Sedimentary environment and paleosols of middle Miocene fluvial and lacustrine sediments in central Japan: Implications for paleoclimate interpretations

Nozomi Hatano[1], and Kohki Yoshida[2]

[1]*Graduate School of Science and Technology, Shinshu University,*
hatano.n6@gmail.com

[2]*Department of Geology, Faculty of Science, Shinshu University*

ABSTRACT

Sedimentary facies analysis and description of paleosols were carried out for the middle Miocene Tokiguchi Porcelain Clay Formation (PCF) in central Japan in order to interpret the soil-forming environments during a long hiatus in the Japanese Islands. The sedimentary facies suggests that deposition occurred mainly in a lacustrine environment, with minor channel-fill and debris-flow deposits associated with alluvial fan environments. The coarse-grained sediments, which are inferred to have been deposited in channel-bar and debris-flow deposits, are present only in the marginal area of the sedimentary basin. Mature paleosols are identified in the Tokiguchi PCF, characterized by illuviated clay, identifiable soil horizons including Bt horizons and many *in situ* plant fossils, and are then similar to Ultisols. Most tree trunk fossils, however, were preserved by burial beneath debris-flow deposits. Most of paleosols formed on lacustrine deposits and were covered by lacustrine clay and silt deposits, without intervening coarse-grained deposits, such as flood-flow deposits. This change of sedimentary facies indicates a dramatic change of hydrologic environment, from stagnant water to entirely desiccated conditions, promoting weathering and soil formation. The relationship between sedimentary facies and Pedotypes, consequently, implies the repetition of specific events, i.e., submergence and emergence of lake bottom, most likely due to formation and drainage of a dammed lake. These isolated events and development of mature paleosols might suggest specific characteristics of middle Miocene weathering conditions, such as seasonally heavy rainfall and/or warm climatic conditions in the Japanese Islands.

KEYWORD

fluvial and lacustrine sediments; Miocene; paleosols; weathering condition; sedimentary facies analysis

INTRODUCTION

Miocene to Pliocene duration is a critical period for considering the history of weathering and climatic conditions in east Asian region because it is considerably recognized as a period that has appeared and greatly changed the East Asian monsoon (Quade et al., 1989, An et al., 2001 and Guo et al., 2002), and that has occurred that some water marine climatic events due to the invasion of the tropical sea water currents as a result of closure of Indonesian Seaway and warm surface water pileup over the far western Pacific (Kennet et al., 1985; Ali et al., 1994; Nishimura and Suparka, 1997; Li et al., 2006). In the Japanese Islands, which are distributed in far eastern Asia, the middle Miocene to the early Pliocene period (5 - 15 Ma) was a time of long hiatus associated with global regression and regional orogenic movement (Makinouchi, 1985 and Yoshida, 1992: Fig. 1-C). Therefore, there are sparse depositional records and little is known about the weathering, climate and environment during this time interval. The middle Miocene Porcelain Clay Formation (PCF), which is interpreted as a fluvial deposit (Akamine, 1954, Fujii, 1967 and Fujii, 1978), is one of the rare geological records preserved during the middle Miocene time interval in the Japanese Islands (Fig. 1-C).

The PCF produces high-quality ceramic material, which is characterized by very high concentrations of aluminium (Fujii, 1967). These isolated sediments are inferred to have formed under warm, wet terrestrial weathering conditions (Fujii, 1967 and Fujii, 1978). The PCF is interpreted as having been deposited in a small sedimentary basin with a radius of several kilometers, in Gifu and Aichi Prefectures, central Japan (Nakayama, 1985 and Todo Collaborative Research Group: TCRG, 1985). In particular, the PCF that is distributed in Gifu Prefecture is called the Tokiguchi Porcelain Clay Formation (Akamine, 1954), and that distributed in Aichi Prefecture is called the Seto Porcelain Clay Formation (Matsuzawa, 1960). Depositional processes of the PCF were interpreted based on sedimentary facies analysis. Nakayama (1991, 1999) carried out sedimentological studies related to the Seto PCF in the southern part of Nagoya in Aichi Prefecture, and proposed a reconstruction during the middle Miocene that consisted of a fine-grained alluvial system with fan, fan delta and lake and/or pond environments. Saneyoshi et al. (2000) and Nakajima et al. (2004) showed that the sedimentary environment of the Tokiguchi PCF, distributed in Toki - Tajimi Cities in Gifu Prefecture, was that of a youthful sandy, braided fluvial system with extensive swamp and stagnant water areas, which were developed proximal to the mountain and/or hilly area.

In the case of fluvial deposits such as the PCF, a sedimentological approach can be interpreted depositional processes, environments and products of sedimentation. However, such an approach can only provide limited information, which is incomplete for successions formed in fluvial environments, because these deposits essentially comprise multiple short hiatuses developed due to sub-aerial erosion and soil formation within the deposits. During the hiatuses, the surface of deposits is influenced by soil formation, characterized by physical, chemical and biological weathering (Retallack, 2001). Indeed, the PCF has yielded many indigenous plant fossils with good preservation, for example, of pine fossils (*Pinus trifolia*: Miki, 1939 and Miki, 1941). Meanwhile, paleopedological reconstruction of paleosols can support interpretations of the history of depositional processes, weathering, climate and other geologic events that influenced the sedimentary basin during the hiatus developed in the middle Miocene to the early Pliocene in the Japanese Islands.

In this study, the results of sedimentary facies analysis and description of the paleosols in the Tokiguchi PCF are reported in order to reconstruct the paleoenvironmental change of the sedimentary basins during the middle Miocene during a long hiatus in southwest Japan. In addition, the relationships of the sedimentary facies and paleosols are important in interpreting conditions within the sedimentary basins, because the depositional processes involved variable depositional rates, flow patterns and accordingly produce micro-relief in the sedimentary basins, which influenced the degree of pedogenic development (Kraus, 1999 and Retallack, 2001).

GEOLOGICAL SETTING AND METHODS

Lower Miocene to Pleistocene sediments are widely distributed in southwest Japan. These sediments have been geographically grouped by area of distribution into the following groups, the Osaka Group (Osaka Group Research Group, 1951) around Osaka, the Kobiwako Group (Nakayama, 1929) around Lake Biwa and the Tokai Group (Ishida and Yokoyama, 1969) around Ise Bay and inland area of Aichi and Gifu Prefectures (Figs. 1-B and 1-C). The Porcelain Clay Formation (PCF), which is assigned to the lower part of the Tokai Group (Akamine, 1954), is a rare geological record preserved during the middle Miocene time interval in southwest Japan (Fig. 1-C). The PCF has been studied in several isolated, small sedimentary basins (Nakayama, 1985 and TCRG, 1985). The clayey sediments in the PCF are mined as a high quality resource of ceramic clay that is widely known for use as raw materials of Mino and Seto Pottery. The Tokiguchi PCF, distributed in four clay mines (Hishiya, Nakayama and Yamakyu Mines) around Toki - Tajimi Cities in Gifu Prefecture, were examined in this study (Fig. 1-D). The Tokiguchi PCF is 10 - 30 m thick and shows near horizontal bedding in those mines. A fission-track age from ash-flow tuff (Oroshi Tephra in the upper part of the

Tokiguchi PCF) is dated at 13.1 ± 0.8 Ma and a U - Pb age is placed at 10.6 ± 0.2 Ma (Hoshi et al., 2015).

The Tokiguchi PCF is overlain by the middle Miocene to the late Pliocene Toki Sand and Gravel Formation, which is composed of sand and gravel rich fluvial sediments (Akamine, 1954: Figs. 1-C and 1-D). The Tokai Group unconformably overlies the Jurassic to Cretaceous accretionary complex (Mino Sedimentary Complex), late Cretaceous to early Paleogene granites (Ryoke Granite) and early - middle Miocene sedimentary rocks (Mizunami Group) in the study area (Kiyono and Ishii, 1927). The lower part of the Tokiguchi PCF, where in contact with the basement rocks, is composed of granule, sand and pebbly sand layers in Toki - Tajimi Cities (Fujii, 1967).

SEDIMENTARY FACIES

Stratigraphic columnar sections (1:100) were described in the three mines in order to classify the lithofacies. Two columnar sections were described only in the Hishiya Mine (Fig. 2). Eventually, the sediments were classified into 10 representative sedimentary facies based on grain size, sedimentary structures, overall lithofacies characteristics and stratum boundary (Table. 1). The sedimentary facies in this paper were then compared with those defined by Miall (1977, 1996).

Facies A

This facies, composed of sandy and pebble sized gravel, has common trough cross-beds and rare, faint cross-beds. Sand grain-sizes range from very coarse- to fine sand-size. These gravels are distinctly sub-rounded gravels, as classified using Pettijohn (1957). Foreset dips of these beds are commonly high-angles (25° - 30°). The sets of cross-strata range from 5 - 10 cm thick and commonly show normal size-grading, and have erosional bases. Facies A rarely contains sand lenses with carbonaceous materials. This facies laterally grades into Facies B, C and F, and has sharp vertical contacts with Facies B, C, E, F, H and J.

The abundances of sub-rounded gravel and trough cross-beds suggest that deposition by traction transport under upper to lower flow-regimes, likely in shallow, gravelly and sandy channel bars. In general terms, Facies A is equivalent to Facies Gt in Miall (1977, 1996), but is different from their Facies Gt in terms of having intercalations of sand lenses with carbonaceous materials.

Facies B

This facies consists of fine- to very fine-grained sand and occasionally coarse-grained sand, has ripple laminae with 5 cm of amplitude, and rare small-scale planar-tabular cross-beds that have erosional bases and normal size-grading. This facies grades laterally into Facies A, C, F and G, and has sharp vertical contacts with Facies A, C, D, F, G, H and J.

The sedimentary structures of this facies, showing ripple laminae and small-scale planar-tabular cross-beds, indicate that deposition was by traction transport under lower flow-regimes. In a broader senses, Facies B is similar to Facies Sr in Miall (1977, 1996).

Facies C

This facies consists of alternating and/or lenticular beds of well-sorted, very coarse- to medium-grained sand and sandy silt including small amounts of carbonaceous materials. Each lamina is generally several centimeters thick. Sand layers have erosional bases, with ripple and foreset laminae (Fig. 3A). This facies commonly has convolute laminae and inverse size-grading. Facies C has sharp vertical contacts with Facies A, B, E and F, and laterally grades into Facies A, B and F. This facies in some instances grades laterally into Facies F.

In general, inverse size-grading is associated with flooding on floodplain, back-swamp and natural levee environments (Masuda and Iseya, 1985). Coarse grain-size and contacts with coarse-grained channel deposits such as Facies A and B, additionally, imply that these formed under high sedimentation rate, such as in the proximal areas of floodplains or on alluvial ridges.

Facies D

This facies consists of poorly-sorted, muddy sand with pebble- to granule- and gravel-sized material. Grain size is generally medium-sand to silt, with an admixture of gravels, which consist of angular to sub-angular grains up to 1 cm in diameter (Fig. 3B). The gravels are dispersed in massive sandy silt with disordered internal arrangement. Concentrations of pebbles to coarse-sand are unevenly distributed in the layers. Facies D laterally grades into Facies H and J, and in a few instances has sharp vertical contacts with Facies B, F and H.

The massive structure and distribution of pebbles with disordered internal arrangement are interpreted as "rigid plug" structures produced by high-viscosity mass flows. In general, matrix-supported massive gravel deposits are formed by mass flows under the conditions of balanced viscosity and shear strength of the fluid (Miall, 1977 and Soh and Taila, 1989). For these reasons, Facies D is interpreted as debris-flow deposits formed by sediment gravity flows with high-strength and high-viscosity, and corresponds to Facies Gmm in Miall (1996).

Facies E

This facies consists of massive beds of gravel, poorly-sorted sandy silt, and concentrations of allochthonous plant fossils (Fig. 3C). The facies also includes angular to sub-angular gravels and rarely rounded gravels. Both clast-supported and matrix-supported lithologies are unevenly distributed in this facies, and the former is often dominant. The allochthonous plant fossils are preserved on bedding planes in the clast supported gravel layers. Facies E grades laterally into Facies H, I and J, and has sharp vertical contacts with Facies A, C, F, H, I and J.

The characteristics of this facies are the dominance of clast-supported gravels. In addition, scattered abundant alloghthonous plant fossils in the gravel suggest poor sorting effects by low-energy water flows. These characteristics are equivalent to those of Facies Gci (Miall, 1996). Facies E, therefore, is interpreted as high-density debris-flow deposits formed under conditions of low water-content and/or low-velocity.

Facies F

This facies consists of alternating beds of well-sorted, medium- to very fine-grained sand and silt to clay, including some sparse carbonaceous materials, however, sand layers are more common than muddy layers (Fig. 3D), and each layer is several centimeters thick. Sand layers have erosional bases, internal foreset laminae, current ripple tops and sharp contacts with clay layers. Convolute bases, flame structures, and bioturbation are common in this facies. Layers of carbonaceous material, up to several millimeters thick, are present within fine-grained layers, but are less common than in Facies G. This facies laterally grades into Facies C, H and J, and has sharp vertical contacts with Facies A, B, C, D, E, G, H and J, however Facies F commonly intertongues with Facies I.

Alternating beds of sand layers, which have foreset laminae, and muddy layers, suggest the repetition of transportation of sediments by traction transport processes followed by weakening of flows and deposition by suspension currents. Sharp layer boundaries between sand and fine-grained layers suggest rapid changes of depositional processes, possibly due to flooding in overbank areab. This facies is equivalent to Facies Fl in Miall (1977, 1996).

Facies G

This facies is consists of alternating beds of thick silt - clay with lignite beds, and lenticular coarse- to fine-grained sand (upper part of Fig. 3E). Sand layers show climbing-ripple and erosional scoured bases. Finer layers commonly contain allochthonous plant fossils, for example, horizontal tree trunks, cones, leaves and branches. Facies G grades laterally into Facies B, C, H, I and J, and has sharp vertical contacts with Facies B, C, D, F, G, H and J, in some instances this facies intertongues with Facies J when traced laterally.

The characteristics of Facies G partially correspond to Facies Fl (Miall, 1977 and Miall, 1996), except for the occurrences of abundant allochthonous plant fossils. Facies G suggests sedimentation on a floodplain in which plants experienced transport and concentration, such as a back-swamp environment.

Facies H

This facies consists of well-sorted silt - clay (Fig. 3E). Facies H grades laterally into Facies A, B, D, E, F and J, and has sharp vertical contacts with these facies. In rare instances, Facies H grades laterally, and is overlain by Facies G and I.

The characteristics of Facies H, composed of silt to clay with parallel laminae, suggest that deposition occurred by suspension flow into a lake center environment. This facies is equivalent to Facies Fsm (Miall, 1977 and Miall, 1996).

Facies I

Facies I consists of dark brown silt to clay, with abundant allochthonous plant fossils and some peat layers. This facies has sharp vertical contacts with Facies E, F and H. However this facies commonly shows both lateral and vertical gradations into Facies G, H and J.

Abundant allochthonous plant fossils and composition of dark brown silt to clay suggest during deposition under suspension flow it was easy to concentrate plant fragments. Facies I, therefore, is interpreted as a marsh deposit and is equivalent to Facies C (Miall, 1996).

Facies J

This facies is composed of muddy lignite with minor silt to clay matrix components (Fig. 3F). Allochthonous plant fossils are very abundant. This facies grades laterally into Facies D, E, F, G, H and I, and has sharp vertical contacts with Facies A, B, E, F, G, H and I. However this facies commonly shows both lateral and vertical gradations into Facies G and I.

Lignite layers and minor silt to clay matrix suggest that deposition was under lower-energy conditions in which was easy to concentrate plant fragments. Facies J, therefore, indicates deposition in swamps with stagnant water, and is equivalent to Facies C (Miall, 1996).

Distribution of sedimentary facies

In the Tokiguchi Porcelain Clay Formation (PCF), lacustrine fine-grained deposits (Facies H, I and J) are most abundant, and coarser-grained channel and bar deposits (Facies A, B and C) and/or high-density debris-flow deposits (Facies E) are relatively rare in the lower part of the PCF, from the bottom to about 27 m up-section, and in the Nakayama Mine. In contrast, low-density debris-flow deposits (Facies D) most common in sharp contacts with lake and back-swamp deposits (Facies H, I and J). These lacustrine deposits show wide lateral extent, to more than 150 m in width (Fig. 3G). Channel and bar deposits are recognized in the upper part of the PCF, from the bottom to about 27m to the top of the section. In addition, channel and bar deposits commonly overlie the high-density debris-flow deposits in the three stratigraphic sections. In summary, the lithologic changes within the PCF are highly irregular.

DESCRIPTION OF PALEOSOLS

The lack of physical sedimentary structures, which is related to presence of bioturbation, plant fossils and soil horizons, is evidence for pedogenic alteration (Retallack, 2001). On the basis of these indicators of paleosols were identified within the PCF. The tops of paleosol profiles were identified by the surface from which root fossils and/or tree trunk fossils emanated. Field features of the paleosols were described, following the paleosol descriptive approaches presented by Retallack (2001). Oriented hand samples were collected in order to describe soil micro-structures in thin sections, which were described following the terminology of Brewer (1976).

Some paleosol horizons were recognized in the Tokiguchi PCF, with as many as 20 to 24 horizons identified in each mine (Fig. 2).

Many *in situ* plant fossils were identified in the outcrops, which consist of fine rootlets, roots and tree trunk fossils (Fig. 4). Root fossils, which characteristically taper and branch downward (Retallack, 2001: Figs. 4A and 4B), are present in most all paleosols. They are up to 150 centimeters long (Fig. 4B). Tree trunk fossils, which can be recognized by branch-ing upward, have diameters of up to 50 centimeters (Fig. 4C) and were observed in six stratigraphic sections (Fig. 2). Furthermore, the *in situ* plant fossils generally showed high plant density in all mines. Most all paleosols have distinctive soil horizons, which can be assigned to A, B and C horizons (Fig. 4D). Some paleosols have a Bt horizon, which is reddish to brownish color, for example, 10YR4/2 - 4/3 and/or 7.5YR4/3 in Munsell rock colors, and shows evidence for clay accumulation, such as illuviated clay pore-fillings and clay skins.

On the microscale, sepic-plasmic microfabrics (Brewer, 1976) were dominant in the paleosols. Clinobimasepic plasmic (i.e., a network of highly birefringent clay arranged two directions and at a low angles: Fig. 5A) and masepic plasmic (i.e., clay arranged as an extensive cross-crossing network: Fig. 5B) were the most common microfabrics in the paleosols. Omnisepic plasmic (i.e., all highly birefringent and oriented clay: Fig. 5C) were microfabrics present mainly in the surface soil horizons, such as A horizon. Many paleosols contain distinctive illuviated clay pore-fillings and clay skins (Figs. 5D, 5E and 5F). These soil microstructures correspond to *cutans* composed of clay minerals (*argillan* in Brewer, 1976). These illuviated clay also show laminated structure formed from successive additions of material washed into soil pores (Fig. 5F). These clayey sediments also commonly contained pedogenic slickenside surfaces, characterized by smooth, polished and striated shear planes.

Relationships between sedimentary facies and paleosols

Relationships between sedimentary facies and paleosols were divided into 6 "Pedotypes" described below and were interpreted within the context of a generally aggradational history of fluvial environments. Typical vertical relationships among sedimentary facies and paleosol horizons, and vertical distributions of the above relationships, are shown in Figs. 6 and 7.

Pedotype 1a: The top of these paleosols is recognized as the surface of the swamp (marsh) deposits (Facies I or J). Soil horizons overprint and modify the lake and/or swamp (marsh) deposits.

These paleosols are covered by lake deposits without intervening coarse-grained sediments like floodplain minor-channel and crevasse-splay deposits. The thickness of the soil horizons ranges from 20 - 70 centimeters. Twenty five paleosols in the stratigraphic columns were assigned to Pedotype 1a.

Pedotype 1b: The top of these paleosols is placed within the swamp (marsh) deposits. Soil horizons were formed in the swamp (marsh) deposits, without intervening coarser sediments. The thickness of these soil horizons are about 40 centimeters. Thirteen paleosols were assigned to Pedotype 1b.

These paleosols of Pedotypes 1a and 1b show lateral extent for up to 150 m (Fig. 3G), and are characterized by distinctive soil horizons, which are A, Bt, Bw and C horizons, long root fossils and abundant pedogenic structures, such as illuviated clay (Fig. 6). The Bt horizons, which are generally reddish to brownish color, attain a maximum thickness of approximately 25 centimeters. Pedotypes 1a and 1b are, then, similar to Ultisols of Soil Survey Staff (1999). These Pedotypes subaerial exposure and pedogenesis, which occurred after the deposition of silt to clay in stagnant waters. In addition, these paleosol horizons were afterwards covered by lake or swamp (marsh) deposits. Pedotypes 1a and 1b paleosols, consequently, demonstrate that the lakes dried up, without major inflouxes of coarser-grained sediments. This indicates considerable hydrologic change, i.e., the onset of dry conditions, which was evidenced by subaerial exposure and soil formation, followed by a return to waterlogged conditions, which is characterized by deposition of finer-grained sediments.

Pedotype 2: The top of these paleosols is defined by the base of the overlying low-density debris-flow deposits (Facies D). Tree trunk fossils are nearly always buried by the debris-flow and lake deposits (Fig. 4C). In addition, the paleosols formed in the lacustrine deposits, which consist of silt and clay layers, covered by the low-density debris-flow deposits with buried trunks. Thicknesses of these paleosols range from several centimeters to 70 centimeters. Three paleosols are assigned to Pedotype 2.

The paleosols of Pedotypes 2 are characterized by identifiable soil horizons, which are thin O horizons (a few centimeters thick) and A, Bt, Bw and C horizons, long root fossils and abundant illuviated clay (Fig. 6). Pedotype 2 is similar to Ultisols of Soil Survey Staff (1999) in that this paleosols include Bt horizons. Pedotype 2 paleosols indicate subaerial exposure of lacustrine deposits followed by soil formation. Furthermore, soil formation was abruptly terminated by deposition of debris-flows.

Pedotype 3: The top of these paleosols is placed at the top of low-density debris-flow deposits. The debris-flow deposits were covered with swamp (marsh) deposits. Lacustrine deposits generally occur beneath the debris-flow deposits. These paleosols thus formed on debris-flow. The thicknesses of the range from several centimeters to 40 centimeters. Six paleosols are assigned to Pedotype 3.

The paleosols of Pedotype 3 have Bt horizons and are penetrated by long root fossils. These characteristics suggest that the Pedotype is equivalent to Ultisols of Soil Survey Staff (1999). Pedoype 3 is evidence for soil formation occurring after the deposition of low-density debris-flows, followed by burial by silt and clay in stagnant water, without intervening of coarser-grained deposits.

Pedotype 4: The top of these paleosols is placed at the top of the back-swamp or floodplain deposits (Facies G and F). Silt to clay layers interpreted as lacustrine deposits overlap and bury the paleosols formed on the back-swamp or floodplain deposits. The thicknesses of the paleosols are thinner than those of other pedotypes and ranges from a few centimeters to 20 centimeters. Ten paleosols are assigned to Pedotype 4. The upper boundary of the paleosols is sometimes difficult to identify. Pedotype 4 is occasionally intercalated with Pedotype 5 (from the bottom to about 7.5 m up-section in the Yamakyu Mine and about 17.0 m up-section in the Hishiya Mine).

The paleosols of Pedotype 4 have thin soil horizons, which are A and C horizons with common color from gray to olive gray, and fine rootlet fossils without long root fossils. Sedimentary structures, such as current ripple and convolute laminae, are commonly remained. Eluviation of clay from the surface horizons was scarce in thin sections. This Pedotype is then similar to Entisols of Soil Survey Staff (1999). Pedotype 4 is evidence for soil formation after the deposition of coarser-grained sediments on floodplains or channel-bar.

Pedotype 5: The top of these paleosols is an unconformity related to erosion by covering strata. Paleosols were formed in the top layer of lake deposits (Facies H), but there was no preservation of the upper part of the paleosols, such as the O and A horizons. The thicknesses of the paleosols are several centimeters. Eight paleosols assigned to Pedotype 5.

The lack of the preservation of the upper part of paleosols is attributed to erosion of the upper part of the developing soils, and is indicative of a dramatic change of sedimentary environments, from lake to inside of river channels. The paleosols of Pedotype 5 are commonly penetrated by long root fossils and have Bw horizon. However it couldn’t be interpreted detailed soil environments due to lacking of the surface horizons.

DISCUSSION

Sedimentary mechanisms and environments

In terms of the general distribution of the sedimentary facies, coarser-grained deposits, which consist of channel, bar and high-density debris-flow deposits are rare in the Nakayama Mine. On the other hand, in the Hishiya and Yamakyu Mines, these coarser-grained deposits are more common. This suggests that the sedimentary basin for the deposits, which is presently exposed in the Nakayama Mine, was located in the more distal areas of the alluvial system, whereas those deposited in the areas of the Hishiya and Yamakyu Mines were in more proximal areas. The existence of two sedimentary basins was previously postulated based on the distribution of the measured elevation above sea level of the base of the Tokiguchi PCF (TCRG, 1999).

The dominant sedimentary facies of the Tokiguchi PCF are Facies H, I and J, which suggests the dominance of deposition in lacustrine environments. These deposits show wider lateral extents, to than 150 m in width (Fig. 3G), thereby indicating the lake was at least 150 m in width.

The debris-flow deposits nearly always show gradational contacts with lacustrine deposits, which suggests that the debris-flows had entered directly into the lacustrine areas. According to some previous researchers, the sedimentary basins of the PCF were small depressions, ranging from several to tens of square kilometers in area (Nakayama, 1991, Nakayama, 1999, Saneyoshi et al., 2001 and TCRG, 1999). These reports indicate that the topography was hilly in the vicinity of the lacustrine area.

The channel deposits are spatially restricted and distributed in the Hishiya and Yamakyu Mines, which were located in the more proximal areas of the basins. These channel deposits overlie high-density debris-flow deposits in three stratigraphic sections, which are located 27 - 30 m from the bottom in the stratigraphic columns (Fig. 2), suggesting appearances of small streams or minor alluvial fans. In addition, there are rare, thinner levee deposits, which suggest there was a small-scale channel system. The main stream channel, however, was not recognized within these mines.

Paleohydrologic environments inferred from paleosols

To date, there are only a few paleobotanical studies conducted in the PCF (Miki, 1941, Miki, 1963, Momohara and Saito, 2001 and Tsukagoshi and TCRG, 1998). However, none of the preceding reported the existence of the paleosols.

The paleosols recognized in this study are characterized by abundant *in situ* plant fossils, such as fine rootlets, roots and tree trunk fossils, and distinctive soil horizons. Some of the paleosols are deeply penetrated by root fossils. In general, the development of deep root fossils indicates that well-drained soil conditions existed (Retallack, 2001). On the microscale, sepic-plasmic microfabrics, illuviated clay pore-fillings and reworked clay coatings are common in the paleosols. It is known that the degree of development of sepic-plasmic microfabrics requires time available for soil formation and the intensity of pedogenesis due to stresses imposed by repeated wetting and drying cycles, with filling and closing of cracks, and other alterations (Brewer and Sleeman, 1969). Illuviated clay suggests that the dominant soil formation process was leaching and illuviation, which are soil formation processes of characterized by flushing of clay particles from surface horizons into pores and cracks of sub-surface horizons (Matsui, 1988 and McCarthy et al., 1998). Palosols of Pedotypes 1a, 1b, 2 and 3, moreover, have Bt horizons, which are characterized by reddish to brownish colors and prominent illuviated clay, and are, then, similar to Ultisols of Soil Survey Staff (1999). Ultisols are, typically, formed in humid and warm climates (Retallack, 2001). The above descriptions related to the characteristics of paleosols, which are especially assigned to Pedotypes 1a, 1b, 2 and 3, attest to mature and well-drained soil environments and/or humid and warm climates developed during the deposition of the Tokiguchi PCF. These paleosols are distributed within all the mines.

The succession of fluvial environments can be interpreted based upon the pedotypes, showing the relationships between sedimentary facies and paleosols (Fig. 6). Firstly, Pedotype 5, which is dominantly in the Hihshiya and Yamakyu Mines, indicates deposition in marginal areas of the basin where coarser-grained sediments were easily derived from surrounding mountain slopes. Also, it is evident that Pedotype 4 is intercalated with Pedotype 5 in the Yamakyu and Hishiya Mines. This relationship possibly indicates lowering of the lake surface water and ground water levels, followed by coarsening of grain-size of sediments, reflecting high sedimentation rates by overbank flows near the channel. Pedotype 4, which are characterized by thin soil horizons and little altered parent materials with relict bedding, are similar to Entisols of Soil Survey Staff (1999). In general, Entisols are formed in a short subaerial exposure time or unfavorable soil conditions, such as infertile or poorly drained soil conditions (Retallack, 2001). In that case of Pedotype 4 in the Tokiguchi PCF, the immature paleosols are considered to reflect the high sedimentation rate near the active channel within fluvial systems because the parent materials of this Pedotype are coarser-grained sediments, such as channel-bar and flood-flow deposits. The soils, then, have become buried by the coarser-grained sediments due to rapid sedimentation.

Secondly, the most common pedotypes of paleosols, which are recognized in all the mines, are Pedotypes 1a and 1b. The paleosols of these pedotypes are developed in the silt to clay deposits interpreted as lacustrine deposits. These paleosols were afterwards by the lacustrine deposits. This specific vertical succession suggests a considerable change of the hydrologic environment, i.e., the lacustrine environment changed to the entirely subaerially exposed environment, in which weathering and soil formation occurred, followed by lake was submergence, ending soil formation. The lacustrine deposits and the paleosols of Pedotypes 1a and 1b show a considerable lateral extent, implying a wide extent for the lakes.

Thirdly, Pedotype 3 paleosols show the effects of pedogenesis was terminated by debris-flows. In addition, after the occurrence of the debris-flows, these deposits were then pedogenically modified further.

Finally, Pedotype 2 paleosols indicate subaerial exposure, which are covered with the debris-flow deposits, and then afterwards by silt and clay deposition in the stagnant water that immediately covered the debris-flow deposits, without any intervening coarser-grained deposits, such as flood-flow deposits.

It is inferred that the pedogenesis was generally active within the floodplain and marsh environments, as exemplified by

Pedotypes1b and 4, reflecting intermittent sediment supply and episodic changes of lake water level. Conversely, based on Pedotypes 1a, 1b and 2, repeated changes of the paleohydrologic conditions are recognized. These changes are characterized by obvious change of lake water level starting from the bottom of lake, followed by subaerial exposure and soil formation, and then returning to the lake bottom environment.

These drastic changes of depositional environments can be attributed to rapid formation of so called “oxbow lakes” in floodplain areas accompanied with abandonment and local avulsion of channels due to migration of an ephemeral and large-scale channel system (Reineck and Singh, 1973). The rapid and drastic migration of a large channel possibly led a large perturbations of surface water levels in laterally adjacent lakes. However, it is unlikely that such a large channel with rapid migration influenced wide areas of the depositional basin of the Tokiguchi PCF, because thick, coarse-grained channel sediments are not recognized in the study area. As another possibility, it is possible that the changes of the lake water level were caused by formation of a natural dam. The areas of the sedimentary basins around Toki and Tajimi Cities were limited and less than several square kilometers (TCRG, 1999). Therefore, it was such a narrow topographic setting that debris-frows derived from the adjacent mountain slope could have easily blocked the river stream and formed several dammed lakes. Fig. 8 shows the paleoenvironmental reconstruction of the paleolandscape of the middle Miocene Tokiguchi PCF in the study area. It is worth noting here that not all lacustrine sediments might be attributable to the dammed lakes, because there are no direct records showing formation of natural dams from the study area. However, the significant changes of sedimentary and hydrologic conditions recorded in these stratigraphic sections implies major hydrological events, which could be associated with formation of dammed lakes. Today, it is well-known that most landslide dams are small and short-lived (Hsu and Hus, 2009), which suggests that geological examples are probably very scarce. However, several examples from different geological ages were reported from the late Pleistocene sediments in New Mexico State, USA (Reneau and Dethier, 1996). Their report interpreted that the paleosols covered with the debris-flow deposits were evidence of the existence of a dammed lake. In the Japanese Islands, Kojima et al. (2014) described the deposits of dammed lakes stemming from landslides in the Miocene period in Toyama Prefecture, and they reported an *in situ* tree trunk fossil that was buried in the lake sediments that were dammed by the landslide. These descriptions showing the dammed-lake deposits are very similar to those hypothesized for the Tokiguchi PCF in this study.

If these damming events were repeated, then this would imply that slope failure and debris-flow were frequent occurrences during the deposition of the Tokiguchi PCF, at about 10 m.y. before present. The trigger event for these occurrences might have been the frequent occurrences of earthquakes around active faults, rapid subsidence of the sedimentary basins, and effects of high-precipitation events such as typhoons. It is also possible that the intense weathering of bedrocks and/or specific climatic conditions may have been potential triggers of damming event. This implication is supported by the common paleosols which are similar to Ultisols showing mature and well-drained soil environments and/or humid and warm climates. In the previous studies, the sediments derived from the weathered granite rocks were fine-grained clayey detritus (Nagasawa and Kunieda, 1970). The granite was decomposed and had a thick weathering crust, which was interpreted to have formed before the deposition of the PCF (Kimiya, 1981). The paleoclimate was inferred to have been strongly maritime, which had high-precipitation and thus was humid, with a relatively cool summers and warm winters (Miki, 1963). The fossil flora of the formation indicates overall warm temperatures with seasonal and/or frequent precipitation such as associated with a maritime climate (Miki, 1963, Nasu, 1972, Ozaki, 1991 and Momohara and Saito, 2001) during the middle Miocene.

The thick weathered crust and frequent high-precipitation events might also have caused occurrencesof debris-flow and construction of dammed-lakes. Consequently, the isolated hydrologic environments and the development of the mature paleosols imply the wet and humid climatic condition during the long hiatus in the Japanese Islands.

The middle Miocene period is significantly recognized as a period that has appeared and greatly changed the East Asian monsoon (Quade et al., 1989, An et al., 2001; Guo et al., 2002). Clift et al. (2008) and Hoang et al. (2010) suggested that the wetter climate and faster erosion caused by strong East Asian summer monsoon between 10 and 15 Ma on the basis of the mineralogical weathering records and a seismic stratigraphic records of sediments in the South China Sea. Moreover, indication of aridification in the Asian inland after 12 Ma has been suggested on the northeastern Tibetan Plateau based on eolian sediment mass accumulation rates, pollen records and stable isotopic records (Fan et al., 2006; Hui et al., 2011; Zhanfang et al., 2014). In addition, during the late - middle Miocene period, the north equatorial currents and the western boundary water current (Kuroshio Current) have been strengthened as a result of closure of Indonesian Seaway and warm surface water pileup over the far western Pacific (Kennet et al., 1985; Ali et al., 1994; Nishimura and Suparka, 1997; Li et al., 2006). The invasion of the warm water into offshore of Japan is recorded as a longitudinal distribution of shallow - marine tropical to subtropical molluscan faunas (Chinzei, 1978, Tsuchi and Shuto, 1984; Ozawa et al., 1995). Duration of deposition of the Tokiguchi PCF is contemporaneous to short warm period in 10 -11 Ma, suggested by relict tropical Kukinaga Fauna (Inoue, 1992; Ozawa et al., 1995). Accordingly, the synchronization of the development of the warm water current and strengthening of the East Asian summer monsoon may have contributed to the development of the mature paleosols and the geologic events, such as damming events, in the middle Miocene period in the Japanese Islands.

CONCLUSION

The sedimentary environments of the Tokiguchi Porcelain Clay Formation (PCF) were mainly lacustrine environments, which were at least 150 m in lateral extent. The coarse-grained deposits, which formed in channel and alluvial fan environments, are confined to the marginal areas of the basins. The debris-flow apparently reached the lacustrine areas directly within the narrow sedimentary basins.

The paleosols, which are distributed in all mines, are characterized by abundant *in situ* plant fossils such as fine rootlets, roots and tree trunk fossils, as well as well-defined paleosol profiles, indicating the development of mature and well-drained soil environments and/or humid and warm climates. The usual relationship between sedimentary facies and paleosols, was such that the pedogenesis was terminated by floodplain deposition. However, large changes of the paleohydrologic conditions, recorded by saturated conditions in the lacustrine and the pedogenic environments, are attributed to the occurrences of debris-flows, which caused natural damming, and considerable changes of the paleohydrologic conditions. If these damming events occurred repeatedly then this implies debris-flow processes were frequent occurrences during the middle Miocene.

ACKNOWLEDGMENTS

We thank Dr. E. Sasao (Japan Atomic Energy Agency) for offering advice about the Tokai Group for critical review of the manuscript, and Prof. K. Hoyanagi (Shinshu University, Japan) for critical comments about sedimentary facies analysis. We would also like to acknowledge Dr. K. Takahashi (Shinshu University) for polite advice about methods for making thin-sections of unconsolidated sediments, Ms. S. Irie (INPEX Co., Ltd.) for meticulous comments and Dr. H. Nagata (Fu-Sui-Do Co., Ltd.) and Mr. K. Ota (Shinshu University) for insightful comments about damming events. We are grateful to the Tokiguchi-Zaisan Department in Toki municipal office, Hishiya-Kenzai Co., Ltd. and

Okumuraceram Co., Ltd. for approval of entry into the Nakayama, Hishiya and Yamakyu Mines.

REFERENCES CITED

Akamine, H., 1954. Geology of the Environments of Seto, with Special Reference to the Sedimentary Condition of the Formation Containing Ceramic Clays and Lignite. Miscellaneous reports of Research Institute for Natural Resources 34, 25–39 (in Japanese, with English Abstr.).

Ali, J.R., Roberts, S.J., Hall, R., 1994. The closure of the Indo-Pacific Ocean gateway: a new plate tectonic perspective. In: Hehuwat, F. et al. (Eds.), Proceedings of the international workshop on Neogene evolution of Pacific Ocean gateways, Nishimura, Kyoto 10-20.

An, Z., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. Nature 411, 62-66.

Brewer, R., 1976. Fabric and Mineral Analysis of Soils [2nd edition]. Huntington, New York, Robert, E. Krieger Publishing Co. (482 pp.).

Brewer, R., Sleeman, J.R., 1969. The arrangement of constituents in Quaternary soils. Soils Science 107, 435–441.

Chinzei, K., 1978. Neogene molluscan faunas in the Japanese Islands: An ecologic and zoogeographic synthesis. Veliger 21, 155-170.

Clift, P.D., Hodges, K.V., Heslop, D., Hannigan, R., Van Long, H., Calves, G., 2008. Correlation of Himalayan exhumation rates and Asian monsoon intensity. Nature Geoscience 1, 875-880.

Fan, M.J., Song, C.H., Dettman, D.L., Fang, X.M., Xu, X.H., 2006. Intensification of the Asian winter monsoon after 7.4 Ma: grain-size evidence from the Linxia Basin, northeastern Tibetan Plateau, 13.1 to 4.3 Ma. Earth and Planetary Science Letters 248, 186–197.

Fujii, N., 1967. Study on the Fireclay Deposits in Tajimi and Toki Districts, Gifu Prefecture. Bulletin of the Geological Survey of Japan 18, 649–667 (in Japanese, with English Abstr.).

Fujii, N., 1978. Kaolin Clay Deposits in Japan. Journal of the Clay Science Society of Japan 18, 90–105 (in Japanese, with English Abstr.).

Guo, Z., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y., Liu, T.S., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature 416, 159-163.

Hoang, L.V., Clift, P.D., Schwab, A.M., Huuse, M., Nguyen, D.A., Zhen, S., 2010. Large-scale erosional response of SE Asia to monsoon evolution reconstructed from sedimentary records of the Song Hong-Yiggehai and Qiongdongnan basins, South China Sea. Geological Society, London, Special Publications 342, 219-244.

Hoshi, H., Tamura, I., Komatsu, T., 2015. Radiometric ages and petrographic properties of the Oroshi volcanic ash in the lower Tokai Group. The 122nd Annual Meeting of the Geological Society of Japan, Geological Society of Japan, Tokyo, p. 234 (in Japanese, with English Abstr.).

Hsu, Yin-Sung, Hus, Yu-Hsiung, 2009. Impact of earthquake-introduced dammed lakes on channel evolution and bed mobility: Case study of the Tsaoling landslide dammed lake. Journal of Hydrology 374, 43-55.

Hui, Z.C., Li, J.J., Xu, Q.H., Song, C.H., Zhang, J., Wu, F.L., Zhao, Z.J., 2011. Miocene vegetation and climatic changes reconstructed from a sporopollen record of the Tianshui Basin, NE Tibetan Plateau. Palaeogeography, Palaeoclclimatology, Palaeoecology 308, 373–382.

Inoue, K., 1992. Stratigraphy and geologic age of the Miocene Kukinaga Group in Tanegashima Island, Kagoshima Prefecture, Japan. Bulletin of the Mizunami Fossil Museum 19, 347-362 (in Japanese).

Ishida, S., Yokoyama, T., 1969. Tephrochronology, paleogeography and tectonic development of Plio-Pleistocene in Kinki and Tokai districts, Japan –The research of younger Cenozoic strata in Kinki province, part 10-. Quaternary Research 8, 31-43 (in Japanese, with English Abstr.).

Kennett, J.P, Keller, G., Srinivasan, M.S., 1985. Miocene planktonic foraminiferal biogeography and Paleoceanographic development of the Indo-Pacific region. In: Kennett, J.P. (Ed.), The Miocene Ocean: Paleoceanography and biography. Geological Society of America Memories 163, 197–236.

Kimiya, K., 1981. Distribution of weathering crusts and their formative period in the Mikawa Highland, Central Japan. Journal of the Geological Society of Japan 87, 91–102 Distribution of weathering crusts and their formative period in the Mikawa Highland, Central Japan (in Japanese, with English Abstr.).

Kiyono, N., Ishii, K., 1927. Geological Map of Japan, Tajimi with Explanatory Text. Geological Survey of Japan, scale 1:75,000 (in Japanese).

Kojima, S., Nozaki, T., Nagata, H., Tanahashi, R., Kondo, R., Okamura, N., Suzuki, K., Ikeda, A., Nakamura, T., Ohtani, T., 2014. Large-scale landslides in Toyama Prefecture, central

Japan, and their probable relationship with earthquakes. Environment Earth Science 71, 2753–2763.

Kraus, M.J., 1999. Paleosols in clastic sedimentary rocks: their geologic applications. Earth-Science Reviews 47, 41–70.

Li, Q., Li, B., Zhong, G., McGowran, B., Zhou, Z., Wang, J., Wang, P., 2006. Late Miocene development of the western Pacific warm pool: Planktonic foraminifer and oxygen isotopic evidence. Palaeogeography, Palaeoclclimatology, Palaeoecology 237, 465-482.

Makinouchi, T., 1985. Some Problems in the generation stage of the "Second Setouchi Sedimentary Province", with special reference to the sedimentary basin of Lake Tokai. Association for the Geological Collaboration in Japan 29, 53–64 (in Japanese, with English Abstr.).

Makiyama, J., 1950. Regional Geology of Japan 4: Chubu District. Asakura-shoten (233 pp., in Japanese).

Masuda, F., Iseya, F., 1985. "Inverse grading": A Facies structure of flood deposits in meandering rivers. Jounal of the Sedimentological Society of Japan 22 and 23, 108–116 (in Japanese, with English Abstr.).

Matsui, K., 1988. An introduction of soil geography. Tsukiji-shokan (316 pp., in Japanese).

Matsuzawa, I., Kato, R., Kuwahara, T., Kimura, T., Uemura, T., Tsuzuki, Y., 1960. Geology of the southwestern part of Mt. Sanage -With emphasis on geology of the clay as pottery raw material-. Aichi-ken Chita Koyo-atogun Supplementary edition, 1-35 (in Japanese).

McCarthy, P.J., Martini, I.P. and Leckie, D.A., 1998. Use of micromorphology for paleoenvironmental interpretation of complex alluvial paleosols: an examples from the Mill Creek Formation (Albian) of southwestern Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 143, 87-110.

Miall, A.D., 1977. A review of the braided-river depositional environment. Earth-Science Review 13, 1–62.

Miall, A.D., 1996. The Geology of fluvial deposits: Sedimentary Facies, Basin analysis, and Petroleum geology. Springer-Verlag, Berlin (582 pp.).

Miki, S., 1939. On the remains of *Pinus trifolia* n. sp. in the Tertiary from Central Honshu in Japan. The Botanical Magazine 53, 239–246.

Miki, S., 1941. On the change of flora in Eastern Asia since Tertiary Period (Ⅰ). The clay or lignite beds flora in Japan with special reference to the *Pinus trifolia* beds in Central Hondo. Japanese Journal of Botany 11, 237–303.

Miki, S., 1963. Further study of Plant remains in *Pinus trifolia* beds, central Hondo, Japan. Journal of the Society of Earthscientists and Amateurs of Japan, the 31th Anniversary Special Issue, 79–93 (in Japanese).

Momohara, A., Saito, T., 2001. Change of paleovegetation caused by topographic change in and around a sedimentary basin of the Upper Miocene Tokiguchi Porcelain Clay Formation, central Japan. Geoscience Report Shimane University 20, 49–58 (in Japanese, with English Abstr.).

Nagasawa, K., Kunieda, K., 1970. Geology and Mineralogy of Clay Deposits in the Naegi District, Gifu Prefecture. Mining Geology 20, 361–377 (in Japanese, with English Abstr.).

Nakajima, M., Nakayama, K., Momohara, A., Tsukagoshi, M., 2004. Depositional processes of the Miocene Tokiguchi Porcelain Clay Formation and hydraulic behavior of plant macrofossils in the formation: an example from Ohbora, Tajimi, central Japan. Journal of the Geological Society of Japan 110, 204–221 (in Japanese, with English Abstr.).

Nakamura, S., 1929. Subdivision of Diluvium in Japan. Annual Report of Gakujutsu Association 5, 115-117 (in Japanese).

Nakayama, K., 1985. Sedimentary basins of the Tokai Group in the southern part of Toki City, Gifu Prefecture, Central Japan.

Association for the Geological Collaboration in Japan 29, 119–129 (in Japanese, with English Abstr.).

Nakayama, K., 1991. Depositional process of the Neogene Seto Porcelain Clay Formation in the northern part of Seto City, central Japan. Journal of the Geological Society of Japan 97, 945–958 (in Japanese, with English Abstr.).

Nakayama, K., 1999. Sand- and Mud-dominated alluvial-fan deposits of the Miocene Seto Porcelain Clay Formation, Japan. Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology Ⅵ (Special Publication 28 of the International Association of Sedimentologists Series). Wiley-Blackwell, 393–407.

Nasu, T., 1972. Floral and faunal change during the Quaternary in Japan. Biological Science [Seibutsu Kagaku] 24, 1–10 (in Japanese).

Nishimura, S., Suparka, S., 1997. Tectonic approach to the Neogene evolution of Pacific-Indian Ocean seaways. Tectonophysics 281, 1-16.

Osaka Group Research Group, 1951. Osaka Group and the related Cenozoic Formations. Earth Science [Chikyu Kagaku] 6, 49-60 (in Japanese).

Ozaki, K., 1991. Late Miocene and Pliocene floras in central Honshu, Japan. Natural Science Special Issue, Bulletin of

Kanagawa Prefectural Museum, Yokohama (244 pp., in Japanese, with English Abstr.).

Ozawa, T., Inoue, K., Tomida, S., Tanaka, T., Nobuhara, T., 1995. An outline of the Neogene warm-water molluscan faunas in Japan. Fossils 58, 20-27 (in Japanese, with English Abstr.).

Pettijohn, F.J., 1957. Sedimentary Rocks [2nd edition]. Harper and Brothers, New York (718 pp.).

Quade, J., Ceiling, T.E., Bowman, J.E., 1989. Development of Asian monsoon revealed by marked ecological shift in the latest Miocene of northern Pakistan. Nature 342, 163-166.

Reineck, H.E., Singh, I.B., 1973. Depositional sedimentary environments: With Reference to Terrigenous Clastics. Springer-Verlag, Berlin (551 pp.).

Reneau, S.L., Dethier, D.P., 1996. Late Pleistocene landslide-dammed lakes along the Rio Grande, White Rock Canyon, New Mexico. Geological Society of America 108, 1492–1507.

Retallack, G.J., 2001. Soils of the past: An introduction to paleopedology. Blackwell Science, Oxford (404 pp.).

Saneyoshi, K., Nakayama, K., Tsukagoshi, M., 2000. Depositional processes of plant material assemblages in fluvial sediments: examples from plant megafossils in Miocene Tokiguchi Porcelain Clay Formation at Onada mine in Tajimi, central

Japan. Earth Science [Chikyu Kagaku] 54, 127–143 (in Japanese, with English Abstr.).

Soh, W., Taira, A., 1989. Review of Flow Mechanism of Subaqueous Flow as Powder–grain-water Mixtures. Journal of Geography 98, 754–760 (in Japanese).

Soil Survey Staff, 1999. Keys to Soil Taxonomy. Pocahontas Press, Blacksburg, Virginia (600 pp.).

Todo Collaborative Research Group, 1985. A collapse basin in the eastern margin of the Lake Tokai Tokai Group around Nakatsugawa City, Gifu Prefecture. Monograph, Association for the Geological Collaboration in Japan 29, 101–117 (in Japanese, with English Abstr.).

Todo Collaborative Research Group, 1999. Fault bounded inland basin of multiple blocks: an example from the sedimentary basin of the Tokai Group around Tajimi City in Gifu Prefecture, central Japan. Earth Science [Chikyu Kagaku] 53, 291–306 (in Japanese, with English Abstr.).

Tsuchi, R., Shuto, T., 1984. Western Pacific molluscan bio-events and their relation to Neogene planktonic datum planes. In: Ikebe, N., Tsuchi, R. (Eds.), Pacific Neogene Datum Planes Contributions to Biostratigraphy and Chronology. Tokyo Univ. Press, Tokyo, Japan, pp. 75-81.

Tsukagoshi, M., Todo Collaborative Research Group, 1998. *Pinus trifolia* Miki from the Toki Sand and Gravel Formation in Gifu Prefecture, central Japan. Journal of the Geological Society of Japan 104, 495–498 (in Japanese).

Yoshida, F., 1992. Geologic development of the Setouchi Geologic Province since Early Miocene with special reference to the First and Second Setouchi Inland Sea times. Bulletin of the Geological Survey of Japan 43, 43–67 (in Japanese, with English Abstr.).

Yoshida, F., Nakayama, K., Danhara, T., 1997. Fission-track ages from the lower part of Tokai Group, Aichi and Gifu Prefectures, central Japan. Japan Geoscience Union Meeting, Abstracts p. 584 (in Japanese).

Zhanfang, H., Jijun, L., Chunhui, S., Jun, Z., Zhengchuang, H., Shiyue, C., Feng, X., 2014. Understanding Miocene climate evolution in northeastern Tibet: Stable carbon and oxygen isotope records from the Western Tianshui Basin, China. Journal of Earth Science 25, 357-365.

TABLE

Table 1: Sedimentary facies and their interpretations of sedimentary environments in the Tokiguchi Porcelain Clay Formation (PCF).

FIGURE CAPTIONS

Fig. 1: Geological map, stratigraphic nomenclature and correlations of the Tokai Group in the study area of the Toki - Tajimi Cities (modified after TCRG, 1999). Q., Quaternary, Plio., Pliocene, Cret., Cretaceous, Jura., Jurassic, Toki S & G Fm, Toki Sand and Gravel Formation, Tokiguchi PCF., Tokiguchi Porcelain Clay Formation.

Fig. 2: Detailed stratigraphic columns of the Tokiguchi Porcelain Clay Formation (PCF) in three mines.

Fig. 3: Field photographs showing sedimentary Facies. **A)** Facies C; proximal floodplain or alluvial ridge deposit; alternating beds of inversely size-graded sand and sandy silt with carbonaceous material layer (taken in north of the Hishiya Mine). **B)** Facies D; low-density debris-flow deposit; poorly-sorted sandy mud with pebbles and granules. The black arrow indicates concentrations of pebbles to coarse-grained sand (taken in the Yamakyu Mine). **C)** Facies E; high-density debris-flow deposit; the poorly-sorted gravelly sand-silt with allochthonous plant fossils (taken in the Yamakyu Mine). **D)** Facies F; floodplain deposit; alternating beds of inversely size-graded sand and silt - clay with carbonaceous material layer (taken in the north of the Hishiya Mine). **E)** The boundary between Facies G and H. Facies G (upper part of this

picture) shows the back-swamp deposit. Facies H (lower part of this picture) indicates the lake deposit (taken in the north of the Hishiya Mine. **F)** Facies J; swamp deposit; lignite with a small amount of mud matrix (taken in the Nakayama Mine). **G)** Exposure in the Nakayama Mine. The black layer is lignite layer (Facies J). The white arrow indicates the boundary between lake (Facies H) and swamp deposits (Facies J). These lake and swamp deposits show a wide lateral extent, for more than 150 m in width.

Fig. 4: Field photographs of pedogenic structures. For stratigraphic sections see Figure 2. **A)** The black arrows indicate fine rootlet fossils (at the 10.0 m up-section in south of the Hishiya Mine). **B)** The black arrow indicates a root fossil. This paleosol is assigned to Pedotype 1a (at the 4.0 m up-section in the Yamakyu Mine). **C)** Tree trunk fossil buried in low-density debris-flow deposits. This paleosol is assigned to Pedotype 2 (at the 3.5 m up-section in the Yamakyu Mine). **D)** The soil horizons in a paleosol in a paleosol (at the 10.0 m up-section in the north of the Hishiya Mine. A; A horizon, B; Bw horizon, C; C horizon).

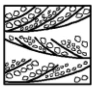
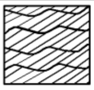
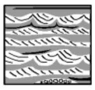
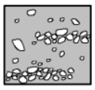
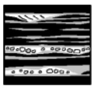
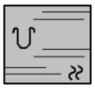
Fig. 5: Thin-section photomicrographs of pedogenic materials. PPL= plane-polarized light, XPL= cross-polarized light. For stratigraphic sections see Figures 2 and 7. **A)** Clinobimasepic

microfabric (XPL); Network of highly birefringent streaks in two preferred directions and at a low angle (Bt horizon within Pedotype 1a at the 5.0 m section in north of the Hishiya Mine). **B)** Masepic microfabric (XPL); Highly birefringent streaks forming an extensive crossing network (Bw horizon within Pedotype 1a at the 21 m section in north of the Hishiya Mine). **C)** Omnisepic microfabric (XPL); All highly birefringent, oriented plasma (Bw horizon in Pedotype 2 at the 1.5 m section in the Nakayama Mine). **D)** The arrows indicate grain cutans (XPL. C horizon within Pedotype 4 at the 3.0 m section in north of the Hishiya Mine). **E)** Burrow filled by clay (PPL. Bt horizon of Pedotype 1a at the 5.0 m section in north of the Hishiya Mine). **F)** Biopore filled by clay showing laminated structure (PPL. Bt horizon within Pedotype 2 at the 4.5 m section in the Yamakyu Mine).

Fig. 6: Pedotypes and the relationships between sedimentary facies and paleosols. For stratigraphic sections see Figures 2 and 7. Pedotype 1a; at the 5.0 m section in north of the Hishiya Mine. Pedotype 1b; at the 14.0 m section in the Nakayama Mine. Pedotype 2; at the 3.5 m section in the Yamakyu Mine. Pedotype 3; at the1.0 m section in the Yamakyu Mine. Pedotype 4; at the 12.0 m section in north of the Hishiya Mine. Pedotype 5; at the 5.0 m section in the Yamakyu Mine.

Fig. 7: The stratigraphic distributions of the Pedotypes shown in Figure 6.

Fig. 8: Paleoenvironmental and paleolandscape reconstruction of the middle Miocene Tokiguhi PCF in the Hishiya and Nakayama Mines.

Facies	Typical column	Lithofacies	Sedimentary structures	Adjacent facies: Vertical	Adjacent facies: Lateral	Thickness (cm)	Interpretation: Mechanism	Interpretation: Sedimentary environment	Facies (Miall, 1977; 1996)
A		trough cross-beds of sandy and pebble sized gravel, sand graine-sizes range from very coarse- to fine-grained	trough cross-beds, faint cross-beds, normal size-grading, erosional bases	B, C, E, F, H, J	B, C, F	40～110	traction (upper to lower flow -regime)	gravelly and sandy channel bar	Gt
B		ripple laminated fine- to very fine-grained sand and occasionally coarse-grained sand	ripple, small planar cross-beds, normal size-grading, erosional bases	A, C, D, F, G, H, J	A, C, F, G	30～50	traction (lower flow -regime)	sandy channel bar	Sr
C		alternating and/or lenticular beds of well-sorted, very coarse- to medium-grained sand and sandy silt with small amounts of carbonaceous materials	ripple, foreset laminae and convolute laminae, normal and reverse size-gradings, erosional bases	A, B, E, F	A, B, F	20～40	traction, suspension	proximal floodplain or alluvial ridge	–
D		massive beds of poorly-sorted muddy sand with pebble- to granule- and gravel-sized materials	matrix supported, gravels are dispersed in massive sandy silt with disordered internal arrangement	B, F, H	H, J	20～60	low-density debris-flow	lake or swamp	Gmm
E		massive beds of gravel, poorly-soted sandy silt, and concentrations of allochthonous plant fossils	clast supported gravel layer with abundant allochthonous plant fossils	A, C, F, H, I, J	H, I, J	30～90	high-density debris-flow	lake or swamp	Gci
F		alternating beds of well-sorted medium- to very fine-grained sand and silt to clay with some sparse carbonaceous materials	faint parallel laminae, foreset laminae, convolute bases, flame structure, bioturbation	A, B, C, D, E, G, H, J	C, H, I, J	20～130	traction, suspension	floodplain	Fl
G		alternating beds of thick silt to clay with lignite beds, and lenticular coarse- to fine-grained sand layer and gravelly sand layer	climbing-ripple and erosional scoured bases by coarse grained layers	B, C, D, F, G, H, J	B, C, H, I, J	40～150	traction, suspension	back-swamp with crevasse splay	(Fl)
H		well-sorted silt to clay	faint parallel laminae, tubular burrows	A, B, D, E, F, G, I, J	A, B, D, E, F, G, I, J	30～280	suspension	lake center	Fsm
I		carbonaceous silt to clay with allochthonous plant fossils and some peat layer	abundant allochthonous plant fossils are preserved on bedding planes	E, F, G, H, J	G, H, J	30～120	suspension	marsh	C
J		lignite with minor silt to clay matrix	abundant allochthonous plant fossils are preserved on bedding planes	A, B, E, F, G, H, I	D, E, F, G, H, I	30～120	suspension	swamp	

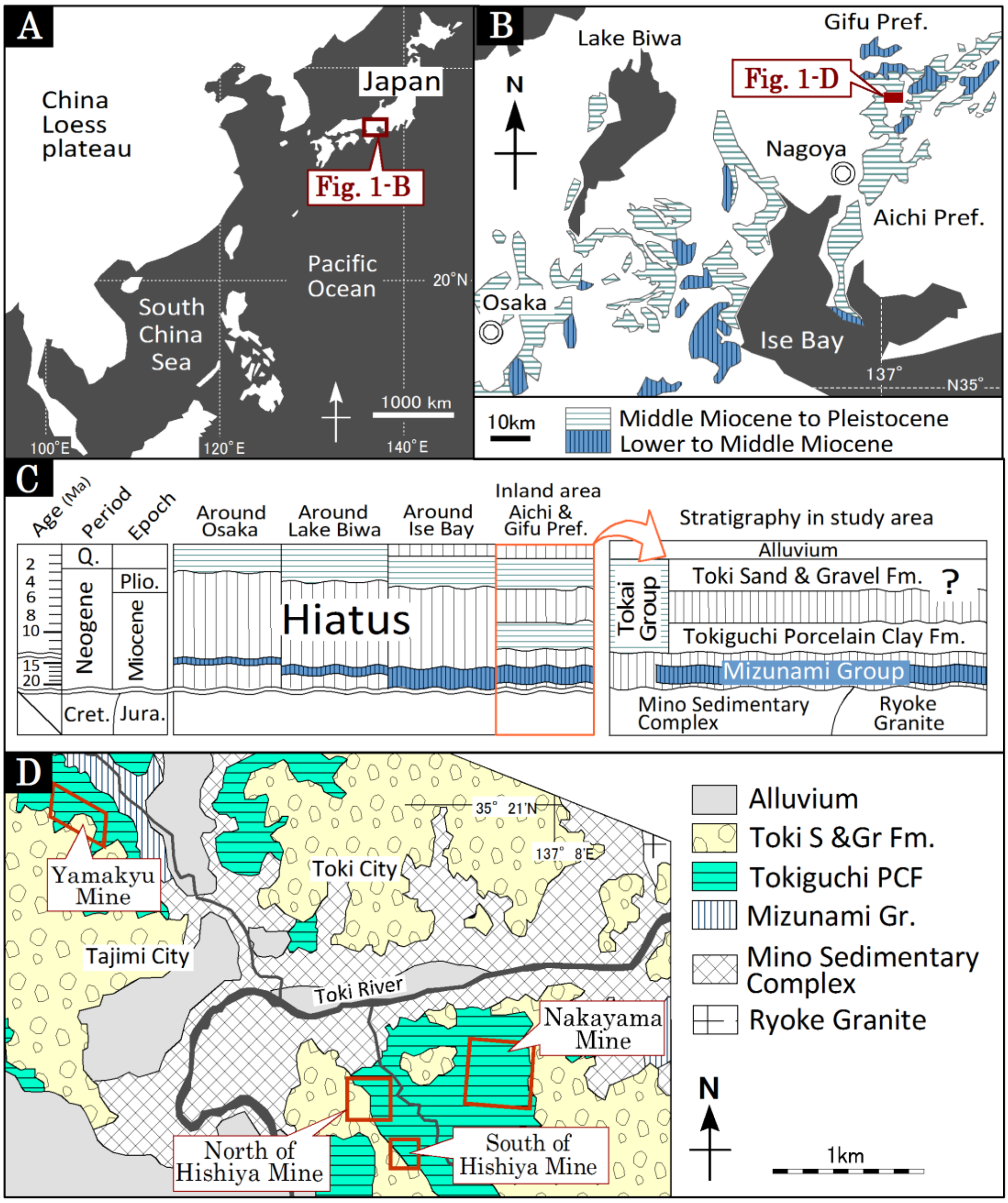
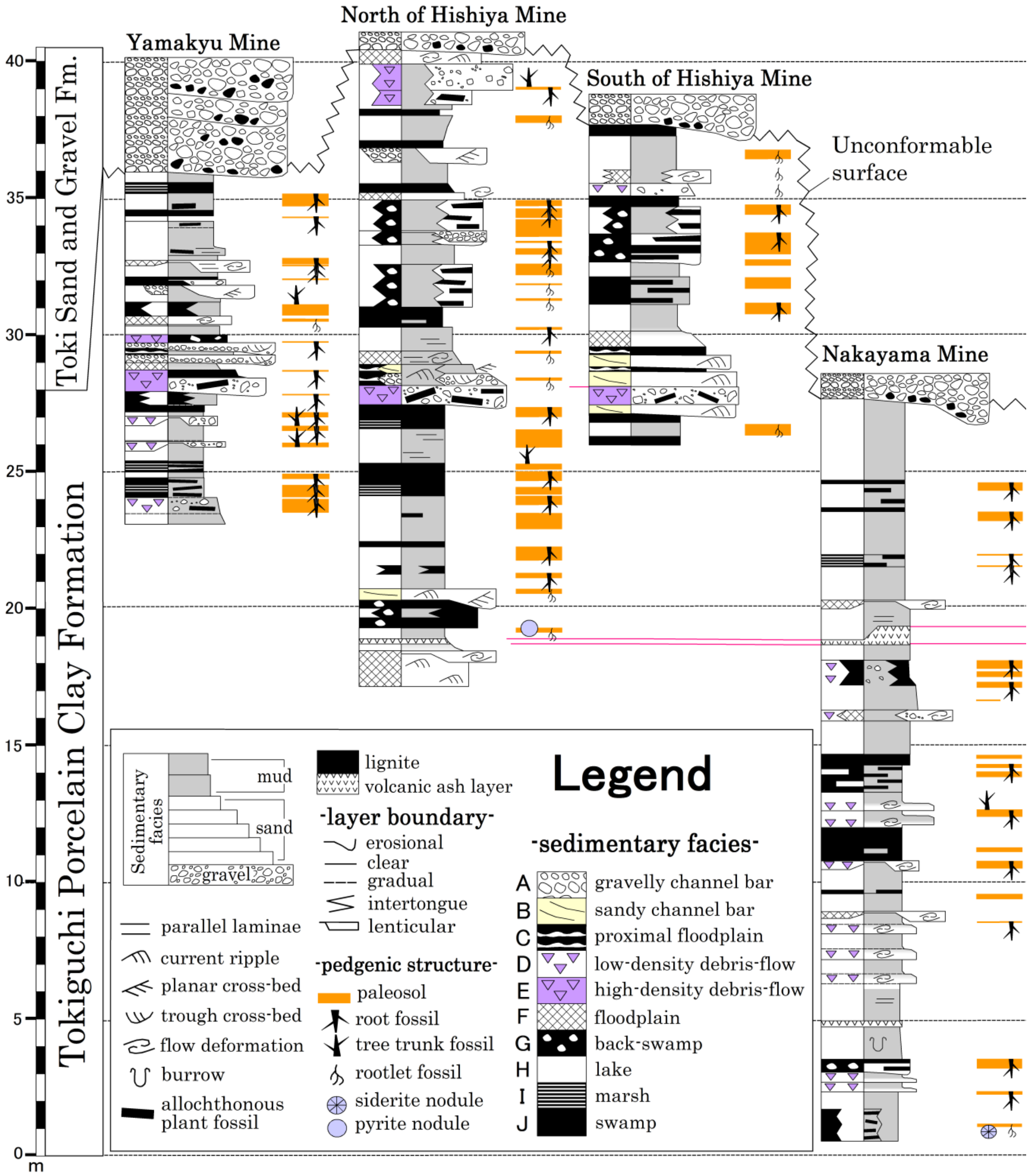

A
China
Loess
plateau
Japan
Fig. 1-B
Pacific
Ocean
20°N
South
China
Sea
1000 km
100°E
120°E
140°E
B
Lake Biwa
Gifu Pref.
Fig. 1-D
N
Nagoya
Aichi Pref.
Osaka
Ise Bay
137°
N35°
10km
Middle Miocene to Pleistocene
Lower to Middle Miocene
C
Age (Ma)
Period
Epoch
Around Osaka
Around Lake Biwa
Around Ise Bay
Inland area Aichi & Gifu Pref.
Stratigraphy in study area
Q.
Plio.
Neogene
Miocene
Cret.
Jura.
Hiatus
Alluvium
Toki Sand & Gravel Fm.
?
Tokai Group
Tokiguchi Porcelain Clay Fm.
Mizunami Group
Mino Sedimentary Complex
Ryoke Granite
D
Yamakyu Mine
Toki City
35° 21'N
137° 8'E
Tajimi City
Toki River
Nakayama Mine
North of Hishiya Mine
South of Hishiya Mine
Alluvium
Toki S &Gr Fm.
Tokiguchi PCF
Mizunami Gr.
Mino Sedimentary Complex
Ryoke Granite
N
1km

Fig. 1



Yamakyu Mine
North of Hishiya Mine
South of Hishiya Mine
Nakayama Mine
Unconformable surface
Toki Sand and Gravel Fm.
Tokiguchi Porcelain Clay Formation
40
35
30
25
20
15
10
5
0
m
Legend
Sedimentary facies
mud
sand
gravel
lignite
volcanic ash layer
-layer boundary-
erosional
clear
gradual
intertongue
lenticular
parallel laminae
current ripple
planar cross-bed
trough cross-bed
flow deformation
burrow
allochthonous plant fossil
-pedgenic structure-
paleosol
root fossil
tree trunk fossil
rootlet fossil
siderite nodule
pyrite nodule
-sedimentary facies-
A gravelly channel bar
B sandy channel bar
C proximal floodplain
D low-density debris-flow
E high-density debris-flow
F floodplain
G back-swamp
H lake
I marsh
J swamp

Fig. 2

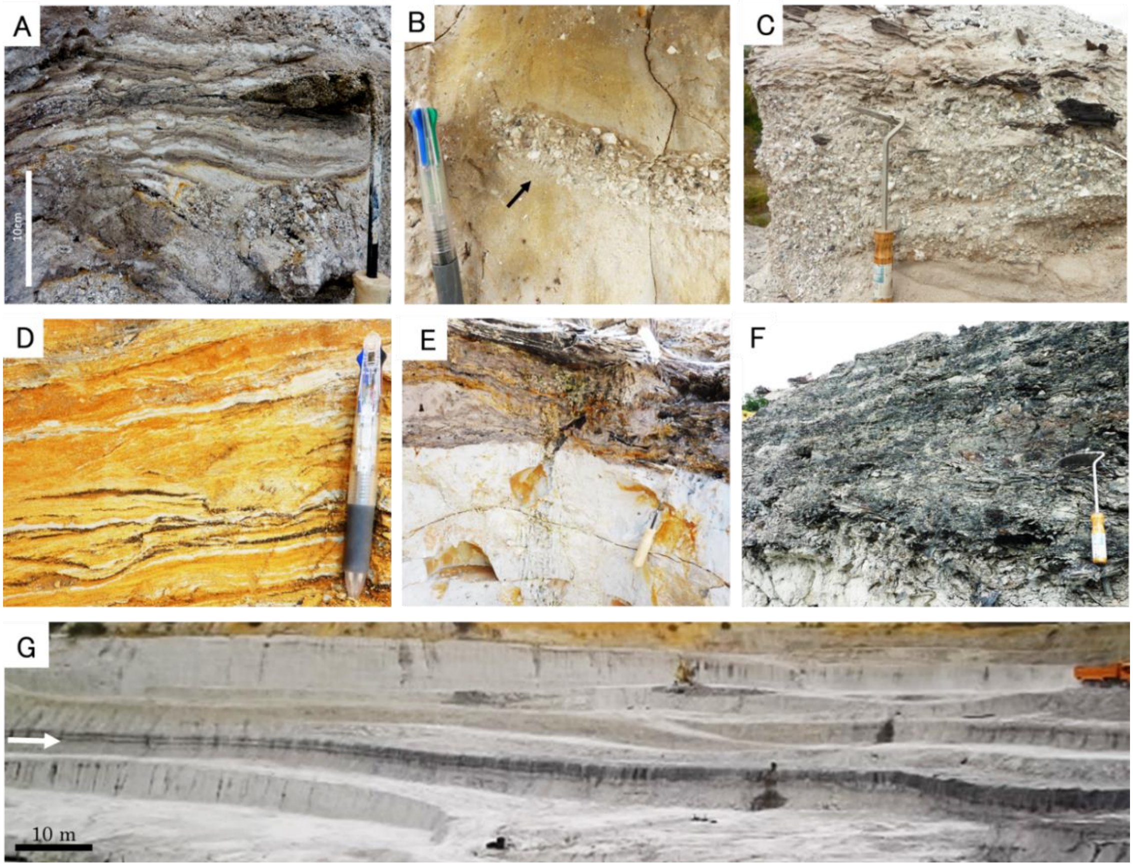


Fig. 3

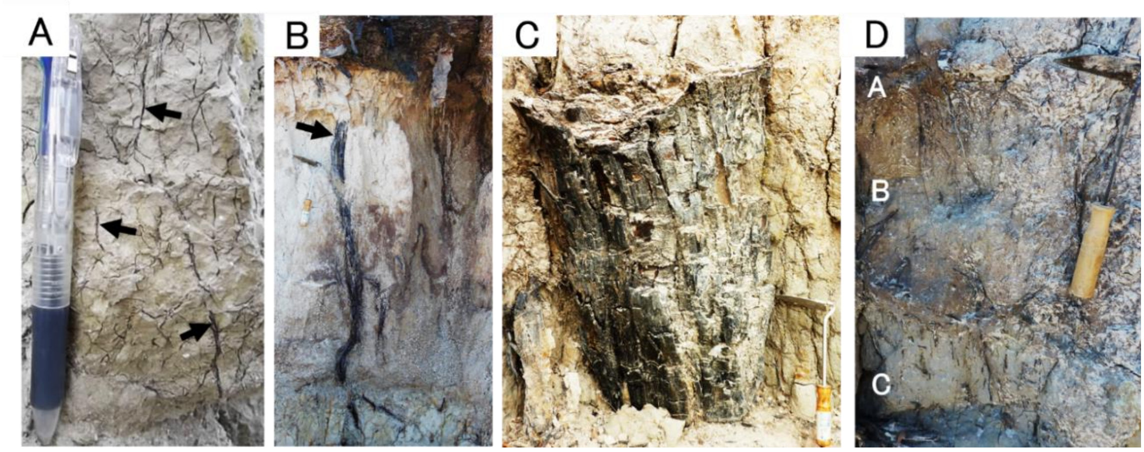


Fig. 4

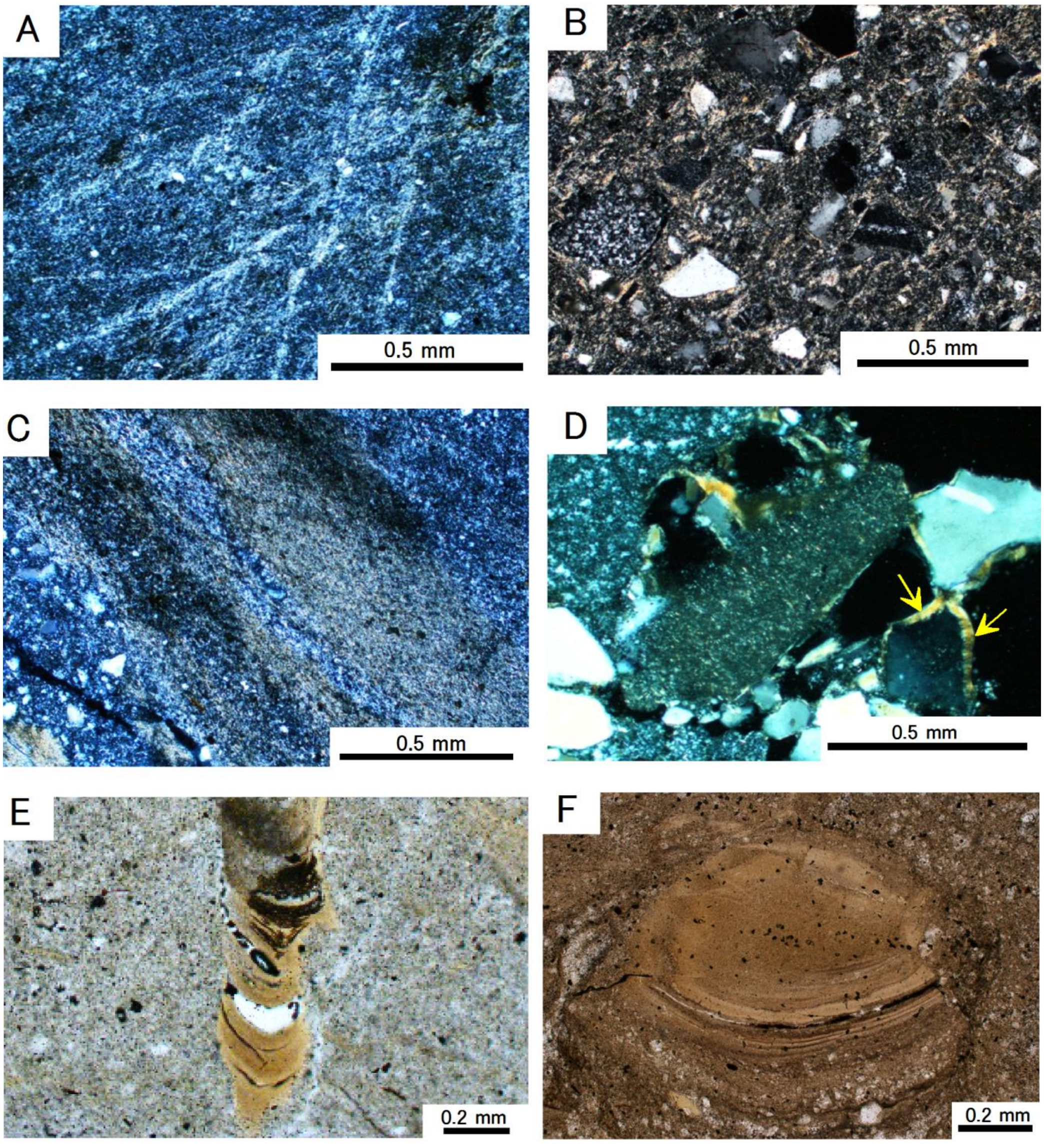
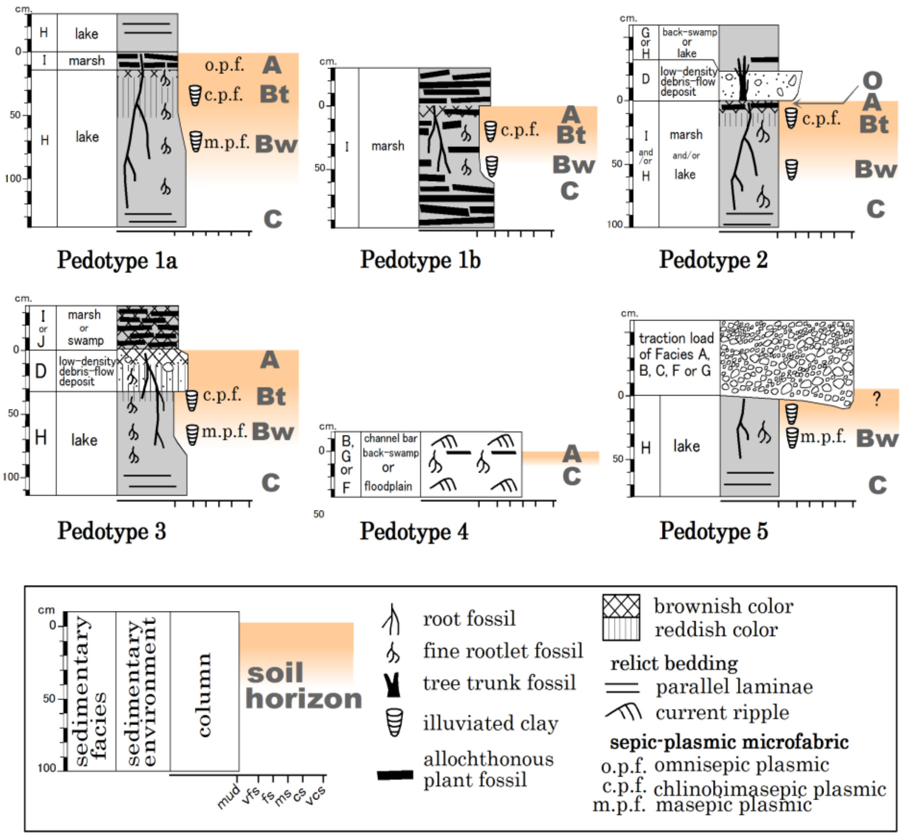
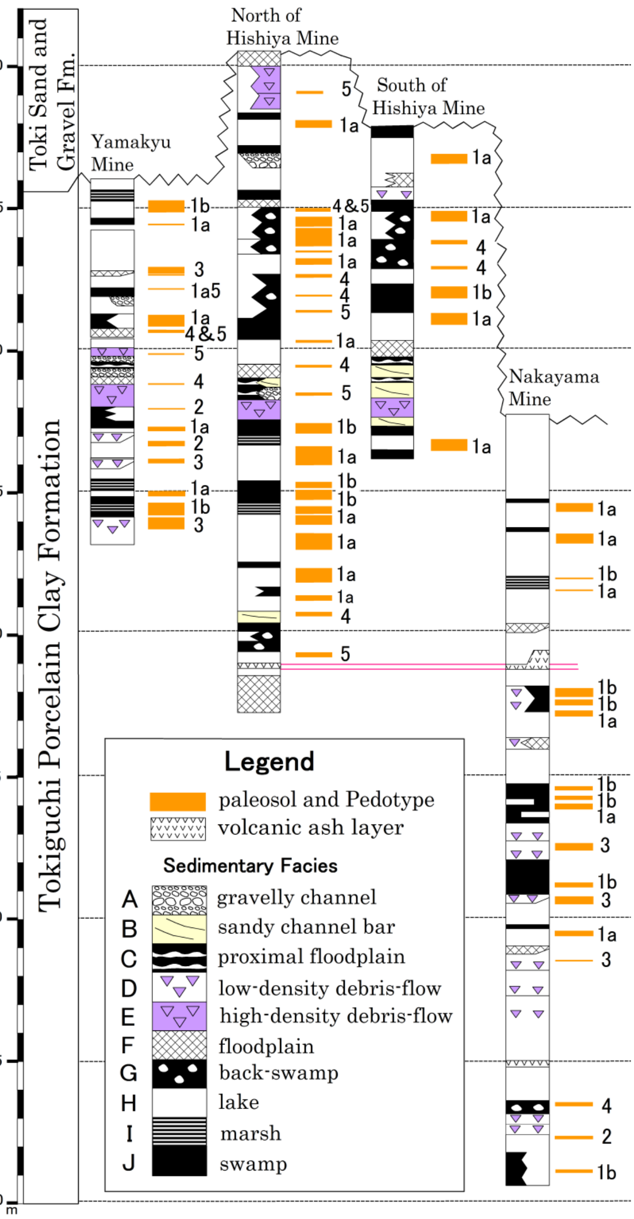


Fig. 5



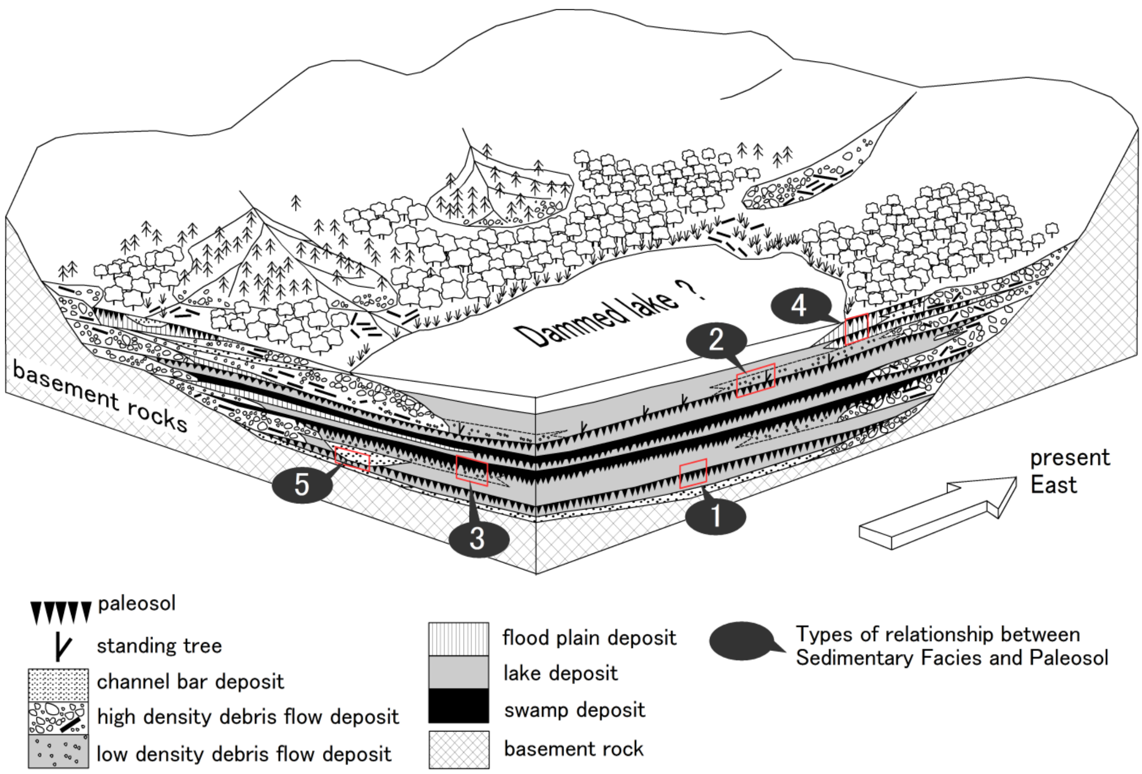
Pedotype 1a
Pedotype 1b
Pedotype 2
Pedotype 3
Pedotype 4
Pedotype 5
lake
marsh
marsh or swamp
back-swamp or lake
low-density debris-flow deposit
marsh and/or lake
channel bar back-swamp or floodplain
traction load of Facies A, B, C, F or G
o.p.f.
c.p.f.
m.p.f.
O
A
Bt
Bw
C
?
sedimentary facies
sedimentary environment
column
soil horizon
mud
vfs
fs
ms
cs
vcs
root fossil
fine rootlet fossil
tree trunk fossil
illuviated clay
allochthonous plant fossil
brownish color
reddish color
relict bedding
parallel laminae
current ripple
sepic-plasmic microfabric
o.p.f. omnisepic plasmic
c.p.f. chlinobimasepic plasmic
m.p.f. masepic plasmic

Fig. 6



Toki Sand and Gravel Fm.
Tokiguchi Porcelain Clay Formation
Yamakyu Mine
North of Hishiya Mine
South of Hishiya Mine
Nakayama Mine
Legend
paleosol and Pedotype
volcanic ash layer
Sedimentary Facies
A gravelly channel
B sandy channel bar
C proximal floodplain
D low-density debris-flow
E high-density debris-flow
F floodplain
G back-swamp
H lake
I marsh
J swamp

Fig. 7



Dammed lake ?
basement rocks
present
East
1
2
3
4
5
paleosol
standing tree
channel bar deposit
high density debris flow deposit
low density debris flow deposit
flood plain deposit
lake deposit
swamp deposit
basement rock
Types of relationship between
Sedimentary Facies and Paleosol

Fig. 8