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# Comparative Study of Sedimentary Processes Forming Bone-bearing Beds between the Early Cretaceous Kuwajima Formation, Central Japan, and Wonthaggi Formation, South Australia

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**Abstract** The Early Cretaceous Kuwajima Formation, Tetori Group, central Japan, and Wonthaggi Formation, southeastern Australia, have yielded abundant terrestrial and fresh-water vertebrate fossils. Bone-bearing beds in the Kuwajima and Wonthaggi formations are observed in fluvial systems having different channel styles. In the Kuwajima Formation, varied bone-bearing beds were preserved in the broad, stable flood-plain deposits of a meandering river system. In the Wonthaggi Formation, fossils accumulated in a channel lag because of rapid deposition of channel bars and easily eroded interchannel deposits in a braided river system. Consequently, the mode of fossil accumulation and preservation is considered to have been controlled by channel styles.

**Key words:** sedimentary environments, sedimentary processes, Cretaceous, Kuwajima Formation, Wonthaggi Formation, bone-bearing beds.

The purpose of this study is to deduce sedimentary environments and processes involved in the formation of bone-bearing beds. The sedimentary condition that cause terrestrial and fresh-water fossils to be accumulated and preserved are discussed by comparing two Cretaceous fluvial systems, the Kuwajima Formation, Japan, and the Wonthaggi Formation, southeastern Australia. Sedimentary analysis of the two formations has demonstrated that the channel style of a fluvial system is an important factor in the accumulation and preservation of vertebrate fossils.

The Early Cretaceous Kuwajima Formation, Tetori Group, is distributed in Kuwajima, Hakusan City, Ishikawa Prefecture (Fig. 1). The formation consists of shallow marine to fluvial deposits and has yielded abundant vertebrate fossils. A number of paleontological and stratigraphical studies have been conducted and reviewed by Isaji *et al.* (2005). The sedimentological results of the formation have also been described in some reports (Taira and Matsuo, 1983; Kumon, 1991; Masuda *et al.*, 1991). The uppermost part of the Kuwajima Formation is observed at Kaseki-kabe in Kuwajima, which is a well-known fossil locality. At this locality, huge numbers of vertebrate fossils, including fishes, anurans, turtles, choristoderes, lizards, pterosaurs, sauropods, theropods, hypsilophodontian-grade ornithopods, iguanodontids,

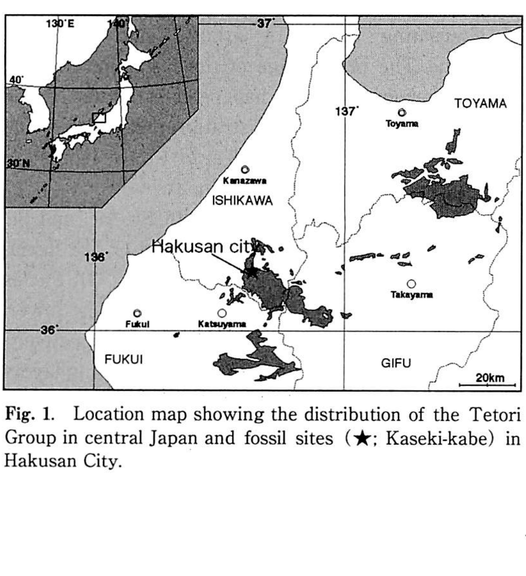


**Fig. 1.** Location map showing the distribution of the Tetori Group in central Japan and fossil sites (★; Kaseki-kabe) in Hakusan City.

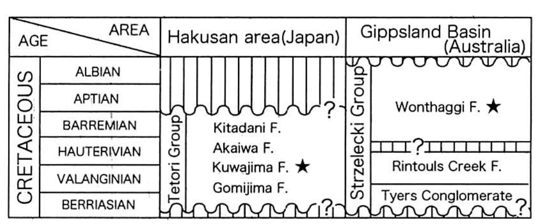


**Fig. 2.** Stratigraphy of the Hakusan area, Japan (from Sato *et al.*, 2003; Kubota, 2005; Rougier *et al.*, 2007), and of the Gippsland Basin, Australia (from Holdgate and McNicol, 1992; Chiupka, 1996) (★ indicating the formation including a bone-bearing bed).

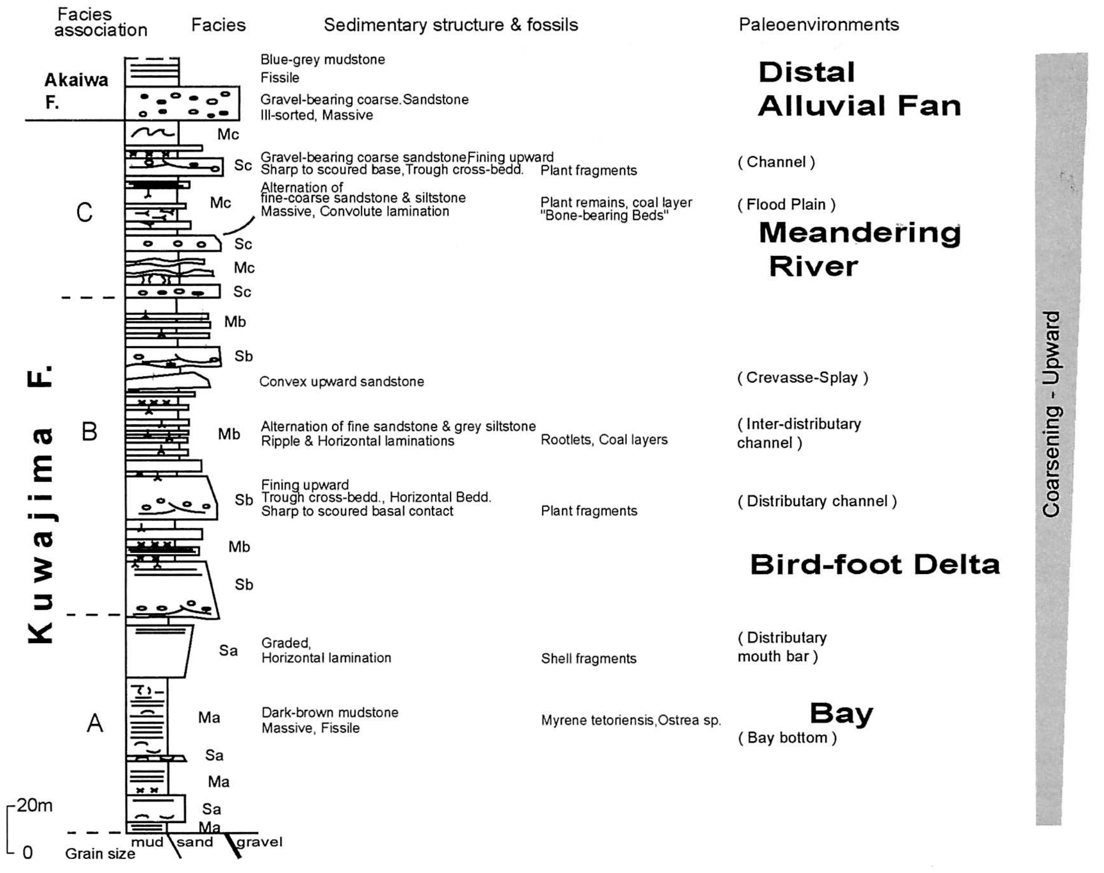


**Fig. 3.** Columnar section of the Kuwajima Formation. This section is compiled from two outcrop sections (Nishijima-touge and Kaseki-kabe).

birds, a tritylodontid synapsid, and mammals have been found. At Kaseki-kabe, the fossil assemblages are concordant with the lithologic features of the bone-bearing beds (Isaji *et al.*, 2005), suggesting that sedimentary processes controlled their modes of occurrence.

The Early Cretaceous Wonthaggi Formation (Holdgate and McNicol, 1992) in the Gippsland Basin, southeast Victoria, Australia, has been compared in order to examine the relation between bone-bearing beds and sedimentary processes in fluvial systems. The Wonthaggi Formation contains a diverse vertebrate fauna in bone-bearing beds. The assemblage includes fish, turtles, a large temnospondyl amphibian, plesiosaurs, dinosaurs, birds, a tribosphenic mammal, and a monotreme (Rich and Rich, 1989; 1994).

## Methods and Results

Facies analysis was conducted in the Kuwajima Formation in the Hakusan area, and the Wonthaggi Formation at Flat Rocks. Sedimentary facies were basically discriminated on features observable in the field, such as grain size, sedimentary structures, color, bounding-surface type and fossils.

### 1. The Kuwajima Formation

The 400-m-thick Kuwajima Formation is composed of alternating layers of arkosic sandstone and mudstone. The precise age of the formation has not been determined, but it has been estimated to be Neocomian on the basis of stratigraphic correlations with other formations of the Tetori Group (see summary in Rougier *et al.*, 2007) (Fig. 2).

Six sedimentary facies, Ma, Sa, Mb, Sb, Mc, and Sc, and three facies associations, A, B, and C, are distinguished in the Kuwajima Formation (Fig. 3). Facies associations A, B and C are recognized in the lower, middle, and upper parts of the formation, respectively. Facies association A is composed of alternating layers of mudstone (Facies Ma) and sandstone (Facies Sa), with the mudstone dominant. Facies Ma is 2 to 15 m thick and consists of blue-grey to dark brown

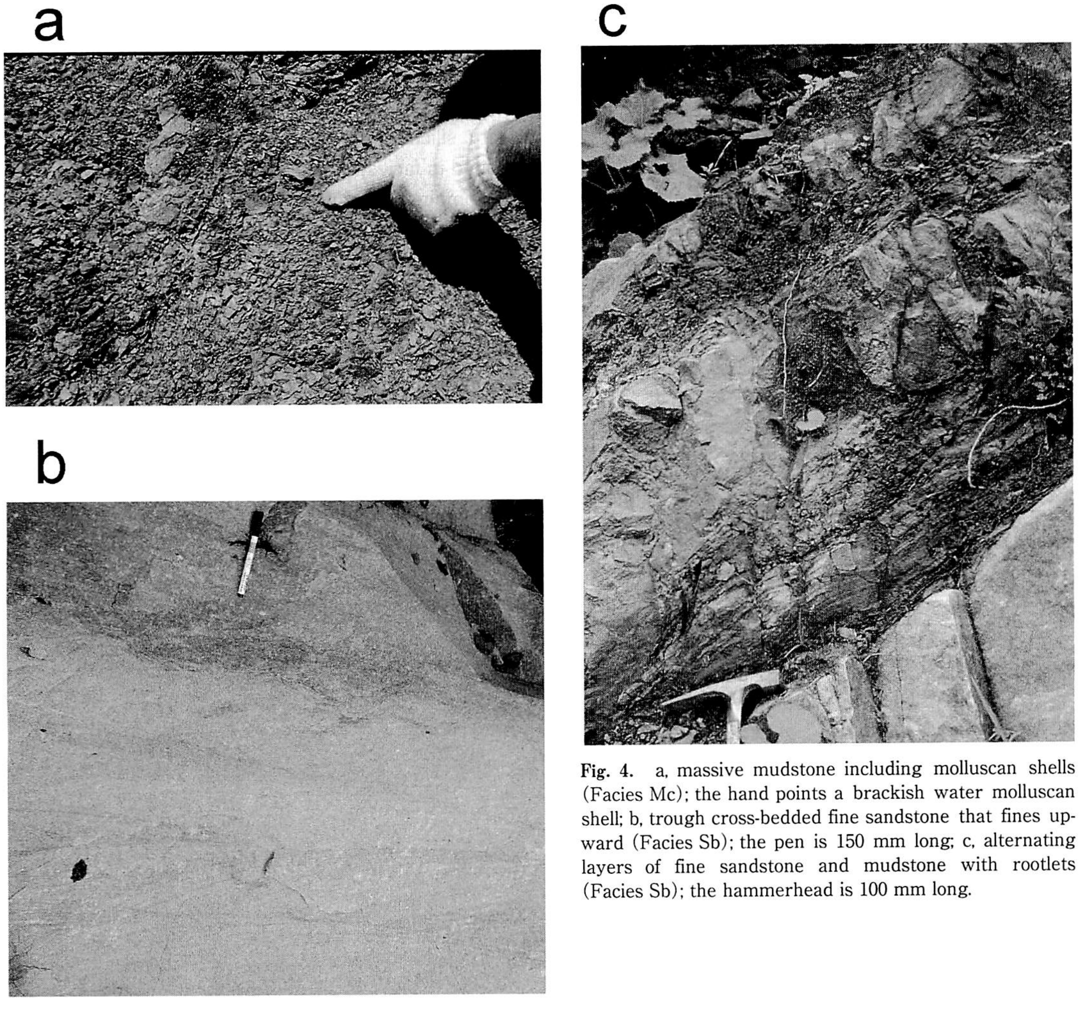


**Fig. 4.** a, massive mudstone including molluscan shells (Facies Mc); the hand points a brackish water molluscan shell; b, trough cross-bedded fine sandstone that fines upward (Facies Sb); the pen is 150 mm long; c, alternating layers of fine sandstone and mudstone with rootlets (Facies Sb); the hammerhead is 100 mm long.

mudstone. This facies is massive to fissile and contains the brackish-water molluscs *Myrene* (*Mesocorbicula*) *tetoriensis* and ostreoid (Fig. 4a). Brown, organic-rich layers are occasionally intercalated. The thickness of Facies Ma decreases upward. Facies Sa is 2 to 5 m thick and composed of fine- to medium-grained sandstone. Above the sharp lower bounding surface of the facies, granules are scattered. This facies is graded normally, or rarely inversely, with horizontal lamination in its upper part. Facies Ma represents deposition in a bay environment. Facies Sa indicates that a density current deposited sand in a bay.

In Facies association B, Facies Sb alternates with Facies Mb. Facies Sb is 4 to 6 m thick and composed of pebbly coarse- to very coarse-grained sandstone (Fig. 4b) representing trough cross-stratification. Facies Mb is 2 to 5 m thick and comprises couplets of fine- to medium-grained sandstone and grey to greenish-grey siltstone. The siltstone has numerous rootlets and plant fragments, and black coal layers are intercalated. The sandstone layers intercalated among the siltstone layers exhibit ripple and horizontal lamination and include rootlets intruded from the siltstone (Fig. 4c). Facies Sb is posited to have formed in a river channel. Facies Mb indicates interchannel deposits.

Therefore, these facies are interpreted as bay (prodelta) (Ma), river-mouth bar (Sa), distributary-channel fill (Sb) and inter-distributary channel deposits (Mb) of a fluvial-dominated delta.

In Facies association C, Facies Sc alternates with Facies Mc. Facies Sc is 2 to 6 m thick and composed of pebbly coarse- to very coarse-grained sandstone. It fines upward slightly. This facies has an apparent erosional base on which pebbles and fragments of driftwoods are present. Trough cross-bedding is commonly observed in the facies. Facies Mc, which is 2 to

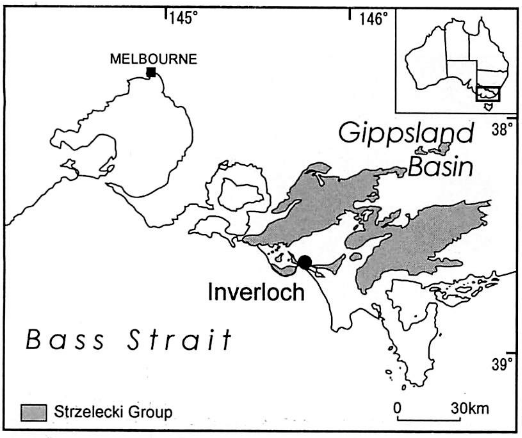


**Fig. 5.** Location map showing the distribution of the Strzelecki Group, which contains the Wonthaggi Formation, in the Gippsland Basin, southern Victoria, Australia, and the fossil site at Inverloch (● indicating Flat Rocks).

6 m thick, resembles Facies Mb, but the thicker siltstone is massive, poorly sorted, and blue-grey to dark-grey. Slump structures are also visible in some beds of the siltstone. This facies commonly contains in situ silicified woods. Bone-bearing beds have been found in facies Mc. Facies association C is identified as a combination of river-channel (Facies Sc) and flood-plain deposits (Mb).

**2. The Wonthaggi Formation**

The Wonthaggi Formation has been palynologically dated as Aptian (Constantine *et al.*, 1998) (Fig. 2). The bone-bearing beds crop out as coastal cliff exposures at Flat Rocks, Inverloch, southeast Victoria (Fig. 5). The 200-m-thick Wonthaggi Formation is composed of alternating layers of sandstone and mudstone at Flat Rocks along 1 km of coastal cliff. Three sedimentary facies, Wa, Wb, and Wc, are distinguished in the For-

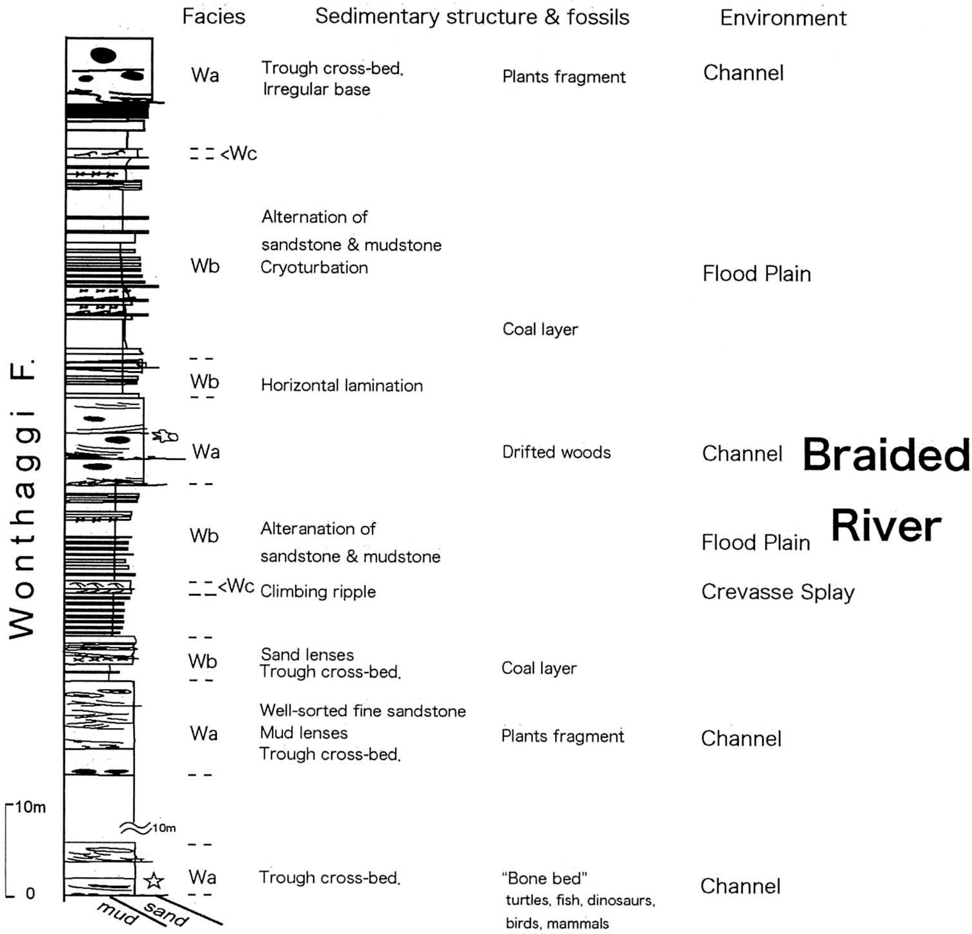


**Fig. 6.** Columnar section of the Wonthaggi Formation at Flat Rocks. ☆ indicating bone-bearing bed.


**Fig. 7a.** Trough cross-bedded fine sandstone with an irregular erosional base (Facies Wa). Numerous mud clasts are observed in the sandstone. The cliff is about 10 m high.

mation (Fig. 6).

Facies Wa, 10 to 30 m thick, consists of well-sorted fine-grained sandstone with homogeneous grain size (Fig. 7a). Irregular erosional bases and trough cross-stratification are commonly observed. This facies is interpreted as channel deposits. Boulder-sized or lens-shaped mudstones are contained in the sandstones. These mud clasts were originally flood-plain deposits, which fell into the channel by collapse of the flood-plain slope as the river channel migrated laterally. The bone-bearing beds, 1m thick, consist of pebble-sized conglomerates at the base of the channel deposits. These conglomerate layers are replaced by well-rounded mud clasts near the channel edges (Seegets-Villiers, 2002).

Facies Wb, 15 to 25 m thick, alternates with Facies Wa and consists of couplets of fine-grained sandstone and mudstone (Fig. 7b). The mudstone contains coal layers and cryoturbation structures (Fig. 7c). Cryoturbation structures are characteristic of flood plains in periglacial regions (Vandenberge, 1988; Constantine *et al.*, 1998). Facies Wb corresponds to overbank deposits.

Facies Wc is sometimes interbedded with Facies Wb. Facies Wc is 1 to 3 m thick and is composed of wedge-shaped sandstone layers (Fig. 7b). Climbing ripple lamination is often observed in Facies Wc. The facies is interpreted as crevasse splay deposits. The climbing ripple lamination is formed by floodwaters carrying abundant suspended sand from a channel onto the flood plain.

Thus, the facies correspond to channel (Facies Wa) and interchannel (Facies Wb and Wc) deposits, suggesting a sandy braided river system. Braided rivers have highly variable discharge rates and large volumes of sediment. They are also common in semiarid or arid areas and on periglacial outwash plains (Mial, 1992).

### 3. Bone-bearing bed

The bone-bearing beds found in the uppermost part of the Kuwajima Formation, Facies Mc, indicate three different facies (Subfacies I, II and III).

Subfacies I (Carbonaceous sandstones): all vertebrate fossils are isolated bones and teeth, abraded to varying degrees and commonly fragmented or heavily weathered. The most abundant elements are aquatic vertebrate remains, such as fish scales and dermal bones of turtles. This facies is rich in coal, but lacks *in situ* plant remains. Molluscan fossils, including unionid bivalves and viviparid gastropods, are poorly preserved, due to post-burial diagenesis.

Subfacies II (Dark grey fine-grained silty sandstones): vertebrate fossils are well preserved but generally small. Large bones (more than 100 mm in size) are extremely rare and heavily fractured and weathered where present. The fossil assemblage is characterized by aquatic vertebrate remains similar to Subfacies I, but occasional associated or articulated skeletons of turtles are also present. This facies also contains fractured leaves and stems, which are not accumulated in layers, but *in situ* rootlets are rare. Numerous viviparid gastropods and unionid bivalves occur, with the latter commonly articulated and often found in life position.

Subfacies III (Dark greenish-grey mudstones): vertebrate fossils are mostly isolated. Some articulated specimens have also been found (Evans *et al.*, 2006) and sometimes heavily modified (*i.e.* abraded, fragmented and weathered) bones occur in association. The fossil assemblage is characterized by the common occurrence of terrestrial lizards, tritylodontid

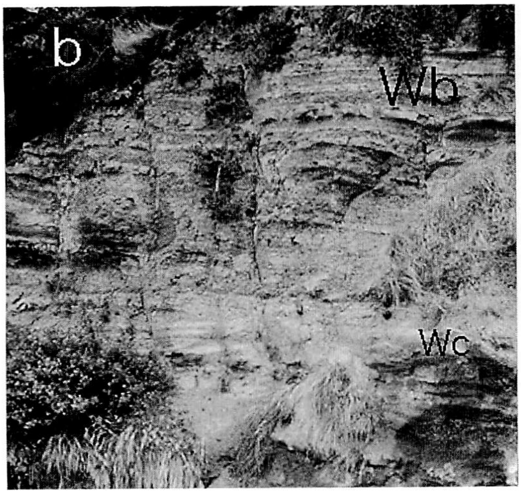


**Fig. 7b.** Thin, alternating layers of fine sandstone and mudstone (Facies Wb). Wedge-shaped sandstone layers (Facies Wc) are interbedded within Facies Wb. The cliff is about 7 m high).

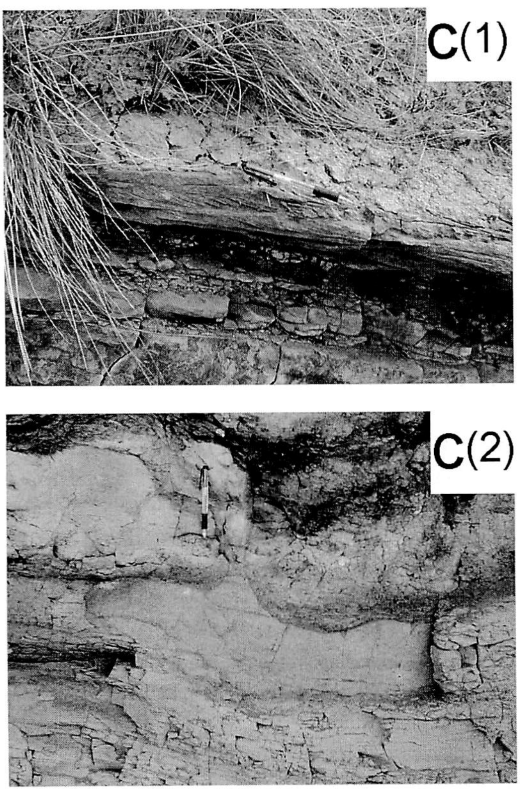


**Fig. 7c.** (1) Climbing ripple lamination of Facies Wc; (2) a cryoturbation structure composed of alternating sandstone and siltstone beds with a thin coal layer, which have been deformed by seasonal melting and refreezing (the pen is 150 mm long).

synapsids and mammals, although aquatic elements are also preserved. Hundreds of tritylodont teeth have been found, despite the loss of other skeletal elements. Mammals have been discovered only from this facies, and numerous *in situ* rootlets have been observed. Unionid bivalves and viviparid gastropods are extremely rare but tiny pulmonate gastropods, never recovered in Subfacies I and II, are common.

In the Wonthaggi Formation, the bone-bearing beds at Flat Rock site have yielded fish, turtles, a temnospondyl amphibian, plesiosaurs, dinosaurs, birds, a tribosphenic mammal, and a monotreme. The site has a huge concentration of fossil bones and teeth, with fragments of turtle and fish as the most common elements. Vertebrate fossils are generally small and isolated, for example mammal bones and dinosaur teeth are less than 30 mm in size (Kool, 2002). The fossils are preserved in thin conglomerate layers, sandwiched between thick underlying mudstones and overlying sandstone. The bone-bearing bed is interpreted as part of a lag deposit in the base of a channel.

## Discussion

In the Kuwajima and overlying Akaiwa formations, bay, river-dominated delta, meandering river, and distal alluvial fan deposits are found in ascending order and indicate a regressive sequence (Okazaki and Isaji, 2002). In this sequence, a large flood plain might have been produced by extensive overbank deposition of muddy and sandy sediments alongside a meandering river. Three bone-bearing beds with different fossil assemblages have been distinguished in the flood-plain deposits; carbonaceous sandstone containing rich plant fragment and aquatic vertebrate remains, dark-grey silty fine-grained sandstones with aquatic vertebrate remains, and dark greenish-grey siltstone characterized mainly by terrestrial lizards (Isaji, 2000; Isaji et al., 2005). Each bed corresponds to sub-environments of the flood plain: peat marsh, shallow lake, and back swamp. These subenvironments were formed on a stable, humid and vegetated flood plain. The accumulation of vertibrate remains on the flood plain occurred during flooding of the stream.

The Wonthaggi Formation at Flat Rocks consists of channel (Wa) and interchannel (Wb and Wc) deposits in a sandy braided river system. In the Wonthaggi Formation, the bone-bearing beds were preserved in the base of channel deposits. Abundant turtle and fish fossils are found in a channel deposit because they had lived there and the bones of dinosaurs, birds and mammals were washed into the channel during periodic flooding events (Kool, 2002).

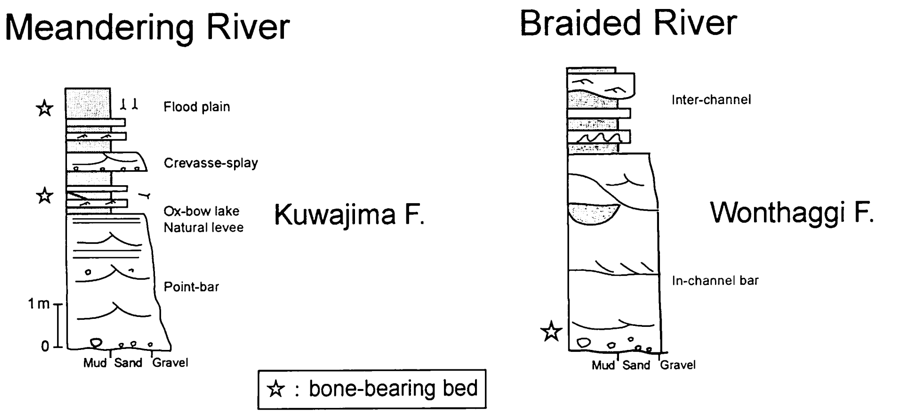


**Fig. 8.** Schematic facies successions at Kaseki-kabe and Flat Rock.

The sedimentary processes which fossils were deposited in the systems of two formations suggest the following (Fig. 8). The sediments of upper part of the Kuwajima Formation, Facies Mc, were deposited by a meandering river system with a relatively restricted stream channel and a broad, stable flood plain. As a result, a varied terrestrial fauna has been preserved in the flood-plain deposits. In contrast, the facies of the Wonthaggi Formation at Flat Rocks indicate deposition by a braided river system. The thick, homogeneous channel deposits reflect the high sediment discharge and the interchannel deposits easily eroded by lateral change of the streams. Therefore, in the Wonthaggi Formation, fossil assemblages tended to preserve in the channel lag as a result of the rapid deposition of bars. Consequently, the mode of fossil accumulation and preservation in the two areas is considered to have been controlled by channel styles.

From the observations in this study, sedimentary system can be used to predict the likely locations and sedimentary processes for deposition of terrestrial remains. Taphonomic features such as disarticulation, abrasion and the size of the remains, also represent the degree of fluvial transport and reworking. Therefore, both sedimentological and taphonomic analyses will be able to contribute to the reconstruction of the paleodrainage and paleoclimate systems.

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## 下部白亜系手取層群桑島層と南部オーストラリアWonthaggi層の化石密集層形成過程の比較研究

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要 旨　下部白亜系である中部日本の手取層群桑島層と南部オーストラリアのWonthaggi層は豊富な陸生および淡水生脊椎動物化石を産出する．桑島層とWonthaggi層のボーンベッドは異なる河道形態をもつ河川システム中に認められる．桑島層では，多様なボーンベッドが蛇行河川の広く安定した氾濫原に保存された．Wonthaggi層では，網状河川内での河道砂州の急速な堆積と河道間堆積物の容易な浸食のために，化石は河道のラグ中に集積した．これらの結果から，化石の集積と保存は河道形態に支配されていたと考えられる．