Palaeoenvironments and taphonomic preservation of dinosaur bone-bearing deposits in the Lower Cretaceous Hasandong Formation, Korea

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Dinosaur (mostly sauropod) bone-bearing deposits of the Lower Cretaceous Hasandong Formation of the Gyeongsang Supergroup, Korea, were examined for context, bone mineralogy, geochemistry, and clay mineralogy of palaeosols, and for palaeoenvironmental and preservational interpretation. Most of the Hasandong dinosaur remains are in proximal to distal floodplain deposits. Dinosaur bones commonly occur as fragments, except at the Galsari locality where partially articulated cervical vertebrae, a dorsal vertebra, a dorsal rib, and a caudal rib are associated. It is characteristic that the Hasandong bone-bearing deposits are preserved as calcic and vertic palaeosols, and that the bone fragments are thus commonly encrusted by micrite to form nodules. The bones are composed of well-crystallized francolite. Illite is the most abundant clay mineral. Relatively low $^{87}Sr/^{86}Sr$ ratios of the dinosaur bones and acid-leachable fractions of the host rocks suggest that both the bones and leachable fractions were derived from a low $^{87}Sr/^{86}Sr$ source such as contemporaneous volcanics. Early Cretaceous sauropods of the Korean peninsula inhabited dry woodlands with oxidized soils. The carcasses lay on floodplains and were scavenged by carnivores and carrion beetles, and severely weathered before burial. Volcanic activity near the basin sometimes resulted in rapid burial of unweathered bones on distal floodplains as in the Galsari bone deposits. After burial, the bone deposits experienced calcareous pedogenesis, which assisted preservation. The predominance of bone deposits in the Hasandong Formation may be attributable to the abundance of calcic palaeosols.

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1. Introduction

Dinosaur habitats ranged from upland to coastal environments, and from humid to arid climates (Dodson, 1997). Our knowledge of dinosaur habitats has been acquired mostly from dinosaur deposits in North America. Despite an abundance of dinosaur remains in Asia, aspects of their palaeoenvironment have rarely been studied. Although dinosaur-bearing strata occur widely in China (Dong, 1992), most studies have concentrated on their palaeontology and stratigraphy. The palaeoenvironmental reconstruction of dinosaur beds in

Asia is thus essential to widen our understanding of dinosaur habitats.

In the southern part of Korean Peninsula abundant dinosaur tracks are preserved in Late Cretaceous lake-margin deposits (Lim, 1990; Lim *et al.*, 1994; Huh *et al.*, 1997; Lee *et al.*, 2000). Dinosaur bones have, however, been discovered in very few beds, most of which are in the Lower Cretaceous Hasandong Formation. The general lithology and depositional environments of this formation appear to be similar to those of the Morrison Formation (Upper Jurassic) of North America (Dodson *et al.*, 1980).
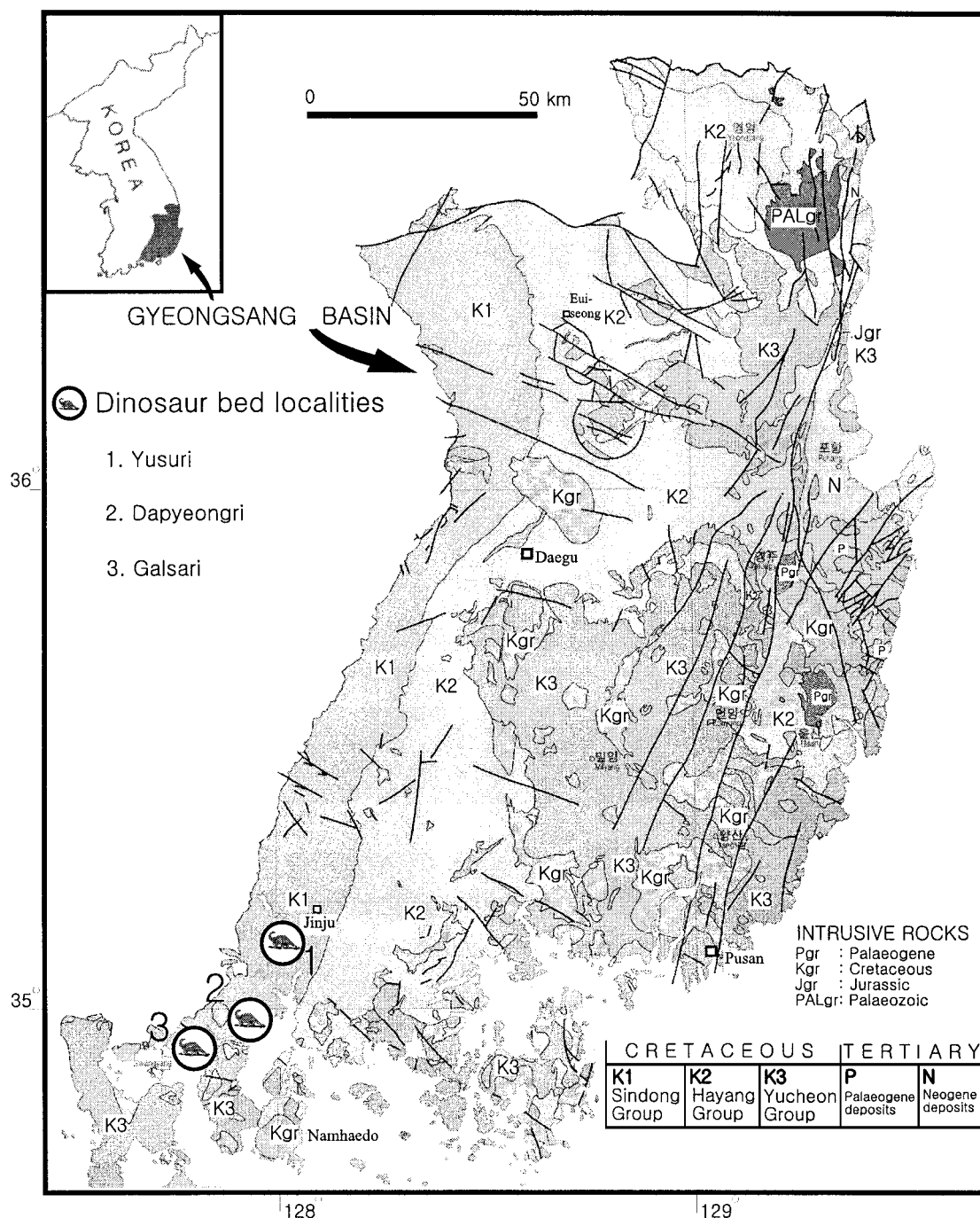
Figure 1. Geological map of Gyeongsang Basin (after Kang *et al.*, 1995) and dinosaur-bed localities studied.

The Hasandong dinosaur bone beds are fluvial deposits and mostly vertic-calcic palaeosols. Calcic and vertic palaeosols occur frequently in the great dinosaur-bearing formations of the world. These not only indicate the nature of the palaeoenvironment inhabited by dinosaurs, but also their environment of preservation (Retallack, 1997).

In this study, dinosaur deposits from three exposures of the Hasandong Formation (Figure 1) have been examined for context, geochemistry, bone mineralogy, and clay mineralogy of the palaeosols. On the basis of this study, the palaeoenvironments and mode of preservation of the deposits are identified. The results of this study provide additional

information on the palaeoecology of dinosaurs during the Early Cretaceous for which dinosaur-bearing deposits are not globally abundant.

2. Geological setting

The Cretaceous sedimentary basins in South Korea were formed by continuous and intermittent transtensional tectonic movements related to sinistral strike-slip fault systems (D. W. Lee, 1999). They are marked by extensional block faulting, little or no metamorphism, rapid lateral facies change, and voluminous post-depositional volcanic activity. These basins are exclusively composed of non-marine epiclastics and volcaniclastics. The Gyeongsang Basin (Figure 1) is the largest, and consists of a 9000-m-thick succesion of deposits assigned to the Gyeongsang Supergroup. This is divided into the Sindong, Hayang, and Yucheon groups, in ascending stratigraphical order. The Gyeongsang Supergroup was deposited cyclically in alluvial fan, fluvial, and lacustrine environments (Um et al., 1983; H. I. Choi, 1985), and contains abundant dinosaur footprints at some levels (Lim, 1990; Lim et al., 1994). During the Cretaceous, the Korean Peninsula was situated in mid-latitudes, as today (Lee et al., 1987; Kim et al., 1993). Based on fossils, palaeosols, and lithology the general palaeoclimatic regime during the deposition of the Gyeongsang Supergroup was warm and dry (Paik & Kim, 1997).

The Hasandong Formation is the middle stratigraphic unit of the Sindong Group, which has generally been assigned a Hautervian age on the basis of charophytes (Seo, 1985) and spores and pollen (D. K. Choi, 1985), although an early Aptian age was suggested by a palaeomagnetic analysis (Doh et al., 1994). The formation is underlain by the Nagdong Formation, which consists of alluvial fan and fluvial deposits, and is overlain by the Jinju Formation, which consists of lacustrine and some fluvial beds. The Hasandong Formation consists of alternating channel and interchannel sediments, including some floodplain-lake deposits. The interchannel accumulations are commonly reddish and typically contain calcic and vertic palaeosols (Um et al., 1983; Paik & Kim, 1995; Paik, 1998; Paik & Lee, 1998). The palaeoclimate linked with the Hasandong Formation has, thus, been interpreted to have been semiarid and seasonal with wet and dry cycles (Paik & Kim, 1995; Paik & Lee, 1995, 1998). Both herbivorous and carnivorous dinosaur fossils have been discovered in the formation (Lee et al., 1997; Paik et al., 1998a, b), and some plant, bivalve, and gastropod fossils have been reported (Geological Society of Korea, 1999).

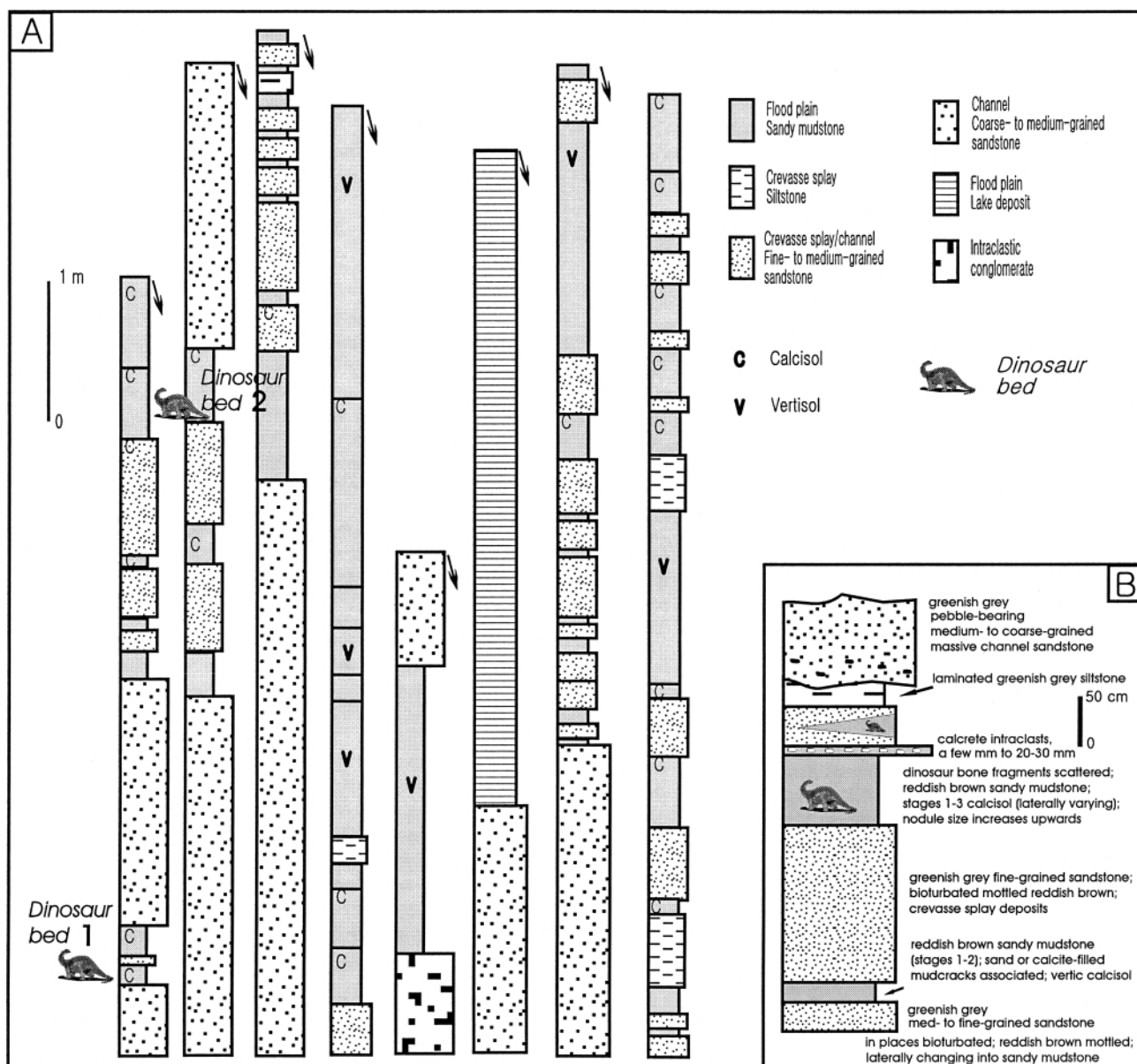## 3. Occurrences

3.1. Yusuri locality

This locality is situated in a valley where an extensive sequence of meandering river deposits is exposed. Channel sandstones and crevasse channel/splay sandstones alternate with fine overbank deposits. Calcic and vertic palaeosols are commonly preserved in the floodplain deposits (Figure 2). Between some channel accumulations, channel plug deposits occur. Two dinosaur bone-bearing beds are recognized in the floodplain deposits (Figure 2).

Dinosaur bed 1 consists of reddish brown muddy sandstone to sandy mudstone overlying a channel sandstone. It is 0.4–0.5 m thick, and thin mudcracks are present on the surface in places. Pedogenic nodular and tubular calcretes with development stages 1–2 (sensu Machette, 1985) occur, and some pedogenic slickensides are observed. These features indicate that this deposit is a vertic-calcic palaeosol.

Thirteen partial and fragmentary bones (40–50 mm in size) including a sauropod scapula and limb elements are randomly distributed in this deposit within a distance of 5 m. No gravels are associated with these bone fragments. Dinosaur bones are light grey to greenish grey, and drab halos usually occur around the bone fragments. All of the fragments are encrusted by micrite a few mm to more than few mm thick (Figure 3A, B). Small bone fragments occur as calcareous nodules (Figure 3A). The contact with the micrite rim is gradational in cancellous bone fragments, whereas it is well defined in compact fragments. Some pedogenic features, such as peloidal fabric, circumgranular or semi-circumnodular cracks, and laminar micrite-walled tubules, are present in these micrite rims.

Bone tissue structures are generally preserved, even in central cancellous bone tissues. Internal openings of bones are mostly filled with micrite (wall) and sparite (centre) (Figure 3C), with detrital quartz grains occurring in places. Micrite filling increases towards the bone surface. Drusy filling is common, and peloids (100–200 µm) associated with micrite are occasionally present. The bone surfaces are generally cracked, fractured, and partially brecciated.

Dinosaur bed 2 is composed of reddish brown sandy mudstone occurring above a fine-grained crevasse splay sandstone. It is 0.5–0.6 m thick, and overlain by a thin-bedded calcrete intraclast-bearing deposit (Figure 2). Pedogenic nodular calcretes with development stages 2–3 are scattered throughout, and some pedogenic slickensides are observed, which indicates that this deposit is also a vertic-calcic palaeosol.

Figure 2. Stratigraphic occurrence of dinosaur beds at Yusuri (A), and detailed stratigraphic section of dinosaur bed 2 (B).

Over 400 bone chips and fragments (10–200 mm in size) are randomly distributed within an area of approximately 200 m², and some bivalves and well-rounded pebbles are associated. The bone colour is generally dark greenish grey. All of the bone fragments are also encrusted by micrite rims ten to a few tens of mm thick (Figure 4A, B). They are thus mostly preserved as calcareous nodules, which makes their recognition difficult in the field. Most of the bone fragments are compact, and the micrite rims are usually sharp (Figure 4A). Some cancellous bone fragments, however, have diffuse contacts with micrite rims as in dinosaur bed 1 (Figure 4B). Some pedo-

genic features, such as circumgranular or semi-circumnodular cracks (Figure 4C) and calcite aureols around detrital quartz grains, are observed in the micrite rims.

Bone tissue structures are relatively well preserved. The bone surfaces are usually subangular and generally cracked and fractured. Internal openings of bones are mostly filled with sparite and usually have thin micrite linings.
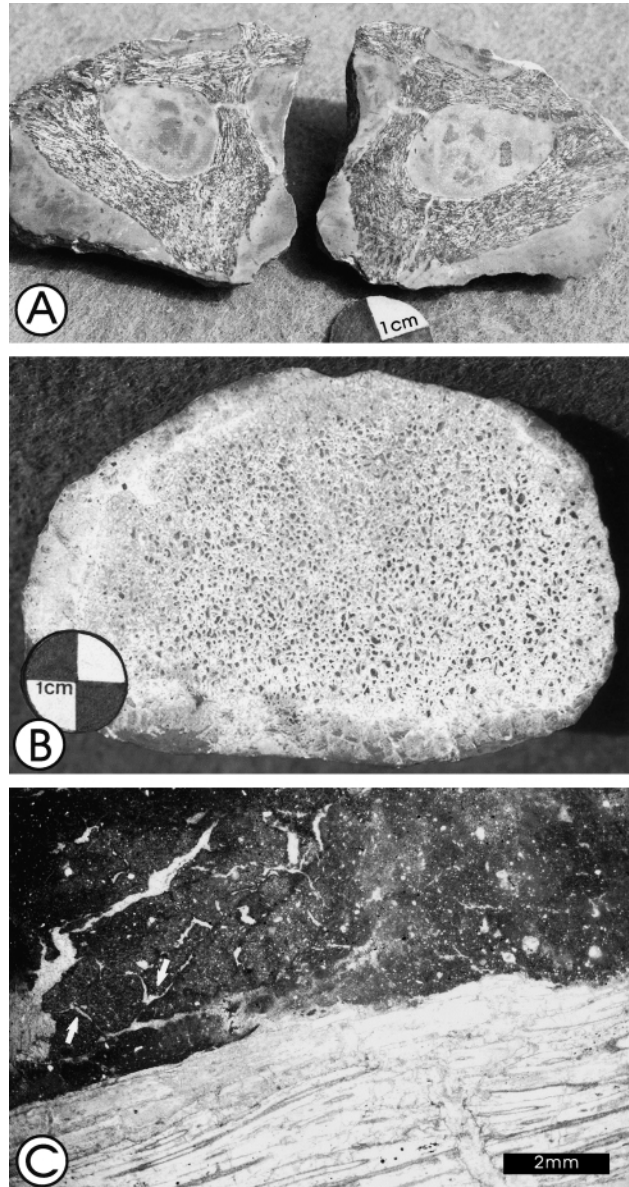
3.2. Dapyeongri locality

This locality is a coastal cliff of alternating channel sandstones, crevasse channel/splay sandstones, and
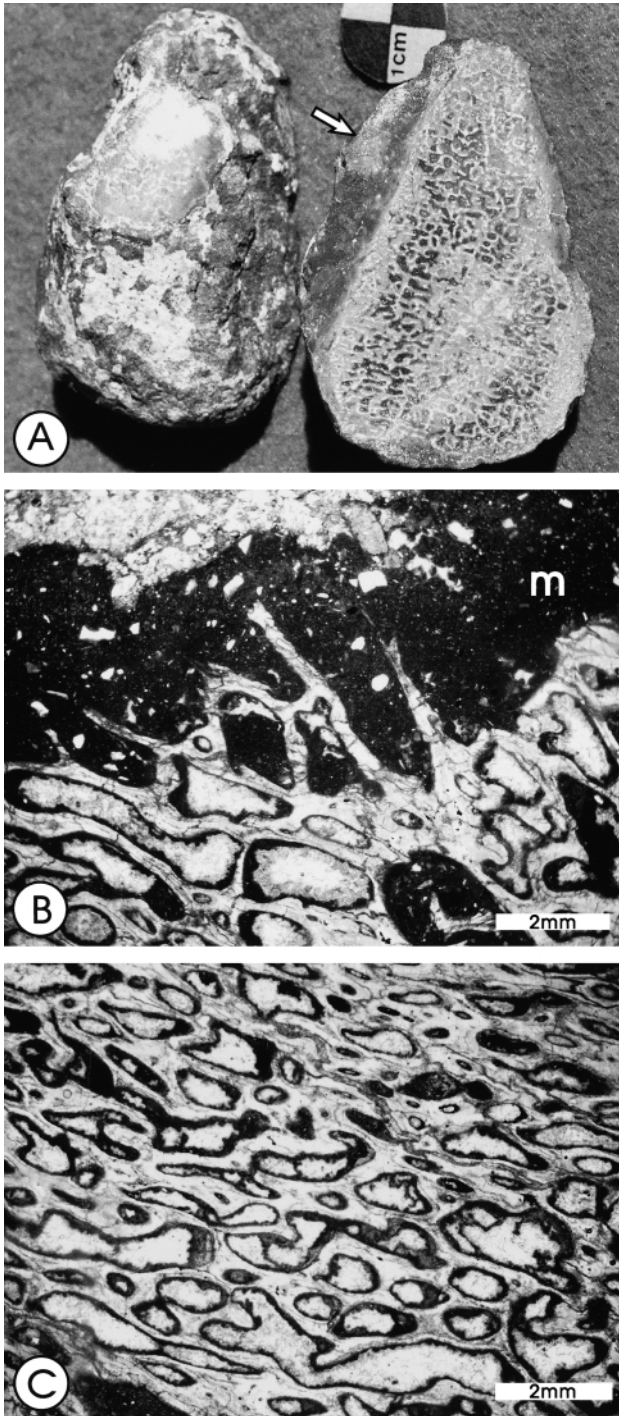
Figure 3. Bone occurrence in dinosaur bed 1 at Yusuri. B and C are thin-section photomicrographs. A, nodular occurrence of dinosaur bone fragment encrusted by micrite (arrow). B, micrite crust (m) on bone fragment. C, internal openings filled with micrite (wall) and sparite (centre).
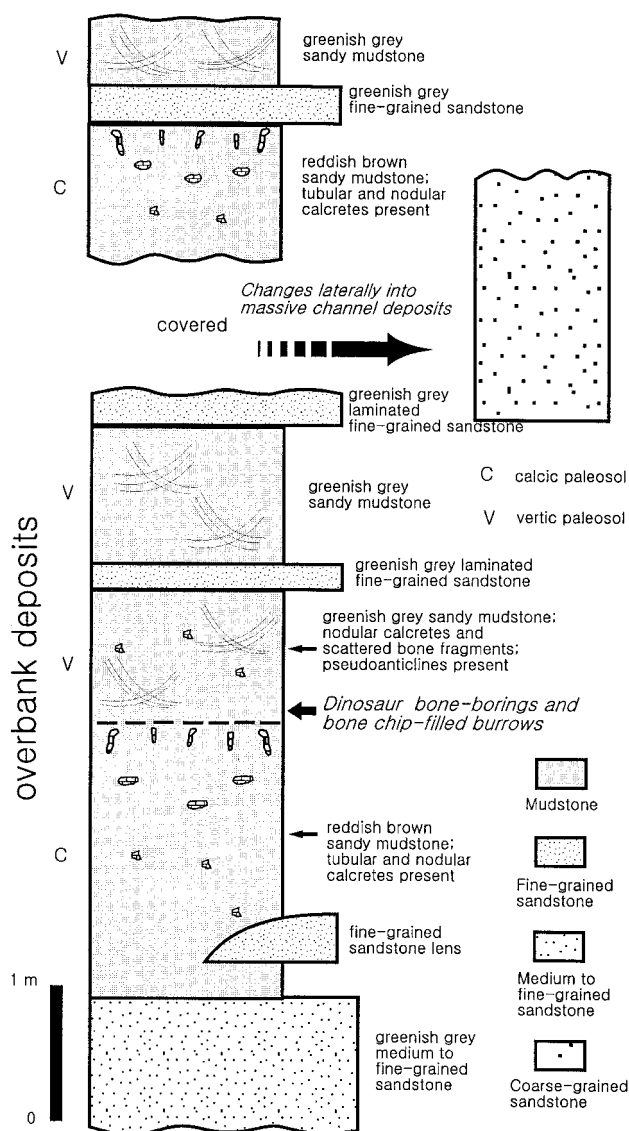

Figure 4. Bone occurrence in dinosaur bed 2 at Yusuri. A, B, sawn slabs of bone fragments showing the development of micrite crusts on bone forming nodules. Compact bone fragment (A) has a sharp contact with micrite crust, whereas the cancellous bone has a diffuse contact. C, pedogenic curved to circumgranular cracks (arrows) in micrite crust on bone; thin-section photomicrograph.

fine overbank deposits (Figure 5). Calcic and vertic palaeosols are commonly preserved in the floodplain deposits. The dinosaur bed at this locality is a greenish grey sandy mudstone in which pedogenic pseudoanticlines and nodular calcretes occur. It is thus a vertic-calcic palaeosol. In places, *Scoyenia*-type invertebrate traces also occur. Calcic palaeosols at stage 2–3 calcrete development underlie this deposit.
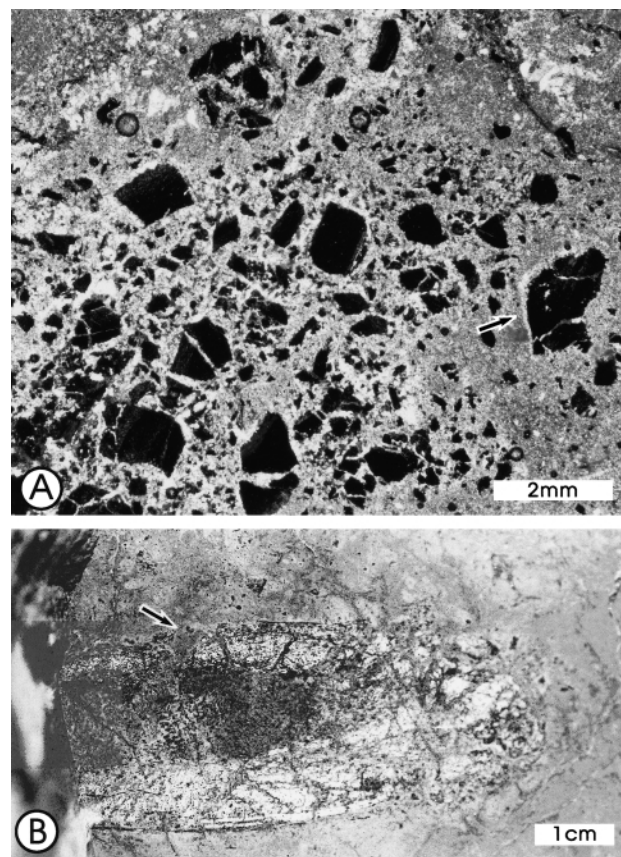
In the basal part of this vertic-calcic palaeosol, a sauropod scapula fragment, a rib fragment, and theropod tooth fragments occur within a distance of 7 m.

Figure 5. Stratigraphic section of dinosaur bed at Dapyeongri.

Figure 6. Occurrence of dinosaur bones at Dapyeongri. A, calcite aureoles (arrow) on bone chips; thin-section photomicrograph. B, fractures, brecciation, and boring (arrow) into bone; polished slab.

Bone fragments and chips are generally encrusted by micrites and thus preserved as nodules. Irregular micrite patches are present around aggregated bone chips. Curved to circumgranular cracks occur in these micrite nodules and patches, and there are calcite aureoles around bone chips (Figure 6A), which indicates their pedogenic origin.

The scapula is preserved in a severely weathered state. Its surface is generally cracked, fractured, and partially brecciated (Figure 6B). Tissue structures are preserved only in the compact surface bone (a few mm to 20 mm thick), and the central cancellous tissues are mostly disintegrated and filled with sandy mudstone, calcite, and fragmented bone shards. The external

shape of the bone is, thus, partially destroyed as a result of disintegration. Dislocation of bone is also observed in places. Thin cracks normal to the bone surface are common, and generally filled by iron oxides. Sheet cracks along bone layers occasionally occur in compact surface bone. Tiny spalled-off bone chips are scattered around these weathered surfaces. Internal openings of compact and cancellous bones are mostly filled with micrite and sparite, and are surrounded by partially silicified rinds consisting of blocky quartz. Irregular calcrete encrustation occurs around the weathered scapula surface, and small pedogenic calcrete nodules are present in the disintegrated internal part. It is a characteristic that bone borings and bone chip-filled burrows of dermestid beetles are common within and around the scapula (Paik, 2000).

3.3. Galsari locality

This locality is a nearshore islet, most of which is submerged at high tide. The exposed succession is
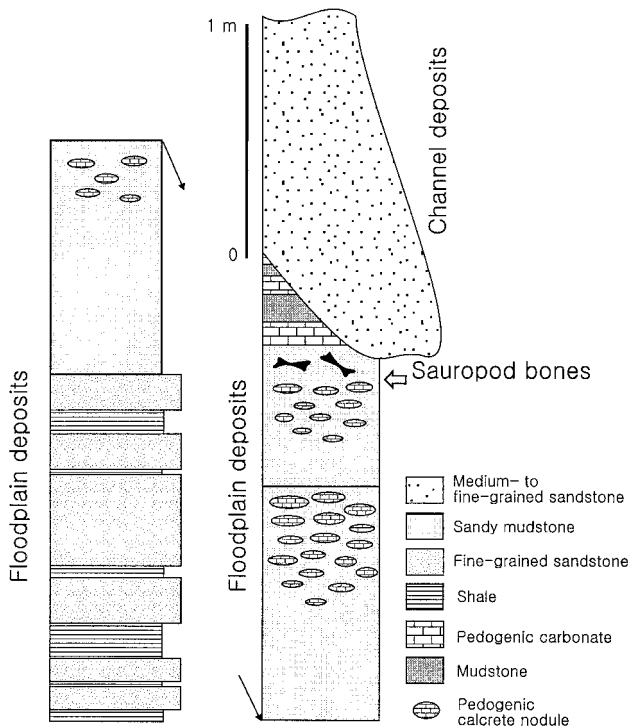
Figure 7. Stratigraphic section of dinosaur bed at Galsari.

Figure 8. Pedogenesis of dinosaur bed at Galsari. A, nodular calcretes (arrows) developed in bone bed. B, pedogenic circumgranular cracks in micrite; thin-section photomicrograph.

about 5.7 m thick, and consists of floodplain mud-stone and shale, crevasse splay sandstone, and a channel sandstone (Figure 7). The channel sandstone is massively bedded and passes laterally into thin-bedded and fine-grained sandstones and shales. It is characteristic that the channel sandstone has suffered little compaction and is cemented by calcite. In floodplain mudstone, pedogenic nodular calcretes with development stages 1–3 commonly occur, and hardpan calcretes are present below the channel sandstone.

Dinosaur bones occur in sandy mudstone deposits (*c.* 0.7 m thick). The rock colour is reddish brown in the lower part of this section and greenish grey higher up. The grain size generally fines southward, and well-rounded gravels are present in places. This de-posit is overlain by hardpan calcrete in the north and by channel sandstone in the south. Pedogenic nodular calcretes at development stages 1–3 are scattered throughout the deposit (Figure 8A), and circum-granular cracks are present in these micrite nodules (Figure 8B). Pedogenic slickensides occur occasion-ally. This deposit is thus a vertic-calcic palaeosol, and calcrete development increases southward. Rare fragments of turtle carapace and bivalve shells are present. Burrows and trails filled with overlying sand-stone are associated in places. Mudcracks are rarely observed.
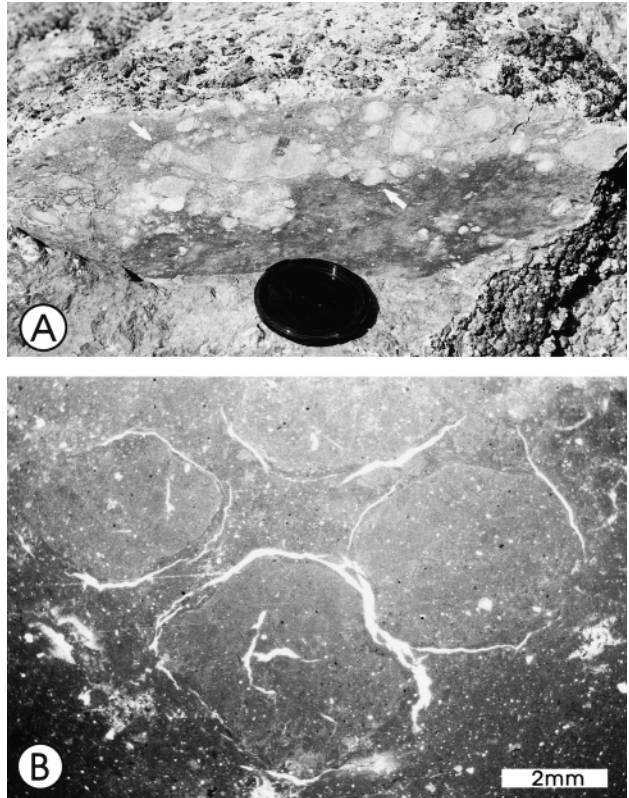
Dinosaur bones occur in the upper part of this bone bed. Most of the preserved bones are cervical ver-tebrae of a sauropod, which are distributed in a nearly linear arrangement. A few well-rounded and polished gravels (a few tens of mm to over 100 mm in diam-eter), which are presumed gastroliths, are associated with one cervical vertebra. Other bones include a dorsal vertebra, a dorsal rib, a caudal rib, and some bone fragments. In the south the bones are concen-trated and some cervical vertebrae are partially articu-lated, whereas in the north the bones are scattered and preserved as fragments and shards. All of the bones are black.

There are little cracks on all of the bone surfaces (Figure 9). However, some bones are fractured owing to compaction during burial. Cervical vertebrae are relatively compressed because of compaction, and some cancellous bones are severely squashed. In general the bone tissue textures are well preserved, and internal openings of compact bones remain un-filled in places (Figure 10) as in some empty bone voids from the Oxford Clay in England (Barker *et al.*, 1997).
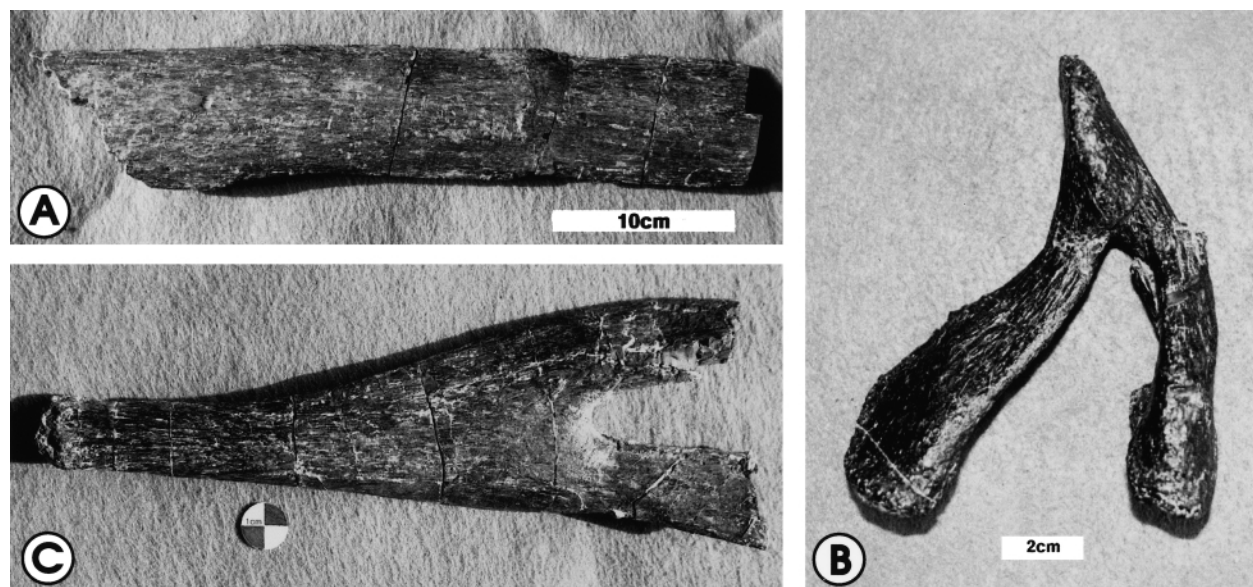
Figure 9. Well-preserved bone surfaces of dorsal rib (A), caudal rib (B), and unidentified long bone (C).

4. Mineralogy and geochemistry of dinosaur bones and deposits

The bones and bone deposits were analyzed mineralogically and geochemically to check the preservation state of the bones, and to interpret their taphonomic preservation.

4.1. Mineralogy of dinosaur bones

X-ray diffraction data of dinosaur bone fragments from the Yusuri, Dapyeongri and Galsari localities were obtained using a Phillips Xpert MPD X-ray diffractometer using CuKa radiation. The crystallinity index (CI) of francolite was determined from the half-height peak width of the (002) peak measured in Δ°2θ (Sillen, 1989). Each sample was run three times and the error in CI is less than 1%.

The fossil-bone mineral is well-crystallized francolite (Figure 11). The peaks on the X-ray diffractograms of the dinosaur francolite have d spacings and relative intensities that closely match those of diagenetic francolite in Upper Cretaceous chalks of NW Europe (Jarvis, 1992) and of dinosaur francolite in the Jurassic Morrison Formation (Hubert *et al.*, 1996). In addition to francolite, the bones also contain detrital quartz and diagenetic calcite and chlorite, which fills openings of the bones. The highly compact Galsari bones have the lowest content of calcite and quartz. CI values of francolite range from 0.16 to 0.19 (Table 1), which is slightly lower than the previous study on Dapyeongri and Yusuri bones (0.2–0.3; Paik *et al.*, 1998a). CI values from Morrison dinosaur bones and from Cretaceous dinosaur and reptile bones in the Iberian Peninsula (Elorza *et al.*, 1999) are in the range 0.22–0.38 and 0.20–0.30, respectively. The lowest CI values reported are 0.15 from a Morrison *Seismosaurus* bone (Chipera & Bish, 1991) and 0.17–0.18 from fluorapatite and hydroapatite crystals (Sillen, 1989). The low CI values of the dinosaur francolite studied may indicate that diagenetic francolite underwent recrystallization during burial resulting in less strain and more ideal chemical composition (Hubert *et al.*, 1996).

4.2. Clay mineralogy of dinosaur deposits

Bulk and clay mineralogical analyses were performed using a Rigaku Model Geigerflex 2301 X-ray diffractometer. The results of X-ray diffraction (XRD) studies of the Hasandong dinosaur succession indicate that illite is abundant in all of the deposits (Figure 12). The illite is of two types: 1 M and 2 M polytype. Chlorite is also present in the deposits, being an Fe-rich variety, based on characteristic 001, 002, and 003 reflections and relative peak intensities (Moore & Reynolds, 1989). There is no direct evidence for the presence of smectite or mixed-layered illite-smectite in the deposits preserved as vertic palaeosols. Quartz as detrital silt, calcite, feldspar and hematite were also observed (Figure 12).

Although not evident in the XRD patterns, the occurrence of vertic features, such as pedogenic slickensides in all deposits, suggests the former presence of an appreciable amount of swelling clays (smectite).
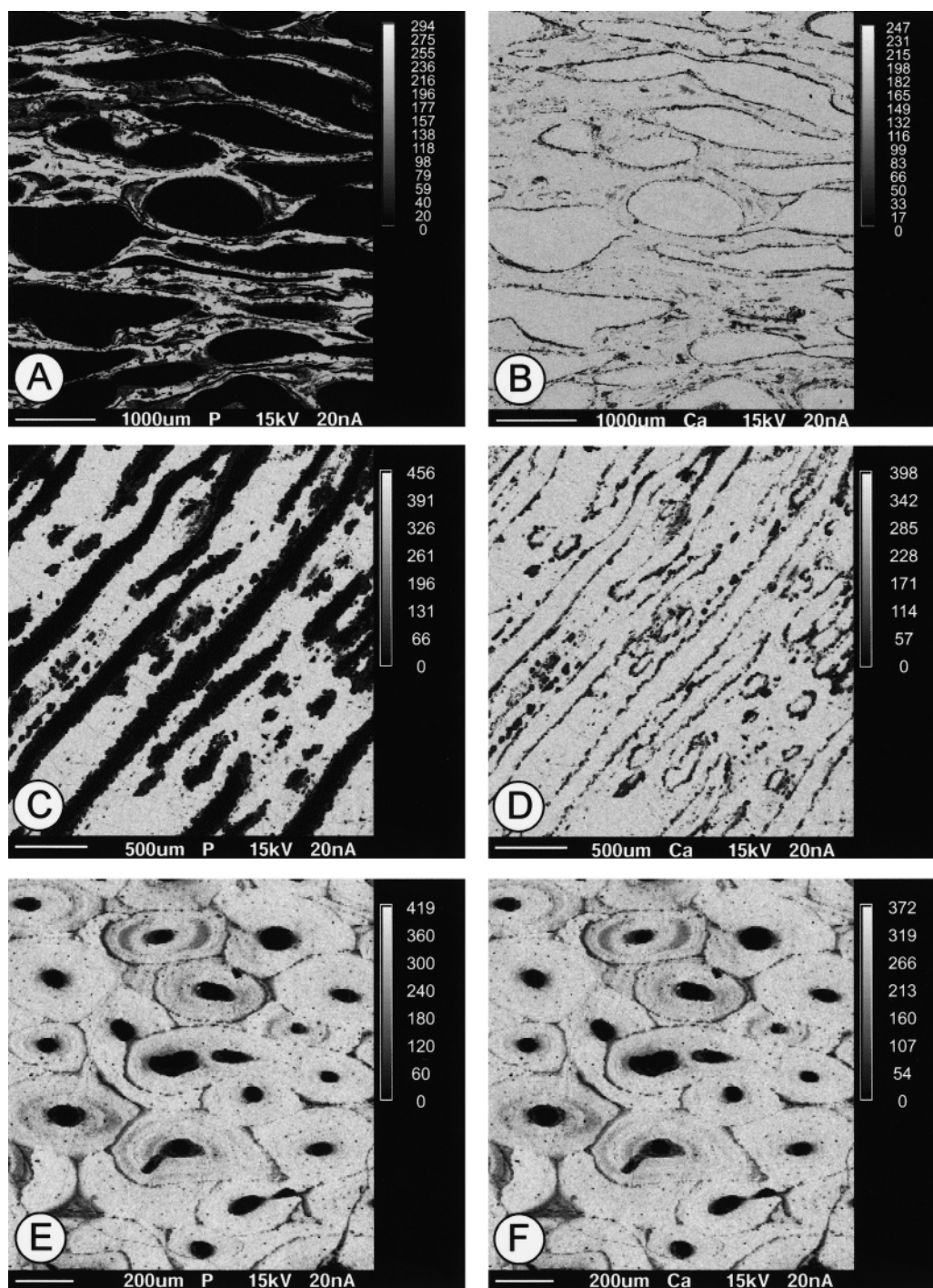
Figure 10. EPMA (electron probe micro-analyzer) chemical maps of P (A, C, E) and Ca (B, D, F) for dinosaur bone samples from the Hasandong Formation. The localities of the samples are Yusuri (A, B), Dapyeongri (C, D), and Galsari (E, F). Bone francolite is indicated by the areas of high phosphorous concentration represented by light grey colour. The Galsari bone samples show that openings within the bone remain void, as evidenced by low P and low Ca abundance areas of black. However, the Yusuri and Dapyeongri bone samples show that their openings are filled with calcium carbonate. The Yusuri bone samples also indicate some alteration of bone francolite.

These smectitic clays are interpreted to have been converted to illite and chlorite through progressive burial diagenesis (Hower *et al.*, 1976). Diagenetic illites converted from smectites have been documented in many studies (Hower *et al.*, 1976; Curtis, 1985; Driese & Foreman, 1992).
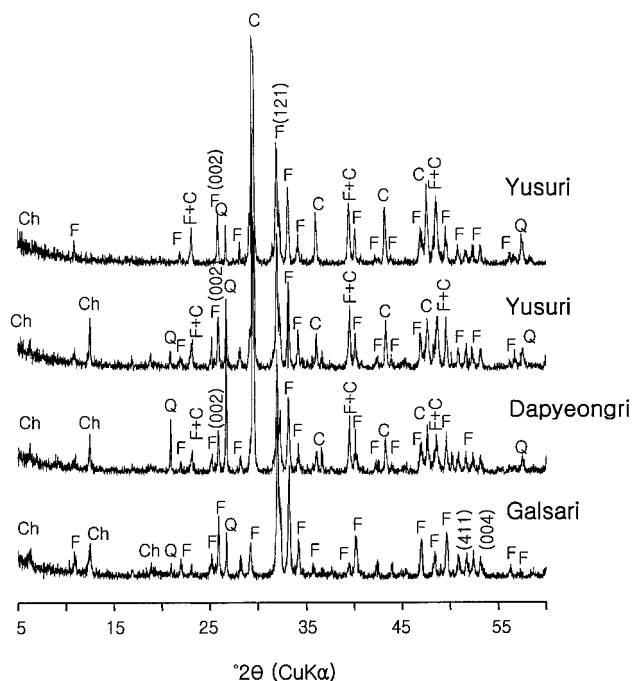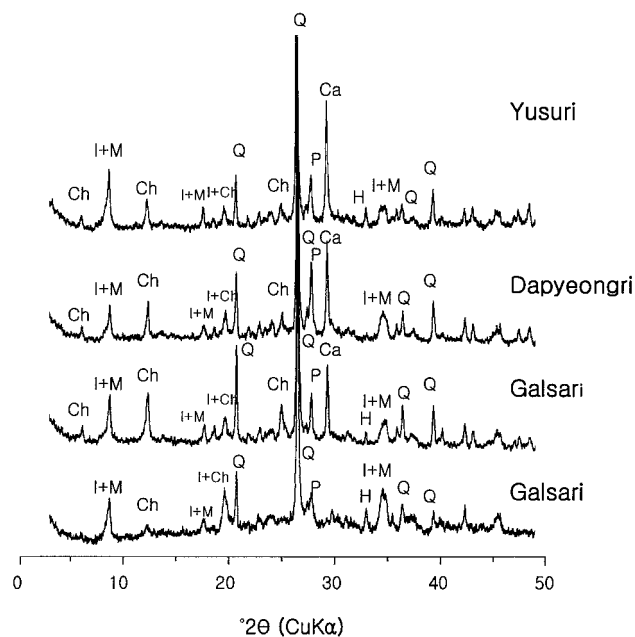
Figure 11. XRD diffraction patterns of Hasandong dinosaur bones (F, francolite; Q, quartz; C, calcite; Ch, chlorite).

Figure 12. XRD diffraction patterns of clay minerals in the Hasandong dinosaur beds (Ch, chlorite; I, illite; M, mica; Q, quartz; P, plagioclase; Ca, calcite; H, hematite).

Smectites are commonly produced by alteration of volcanic glasses (Grim & Güven, 1978). The illites and chlorites in the Neogene volcanogenic deposits of the Green Tuff area in Japan are diagenetic products of smectites that formed by alteration of volcanic glasses (Ijima & Utada, 1972). It is thus inferred that the Hasandong dinosaur deposits contain abundant volcanogenic sediment.

4.3. Geochemistry

Chemical mapping for several elements, including P, Ca, and C, has been conducted for selected dinosaur bone samples using a Cameca SX-51 electron probe microanalyzer at the Korea Basic Science Institute; 15 kV acceleration voltage and 20 nA beam current were used. In Figure 10A–F high phosphorous areas

indicate the distribution of bone-forming francolites whereas low phosphorous areas indicate original openings within the bones. Yusuri bone shows comparatively poor preservation of bone francolite with some alteration features represented by the areas with relatively low phosphorous abundance. However, the Galsari and Dapyeongri bone samples do not show any obvious alteration of bone francolite. The original openings within the Galsari bones remain partially unfilled. In contrast, the Yusuri and Dapyeongri bone samples clearly reveal that their original openings have been completely filled with calcite.

Acid-leaching experiments were applied to detect any differences between the Sr isotopic compositions of the acid leachable secondary filling material and residual bone francolite. It is worth mentioning that the secondary calcite fillings may have significant amounts of Sr with quite different isotopic

Table 1. Crystallinity index and CO_2 content of francolite in the Hasandong dinosaur bones determined by XRD.

Sample	Galsari	Dapyeongri	Yusuri	Yusuri
CI	0.17 ± 0.005	0.18 ± 0.005	0.19 ± 0.005	0.16 ± 0.005
$\Delta 2\theta_{(004)-(410)}$	1.460 ± 0.02	1.199 ± 0.004	1.477 ± 0.025	1.454 ± 0.003
CO_3^{2}-wt %	3	2.2	2.6	3.1

Table 2. ^{87}Sr/^{86}Sr ratios of the dinosaur bones and their host sedimentary rocks in the Hasandong Formation.

Yusuri		Dapyeongri		Galsari	
Bone leachate	0.713639	Bone 1 leachate	0.711024		
Bone residue	0.716825	Bone 1 residue	0.711357		
Bone whole	0.713570	Bone 1 whole	0.711343	Whole bone	0.714840
		Bone 2 leachate	0.711079		
		Bone 2 residue	0.711344		
		Bone 2 whole	0.711366		
Rock 1 leachate	0.714358	Rock leachate	0.711233	Rock 1 leachate	0.714412
Rock 1 residue	0.724548	Rock residue	0.729750	Rock 1 residue	0.717665
Rock 2 leachate	0.713952			Rock 2 leachate	0.714274
Rock 2 residue	0.723580			Rock 2 residue	0.717388

Measurement errors (2 SE) of ^{87}Sr/^{86}Sr ratios are between ± 0.000010 and ± 0.000014.

compositions from their host bone material and that the degree of calcite filling varies between samples.

Sr isotopic compositions were also determined for the host sedimentary rocks, which are composed of not only detrital material but also pedogenic calcareous material and calcareous cement. Such calcareous material may reflect different origins, such as dissolved solutes in the water at the time of deposition, and detrital material, and may retain different isotopic compositions.

4.4. Isotopic analysis

Sr isotopic analyses were conducted at the KBSI. Cold 0.25 N HCl was used for the acid-leaching and mixed acid (HF-HClO$_4$-HNO$_3$) was used for the dissolution of the residues. Isotopic compositions of Sr separated by cation exchange were measured using a VG54-30 thermal ionization mass spectrometer. The average ^{87}Sr/^{86}Sr ratio of NIST SRM-987 was 0.710256 ± 3 (N=7, 2σ SE) during the period that the analyses were undertaken. The total procedural blank level for Sr was around 0.5 ng.

The dinosaur bones studied revealed ^{87}Sr/^{86}Sr isotopic ratios ranging from 0.7110 to 0.7168 (Table 2). The host rocks show a similar minimum value of 0.7112, but extend to the much higher ratio of 0.7298. It is also apparent that acid leachable fractions and host rock residues have distinct Sr isotopic compositions (Figure 13). All of the rock-residues show relatively high and variable ^{87}Sr/^{86}Sr ratios, while acid-leachates of the rocks show lower and quite uniform values. Acid-leachates from the bones also show lower ^{87}Sr/^{86}Sr ratios than corresponding bone residues in the cases of the Dapyeongri and Yusuri samples, but the differences are much smaller. It is noted that the ^{87}Sr/^{86}Sr isotopic ratios of the bone

residues are not as high as the rock residues, but are nonetheless very similar to those of the rock leachates. ^{87}Sr/^{86}Sr isotopic ratios of bone leachates are even closer to the rock leachate values. Such closeness suggests a genetic link between Sr isotopic compositions of the dinosaur bones and acid-leachable fractions of their host rocks.

There are several candidates for the possible sources of Sr in the samples. Precambrian gneisses and Jurassic granites are the main provenance rocks for the Gyeongsang Basin (Choi, 1986; Koh, 1986). Most of the Precambrian gneisses of the Korean Peninsula have much higher ^{87}Sr/^{86}Sr ratios than the bone and host rock samples. The Jurassic granites of the Korean Peninsula have somewhat lower values (c. 0.715) than the Precambrian gneisses (Jin et al.,
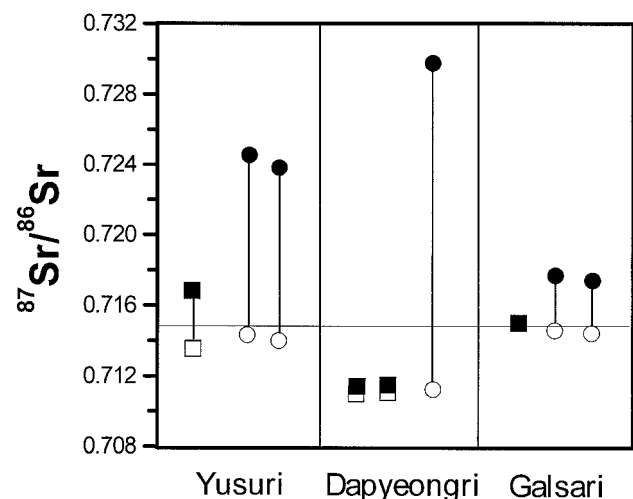
Figure 13. Comparison of the Sr isotopic compositions of the dinosaur bone fossils and their host sedimentary rocks in the Hasandong Formation.

1993; Kwon *et al.*, 1999). Accordingly, the Jurassic granites seem to have average Sr isotopic compositions that are broadly similar to those of the deposits studied at the time of their deposition.

High $^{87}Sr/^{86}Sr$ ratios of the rock residues seem to reflect such Precambrian and Jurassic sources. However, the Precambrian gneisses and the Jurassic granites are unlikely to be the sources of the Sr with low $^{87}Sr/^{86}Sr$ ratios within the bone fossils and acid-leachable fractions of the host sedimentary rocks. Jurassic granites might have provided Sr with relatively low ratios compared with the Precambrian gneisses through chemical weathering of low $^{87}Sr/^{86}Sr$ ratio phases such as plagioclase and apatite. However, this source seems insufficient, because it is hard to imagine that all the Sr of dinosaur bones and the leachable fractions of the host rocks were exclusively derived from such a source. Therefore, it is reasonable to consider that another component played a significant role in providing strontium with low $^{87}Sr/^{86}Sr$ ratios. During the Late Cretaceous there was active volcanism throughout the Gyeongsang Basin and their $^{87}Sr/^{86}Sr$ ratios are sufficiently low (Yun, 1998) to provide a suitable source, as proposed above. The occurrence of such abundant volcanics has not yet been reported from the Hasandong Formation. Nevertheless, the geochemical character of the Hasandong dinosaur deposits does suggest the existence of intermittent volcanic activity during the period of deposition represented by this formation. The presence of volcanogenic mudstone facies in the underlying Nakdong Formation (Cheong & Kim, 1996) indicates that there was volcanic activity around the Gyeongsang Basin during the Early Cretaceous.

5. Palaeoenvironments

The Gyeongsang Basin, in which the Hasandong Formation was deposited, was a continental graben occupied by concentrically arranged alluvial fans, fluvial plains, and lake systems (H. I. Choi, 1985). It extended into the southwestern part of Japan (Matsukawa *et al.*, 1995), and its flora indicates both temperate humid, and tropical–subtropical arid climatic conditions (Kimura & Ohana, 1990). However, it is inferred from palynological records (D. K. Choi, 1985), lithofacies and palaeosols (Paik & Kim, 1997) that an arid climate prevailed. Palaeofloral data for the Early Cretaceous in mid-latitudes of the Northern Hemisphere also indicate arid and semi-arid climatic conditions (Meyen, 1987). By contrast, humid conditions are inferred from the composition of the Lower Cretaceous flora in Japan and NE China (Kimura, 1984), which are located near the Gyeongsang Basin.

The presence of relatively thick floodplain-mudstone deposits in the Hasandong Formation indicates an abundant supply of fine-grained sediments. In general, such sediments are produced by chemical weathering of parent rocks, and the amount of water is crucial to chemical weathering (Macias & Chesworth, 1992). It is thus thought that the source area was in a relatively humid climate. Nevertheless, the arkosic to lithic-arkosic nature of the Hasandong sandstones (Jho, 1994) may indicate that chemical weathering was not intense in the source area, which suggests subhumid climatic conditions. In the depositional area, the repeated development of fluvial plain deposits of 2–7-m-thick, laterally extensive channel sandstones, a characteristic of perennial meandering streams, in the Hasandong Formation indicates that wet conditions for active fluvial processes were dominant. By contrast, the presence of common calcic and vertic palaeosols in the formation suggests that the climate of Hasandong time was semi-arid and seasonal with wet and dry cycles (Paik & Kim, 1995; Paik, 1998; Paik & Lee, 1998; Lee & Lee, 2000). The occurrence of calcrete nodules near the palaeosol surfaces in the formation also suggests the influence of dry conditions (Retallack, 1990). These conflicting aspects of the Hasandong sediments imply that fluvial processes were active but episodic at the time of deposition. The prevailing climate during the accumulation of the bone beds was semi-arid with a mean annual precipitation of 300–600 mm (semi-arid morphoclimatic zone in Summerfield, 1991).

The occurrence of remains of herbivorous dinosaurs in the Hasandong Formation indicates the existence of vegetated landscapes. Carbonized tree stumps and wood fragments, rhizocretions and rootlets occur intermittently. The average carbon isotopic compositions of pedogenic carbonates is -5.6‰ (PDB), suggesting carbonate formation in soils dominated by C_3-type vegetation of dry woodland (Y. I. Lee, 1999). However, there are no coal deposits and leaf fossils are rare. It is common that fossil bones and plants are seldom found together (Retallack, 1997). The scarcity of leaf fossils can be attributed to the oxidized condition of the sediments. The presence of fossil charcoal in the floodplain lake deposits associated with dinosaur deposits in Yusuri (Paik & Lee, 1994) underscores the existence of drought conditions. In the Late Cretaceous Jindong Formation, which contains abundant footprints of herbivorous dinosaurs (Lim, 1990), plant fossils are also very rare despite the common occurrence of dark grey, fine-grained deposits. This formation is interpreted as having been deposited in a partially alkaline lake under semi-arid climatic conditions (Paik *et al.*, 2001). Scarcity of

plant preservation in the formation is also attributed to an arid climate. Such apparently conflicting records of herbivorous dinosaurs and very rare plant preservation have also been noted to some extent in the Jurassic Morrison Formation of the US Western Interior (Dodson *et al.*, 1980). By contrast, plant fossils are common in the formations of the Gyeongsang Supergroup in which dinosaur remains are rare (Kimura, 2000).

The depositional environments of the dinosaur deposits at the three localities described above are all floodplain. On the basis of pedofacies (Kraus, 1987), the proximity to a main channel, and the sedimentation rate indicated by these bone-bearing deposits are, however, interpreted to be different in each case. Dinosaur bed 1 at Yusuri is superjacent to channel sandstone beds and bone preservation is at calcrete development stages 1–2, indicating that it is a proximal floodplain deposit that accumulated at a relatively high rate. Dinosaur bed 2 at Yusuri lies about 3 m above a channel deposit and bone preservation at calcrete development stages 2–3 indicates a distal floodplain where the sedimentation rate was relatively low. The depositional environments of the Dapyeong-gri and Galsari dinosaur beds are also interpreted as distal floodplains on the basis of their pedofacies relationships.

6. Taphonomic preservation of dinosaur bone

During Hasandong times in the Korean Peninsula, both herbivorous and carnivorous dinosaurs inhabited fluvial plains with a dry woodland vegetation under a generally arid climate. This climate, and the consequential low sedimentation rate allowed dinosaur carcasses to be exposed long enough to become weathered. Intense weathering of dinosaur remains prior to burial is supported by the Dapyeongri bones. Scavenging activity by dermestid beetles on dinosaur carcasses, also indicated by the Dapyeongri bones (Paik, 2000), might have facilitated the disintegration of bones. Preservation of bone as fragments at Yusuri further indicates that the bones experienced intense weathering before burial. Dinosaurs are commonly found as naturally weathered fragments, stained and cracked by exposure, in the palaeosols (Retallack, 1997).

Isolated occurrences of rib and postcranial elements in the Galsari bone deposit indicate that the preburial period was protracted (Smith, 1993). The breakage of some vertebrae and postcranial elements also suggest that disintegration of bones occurred before burial. In addition, the depositional environment of the Galsari dinosaur bed (distal floodplain) might have resulted in low sedimentation rates. On the other hand, the smooth bone surface without longitudinal cracks or fissures in a dorsal rib, the articulated preservation of some cervical vertebrae, and the preservation of some unfilled internal openings, indicate that the bones experienced scarcely any weathering and were buried very rapidly (Behrensmeyer, 1978, 1991; Smith, 1993). The nearly linear occurrence and partially articulated preservation of cervical vertebrae suggest that they were preserved near to the site of death. The unsorted occurrences of bones, the presence of some presumed gastroliths associated with bone, and the preservation of large bones in hydraulically incompatible muddy deposits, demonstrate that they are *in situ* remains.

Such contrasting preservation states of the Galsari bones may be resolved by invoking scavenging and volcanic activity. Bakker (1997) interpreted the occurrence of large bones in fine-grained floodplain sediments of the Morrison Formation, in the region of Como Bluff, as the result of allosaur parents transporting giant carcasses to feed their young. There is no unequivocal evidence to support the idea that the Galsari bone deposit originated in such a setting. It is certain that the bones were not hydraulically transported, and were buried rapidly. Nevertheless, the isolated and broken occurrences of bones indicate that some agents helped to disintegrate them. In general, completely preserved sauropod skeletons are exceedingly rare, and distal caudal, foot, and skull elements were usually lost before burial (Dodson, 1992). Although the reason for these occurrences of sauropod remains is not clear, carnivory and scavenging of sauropod carcasses are likely causes of the breakage of non-transported bones. Despite the lack of surface marks to indicate carnivory in Galsari bones, predation by carnivores may have been involved in their taphonomy.

The rapid burial of Galsari bones on a distal floodplain might have resulted from volcanic activity near the Gyeongsang Basin. The former presence of abundant smectites in all of the bone deposits described above suggests that coeval volcanic activity occurred near the Hasandong floodbasin. The Sr isotopic composition of bones and host rocks also suggests the presence of a volcanogenic source. We infer that subsequent flooding accompanied by volcanic eruption might have resulted in the deposition of muds thick enough to bury the bones.

After burial, the Hasandong bone deposits underwent calcareous pedogenesis. This led to the formation of calcite rinds around the bones, which aided preservation. It is known that calcareous deposits are suitable for bone preservation (Retallack, 1997). The
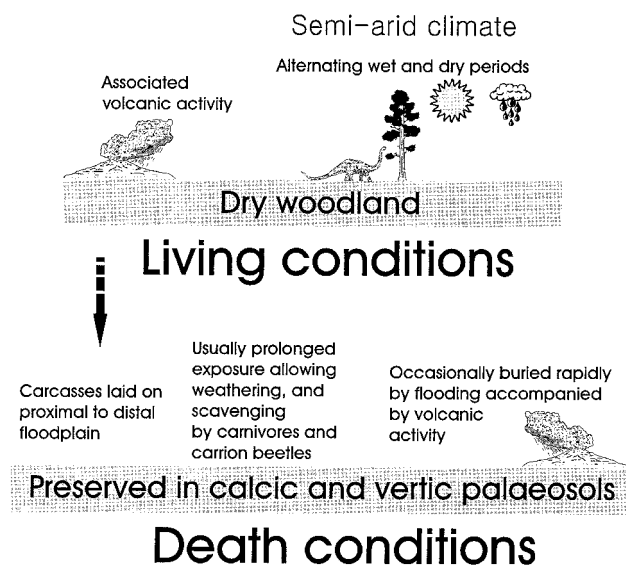
Figure 14. Schematic diagram summarizing taphonomic pathways for the Hasandong dinosaur bone deposits.

predominance of bone-bearing deposits in the Hasandong Formation may in part be attributed to the abundance of calcic palaeosols. Taphonomic pathways of the bone deposits are summarized in Figure 14.

7. Conclusion

The Early Cretaceous sauropods of the Korean Peninsula lived in dry woodlands with oxidized soils. This association is comparable to the habitats of sauropods interpreted from the occurrence of their remains in the Upper Jurassic Morrison Formation of the US Western Interior (Dodson *et al.*, 1980; Retallack, 1997), and in the Upper Cretaceous deposits of Mongolia (Jerzykiewicz & Russell, 1991), India (Sahni *et al.*, 1994), and Utah (Fouch *et al.*, 1983; Bakker, 1986). The carcasses deposited on the Hasandong floodplain were severely weathered and scavenged by carnivores and carrion beetles before burial. Volcanic activity near the basin sometimes resulted in rapid burial of the unweathered bones on distal floodplains, as in the case of the Galsari bone deposits. All of the Hasandong bone deposits were influenced by calcareous pedogenesis, which facilitated bone preservation.

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