SEDIMENTARY ENVIRONMENT OF DINOSAUR FOSSIL BEARING SUCCESSIONS OF THE LOWER CRETACEOUS KITADANI FORMATION, TETORI GROUP, KATSUYAMA CITY, FUKUI, JAPAN

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ABSTRACT

The Lower Cretaceous Kitadani Formation, Tetori Group in the Kitadani Quarry yields a large quantity of nonmarine fossils including dinosaurs. The quarry has large exposure with westward and northward facing surfaces, which allow to analyze three-dimensional variations in composition and geometry. The successions at the quarry consist of clastic rocks of the Point Bar Facies, the Abandoned Channel-fill Facies and the Over Bank Facies. The sandy Point Bar Facies is characterized by sheet like geometry and sedimentary structures caused by lateral accretion. The Abandoned Channel-fill Facies is mainly composed of fine-grained sediments, which were considered to be deposited by suspension fall-out. The depth of abandoned channel is as same as the thickness of the unit of the Point Bar Facies. The Over Bank Facies is characterized by poorly sorted nature of deposits. Crevasse splay sandstones are frequent in the Over Bank Facies. Sedimentary environment of an alluvial plain formed by meandering river is reconstructed.

Key words : sedimentary environment, alluvial plain, meandering river, Kitadani Formation, Tetori Group, Lower Cretaceous

鈴木茂之・柴田正輝・東 洋一・湯川弘一・関谷 透・正岡祐人 (2015) 福井県勝山市,下部白亜系手取層 群北谷層の恐竜発掘露頭から復元される堆積環境.福井県立恐竜博物館紀要 14:1-9.

福井県勝山市の恐竜発掘露頭からは保存が良好な恐竜化石をはじめとする多様な化石を産出している.継続的な発掘によって露頭は拡大し、北向きと西向き及び一部南向きの法面全面に地層が露出している.この入り組んだ露頭形状は地層の三次元的な解析に好都合である.本研究の調査は2013年と2014年の発掘期間中に行われた.露出する白亜紀前期の北谷層は突州堆積相(淘汰の良い粗粒砂岩主体の厚さ3~5m程度のユニット)、オーバーバンク堆積相(泥岩主体で泥質砂岩を挟む)、放棄流路埋積相(泥岩主体で流路を充填する)からなる. 突州堆積相の底は侵食性の明瞭な面で,この相を被うオーバーバンク堆積相とともに上方細粒化をなす. 突州堆積相には側方に地層が形成されたことを示す堆積構造がある.放棄流路埋積相は三日月湖があったことを示す.以上のことからこれらの地層が蛇行河川によって堆積したことが確認できる.

INTRODUCTION

The study site, the Kitadani Quarry, is located in Katsuyama City, Fukui Prefecture, Japan (N $36^{\circ}7'$, E $136^{\circ}32'$). Occurrence of non-marine molluscan fossils and plant fossils has been known

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(Tamura, 1990; Yabe and Shibata, 2011). A number of various dinosaur fossils has been discovered from the excavation site together with turtles, crocodiles, fishes, eggshells and footprints (Azuma, 2003). A continuous paleontological excavation at the site have resulted in the discovery of new species of dinosaur fossils such as *Fukuiraptor kitadaniensis* (Azuma and Currie, 2000), *Fukuisaurus tetoriensis* (Kobayashi and Azuma, 2003), *Fukuittan nipponensis* (Azuma and Shibata, 2010) and *Koshisaurus katsuyama* (Shibata and Azuma, 2015). The

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FIGURE 1. Location of the study site.

successions of the site belong to the Lower Cretaceous Kitadani Formation of the Akaiwa Subgroup, the uppermost subgroup of the Tetori Group. General facies analysis of the Tetori Group was studied by Masuda et al. (1991) and marine to lacustrine, delta and fluvial environments were reconstructed. Okazaki and Isaji (2008) analyzed sedimentary facies of the Kuwajima Formation and interpreted that the successions deposited in bay, bird-foot delta and meandering river environments. Sedimentary environment of the Kitadani Formation was studied by Masuda et al. (1991) as an excursion guide without critical descriptions for facies. Yabe and Shibata (2011) studied plant fossil Brachyphyllum of the Kitadani Quarry and obtained depositional environment of the fossil beds of plant fossils as a floodplain of meandering river together with observation of facies. However studied facies are limited in the fossil bed. Aim of this study is to understand depositional environment of the succession of the Kitadani Quarry. The outcrop of the Quarry with virtually complete exposure was sketched during the dinosaur excavation project in 2013 and 2014. Observations of facies on polished cross sections of hand specimens and thin sections under microscope are also performed. As emphasized by Miall (1985), three-dimensional observation was done to describe facies. The successions are considered to be a meandering river deposits which are characterized by "fining upward unit with sharp base" (Allen, 1964). Information from fossil beds provides very detail reconstruction of paleoenvironments. Facies analysis of individual fossil beds is under investigation and will be published later.

GEOLOGICAL SETTING

The study area (the Takinami River area) is situated in the Hida Belt, distributed in Japan Sea side of Central Japan (Yamashita, 1957). The Hida Belt was a part of the Eurasian Continent in pre-Miocene and is composed of the Pre-Cambrian metamorphic and lower to middle Jurassic granitic basement and Middle Jurassic to Lower Cretaceous sedimentary covers of the Tetori Group (e.g., Suwa, 1990) which yield dinosaur fossils (Figs. 1, 2). The Hida Belt is separated by a large shear zone, often called the Hida-gaien Belt, from the major part of the Japan island arc.

The Tetori Group is generally subdivided into three subgroups; the Kuzuryu, Itoshiro and Akaiwa subgroups in ascending order (Maeda, 1961), but only the Akaiwa subgroup is distributed in this area (Maeda, 1958). The Lower Cretaceous Akaiwa Subgroup in this area comprises lower Akaiwa Formation and upper Kitadani Formation (Maeda, 1958) and the upper part of the latter formation is exposed in the Kitadani Quarry (Fig. 3).

SEDIMENTARY FACIES

The sediments exposed in the Quarry are subdivided into Point



FIGURE 2. Outcrop of the Kitadani Quarry, showing the sketch parts.



FIGURE 3. Stratigraphy of the Tetori Group.

Bar Facies, Abandoned Channel-fill Facies and Over Bank Facies (Figs. 4a, 5a, 6a).

Point Bar Facies

This facies is composed of gravel sandstone subfacies (GS) and coarse- to medium-grained sandstone subfacies (CMS). White colored sandstones of the Point Bar Facies are easy to be distinguished from darker sediments of another facies. The base of the facies has sharp bottom erosion surface. The parallel planar layer of the facies continues laterally more than 80 m with 3 to 5 m in thickness.

Gravel sandstone subfacies (GS): This subfacies is mainly composed of coarse-grained sand and minor granule to pebble size clasts (Fig. 4b). Gravel clasts are rounded to subrounded and are composed of siliceous durable rocks. The GS is limited in at the base of the Point Bar Facies. The bases of the GS are sharp and in places erosional (Fig. 4b, c). The boundary between GS and CMS is not sharp.

Coarse- to medium-grained sandstone subfacies (CMS): Well to moderate sorted, coarse- to medium-grained sandstone characterizes the CMS. Large scale epsilon cross-stratification (Fig. 4c) and trough cross-stratification (Fig. 4d) are typical structures. In Figure 5a, two types of trough cross-stratification are recognized, type A and type B. A geometry of the type A trough cross-stratification is observed in the section of Figure 5a. In longitudinal East to West (EW) section, the trough crossstratification appear as large scale cross-stratification (Fig. 5a, c). Trough structures are obvious in transverse North to South (NS) section (Fig. 5b). The sandstone indicates mainly trough cross-stratification with basal finer-grained laminated thin layer. The thin layer is composed of fine- to coarse-grained laminated sandstone of a few centimeters in thickness or thin millimeter scale layer of plant fragments. Type B trough cross-stratification is composed of medium- to coarse-grained sandstone with well to moderate sorting (Fig. 4d). In the trough cross-stratification of Figure 5a, red arrows indicate that the southern trough laminae cut previous laminae. It indicates the unit was formed by lateral accretion from north to south.

In the case of Figure 5a, the GS is lacking and the CMS has sharp erosional base. Rip up shale clasts are common in the CMS (Fig. 4e). The sandstone of the CMS is characterized by a little mud matrix under microscope (Fig. 4f). The composition of the sandstones is rich in quartz and feldspar and associated with mica and felsic igneous and sedimentary rock fragments (Fig. 4f).

Abandoned Channel-fill Facies

This facies is subdivided into slumped mudstone and sandstone subfacies (SMS), black clayey mudstone subfacies (BCM), alternation of mudstone and sandstone subfacies (AMS) and organic structureless mudstone subfacies (OSM). The Facies filled up the channel structure (about 35 m in width and 7 m in depth) (Fig. 5a, b). The basal surface of the facies is sharp (Fig. 5a).

Slumped mudstone and sandstone subfacies (SMS): The SMS covers the bottom and slope of abandoned channel. The slope dips about 10 to 15 degrees to the bottom. Irregularly deformed disrupted sand and mud lenses and layers are floated in black clayey mudstone. Coarse- to fine-grained sandstone lenses have irregular shape. Tight slump folds with bottom-ward vergence are formed (Fig. 5d). Bivalve fossils are found in mudstone and irregular balls and lenses of coarse-grained sandstone (Fig. 5e).

Black clayey mudstone subfacies (BCM): The BCM is mainly composed of organic black clayey mudstone and characterized by silt-laminated mudstones and thin parallel continuous fine-grained sandstone layers. Intercalated parallel to lenticular fine-grained sandstone layers are 1 to 3 cm in thickness. A few normally graded beds with minor erosional scour are found (Fig. 5f). Crude ripple structures are also found (Fig. 5g).

Alternation of mudstone and sandstone subfacies (AMS): The AMS is composed of black clayey mudstone and 5 to 10 cm planar parallel beds of fine-grained sandstone (Fig. 5h). Parallel lamination (Fig. 5i) in mudstone is common. Sandstone layers comprise multiple structure, for example, normal grading, parallel layer and convolute lamination in Figure 5j. The sandstone layers dips toward center of the channel and form large scale crossstratification (Fig. 5a) which is the typical structure of the AMS.

Organic structureless mudstone subfacies (OSM): The OSM is characterized by homogeneous structureless mudstone. The mudstone is blackish due to high organic contents. It also contains

fine- to medium-grained sand clasts. The fossil of dinosaur bones and teeth, turtles and crocodiles, non-marine molluscan shells, fish scales as well as plants (mainly leaves) and charophyte gyrogonites were yielded in this subfacies. Most bivalve fossils occurred as fragment of disarticulated valves but articulated valves are also found (Fig. 5k).

Over Bank Facies

This facies is subdivided into parallel bedded sandstone subfacies (PBS), lenticular sandstone subfacies (LS), black mudstone subfacies (BM) and gray to green mudstone subfacies (GGM).

Parallel bedded sandstone subfacies (PBS): Darker colored fine- to medium-grained massive sandstone layered unit characterizes the PBS, which is intercalated in mudstone of the Over Bank Facies (generally in the gray to green mudstone subfacies) (Fig. 6a, b). The thickness of the unit is 10 cm to 1 m. The tops of the units vary from sharp to gradational. Foot prints of dinosaurs are found on sharp upper surface of the layers. Poorly sorted nature with mud matrix is quite different from the sandstone of the CMS of the Point Bar Facies (Fig. 6c).

Lenticular sandstone subfacies (LS): The sandstone is grayish fine- to coarse-grained and moderately sorted. The LS have two types of shapes: convex upward shape (Fig. 6d) and convex downward shape. Convex upward type is 50 cm to 1 m thick with cross laminae in some parts. This type occurred in the black mudstone subfacies. Convex downward type, ca. 1 to 2 m thick with erosional bottom surface has also cross laminae. This type of sandstone lenses are continued to the sandstone layer of the PBS.

Black mudstone subfacies (BM): The BM is composed of black sandy mudstone and usually overlie the Point Bar Facies (Figs. 4a, 6a). The boundary with the Point Bar Facies is not sharp. Parallel laminated fine-grained sandstone layer (Fig. 6e, and P in Fig. 6a), current rippled fine-grained sandstone layer and poorly sorted fine- to medium grained sandstone lenses (10 to 30 cm in thickness) are observed. Many fossils were obtained from this subfacies.

Gray to green mudstone subfacies (GGM): The subfacies is mainly composed of grayish to greenish colored sandy massive mudstone. Discontinuous laminae of fine-grained sandstone are occasionally intercalated. Clay mineral rich zone with calcareous nodule characterize the GGM (Fig. 6f). Slaking caused by clay mineral formation penetrates this subfacies (Fig. 6g).

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Point Bar Facies

Erosive base of conglomerate and coarse-grained sandstone followed by coarse- to medium-grained sandstone, which is overlain by mudstone, is a typical fining-upwards unit of alluvial deposit (Allen, 1965a). Well to moderately sorted sandstone is



FIGURE 4. **a**, Sketch of the Point Bar Facies and Over Bank Facies of the Kitadani Quarry. Blank arrows indicate limits of the facies; **b**, Gravel sandstone subfacies (GS) with sharp base.Width of view 40 cm; **c**, Epsilon cross-stratification (arrows) of coarse- to medium-grained sandstone subfacies (CMS). Gravel sandstone subfacies (GS) (about 10 to 20 cm in thickness) is at the bottom of the Point Bar Facies. Width of view 3 m; **d**, Type B trough cross-stratifications of CMS (In the sketch of Fig. 5a). The trough laminae cut previous laminae (arrow). Width of view 4 m; **e**, Well sorted coarse-grained sandstone with shale clast (arrows) of CMS. Width of view 5 cm; **f**, Microphoto of sandstone from CMS. Well sorted clasts with very poor mud matrix. Q: quartz, F: Feldspar, R: Rhyolitic rock fragment. Width of view 1.8 mm.

considered to be deposited under continuous current. Crossstratifications indicate dunes formed by current. Jackson (1976) described fining-upward sand unit with cross-stratifications from the cutbanks and trenches in recent point bar of the lower Wabash River. Large-scale epsilon cross-stratification of the CMS indicates that the subfacies were formed by a lateral accretion (Allen, 1970). The trough cross-stratification of type B in Figure 5a are also considered to be deposited by lateral-accretion. These features support that the units were formed by a meandering river. The GS and CMS are considered to be channel lag and point bar deposits respectively. Upper limit of the facies is almost horizontal and swell structure (Nanson, 1980) described from Beatton River was not remained. The upper part of the point bar is considered to be rarely preserved as Plint (1983) suggested.

Abandoned Channel-fill Facies

Convex downward and channel fill geometry of deposit is most essential feature of the facies. And fine-grained lithofacies are typical (Miall, 1996). The sharp contact between the Abandoned Channel-fill Facies and the Point Bar Facies is also described in the Middle Eocene of southern England (Plint, 1983). It is considered to be caused by rapid abandonment of the channel (Allen, 1965b). A mechanism of chute cutoff, which forms new abandoned channel, is described by Constantine et al. (2010).

Irregularity of lenticular sandstone of the slumped mudstone and sandstone subfacies (SMS) is considered to be caused by a syn-sedimentary deformation. The folds with bottom-ward vergence are regarded as slump folds. Plint (1983) reported a



FIGURE 5. **a**, Sketch of the three Facies in NS and EW direction cut of the Kitadani Quarry. **A**; type A trough cross-stratification. **B**; type B trough cross-stratification; **b**, NS section of sketched outcrop in Figure 5a; **c**, EW section of sketched outcrop in Figure 5a; **d**, Slump fold of the slumped mudstone and sandstone subfacies (SMS). Arrows indicate hinges of tight slump fold; **e**, Bivalve fossils (arrows) in the SMS; **f**, Thin fine-grained graded sandstone layer (G) and very thin layer of fine-grained sandstone (T) in the black clayey mudstone subfacies (BCM). Lens cap 5 cm; **g**, Fine-grained sandstone layers in the BCM. Arrows indicate crude ripples. Lens cap 5 cm; **h**, Alternation of mudstone and sandstone subfacies (AMS). Arrow 1: collecting point of the sample in Figure 5i. Width of view 0.7 m; **i**, Polished sample of mudstone of the AMS. Parallel lamination of mudstone and siltstone/fine-grained sandstone. Width of sample 12 cm; **j**, Polished sample of sandstone of the AMS. Width of sample 7 cm. G; normal grading. C; convolute lamination; **k**, Organic structureless mudstone subfacies (OSM) with non-marine molluscan fossils. Width of view 15 cm.



FIGURE 6. **a**, Sketch of the Over Bank Facies and Point Bar Facies of the Kitadani Quarry. Meshed black: fossil wood, P: horizon of parallel laminated finegrained sandstone; **b**, Parallel bedded sandstone subfacies (PBS) intercalated in gray to green mudstone subfacies (GGM); **c**, Microphoto of sandstone from the PBS. O: plant fragment, M: mud matrix. Width of view 1.8 mm; **d**, Convex upward type of the lenticular sandstone subfacies (LS) which is cut by the fossil stump. Width of view 4 m; **e**, Black mudstone subfacies (BM) with parallel lamination of fine-grained sandstone. Width of view 50 cm; **f**, Gray to green mudstone subfacies (GGM) with calcareous nodules (arrows). Width of view 1.5 m; **g**, Calcareous nodules (arrows) of the GGM. Slaking penetrates this subfacies. Width of view 50 cm.

slump fold at the bottom of "channel-plug". Lenses of coarsegrained sandstone were inferred to be derived from eroded CMS. Bivalve fossils in the SMS were thought to be derived from shallower part. The SMS is interpreted as a slump deposit on the slope and bottom of an abandoned channel.

Mud of the black clayey mudstone subfacies (BCM) is considered to be transported by suspension. Limited fine-grained sand layers with normal grading were inferred to be deposited by waning currents (Plint, 1983). Crude ripples indicate that there were gentle current at the time.

The alternation of mudstone and sandstone subfacies (AMS) is characterized by mudstone dominant fine-grained sediments. Finely laminated mudstone is common in channel-fill deposits (e.g., Reineck and Singh, 1980) and considered to be deposited

by suspension fall-out. The large scale cross-stratification indicates that the unit of AMS was developed from the outer rim to the center of the abandoned channel. The multiple structure of sandstone layer indicates that a variation of transportation had occurred.

Organic structureless mudstone subfacies (OSM) is characterized by abundance and variation of fossil remains. Obtained charophyte indicates very shallow pond environment. Intertonguing relationship between OSM and the Over Bank Facies suggests that there was boundary of water and dry surface. Abundant plant fossils suggest an existence of vegetation. Fossils of turtle and crocodile support a possibility of rich ecosystem.

The succession from SMS to OSM indicates that a lake of abandoned channel was filled by sediments. The thickness of the succession is about 7 m, which is same as the Point Bar Facies. It suggests that the type of stream cut-off is "neck cut-off" by Fisk (1944, 1947).

Over Bank Facies

This facies overlay the Point Bar Facies. The succession from the sharp erosional base of the Point Bar Facies to the Over Bank Facies forms a fining-upwards unit. The Over Bank Facies is considered to be deposited in out of channel of river. Massive, poorly sorted nature of the parallel bedded sandstone subfacies (PBS) indicates abrupt deposition. The sheet like geometry of the PBS supports that the PBS deposited on a floodplain as a crevasse-splay during flooding. The convex upward type of the lenticular sandstone subfacies (LS) was formed as a dune which is thought to be deposited in the proximity of a channel. The convex downward type of the LS is interpreted as a crevassesplay channel deposits. The black mudstone subfacies (BM) is commonly associated with sandy layer (ripple laminated and parallel laminated sandstone layer), which suggest the effect of current. The LS is usually associated with the BM. The association of BM and LS is interpreted to be deposited in a proximal floodplain. Calcareous nodules and slaking nature of the gray to green mudstone subfacies (GGM) suggest that the GGM was affected by soil formation. Clay mineral rich zone with calcareous nodule is considered to be a paleosol. It is interpreted that the GGM was deposited on floodplain at a flooding event and affected by soil formation. The association of GGM and PBS is considered to be deposited in a distal floodplain.

As in the Figures 4 and 6, there is a tendency to overlay in order from the Point Bar facies at the bottom, the BM with the LS and/or the PBS and the GGM with PBS at the top. It indicates an environmental change from channel, proximal floodplain to distal floodplain.

CONCLUSION

The sediments of the Kitadani Quarry demonstrate that there were river channel and floodplain. In the channel, coarse- to medium-grained sand with minor gravel were transported. Lateral accretion of the Point Bar Facies indicates high sinuosity of the river channel. Abandoned channel exists and crevasse splays are very common. These features suggest the typical alluvial plain formed by meandering river and the river might correspond to "the classic sandy meandering stream" proposed by Miall (1985).

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- * : in Japanese with English abstract
- ** : in Japanese

Akaiwa Formation	赤岩層
Akaiwa Subgroup 赤岩亞	臣層群
Chichibu	秩父
Fukui ·····	福井
Hida	飛騨
Itoshiro Subgroup 石徹白豆	臣層群

< 地名・地層名 >

Katsuyama	券山
Kitadani Formation 北谷	谷層
Kuwajima Formation 桑	島層
Kuzuryu Subgroup 九頭竜亜原	膏群
Nagasaki ·····	長崎
Ryoke 1	領家

Sanbagawa 三波川
Sangun 三郡
Shimanto 四万十
Takinami 滝波
Tetori Group 手取層群