reveals that the Tectono-sedimentary History developed in the following four stages. 1) From the Pliocene to the early Early Pleistocene, inland basins formed and turbidite accumulated in deep sea basins. 2) From the late Early Pleistocene to the early Middle Pleistocene, the uplift of the island arc occurred, and the subsiding areas of the inland basins expanded and differentiated, while in marine areas the slopes were buried by fan-deltas as the fan area expanded. 3) In the late Middle Pleistocene, the crustal uplift of the island arc was accelerated, and at the same time sediments accumulated in coastal basins in correspondence with sea-level changes. 4) Since the Late Pleistocene, terraces were formed due to falling sea-level and crustal uplift. It is considered that these characteristics of such Quaternary crustal movements were formed through large-scale uplift of island arc crust and sea-level change. Especially after the late Middle Pleistocene (0.43 Ma), it is possible that the current topography was formed by a new large uplift movement and sea-level rise of about 1,000 m. The formation of the island arc by large-scale uplift and sea-level rise cannot be explained by the plate subduction or collision.

Key Word: Pleistocene, Tectono-sedimentary History, large-scale uplift, sea-level rise, Neotectonic Movement, MIS.

Introduction

Matsuda and Kinugasa (1988) described the characteristics of the Quaternary crustal movement in the Japanese Islands as follows: the present major mountain ranges were uplifted rapidly and the land area expanded with the development of gravelly sediments around them, while subsidence occurred in coastal and inland areas, and fault movement, especially in central Honshu, started in the late Early Pleistocene (Calabrian), causing the land mass to block. In the central part of Honshu, the fault movement started in the latter half of the Early Pleistocene. Matsuda and Kinugasa (1988) proposed that the Quaternary is a special period (age of collision) that differs from the earlier Neogene in the history of plate motions, because the Japanese Islands were generally compressed in an east-west (or west-northwest to east-southeast) direction during the Quaternary and such areas were located at and near the convergence-collision boundary of the plates around Japan.

Japanese Islands during the Quaternary, Hujita (1968, 1983) called the large-scale uplift of the island arc after the Middle Pleistocene the Rokko Movement, and reconstructed that huge coastal fans were formed by a large amount of coarse-grained debris supplied from the rapidly rising mountains and sea-level rise at that time. Fujita (1970, 1982) proposed that the Quaternary crustal movement was a new movement distinct from the earlier the Green-tuff Movement and called the island Arc Disturbance. This uplift and tilting movements that began in the Pliocene and reached their peak in the Middle Pleistocene. Hoshino (1983, 1991) proposed that the Late Miocene and Early Pleistocene sea-levels were at 2,000 m and 1,000 m in present depth, respectively, and that the present topography was formed by large-scale uplift of the crust including the seafloor and sea-

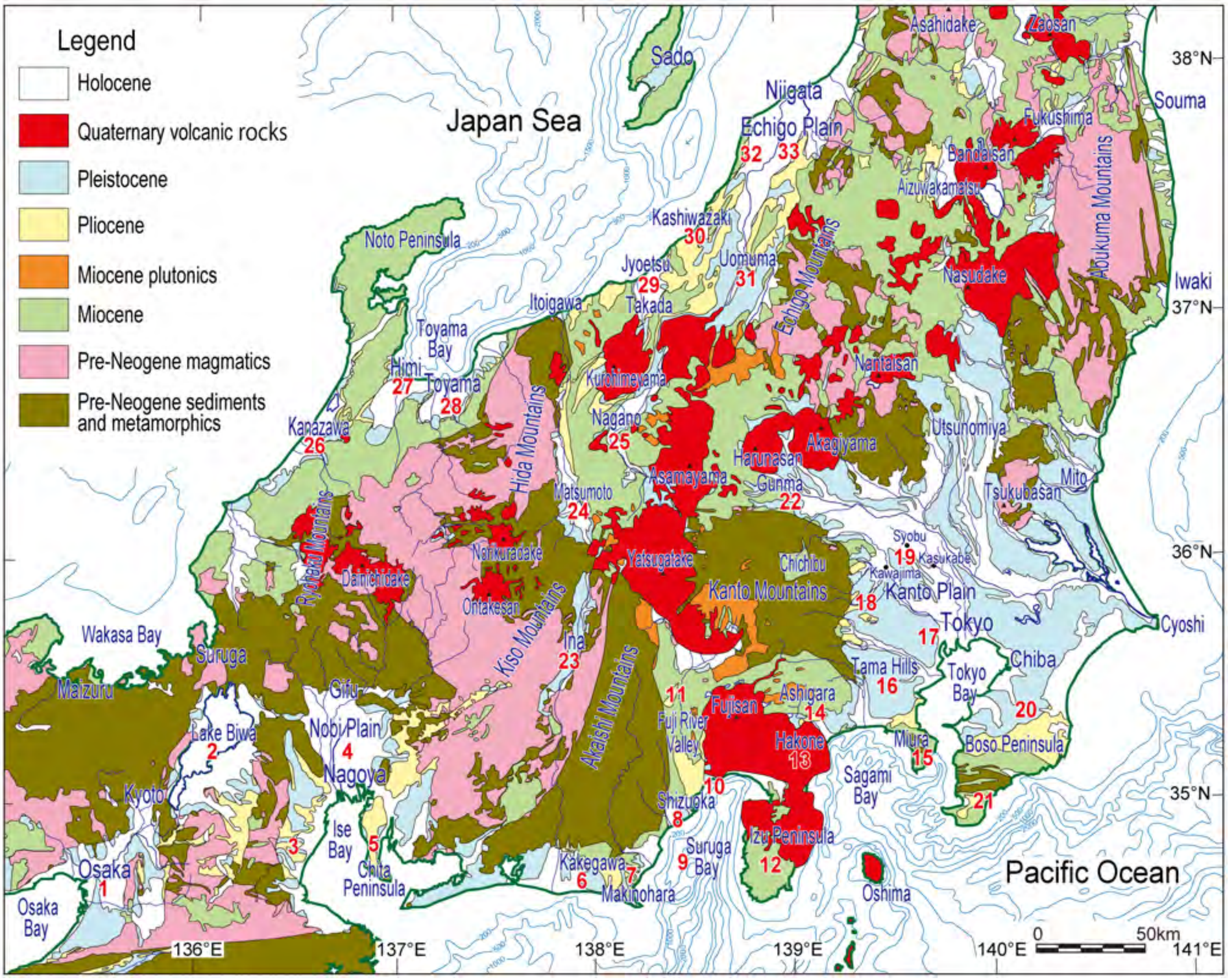

Fig. 1 Geological map of central Honshu showing the distribution of Pliocene and Pleistocene series (after Shiba and Committee of the science symposium 2020). Numbers indicate the locations of the stratigraphic columns in Fig. 2.

level rise, and called the post-Pliocene changes the Neotectonic Movement.

The topographic undulations in the central part of Honshu are the largest in the Japanese archipelago, consisting of large undulating landforms of over 3,000 m, which were formed in the latest period (Kaizuka, 1989). Such large-scale Quaternary uplift is the very tectonics of the present-day island arc-trench system, which seems to have been very different from the tectonics up to the Neogene. Although these concepts are widely shared, the reality of when and how Quaternary uplift movements began and progressed is not always clear.

The author has studied the upper Cenozoic series in the Pacific region of central Japan and the southern Fossa Magna region for many years. Based on the age, paleoenvironment, and depositional process of these series, the author has also reconstructed the uplift process of the Akaishi Mountains, the Kanto Mountains, and the Tanzawa Mountains with high chronological accuracy (Shiba, 1991, 2017a, 2017b). Recently, the depositional ages and details of depositional environments of sediments in inland basins, coastal plains, and submarine sedimentary basins in central Honshu and surrounding areas (Fig. 1) have also been clarified. If these findings can be synthesized, it will be possible to elucidate the entire uplift process in the Great Rise Mountains of central Honshu and surrounding areas with a high degree of chronological accuracy.

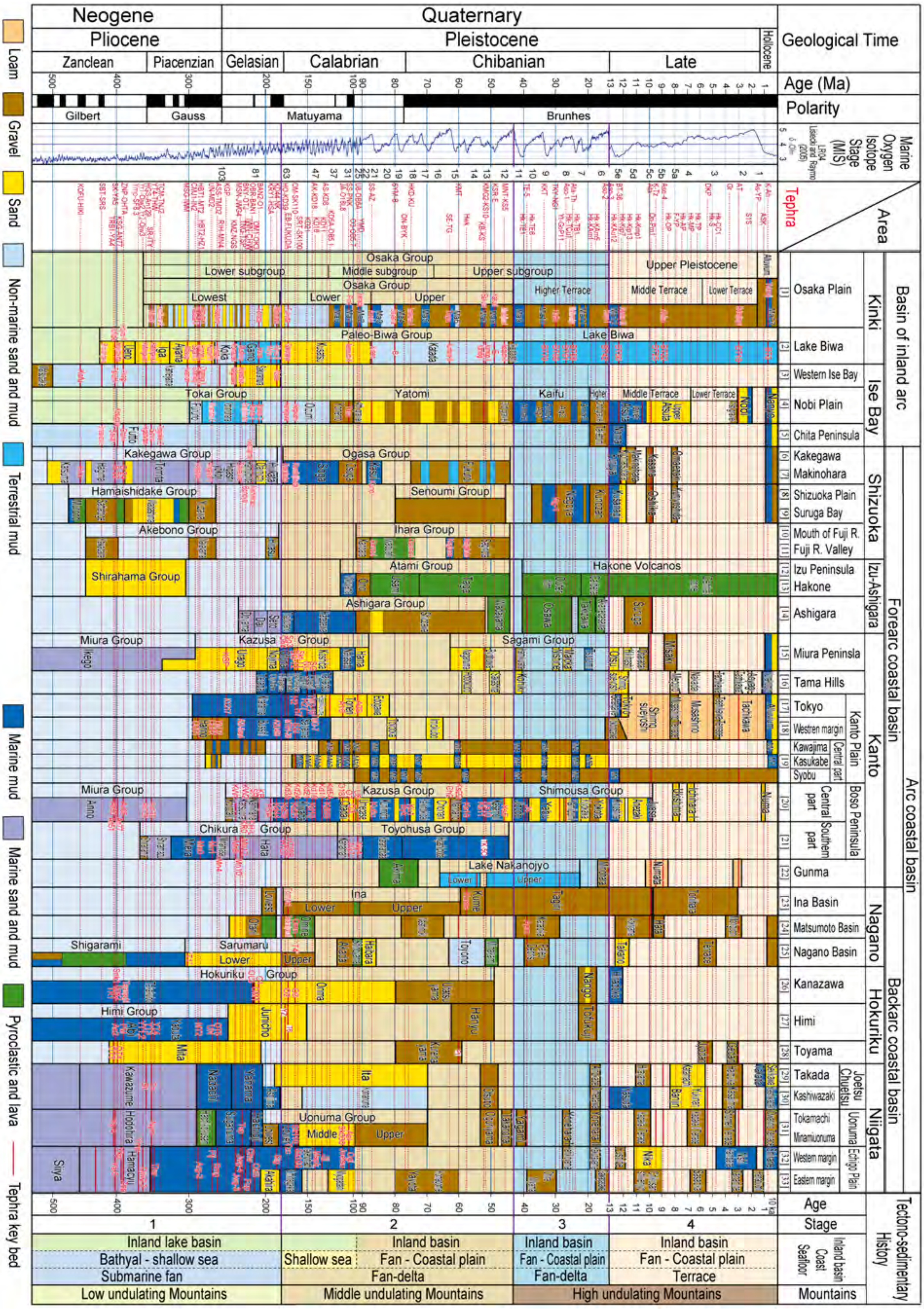

Fig. 2 Stratigraphic correlation and the stages of Tectono-sedimentary History of Pliocene to Holocene sediments of 33 areas in central Japan (modified after Shiba and Committee of the science symposium, 2020; Shiba, 2021a). Numbers in Tectono-sedimentary History show stages (1: Pliocene–early Early Pleistocene, 2: late Early Pleistocene–early Middle Pleistocene, 3: late Middle Pleistocene, and 4: Late Pleistocene–Holocene). “Formation” in the Formation name is omitted.

The purpose of this paper is to analyze the depositional processes of the Pliocene to Quaternary series based on the stratigraphic correlation diagrams (Fig. 2) of the various areas in reconstruct the uplift process of the central Honshu mountains recorded in the deposits around these mountains, according to Shiba (2021a). The four developmental stages, the structural position of each region within the island arc, the main depositional environments, and the undulating characteristics of the mountains are shown in the Tectono-sedimentary History column of Fig. 2.

Pliocene to Quaternary series in various regions of central Honshu

Kinki region

The Osaka Group is distributed in the hills around the Osaka Plain (area number [1] in Figs. 1 and 2, and the same applies hereafter), and is composed of gravel, sand, silt, and clay beds with marine clay beds (Ma number) in between (Yoshikawa, 2012). The Osaka Group is also distributed in the basement of the Osaka Plain. The post-Pliocene strata beneath the Osaka Plain consist of 1,500 m thick clay, silt, sand, and gravel beds unconformably overlying basement rocks, and are divided into freshwater beds in the lower, and marine and freshwater beds in the upper (Yoshikawa and Mitamura, 1999). The stratigraphy of marine clay beds interbedded with sedimentary layers are correlated with the marine oxygen isotope stages (MIS) (Yoshikawa and Mitamura, 1999).

Yoshikawa (2012) found that the Ma3 (MIS 21), Ma6 (MIS 15.5), and Ma9 (MIS 11) sedimentation periods were particularly warm during the high sea-level period when a large amount of open ocean water flowed into the Osaka Plain, and that these periods are also important in relation to global climate change. The Ma9 bed was formed by the most extensive transgression during the Middle Pleistocene, and corresponds to the warmest and highest sea-level interglacial (Shackleton, 1987), which coincides with the Mid-Brunhes Event (MBE) (EPICA Community Members, 2004), a period of climate system transformation (Yoshikawa, 2012).

Hujita (1976) divided the development process of mountains and basins in the Kinki region into three periods: the first period up to about 2 Ma (million years ago) was Period of basin occurrence, the second period from then to about the Ma9 bed of the Osaka Group was Period of basin subsidence and expansion to movement and differentiation, and the third period after the Ma9 bed was Period of mountain uplift and terrace formation.

The Paleo-Biwa Group is distributed around Lake Biwa [2], and the Lake Biwa Formation is distributed on the bottom of Lake Biwa (Yoshikawa and Yamazaki, 1998). The Paleo-Biwa Basin, in which the Paleo-Biwa Group was deposited, originated in the Iga and Ueno Basins around the Pliocene, and later the lake basin migrated northward to become the present Lake Biwa (Kawabe, 1981). According to Kawabe (1981), the cause of the movement was a stepwise subsidence and tilting of six blocks (each block is 3–6 km^2) of the Paleo-Biwa Group during deposition, caused by mutually orthogonal faults and flexure in the NNW-SSE and ENE-WSW directions.

Looking at the movement of the Paleo-Biwa Basin, the Gamo Sedimentary Basin, which occurred around 2 Ma, moved and expanded northward and westward more rapidly than the sedimentary basins of the Ueno to Koga Formations (Hayashi and Paleo-Biwa Lake Research Group, 1981). The largest depositional area is located in the northern part of the Gamo Sedimentary Basin, and during the depositional period of the uppermost part of the Gamo Formation, the water retention area was reduced by the supply of coarse-grained sediments mainly composed of Koto rhyolite gravel from the mountains on the northern side (Kawabe, 1983).

According to Kumon (1999), the basal age of the Lake Biwa Formation (Clay beds) at the bottom of Lake Biwa is estimated to be about 400 ka (thousand years ago). Since then, the sedimentation rate of Lake Biwa and the surrounding Omi Basin has varied considerably depending on the location, and the current changes in Lake Biwa and the Omi Basin are thought to reflect new changes that began about 400 ka. Satoguchi (2010) also states that sedimentation in the northern area of Lake Biwa became more active after 600–450 ka, and the central flexure that stretched from north to south in the center of the lake disappeared at least by 440 ka.

As described above, in the Kinki area [1–2], (1) the sedimentary basins were generated in the Pliocene, (2) the sedimentary basins began to move and expand about 2 Ma with the start of new subsidence due to land mass movement, and marine clay beds began to be deposited in the Osaka Plain. Then, (3) about 400 ka, rapid land mass uplift of the mountains began, forming the framework of the present sedimentary basin, followed by a period of mountain ascent and terrace formation, and the marine clay beds corresponding to MIS were periodically deposited in the coastal plain. After 130 ka, the middle and lower terraces were formed almost in line with the present topographic layout (see Fig. 2).

Ise Bay Area

The Pliocene to Pleistocene series are distributed in the west coast of Ise Bay [3], the Nobi Plain [4], and the Chita Peninsula [5], the Pleistocene to Holocene series are distributed in the basement of the Nobi Plain [4], and the middle to upper Pleistocene series are distributed in the Atsumi Peninsula to Hamamatsu area.

Yoshida (1990) describes the paleogeographic evolution of the Tokai Basin, where the Tokai Group was deposited, as follows. At the beginning of the Pliocene, an uplifted zone was generated in the direction connecting the southern part of the Chita Peninsula and the southern part of the western shore of Ise Bay, and Lake Tokai was formed in the subsidence area on the north side of the uplifted zone, and the sand and gravel sediments were supplied from the southern uplifted zone throughout the Pliocene. At the end of the Pliocene, the sediments were predominantly supplied from the volcanic rocks and Nobi rhyolites in the eastern to northeastern part of the Lake Tokai Basin. In the first half of the Early Pleistocene, the depositional area of the lake basin moved further northwest to west, and the sediments were newly supplied from the Yoro Mountains and the Suzuka Mountains to the north and west. In the latter half of the Early Pleistocene, the depositional area moved to the northwestern margin of the lake basin, and the Yoneno Formation, consisting of coarse-grained sediments derived from the Suzuka Mountains, finally accumulated in the depositional area at the eastern foot of the Suzuka Mountains.

After the disappearance of the Tokai Lake Basin, which existed from the Pliocene to the Early Pleistocene, the fault landmass movement became active in the area around Ise Bay, and three distinct regions were distinguished: a mountainous mass in an ascending region, a hilly region in a subuplifting region, and a basin in a subsiding region (Kuwahara, 1980). Then, in the basin of the subduction area, the Nobi Tilting Basin was formed in which the strata after the Middle Pleistocene became thicker and deeper to the west (Kuwahara, 1968). However, the lower part of the Tokai Group equivalent formation and lower strata in the basin basement are rather thick to the east, and have not been affected by tectonic movements since the Middle Pleistocene, suggesting that the tectonic movements started from the depositional stage of the Yoneno Formation at the top of the Tokai Group equivalent formation (Makinouchi, 2005). In other words, the lower Pleistocene around Ise Bay inherited the Neogene sedimentary environment, while the strata after the Middle Pleistocene were formed in a new sedimentary basin, and there is a clear difference between the two (Makinouchi, 2005).

According to Kuwahara (1980), the uplift of the northern part of the Suzuka Mountains is reflected in the deposition of the Yoneno Formation, which consists of thick fan gravel beds, and the uplift movement of the basement mountains around Ise Bay was already seen in its budding in the late Early Pleistocene. Kuwabara (1980) stated that the marine deposits are also recognized in the Yatomi Formation, but the prominent marine clay beds are interspersed from the base of the Kaifu Formation. According to Sugai et al. (1999), the deposition of the Nobi Plain over the past 900,000 years can be compared to that of the Osaka and Kanto Plains in terms of MIS.

As described above, in the area around Ise Bay [3–5], (1) the Tokai Lake Basin occurred during the Pliocene, and the sedimentary basin moved northwest during the first half of the Early Pleistocene. (2) The Tokai Lake Basin disappeared in the latter half of the Early Pleistocene due to the supply of coarse-grained sediments from the Suzuka Mountains on the west side, followed by the formation of the Nobi Tilting Basin in the area around Ise Bay due to active faulting landmass movement. (3) Since about 400 ka, a prominent marine clay beds were deposited in the Nobi Tilting Basin, and the marine clay beds were periodically deposited reflecting sea-level changes corresponding to MIS. (4) After 130 ka, the Atsuta and Nobi Formations were deposited, and at the same time, the middle and lower terraces were formed (see Fig. 2).

Shizuoka area

In the Kakegawa area [6], the Pliocene to lower Pleistocene Kakegawa Group and the upper lower Pleistocene to lower middle Pleistocene Ogasa Group are distributed, and in the Makinohara Plateau [7], inlet to fan deposits and marine terrace deposits of the upper Pleistocene are distributed (Shiba, 2017a, 2017b). The Kakegawa Group consists mainly of submarine fan deposits of turbidite, and when the Akaishi Mountains began to uplift on a large-scale about 1.8 Ma, the entire area was also uplifted, and the gravelly fan-delta was advanced and expanded by coarse-grained sediments supplied from the Akaishi Mountains to fill the seafloor and deposit the Ogasa Group (Shiba, 2017a, 2017b).

Regarding the depositional process of the Ogasa Group, Shiba (2017a, 2017b) states the following: The uplift that began about 1.8 Ma brought land north of the Ogasa Hills, and the entire land shelf slope in the eastern part of the Ogasa Hills also became a shallow sea. Gravels from the Tenryu River buried the northwest-southeast channel 1.2–1.0 Ma, and subsequently large amounts of gravelly sediments from the Oi River formed a large fan-delta foreset along the eastern foot of the Ogasa Hills, rapidly burying the seafloor above the shelf slope from north to south. Then, between 900–780 ka, a broad shallow sea intruded from the Ogasa Hills to the Tenryu River area on the west side, followed by the expansion of the river fan to the south until about 400 ka.

On the Makinohara Plateau, the Late Pleistocene inlets mud beds are distributed above a basement composed of upper Miocene and Pliocene, overlying beach sand and fan gravel deposits, and several marine terrace deposits are distributed above it in a staircase-like pattern toward the coast (Shiba, 2017a, 2017b).

In the Shizuoka Plain [8], the marine Pliocene Hamashidake Group occurs in the northeastern mountains, and the middle to upper Pleistocene occurs in the Udo Hills in the southern part of the Shizuoka Plain. The Hamashidake Group consists mainly of conglomerates and sandstones deposited in submarine channels and submarine fans (Shiba, 1991, 2017a, 2017b). The Pleistocene that constitutes the Udo Hills consists of gravelly fan-delta deposits since about 300 ka, and there were at least six sea-level rise and gravelly fan-delta development during the depositional period of the Negoya to Kusanagi Formations, and each sea-level rise period can be contrasted with MIS (Shiba et al., 2012; Shiba, 2017a, 2017b) (Fig. 3).

On the seafloor of western Suruga Bay [9], there is an uplifted topographic feature called the

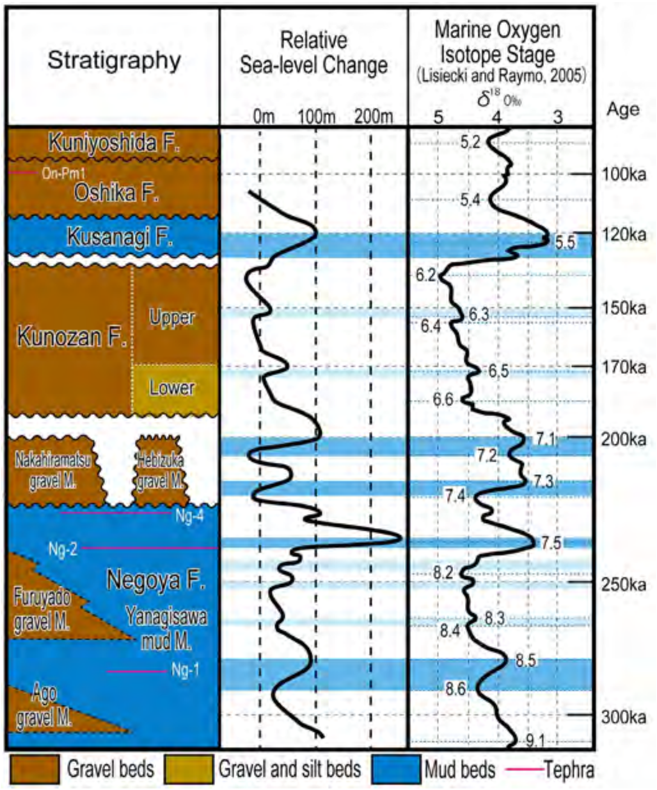

Fig. 3 Sea-level change curve for the strata from the Negoya Formation to Kuniyoshida Formation in Udo Hill (modified after Shiba 2017a). Numbers on marine oxygen isotope curve are MIS. ka: a thousand years. F, Formation; M, Member.

Senoumi Bank with a top depth shallower than 100 m, separated by a basin with a maximum depth of about 900 m from the shelf slope. The Senoumi Bank consists of the Senoumi Group (Okamura et al., 1999), which consists of fan-delta deposits such as gravel beds of the lower to middle Pleistocene, and the gravels of the gravel beds are derived from the Abe River (Shiba et al., 1991a). An erosional unconformity between the Pliocene and Pleistocene has been identified on the continental slope of the western coast of the Izu Peninsula (Koyama et al., 1992; Okamura et al., 1999).

The lower to middle Pleistocene Ihara Group distributed at the mouth of the Fuji River [10] consists of gravelly fan-delta deposits, interbedded with volcanic rocks (Sugiyama and Shimokawa, 1982; Shiba, 1991, 2017a, 2017b). The Ihara Group are composed of the Kanbara, Iwabuchi, and Saginota Formations in ascending order, the Kanbara Formation consists of gravel beds deposited on the foreset of a fan-delta about 1 Ma, the Iwabuchi Formation consists mainly of volcanic rocks formed by onshore volcanic activities, and the Saginota Formation consists of inner bay to fan deposits (Shiba, 2017a, 2017b). The depositional process of the Ihara Group is similar to that of the Ogasa Group of the same stratigraphic unit, except for the volcanic activity of the Iwabuchi Formation. The gravels of the Ihara Group are mainly supplied by the Fuji River from the Akaishi Mountains and the Misaka Mountains, while the gravels of the northeastern part of the formation are derived from the Tanzawa Mountains (Shiba et al., 1991b).

In the Fuji River Valley [11], the Fujikawa Group, consisting of the Late Miocene submarine fan deposits and submarine volcanic deposits, is unconformably covered by the Akebono Group, consisting of Pliocene gravelly fan-delta deposits in the northwest part of the valley (Shiba et al., 2013).

The upper Miocene to Pleistocene basement of the Fuji River Valley and the northern part of the Shizuoka Plain is composed of basement blocks separated by NNW-SSE, NW-SE, and NE-SW oriented faults, and the strata were deposited in basins between elevations formed by the individual uplifting, and the deposited strata formed fold structures simultaneously with deposition by the elevation of basement blocks (Shiba, 1991). The uplift of the basement block began during the Late Miocene in conjunction with the uplift of the Kanto Mountains on the northeast side. During the Pliocene, the Misaka Mountains in the northeastern part of the area appeared on land, followed by the uplift of the Akaishi Mountains in the western part, and during the Middle Pleistocene, the Akaishi Mountains side rose rapidly, forming a north-south, west-trending, thrust fault group (Shiba, 1991).

As described above, in the Shizuoka area [6–11], (1) the gravelly fan-deltas and submarine fans developed in the Pliocene in the Fuji River Valley, and submarine fans developed in the Kakegawa area until the Early Pleistocene. The Akaishi Mountains were uplifted on a large-scale from about 1.8 Ma to 400 ka, and the gravelly sediments supplied from the uplift buried the shelf slope of the Enshu-nada Sea to the west coast of Suruga Bay (Pacific coast of Shizuoka Prefecture), forming a large fan. (3) After about 300 ka, gravelly fan-deltas were formed in the coastal area due to uplift of the hinterland and sea-level rise, and (4) during the Late Pleistocene, marine terraces were formed due to sea-level rise followed by sea-level fall.

Izu-Ashigara area

The Izu Peninsula [12] was in a terrestrial erosion zone during the Late Pliocene, and the Atami Group was deposited in its northern part during the Early to Middle Pleistocene (Koyama, 1986). The Yokoyama Siltstone and Ono Conglomerate Formations at the base of the Atami Group are fan-delta deposits that buried the continental slope, and are correlated with the Hatasawa and Shiozawa Formations of the Ashigara Group [14]. The main part of the Atami Group consists of terrestrial ejecta from the Usami and Taga volcanos in the late Early Pleistocene to early Middle Pleistocene, and the activity of both volcanos continued as the Hakone volcano [13] after about 400 ka (Nagai and Takahashi, 2008).

The Ashigara Group of Pleistocene age is distributed in the Ashigara area [14] on the north to northeast side of Hakone volcano (Ashigara Research Group, 1986). The Ashigara Group consists of sand and mud beds deposited on a submarine fan up to the Seto Formation, but from the Hatasawa Formation, the sediments become fan-delta gravels (Imanaga, 1999; Ito, 1985). According to Imanaga (1999), the gravels in the lower part of the Ashigara Group are derived from the Kanto Mountains and the Tanzawa Mountains, but the gravels of the Shiozawa Formation are all from the Tanzawa Mountains, suggesting that the Tanzawa Mountains was uplifted rapidly during the deposition of the Shiozawa Formation. The Shiozawa Formation is a southeast-trending fan-delta deposit on the frontal margin of the Tanzawa Mountains, but it now dips steeply to the northwest, indicating that the southeast side was uplifted to a large extent after the Ashigara Group was deposited.

As described above, in the Izu-Ashigara area [12–14], (1) the Izu Peninsula was in the terrestrial erosion zone during the Late Pliocene, but a submarine fan developed in the Ashigara area to the northern part of the Izu Peninsula during the Early Pleistocene. In the late Early Pleistocene, a gravelly fan-delta developed above the submarine fan due to the rapid rise of the Tanzawa Mountains, and the Taga volcanic activity began on land in the northern Izu Peninsula shortly after the Tanzawa Mountains. The volcanic activity continued thereafter, and (3) the outer rim and caldera of Hakone volcano were formed in the late Middle Pleistocene, and (4) the central crater hill was formed in the Late Pleistocene (see Fig. 2).

Kanto region

In the southern part of the Kanto area, the Tanzawa-Mineoka Uplift Zone (Koike, 1957) extends from Hayama on the Miura Peninsula to Kamogawa on the southern Boso Peninsula, and it marks the southern margin of the Kanto Sedimentary Basin. To the north of this uplift zone, the Miura Group of Middle Miocene to Pliocene age and the Pleistocene Kazusa and Shimousa Groups are successively overlain toward the center of the Kanto Sedimentary Basin (Kodama et al., 1986). The Miura, Kazusa, and Shimousa Groups and their equivalents are composed of Pliocene-Pleistocene series in the area from the Miura Peninsula [15], to the Tama Hills [16], Tokyo [17], the western margin of the Kanto Plain [18], the central part of Kanto Plain [19], and the central [20] and southern [21] part of the Boso Peninsula and its basement. The areas that became land after the late Middle Pleistocene were successively covered by tephra layers derived from the Hakone and Fuji volcanoes, the so-called Kanto Loam Formation.

The Kazusa Group has a thickness of 3,000 m, and the turbidite sediments show a repetition of predominantly sandy and muddy facies. Horizontally the sediments become coarser grained toward the southwest, and a northeastward paleocurrent direction generally prevails (Hirayama and Nakajima, 1977). The lower part of the Early Pleistocene Kazusa Group is characterized by deep-water basin floor, submarine fan, and lower slope deposits in the northeast area, and upper slope to continental shelf deposits in the southwest area (Katsura, 1984). In the lower part of the Kazusa Group, the lithology shows a transgressive pattern from the base to the Kd18 tephra horizon and a regressive pattern above the Kd18 tephra (Ito and Katsura, 1993).

The sedimentary field of the Kazusa Group in the eastern part of the Musashino Plateau in the western part of the Kanto Plain was pelagic to semi-bathyal at 1.7–1.5 Ma, but shifted to shallow-water at about 1.3 Ma (Sato et al., 2004). The equivalent layers of the Kazusa and Shimousa Groups are 600 m thick beneath the central Kanto Plain, and the Kazusa Group equivalent layers were bisected around 1.6 Ma by an unconformity with a sedimentary gap of 500,000 to 1 million years, after which the land and marine formations formed repeatedly and continuously, reflecting sea-level changes corresponding to MIS (Naya et al., 2017). The upper part of the Kazusa Group (ca. 720–450 ka) consists of six sedimentary sequences with a period of ca. 20,000 to 90,000 years corresponding to MIS, including northeastward advancing shelf-to-shelf slope deposits and some coastal deposits (Ito, 1992).

Kaizuka (1987) pointed out that the central part of the Kanto Plain is the present-day sedimentation center in the Kanto Plain based on the elevation distribution of topographic surfaces formed during the last interglacial period, and that this area has been continuously sedimented throughout the Quaternary period. In the central part of the Kanto Plain, Hirakoso (2008) pointed out that the sedimentation center moved to the lowland of the middle reaches of the Tone River in the northwest about 430 ka.

Sugai et al. (2013) obtained an altitude age curve based on glacial sea-level change and local base-level change (relative height to glacial sea-level) in various areas of the Kanto Plain. The results show that around MIS 11, when the transgression reached its maximum, the tectonic movement began to shift from subsidence to uplift in the Miura Peninsula to the eastern Kanto Plain, and this shift extended from the central to the northwestern Kanto Plain with time. Furthermore, Sugai et al. (2013) stated that the Kanto Plain became Period of repeated shallow seafloor and lowlands in response to the repetition of interglacial and glacial periods after MIS 12/11 and evolved into Period of Hilly terrain after MIS 5/4.

In the western margin of the Kanto Plain, the Kanto Mountains were actively uplifted during the depositional period of the upper Hanno Gravel Formation, and fans were widely formed at the locations of various hills on the western margin of the Kanto Plain (Syoda et al., 2005). In the Gunma area [22], northwest of the Kanto Plain, the lake sediments were deposited in the Nakanojo and Numata Basins during the Middle and Late Pleistocene (Arai, 1986; Takemoto, 1986).

As described above, in the Kanto area [15–22], (1) a submarine fan developed on the Miura and Boso Peninsulas during the Pliocene, the Kanto Plain in the north was terrestrial, and a shallow-water area extended along the western margin of the Kanto Plain in the Early Pleistocene. In the late Early Pleistocene to early Middle Pleistocene, the sea area changed from a shallow-water to a coastal plain, and especially in the central part of the Kanto Plain, land and marine strata were formed repeatedly and successively, reflecting sea-level changes corresponding to MIS, including the later period. (3) After 430 ka, sedimentation was repeated on the shallow seafloor and coastal plain as in the preceding period, but the terrestrialization progressed gradually from the Boso and Miura Peninsula area and the eastern part of the plain to the central to northwestern part of the plain, and the terrestrialized area was covered by the Kanto Loam Formation. (4) After the Late Pleistocene, the middle and low terraces were formed successively (see Fig. 2).

Nagano area

In the Ina Basin of Nagano Prefecture [23] at the west of the Akaishi Mountains, the fan gravels such as the Ina and Kume Formations of Pleistocene age are distributed (Matsushima, 1995; Suganuma et al., 2003). Suganuma et al. (2003) revealed that uplift of the Akaishi Mountains began 1.4 to 1.0 Ma and that uplift of the Kiso Mountains began after about 600 ka, based on a comparison of the widespread tephra layers between the two. Moriyama and Mitsuno (1989) called the Ina-Akaishi Tectonic Movement the crustal movement since the late Early Pleistocene, which formed an eastward trending topography with a specific height of 2,500 m in the Ina Valley-Akaishi Mountains.

The Matsumoto Basin [24] on the western margin of the northern Fossa Magna is composed of the lower terrestrial Pleistocene of the Omine Belt, which is fault-tied to the marine Neogene, and the Middle Pleistocene to Holocene, which comprises many topographic surfaces in and around the Matsumoto Basin (Yano et al., 2020). Takeshita et al. (2007) estimated that the Nashinoki Gravel Member was deposited between 780 and 640 ka, reflecting the uplift of the Hida Mountains, based on a comparison of tephra layers intercalated with the Nashinoki Gravel Member, which forms the oldest topographic surface. Harayama et al. (2003), based on their study of volcanic rocks in the northeastern Hida Mountains, divided the uplift of the Hida Mountains into two stages: Stage 1 (the Late Pliocene to Early Pleistocene) and Stage 2 (the late Early Pleistocene, 1.3 Ma~), and found that Stage 1 was a curved uplift movement and Stage 2 was a large-scale uplift movement with eastward tilting.

The Pliocene to lower Pleistocene series in the northwestern part of the Nagano Basin [25] consists of marine Shigarami and Sarumaru Formations in ascending order (Kato and Akahane, 1986). The Shigarami Formation is divided into three parts: the lower part consisting of mud and sandy gravel beds, the middle part consisting of andesitic pyroclastic rocks, and the upper part consisting of sandy mud beds containing warm-water mollusks (Yano et al., 2020). The Sarumaru Formation consists mainly of sand and gravel beds and is characterized by a series of upward coarse-grained stratigraphic units, with the lower part consisting of shallow-water sand beds and the upper part consisting of reticulated fluvial gravelly sediments (Yano et al., 2020).

From the upper half of the lower part of the Sarumaru Formation, gravels derived from the Pre-Neogene basement rocks of the Hida Mountains dominate and rapidly coarse-grained upward. Yano (1989) estimated that uplift movement in the Hida Mountains became apparent around 2.5 Ma, which is consistent with the results of Harayama et al. (2003) in the Hida Mountains. In the Sai River Basin on the west side of the Nagano Basin, the Omine Plain, which is an erosional flattening of Miocene to Lower Pleistocene fold structures, is widely developed at 700 to 1,500 m elevation (Nishina, 1972). The Omine Plain is unconformably covered by fan terrace gravels and other strata since the Middle Pleistocene (Kato and Akahane, 1986).

As described above, in the Nagano area [23–25], (1) the central and southern parts were terrestrial in the Pliocene, and the northern part was an inner bay shallow-water environment opening to the Paleo-Japan Sea. (2) In the Early Pleistocene, uplift movements became widely apparent, and the Akaishi and Hida Mountains began to grow, while large-scale fold structures were formed in the northern part of the region. After the formation of the Omine Plain, (3) the mountains were rapidly uplifted during the Middle Pleistocene, and the basic framework of the present inland basin was formed. (4) In the Late Pleistocene, the inland basin was buried by fan gravels and other fluvial deposits (see Fig. 2).

Hokuriku region

The Pliocene to lower Pleistocene Hokuriku and Himi Groups in the Kanazawa [26], Himi [27], and Toyama [28] areas of the Hokuriku region are marine deposits along the Paleo-Japan Sea coast. In the foothills of the Ryohaku Mountains to the Hida Mountains, fan gravel beds, mainly of the Middle Pleistocene age, are widely distributed unconformably overlying them. They are called the Hanyu Formation, Utatsuyama Formation, and Kurehayama Gravel Member (Sakamoto and Nozawa, 1960), and have attracted attention as sediments that indicate the timing of uplift of mountain ranges (Kaseno, 1993).

According to Nakajima et al. (2019), the Kurehayama Gravel Member in eastern Toyama Prefecture is estimated to be 600 ka or slightly older, and there is an unconformity with a time gap of about 1 million years between it and the lower Mita Formation. These fan gravel beds were tilted by the Isurugi Movement (Fujii et al., 1976) along with the Neogene, and were unconformably covered by higher terrace beds such as the Tofukuji Formation in the upper part of the Middle Pleistocene, suggesting that new and different movements began after the depositional period of the higher terrace beds (Fujii et al., 1976; Kaseno et al., 1988).

In the Noto Peninsula, the upper Pleistocene in the Hokuriku region is represented by the shallow-water beds with abundant shell fossils and the marine middle terrace that is intercalated with marine clay beds deposited during the transgressive stage. In the eastern part of Toyama Prefecture and its foothills, the middle and lower fluvial terraces or paleo-fans are distributed (Kaseno et al., 1988).

As described above, in the Hokuriku area [26–28], (1) the shallow sea along the Paleo-Japan Sea coast extended during the Pliocene to Early Pleistocene. The gravel beds in the fan area developed with the uplift of the Ryohaku Mountains and the Hida Mountains in the early Middle Pleistocene, and these strata also underwent tilt deformation associated with a stepwise uplift of the mountain range. (3) In the late Middle Pleistocene, these fan gravels were unconformably overlain by higher terrace gravels, and (4) in the Late Pleistocene, terraces or fans were formed after the transgression (see Fig. 2).

Niigata area

In the Niigata area (Takada in the Joetsu area [29], Kashiwazaki in the Chuetsu area [30], Uonuma area [31], and the western and eastern margins of the Echigo Plain [32, 33], the Pliocene to Early Pleistocene strata consist mainly of marine deposits, while the strata after the Middle Pleistocene consist of terrace and fan deposits, and the land area extended from southeast to northwest (Kobayashi et al., 1986).

The lower to middle part of the Kawazume Formation of the Pliocene in the Joetsu and Chuetsu areas [29, 30] consists mainly of a gravelly to sandy turbidite facies indicating the upper to middle part of a submarine fan, and the upper part of this Formation consists of mud facies of a shelf slope environment (Endo and Tateishi, 1985; Omura, 2000). The Nadate and Tanihama Formations above the Kawazume Formation are mainly composed of sandy mudstone, and the Nadate Formation mainly represents the depositional environment of the outer to inner continental shelf and the

Tanihama Formation the outer continental shelf (Omura, 2000). Arato and Hoyanagi (1995) divided the depositional history of the Niigata Sedimentary Basin into two phases: the basin-bottom turbidite depositional phase during the Late Miocene to Early Pleistocene (6.5–1.4 Ma) and the shelf slope progress, shelf extension, and delta progress phase during the late Early Pleistocene (1.4–0.7 Ma).

The Uonuma Group in the Uonuma area [31] consists mainly of gravel, sand, and silt, and shows a general upward coarse-grained trend. The stratigraphic facies is divided into marine and terrestrial sediments, and the boundary between the sea and land moves northwestward with time, showing a regressional trend (Kazaoka et al., 1986). The hinterland of the clastic materials of the Uonuma Group is the Echigo Mountains in the east and the distribution area of volcanic rocks near the Niigata and Nagano border in the south, and the Echigo Mountains began to uplift from the early deposition of the Uonuma Group (Kazaoka et al., 1986).

Kazaoka (1988) estimated the depositional process of the Uonuma Group as follows: During the lowermost depositional stage, the earlier shallow-water areas were rapidly filled by deltas or fan-deltas, and by the end of the stage, swampy lands were widely spread. In the lower sedimentary period, deltas and fans shrank and swampy areas spread more extensively. During the middle sedimentary period, a large river was formed, and from the middle of the sedimentary period, a large fan began to develop from the Echigo Mountains side in the east. During the upper depositional period, the fan expanded further in the eastern part, and part of the Uonuma Hills began to rise.

According to Takahama (1987), there were two unconformities in the middle part of the Uonuma Group about 1.5 Ma and in the base of the upper part about 1 Ma, and the formation of these unconformities supplied a large amount of gravel at the margin. Furthermore, about 700 ka, the Uonuma Sedimentary Basin was landed, and the block uplift of the mountains to the east formed the Gotou unconformity between it and the upper layers. According to Kubota et al. (2018), the southern part of the Echigo Mountains was greatly uplifted before about 800 ka (the end of the Early Pleistocene) and supplied a large amount of debris from the Muikamachi (the South Uonuma) Basin, but the supply of gravel from the Echigo Mountains ceased thereafter as the South Uonuma Basin started uplifting.

The lowermost part of the middle to upper Pleistocene series of the coastal areas of the Niigata, Takada, and Kashiwazaki Plains, and along the Shinano and Agano Rivers consist of sand and gravel, unconformably overlying the Pliocene to Middle Pleistocene, with higher terrace deposits widely distributed above them (Yoshikoshi, 1988). According to Watanabe and Urabe (2003), the displacement of the Shinano River terrace surface indicates that no significant tectonic uplift movement was observed on the northwest side until the early middle terrace formation period, but later, uplift movement became active.

As described above, in the Niigata region [29–33], (1) submarine fans developed during the Pliocene, but the sea became shallow during the early Pleistocene. (2) During the late Early Pleistocene to early Middle Pleistocene, the mountains were uplifted on a large-scale, and the shallow-water areas were rapidly filled by deltas or fan-deltas and became land. (3) In the late Middle Pleistocene, the high terraces were formed on the coastal plain and along the Shinano and Agano Rivers. During the Late Pleistocene, the middle and lower fluvial terraces were formed (see Fig. 2).

Characteristics of uplift movements and sea-level changes since the Pliocene

Based on the detailed stratigraphic and biostratigraphic correlation of the Pliocene to Quaternary in the central Honshu area, the characteristics of their lithology, sedimentary facies, hinterland and its movement were extracted. The results show that the characteristics of these stratigraphic processes are different in each area, but that the central Honshu area has the following four stages (Stages 1–4) of Tectono-sedimentary History in common with each other. Stage 1 is the Pliocene to early Early Pleistocene, Stage 2 is the late Early Pleistocene to early Middle Pleistocene, Stage 3 is the late Middle Pleistocene, and Stage 4 is the Late Pleistocene to Holocene, with conversion ages of 1.8 Ma, 430 ka, and 129 ka, respectively (see Fig. 2). Fig. 4 shows the paleogeographic maps of central Honshu at four of these stages.

Stage 1: The Pliocene to early Early Pleistocene

The Kinki area is characterized by the occurrence of sedimentary basins in the Pliocene, and inland basins also occurred in the areas around Lake Biwa and Ise Bay, where land masses divided by faults and flexure underwent stepwise subsidence and tilting movements, and sedimentary basins moved to the north or west (Kawabe, 1983; Yoshida, 1990). This stage roughly corresponds to the period of terrestrial inland basin development up to about 2 Ma in the development process of mountainous areas and basins according to Hujita (1976).

In the Shizuoka area, gravelly fan-deltas and submarine fans developed in the Fuji River Valley, and sediments were supplied by the uplift of the Akaishi and Misaka Mountains in the hinterland. In the Kakegawa area, the Kakegawa Group was deposited by the expansion of the shallow-water area due to sea-level rise and the deepening of the sea basin (Shiba, 2017a, 2017b). The lack of strata in the area from the Shizuoka Plain to the Izu Peninsula until 3 to 1 Ma suggests that most of this area may have been a terrestrial erosion zone during this period.

In the Kanto area, a submarine fan developed on the Miura and Boso Peninsulas during the Pliocene, and the Kanto Plain between the two peninsulas was a land area. During this period, the Kazusa Group, characterized by basin bottoms, submarine fans, shelf slopes and shelf deposits, began to be deposited. The Kurotaki unconformity is at the base of the Kazusa Group, and according to Kameo and Sekine (2013), the upper limit of the Anno Formation of the Miura Group in the western Boso Peninsula is estimated to be roughly 3 Ma, suggesting that the western Boso Peninsula was at least partially land at that time. The fact that the sediments of the Kazusa Group were supplied from the southwest and that the depositional part moved northeastward suggests that the Tanzawa-Mineoka Uplift Zone, which forms the southwest margin of the sedimentary basin of the Kazusa Group, was uplifted and made land during the deposition of the Kazusa Group (Kaizuka, 1987). The absence of deposits in the Kanto area, especially from the Tama Hills to the central part of the Kant Plain, except for the Miura and Boso Peninsulas, until 3 Ma, suggests that this area was terrestrial until then.

In the western margin of the Kanto Plain, a fan area was widely formed after about 3 to 2.5 Ma due to the uplift of the Kanto Mountains (Shyoda et al., 2005). This suggests that uplift movements in the Kanto region and surrounding areas became more active after this period. Kaizuka (1987) estimated that the Kanto, Ashio, and Abukuma Mountains were small rolling mountains (so-called Peneplains) around 3 Ma, and that subsequent uplift supplied gravel from these mountains to the Kazusa Group at their foot.

During the Pliocene, the central and southern parts of the Nagano area were terrestrial, and the northern part was an inner bay shallow-water environment opening to the Paleo-Japan Sea. In the Hokuriku area to the northwest of the area, a shallow sea spread along the Paleo-Japan Sea coast, and in the Niigata area to the northeast, a submarine fan developed and the sea became shallow in the early Early Pleistocene. In the Niigata Sedimentary Basin, it roughly corresponds to the basin-

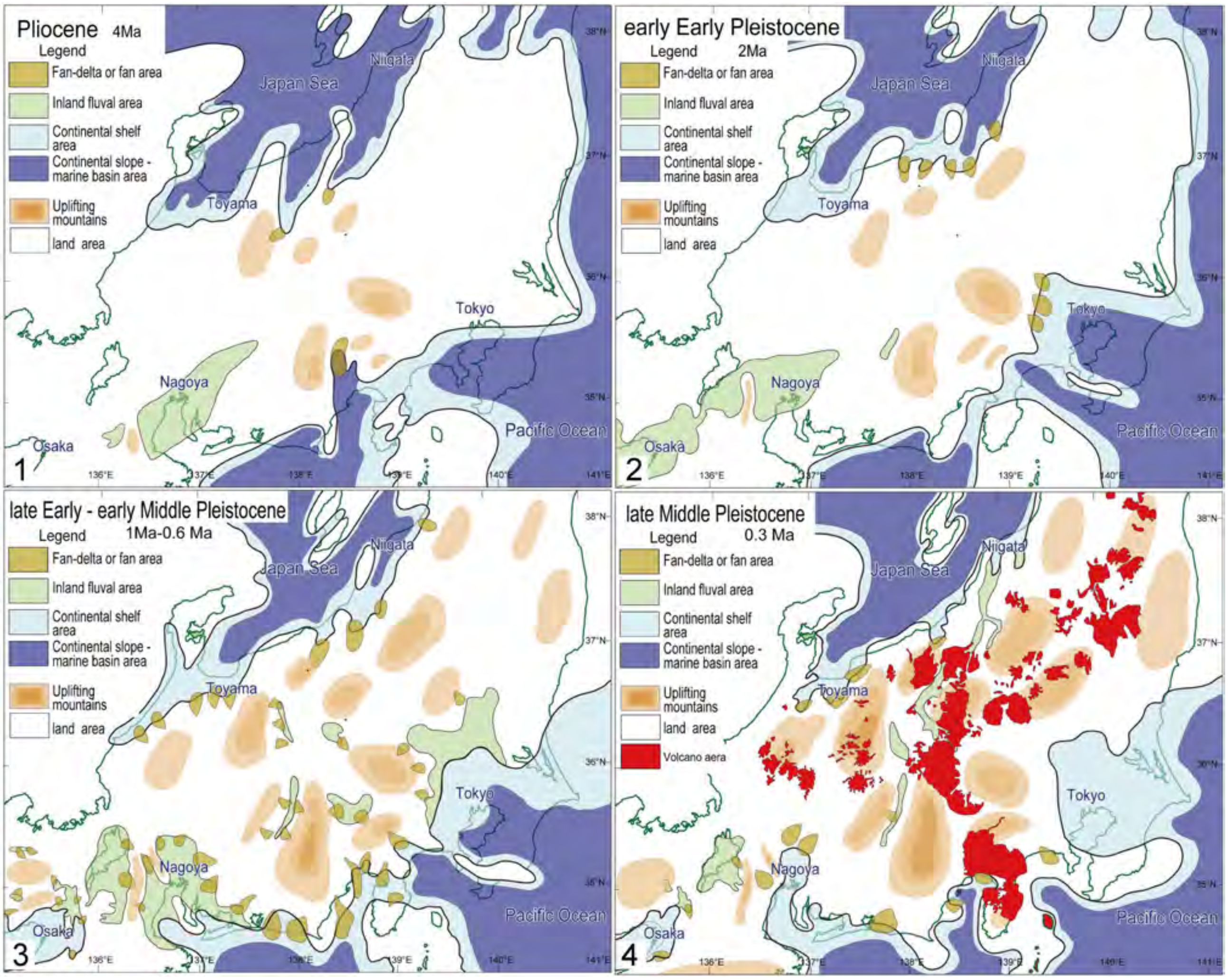

Fig. 4 Pliocene to late Middle Pleistocene paleogeographic maps of central Honshu. 1: Pliocene (4 Ma), 2: early Early Pleistocene (2 Ma), 3: late Early Pleistocene－early Middle Pleistocene (1 Ma–0.6 Ma), 4: late Middle Pleistocene (0.3 Ma, with the distribution of volcano area since Middle Pleistocene).

bottom turbidite depositional phase (ca. 6.5–1.4 Ma) of Arato and Hoyanagi (1995). Takano and Nakajima (2019) stated that a stepwise increase in debris supply due to the uplift of the hinterland and the development of simultaneous sedimentary folds within the sedimentary basin became more pronounced, and the shallow-water and progradation of the sedimentary system of trough-filled submarine fan, slope, land shelf, delta, and river occurred significantly from the southern to northern Shinetsu Sedimentary Basin, resulting in shallow-water and burial of the basin.

In this stage, rivers and lakes spread in inland basins (Inner-arc Basin) from the Osaka Plain to the Ise Bay area, and submarine fans, shelf slopes, or continental shelf areas spread on the Pacific Ocean side from the Kakegawa area to the Boso Peninsula (Forearc Coastal Basin) and on the Japan Sea side from the Matsumoto basin to the Niigata area (Back-arc Coastal Basin). Therefore, the land area in central Honshu at that time was narrower than today, and the shallow to moderately deep-sea area was wider (Figs. 2, 4-1 and 4-2).

Fan-delta to fan deposits before 3 Ma are found in the Akebono Group in the northern Fuji River Valley and the lower part of the Shigarami Formation in the Nagano area. In the terrestrial area, the Akaishi and Hida Mountains appeared as a prominent uplift area and supplied gravelly deposits. After 3 Ma, fan-delta to fan deposits were also observed along the western margin of the Kanto Plain (the Hanno Formation) and in Niigata Minami-uonuma (the lowest part of the Uonuma

Group), suggesting that the Kanto and Echigo Mountains were uplifted significantly.

The Tama Hills and the central Kanto Plain were terrestrial until about 3 Ma, while the Shizuoka area and the Izu Peninsula, excluding the Kakegawa area, were terrestrial until 3 to 1 Ma. In other words, there is a possibility that there was some kind of structural or sea-level change around 3 Ma. The paleogeographic map of this stage is divided into two parts: the first part, about 4 Ma in the Pliocene (Fig. 4-1), and the second part, about 2 Ma in the Early Pleistocene (Fig. 4-2).

The characteristics of the Tectono-sedimentary History of this stage are well described by Hujita (1976) in the terrestrial area as Period of basin occurrence and by Arato and Hoyanagi (1995) in the marine area as the basin-bottom turbidite depositional phase. Shiba (2017 a, 2017b) called this stage as the Kakegawa Movement and characterized it as the uplift of an island arc and sea-level rise that resulted in the widening of a shallow-water area, the deepening of an ocean basin, and the development of a submarine fan.

In other words, in this stage, the blocks of ground divided by the basement faults has continued rose since the Late Miocene, and the strata were formed by sediments supplied by the mountains in the hinterland that began to uplift into the basin formed by the uplift (Shiba, 1991, 2017a, 2017b). The uplift may have caused some areas to become shallower or more terrestrial, while the sea-level rise that occurred at the same time may have caused the sea area to expand and deepen.

Stage 2: The late Early Pleistocene to early Middle Pleistocene

In the Kinki region, sedimentary basins moved and expanded about 2 Ma when new subsidence due to the landmass movement began. This stage roughly corresponds to the second period of Hujita (1976) from about 2 Ma to almost Ma9 of the Osaka Group (about 430 ka), i.e., Period of basin subsidence and expansion to movement and differentiation. In the vicinity of Lake Paleo-Biwa, the uplift of the Suzuka Mountains to the east supplied a large amount of gravel and reduced the freshwater area (Kawabe, 1983). In the area around Ise Bay, the sedimentary basin moved to the northwest and the surrounding mountains such as the Suzuka Mountains were uplifted, causing the disappearance of the Tokai Lake Basin and the formation of the Nobi Tilting Basin after the Middle Pleistocene (Kuwahara, 1968).

In the Shizuoka area, the entire area was uplifted along with the large-scale uplift of the Akaishi Mountains, and the deep-sea area became shallow-water and large gravelly fan-delta deposits were formed. The Ogasa Group in the Kakegawa area, the Senoumi Group in western Suruga Bay, and the Ihara Group at the mouth of the Fuji River (Shiba, 2017a, 2017b). In particular, there was a large supply of gravelly sediments from 1 Ma to 900 ka, the shelf slope was buried and the fan area expands, and the transgression occurred between 900 and 800 ka, forming an inner bay, followed by the formation of a vast fan (Shiba, 2017a, 2017b). Shiba (2017a, 2017b) called this stage of movement the Ogasa Movement.

Fan-delta deposits were also formed in the Izu-Ashigara area. In the northern part of the Izu Peninsula, the Atami Group was deposited by uplift of the Izu Peninsula and volcanic activity, and in the Ashigara area, the upper part of the Ashigara Group was deposited in a gravelly fan-delta by rapid uplift of the Tanzawa Mountains (Imanaga, 1999).

In the Kanto area, the former sea area was transformed from a shallow sea to a coastal plain, and in the central part of the Kanto Plain, the terrestrial and marine sediments formed repeatedly and successively, reflecting sea-level changes corresponding to MIS, including subsequent stages. The upper part of the Kiwada Formation of the Kazusa Group and its equivalents are deposited in the sea area of this stage, in the western part of the Kanto Plain, pelagic to semi-bathymetric seas shifted to shallow-waters after about 1.3 Ma (Sato et al., 2004). In the central part of the Boso Peninsula, the sedimentary pattern of regression pattern began at about the same time (Ito and Katsura, 1993), and the sedimentary basins of the Kazusa Group were rapidly buried and became shallow seafloor. In the subsurface of the central Kanto Plain, the Kazusa Group equivalent layers were bisected by an unconformity around 1.6 Ma, and since then, the terrestrial and marine sediments formed repeatedly and successively, reflecting sea-level changes corresponding to MIS (Naya et al., 2017).

In the Nagano area, the Akaishi Mountains began uplift 1.4–1.0 Ma, and uplift of the Kiso Mountains began after about 600 ka (Suganuma et al., 2003). Sueoka et al. (2011) suggested that the true uplift of the Akaishi Mountains may have been several km greater than the present specific elevation, because the zircon He ages show a systematic rejuvenation from west to east in the Akaishi Mountains, which was caused by the uplift and cooling of rock bodies due to uplift and denudation since the Pliocene.

In the Matsumoto Basin, the Hida Mountains to the west of the Matsumoto Basin underwent a large-scale uplift movement with eastward tilting after 1.3 Ma (Harayama et al., 2003), unlike the widespread uplift that occurred before that. The Nashinoki Gravel Member was formed approximately 780 to 640 ka, reflecting the uplift of the Hida Mountains (Takeshita et al., 2007). In the Nagano area from both banks of the Sai River, the Omine Plain, an erosional flat surface, was formed in stages by widespread uplift in the late Early Pleistocene (Nishina, 1972).

In the Hokuriku area, the fan gravel beds developed with the uplift of the Ryohaku Mountains to the Hida Mountains in the hinterland, and these strata were also tilting deformation associated with a stepwise uplift of the mountain range. The fan gravel represented by the Kurehayama Formation in the Toyama area was deposited a little earlier than 600 ka (Nakajima et al., 2019). In the Niigata area, the uplift of the Echigo Mountains and other hinterlands to the east caused sedimentary basins to shift from marine to terrestrial fan deposits, with the southeastern part of the region showing earlier landward extension and the northwestern part remaining sea until later (Kobayashi et al., 1986). In the Niigata Sedimentary Basin, it corresponded roughly to the shelf slope progress, shelf extension, and delta progress phase (approximately 1.4 to 0.7 Ma) of Arato and Hoyanagi (1995). In the Uonuma Group, a large amount of gravel was supplied from the eastern mountains about 1.5 and 1.0 Ma with the formation of a partial unconformity on the eastern margin, and the Uonuma Sedimentary Basin disappeared about 700 ka due to block uplift of the eastern mountains (Takahama, 1987).

In this stage, the entire central Honshu region has a marked tendency to shift to shallow-water and land, and especially from about 1.0 Ma, gravel beds were widely deposited due to the formation of fan-deltas that buried shelf slopes and developed fans (Figs. 2 and 4-3). On the other hand, marine deposits are seen in the Osaka Plain, the Nobi Plain, and the central part of the Kanto Plain, which were previously terrestrial areas. Especially after 900 ka, the Osaka Group, the basement of the Kanto Plain, and the Boso Peninsula commonly show repeated accumulation of marine mud beds and deltaic or fan sand and gravel beds, reflecting sea-level changes that correspond to MIS.

In this stage, gravelly deposits developed over a wide area in the central part of Honshu, and as mentioned earlier, the hinterland mountains began to uplift in general. In other words, the Akaishi Mountains underwent rapid uplift after 1.4–1.2 Ma, which together with the Ina Basin formed a gravelly fan-delta along the coast of Enshu-nada Sea and Suruga Bay. Uplift of the Hida Mountains became apparent about 800 to 600 ka, supplying coarse-grained sediments to the Toyama area and the Matsumoto Basin. In addition, the Suzuka Mountains, the Tanzawa Mountains, the mountains around the Kanto Plain, the Ryohaku Mountains, and the Echigo Mountains were also uplifted on a large-scale and supplied coarse-grained sediments to the adjacent sedimentary basins.

On the other hand, in the coastal plain, marine mud beds and deltaic sand and gravel beds accumulated repeatedly due to sea-level changes corresponding to MIS after about 900 ka. This suggests that a rather large sea-level rise equivalent to MIS 21 occurred about 900 ka, as seen in the Ma3 bed of the Osaka Group and the Kasui Formation of the Ogasa Group, and that the sea area expanded over the coastal fan that had spread out by then, facilitating the recording of subtle relative sea-level changes after that time.

Paleoinvertebrate studies have shown that the Japanese Islands were connected to the continent several times during this stage. Kawamura (2014) reported that *Mammuthus trogontherii* arrived in the Honshu area from China about 1.2 Ma (MIS 36), *Stegodon orientalis* from the south via the East China Sea about 630 ka (MIS 16), and *Paleoloxodon naumanni* from northern China about 430 ka (MIS 12). The Japanese islands was connected to the Asian continent about 120 ka, 63 ka, and 43 ka. These three periods indicated by Kawamura (2014) roughly coincide with and reflect the periods of active uplift of the Japanese Islands at 1.4–1.2 Ma, 700–600 ka, and 430 ka.

Stage 3: The late Middle Pleistocene

This stage corresponds to the stratigraphic level of MIS 11 to MIS 6 (Figs. 2 and 4-4). In the Kinki region, rapid land mass uplift of the mountains began at this time, forming the framework of the present sedimentary basin. This stage is included in the third period of Hujita (1976), when uplift increased due to active fault landmass movement, i.e., it corresponds to Period of mountain uplift and terrace formation. Around Lake Biwa, deposition of the Lake Biwa Formation began in the present-day Lake Biwa, initiating new movement that continue to the present day (Kumon, 1999). Around Ise Bay, the sea area widely intruded into the Nobi Tilting Basin, and marine and higher terrace beds consisting of marine clay and gravel beds were formed repeatedly.

In the Shizuoka area, the Negoya and Kunozan Formations of the Middle Pleistocene that consist of the Udo Hills are characterized by the development of gravelly fan-deltas and sea-level rise (Shiba et al., 2012). Shiba (2017a, 2017b) inferred that the development of the fan-delta in the Udo Hills was caused by increased uplift, and that the sea-level falling in the relative sea-level curve was only apparent due to uplift, and that the sea-level continued to rise, reaching more than 900 m, including the time of deposition of the upper Kusanagi Formation (the upper Pleistocene).

The gravels of the gravel beds of the Senoumi Group, which consists of the Senoumi Bank in Suruga Bay, were supplied from the Abe River (Shiba et al., 1991a). There is an erosional unconformity between the Pliocene and Pleistocene on the continental slope of the west coast of the Izu Peninsula (Koyama et al., 1992; Okamura et al., 1999). Based on these facts, Shiba (2017a, 2017b) estimated that after about 400 ka, the landward side of both banks of Suruga Bay and the Senoumi Bank were uplifted, and in parallel, the sea-level rose more than about 900 m. The Senoumi Basin and the continental slope of the Izu Peninsula were left behind by the uplift and submerged against the rising sea-level (Fig. 5).

The deposition of the upper part of the Middle Pleistocene in the Udo Hills and the geomorphic formation of Suruga Bay both occurred at the same time. The rise of about 900 m in sea-level that formed the strata of the Udo Hills and the relative subsidence of about 900 m in the Senoumi Basin occurred simultaneously. Based on this, Shiba (2017a, 2017b) concluded that large-scale uplift of the crust and sea-level rise of about 1,000 m occurred simultaneously after about 400 ka during the Middle Pleistocene, forming the topography and stratigraphy of Suruga Bay. Shiba (2017a, 2017b) called this movement the Udo Movement.

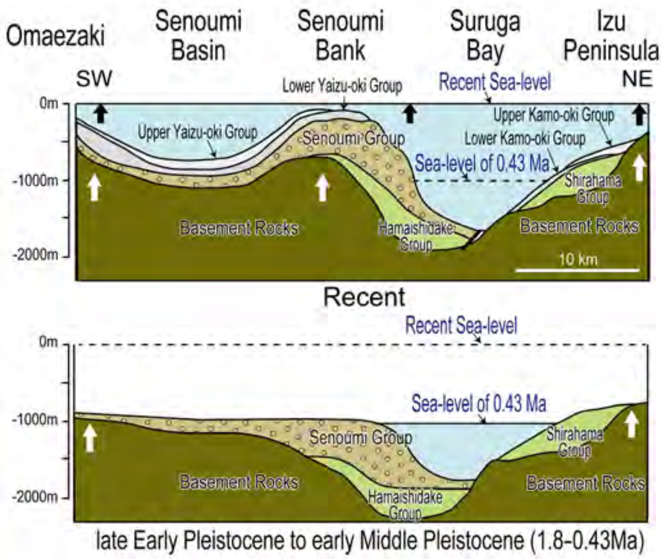

Fig. 5 Northeast-southwest geological profile of Suruga Bay and its formation model since the late Middle Pleistocene (modified after Shiba 2017). The sea level at 0.43 Ma was 1,000 m lower than that of the current one, and the subsequent uplifting and rising sea-level formed the current Suruga Bay. White arrow indicates uplifting and black arrow indicates sea-level rise.

In the Kanto area, the Shimousa Group and its equivalents were deposited beneath the Boso Peninsula and the central part of the Kanto Plain. These strata were continuously deposited on the shallow sea-floor and lowlands since about 900 ka in Stage 2, but landward progressed gradually from the Boso and Miura Peninsulas area and the eastern part of the Kanto Plain to the central to northwestern part of the plain. The landward areas were then covered by the Kanto Loam Formation. Sugai et al. (2013) called this period Period of repeated shallow seafloor and lowlands in the Kanto Plain.

In the Hokuriku area, according to Fujii et al. (1976) and Kaseno et al. (1988), this was the depositional stage of the Tofukuji Formation and other high terraces and a new and different type of movement began at this time. In the Niigata area, high terrace deposits unconformably overlying the Pliocene to Middle Pleistocene are widely distributed (Yoshikoshi, 1988).

MIS 11, which is the base of the sedimentary layers of this stage, consists of marine mud beds such as the Ma9 bed in the Osaka Plain, the Amg1 bed in the Nobi Plain, and the Jizodo Formation and its equivalent in the Shimousa Group in the Boso Peninsula to the central Kanto Plain, suggesting that large-scale transgression occurred in these beds (Yoshikawa, 2012). After that, reflecting the sea-level change corresponding to MIS, the accumulation of transgressive and regressive strata is seen in the Plains and the Negoya Formation of the Udo Hills, and the transgressive strata are recognized in almost the same horizon everywhere.

This stage was marked by relative sea-level change, but it was also marked by intense mountain rises and increased crustal uplift due to active fault land mass movement. The geomorphic framework of today's central Honshu, including the sea-land distribution, large undulating mountains, and large water systems, was nearly complete. The uplift movement after this stage is considered to have been a new uplift movement that formed the present topography, rather than a continuation of the previous tilting uplift movement.

Stage 4: The Late Pleistocene to Holocene

The base of the sedimentary layer of this stage is characterized by the transgression of MIS 5e, followed by the formation of so-called middle to low terraces throughout the area, and the deposition of alluvium in the Holocene. Sugai et al. (2013) stated that the Kanto Plain evolved into Period of Hilly due to uplift after MIS 5/4. The main factors in the Tectono-sedimentary History of this stage are glacial sea-level changes and uplift movements since the last interglacial. The sea-level rise during the last interglacial period led to the deposition of transgressive bed in MIS 5, followed by the formation of marine or fluvial terraces with a stepwise lowering of the sea-level toward the last glacial sea-level. The reason why marine terraces can be observed on land today is thought to be due to post-formation uplift.

On the Makinohara Plateau in the Shizuoka area, the marine mud deposits (the Furuya Formation) of MIS 5 strata are now uplifted to 150 m above sea-level, and subsequent marine terraces are distributed topographically subordinate to the sea in a step-like shape (Shiba 2017a, 2017b). Calculating the average annual uplift since 129 ka based on the present sea-level, the Makinohara Plateau has risen about 1.16 mm per year. After the last glacial stage, the sea-level rose and settled to the present sea-level, which led to the formation of alluvium in coastal areas. Shiba (2017a, 2017b) called this stage of movement the Makinohara Movement.

Mountain uplift and sea-level rise

The stratigraphic processes in central Honshu since the Pliocene are characterized by the uplift of mountains, subsidence of basins, and expansion of sea and land areas, which resulted in the formation of sedimentary layers in a variety of environments. The Tectono-sedimentary History is considered to have differed in each of the four stages, as described above. The reason for this is thought to be the different nature of the uplift movements and sea-level changes at each stage.

The Quaternary crustal movement is characterized by rapid uplift of mountainous areas and subsidence in coastal and inland areas, and by the blocking of land masses duo to fault movement (Matsuda and Kinugasa, 1988). Regarding the paradox of simultaneous uplift and subsidence that characterizes crustal movement during the Quaternary, Kikuchi (1997) discussed the following four conventional theories, using the formation process of the Shimousa Group, which buried the Kanto Tectonic Basin, as an example.

The first theory proposes that in an uplifting sedimentary basin, sediments gradually filled the basin, resulting in a shallow sea. This cannot be fully explained by the accumulation of strata with depositional cycles in the upper levels without ablation, since they are affected by sea-level changes while uplift movements continue.

The second theory is that sedimentary movement continues to form cumulative structures, which later change to uplift movement. There are two cases: one in which a land mass including the entire tectonic basin changes from subsidence to uplift motion all at once (the tectonic basin inversion: Okamura and Nakamura, 1995), and the other in which a subsidence area on one side of a tilting land mass is gradually expanded as the uplift area on the other side is converted into an uplift area. This theory is questionable, considering that the Kanto Tectonic Basin was originally uplifted, and that an inversion occurred.

The third theory is explained by isostatic subsidence movements of the sediments that fill the basin. Isostatic subsidence is thought to occur when sea-level rises and strata are deposited, but there are no examples of studies based on this theory in the Kanto Tectonic Basin.

The fourth theory proposes that the Kanto Tectonic Basin was uplifted while the cumulative structure of the strata was formed by eustatic sea-level rise. The idea is that what appeared to be a tectonic subsidence movement was a eustatic sea-level rise, i.e., a subsidence event caused by tectono-eustasy. This theory is in common with that asserted by a series of studies by Hoshino (1968, 1983, 1991), and Kikuchi (1997) agrees with this theory.

Hujita (1983), regarding the sedimentation and tectonic movement of the Quaternary system in the Kinki region, also points out the fact that there are deposits in the mountain basins of the Kinki region, which are uplifted areas, that retain foothill fans and deltas, and that these can only be explained by absolute sea-level rise.

The Pleistocene sedimentary basin strata we have studied so far commonly contain recurring layers of marine mud and delta and fan sand and gravel, reflecting sea-level changes corresponding to MIS. In other words, the strata reflecting sea-level changes are continuously accumulated and preserved. This requires relative subsidence of the sedimentary basin for accumulation and preservation of the strata, since sea-level change alone would abrade the deposited strata. However, to explain relative subsidence in uplifting sedimentary basins such as Pleistocene sedimentary basins, absolute sea-level rise must be assumed.

The marine mud beds formed by such stratigraphic processes are commonly found in many sedimentary basins in central Honshu with almost the same depositional time. This strongly suggests that the cause cannot be explained by regional basin subsidence, but rather by absolute, or eustatic sea-level rise. The relative sea-level changes corresponding to MIS observed in many sedimentary basins are the result of the difference between the absolute sea-level rise and the amount of uplift of the sedimentary basin. The common occurrence of this phenomenon, especially after 430 ka, suggests that the amount of sea-level rise was large.

Shiba (2017a, 2017b) estimated that a large-scale gravelly fan-delta was formed on the western side of Suruga Bay by the uplift of the Akaishi Mountains since the beginning of the late Early Pleistocene (about 1.8 Ma), and that the present topography was formed by the subsequent large-scale uplift of the east and west shores of Suruga Bay since 430 ka and a 1,000 m sea-level rise. The movements that occurred after 430 ka that formed the topography of Suruga Bay and the mountains surrounding the bay (the Udo Movement) consisted of large-scale uplift of the crust, including the seafloor, and a 1,000 m rise in sea level. This significant change is considered to have been a large-scale crustal uplift movement that not only formed Suruga Bay and its surrounding mountains, but also shaped the entire topography of the present-day Japanese island arc, including the continental slope and trench (Shiba, 2017a, 2017b).

This movement since the Middle Pleistocene are known not only in the terrestrial area but also in the seafloor including Suruga Bay. Inouchi et al. (1978) showed that the uppermost layers of the upper continental slope of the Kii Channel were deposited horizontally in the basin harmonically with the present topography, but the lower layers were distributed incongruently with the topography of the upper continental slope, indicating that the upper continental slope was formed after the Middle Pleistocene. Okamura (1990) suggested that at Tosa-bae, located off Cape Muroto in eastern Kochi Prefecture, a combination of deltaic strata (clinosem), which have been advancing seaward since the Middle Pleistocene, were accumulated from the continental shelf to the shelf slope. The formation of these clinosem and the topography of Tosa-bae suggest that the present north-south direction or outer ridge along the island arc began to rise in Quaternary time and continued growing until recently. The amount of uplift is said to range from 1,000 to 2,000 m in some places. These suggest that the seafloor of the continental slope was also uplifted on a large-scale during this period.

It may seem hard to believe that sea-level has risen 1,000 m in the last 430 ka since the late Middle Pleistocene. However, it is an important hypothesis to consider in order to explain the widespread, large-scale uplift and sea-level rise shown in this paper. A rise in sea-level of 1,000 m over 430 ka would mean an average rise in sea-level of 2.33 mm per year. If sea-level continues to rise at such a rate, it would be 2.33 m in 1,000 years. However, assuming that the land area would have risen by the same amount or more, shoreline movement during that period may have been less pronounced.

According to Hoshino (1991), sea-level rise is caused by the uplift of the deep-sea floor, ridges, and swells due to the intrusion of magma into the oceanic crust, and by lava outflow at a submarine volcanos. The cause of the large-scale uplift of the crust that brought about this sea-level rise is thought to be the rise of tholeiitic basaltic magma from the upper mantle and its intrusion into the crust, as described by Hoshino (1991, 1998, 2007). The present land area is considered to have remained land because the amount of uplift was greater than the amount of sea-level rise, while the area with less uplift became seafloor because it was submerged in relation to the rising sea-level.

Since the late Early Pleistocene (Calabrian, about 1.8 Ma) of the Quaternary, uplift has increased in the central part of Honshu. From the late Middle Pleistocene (about 430 ka) onward, a new crustal uplift movement occurred, instead of the continuous uplift movement that had occurred before that time, and sea-level rose about 1,000 m at the same time. From the Late Pleistocene, the final stage of the Pleistocene, to the present, the amount of uplift in relation to sea-level rise has been large, and the expansion of the coastal plain has become more pronounced.

The distribution of volcanic areas after the Middle Pleistocene is shown on the paleogeographic map after the Late Middle Pleistocene in Fig. 4-4. The volcanic areas in central Honshu are distributed along the northern extension of the Izu Ridge in the NNW-SSE direction and along the uplift axis of the Honshu Arc in the ENE-WSW direction. The intersection of these two uplift axes corresponds to the center of the central part of Honshu, which forms a large undulating topography of more than 3,000 m. The volcanic area is characterized by its location at the margins of each uplifted mountain range in central Honshu. This strongly suggests that the uplift movement since the Middle Pleistocene may have been caused by magma rising in the crust.

The hypothesis of a large-scale sea-level rise after the late Middle Pleistocene may reveal the existence of a land bridge to solve the mystery of the distribution of endemic mammals on islands around the world, including the Japanese Islands (Shiba, 2020, 2021b), and together with the reality of large-scale uplift, will be one of the most important issues in future geological research during the Quaternary.

Conclusion

The Quaternary crustal deformation in the central part of the Japanese Islands is characterized by rapid uplift of mountainous areas and subsidence in coastal and inland areas. In this paper, the author summarizes the characteristics of stratigraphic processes in the central Honshu area based on the stratigraphy and stratigraphic correlation, and classify the Tectono-sedimentary History into the following four stages, based on their evolution since the Pliocene. Fig. 6 shows the changes in the topographic cross-sectional overview of the Kiso Mountains to Enshu-nada Sea with respect to the image of uplift and sea-level rise at each stage.

Stage 1 (the Pliocene to early Early Pleistocene) A terrestrial inland basin occurred, turbidite was deposited mainly in deep-water basins in the marine area, and fan deltas and shallow-water sediments were thickly deposited in the coastal area.

Stage 2 (the late Early Pleistocene to early Middle Pleistocene) General uplift of the island arc occurred, and the inland basins expanded their subsidence areas, followed by basin migration and differentiation. In coastal waters, fan-deltas buried and landed the shelf slopes, and fans expanded.

Stage 3 (the late Middle Pleistocene) Rapid uplift of mountains and sea-level rise occurred, and the geomorphic framework of today's central Honshu was almost complete, including land and sea distributions, large undulating mountains, and large water systems. The relative sea-level change corresponding to MIS, caused by the difference between uplift and sea-level rise, is reflected in the formation of a layer of marine mud and deltaic sand and gravel that repeatedly overlaps the layer.

Stage 4 (the Late Pleistocene to Holocene) After the sea-level rise during the last interglacial period, there was a sea-level fall toward the last glacial period and a subsequent rise, which was

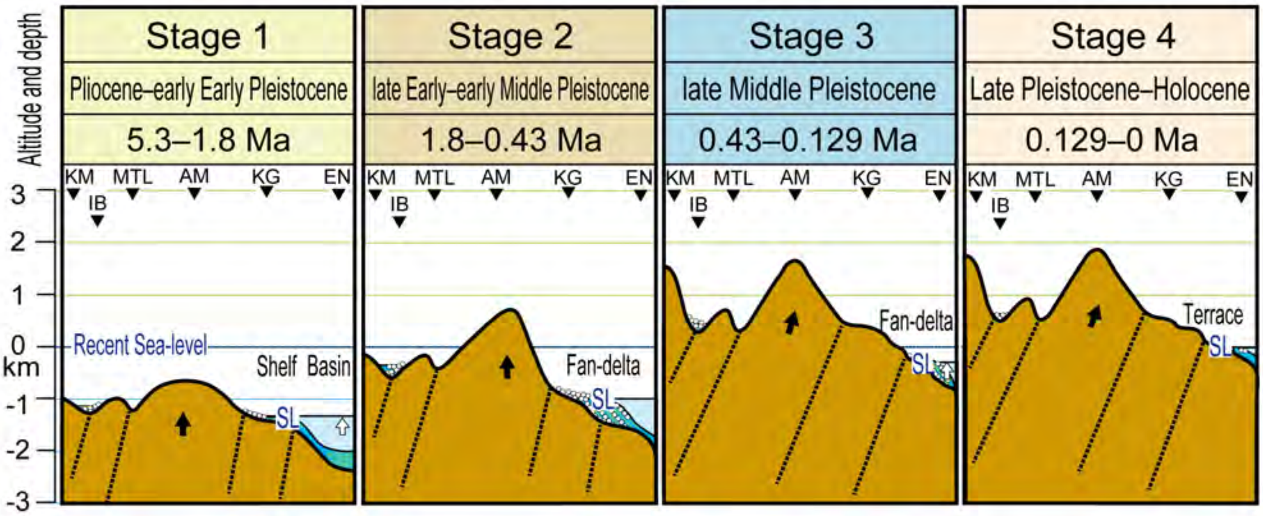

Fig. 6 Topographic image of each stage of Tectono-sedimentary history from the Pliocene to the Holocene from the Enshu-Nada to the Kiso Mountains in central Honshu. Stage 1: Pliocene–early Early Pleistocene (5.3 Ma–1.8 Ma), Stage 2: late Early Pleistocene–early Middle Pleistocene, Stage 3: late Middle Pleistocene (0.43 Ma–0.129 Ma), Stage 4: Late Pleistocene–Recent (0.129 Ma－0). Solid and open arrows indicating crustal uplift and sea-level rise, respectively. KM, Kiso Mountains; IB, Ina Basin; MTL, Median Tectonic Line; AM, Akaishi Mountains; KG, Kakegawa; EN; Enshu-nada Sea (Pacific Ocean).

accompanied by uplift, forming marine or fluvial middle terraces and alluvial deposits.

The Quaternary Tectono-sedimentary History of the central Honshu area is considered to have been formed by a large-scale uplift of the crust and sea-level rise, as seen in the uplift of the island arc. In the late Early Pleistocene (ca. 1.8 Ma), uplift of the Honshu Arc increased around the central part of Honshu, and from the late Middle Pleistocene (ca. 430 ka), a new large-scale uplift of the crust occurred, which was different from the previous uplift movements, and sea-level rose approximately 1,000 m at the same time, forming the present landform. As the author has discussed, the formation of island arcs during Quaternary was caused by tectonic movements different from those of the preceding Neogene, and the formation of the island arc by large-scale uplift and sea-level rise cannot be explained by the plate subduction or collision.

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