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Time, Space and Structure on the Korea Cretaceous Dinosaur Coast: Cretaceous Stratigraphy, Geochronology, and Paleoenvironments

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The stratigraphy, geological ages, and paleoenvironments of the Korea Cretaceous Dinosaur Coast (KCDC) are reviewed and synthesized in order to understand the occurrence and diversity of the vertebrate fossils and track remains in time and space. Various absolute age measurements obtained during the last decade yield new age data to correlate with the dinosaur fossil-bearing Cretaceous deposits in Korea. The radiometric age of the lower (Sindong Group) and middle (Hayang Group) parts of the Gyeongsang Basin (the largest basin of the KCDC) located in the eastern part of the KCDC gives dates ranging from Aptian to Campanian, which is younger than the previous biostratigraphic age estimates, but the results may be influenced by metamorphism. Likewise, radiometric dates from the Cretaceous sequence in the western part of the KCDC give numerical values suggesting a correlation with the Upper Cretaceous Yucheon Group of the Gyeongsang Basin. Dinosaur evidence (e.g., tracks, eggs, bones) along the KCDC is variable in relation to stratigraphy and paleoenvironment. Dinosaur tracks are preserved mostly in stratigraphically higher Cretaceous lake margin deposits, whereas dinosaur bones occur mostly in older Cretaceous floodplain deposits. Most dinosaur eggs are found in Upper Cretaceous deposits, and they occur in floodplain deposits of alluvial fan and meandering river settings. Thus, we conclude that dinosaurs inhabited volcanically influenced, alluvial fan, fluvial plain, and lake margins on the Korean Peninsula throughout the Cretaceous under a semi-arid climate with strong seasonality. The rarer occurrence of dinosaur tracks in older Cretaceous deposits in some basins might be attributed to the limited exposures of lake-margin deposits. It is inferred that the presence of large lakes as water sources, rich vegetation of gymnosperm trees as food, and semi-arid paleoclimatic conditions formed a general landscape and environmental setting favorable for dinosaurs and their preservation in the Cretaceous deposits of South Korea.

Keywords Cretaceous, Stratigraphy, Geological ages, Paleoenvironments, Dinosaur, Korea

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INTRODUCTION

The Cretaceous sequences in the southern coastal regions of the Korean peninsula are so rich in dinosaur remains, especially tracks, that they have been referred to as the Korea Cretaceous Dinosaur Coast (KCDC) and were considered of sufficient paleontological significance to have five representative sites (all national natural monuments) nominated for World Heritage inscription. These sites and others are discussed elsewhere in this volume. The KCDC serves as a unifying theme for Cretaceous geology and paleontology in Korea. We discuss some of the problems of understanding how the various sites, stratigraphic units, and paleoenvironmental interpretations can be integrated to better understand the spatial and temporal relationships (time and space) of the KCDC.

During the late Mesozoic, the Paleo-Pacific (Izanagi) Plate underwent subduction beneath the East Asian continent, including the Korean Peninsula, which was situated at an active continental margin much like today. During the Middle Jurassic, the Korean Peninsula was bounded by the resulting trench to the southeast and the Jurassic Mino accretionary complex, now located in SW Japan, was accreted to the southeastern Korean Peninsula (Joo et al., 2007). However, the subduction direction of the Izanagi Plate changed to oblique during the Late Jurassic to Early Cretaceous (Maruyama et al., 1997), resulting in multiple large-scale, left-lateral, strike-slip movements along the East Asian continental margin (D. W. Lee, 1999; Okada, 1999, 2000). Such strike-slip movement induced development of more than 10 nonmarine pull-apart basins in the Korean Peninsula along the NE-SW-trending Gongju and Gwangju fault systems (D. W. Lee, 1999) (Fig. 1), including the KCDC. All of these Cretaceous nonmarine basins were filled with Lower to Upper Cretaceous alluvial to lacustrine deposits. Intermittent volcanism was associated with, and was a cause of, sediment deposition in these basins.

The Gyeongsang Basin, located in the southeastern part of the Korean Peninsula (Fig. 1), is the largest of these

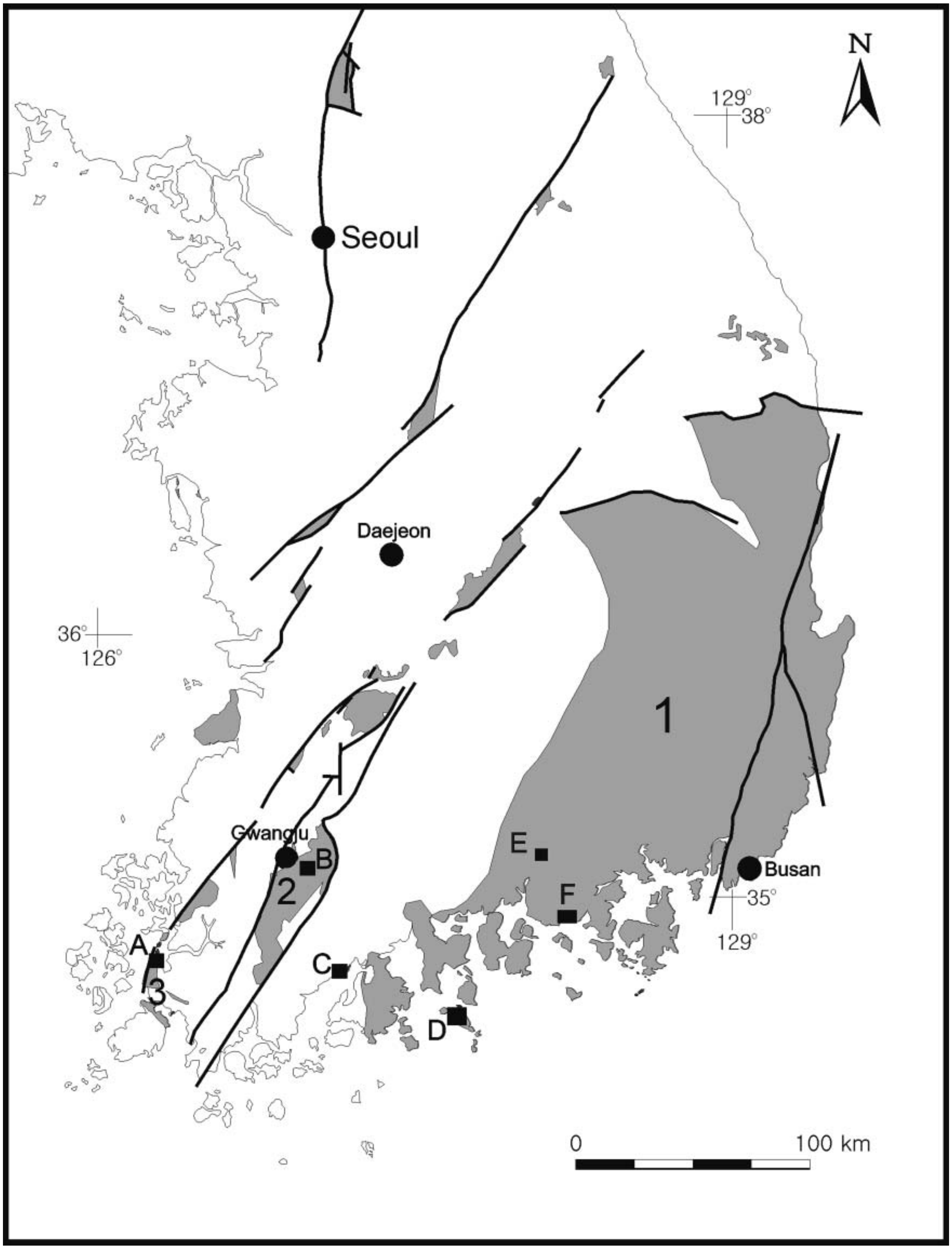

FIG. 1. Distribution map of the Cretaceous nonmarine basins in South Korea (Kang et al., 1995; Lee, D. W., 1999) and location of major dinosaur fossil sites on the KCDC. 1. Gyeongsang Basin; 2. Neungju Basin; 3. Haenam Basin; **A.** Haenam (Uhangri) site; **B.** Hwasun (Seoyuri) site; **C.** Boseong (Bibongri) site; **D.** Yeosu (Sado and Chudo) site; **E.** Gajinri site; and **F.** Goseong site.

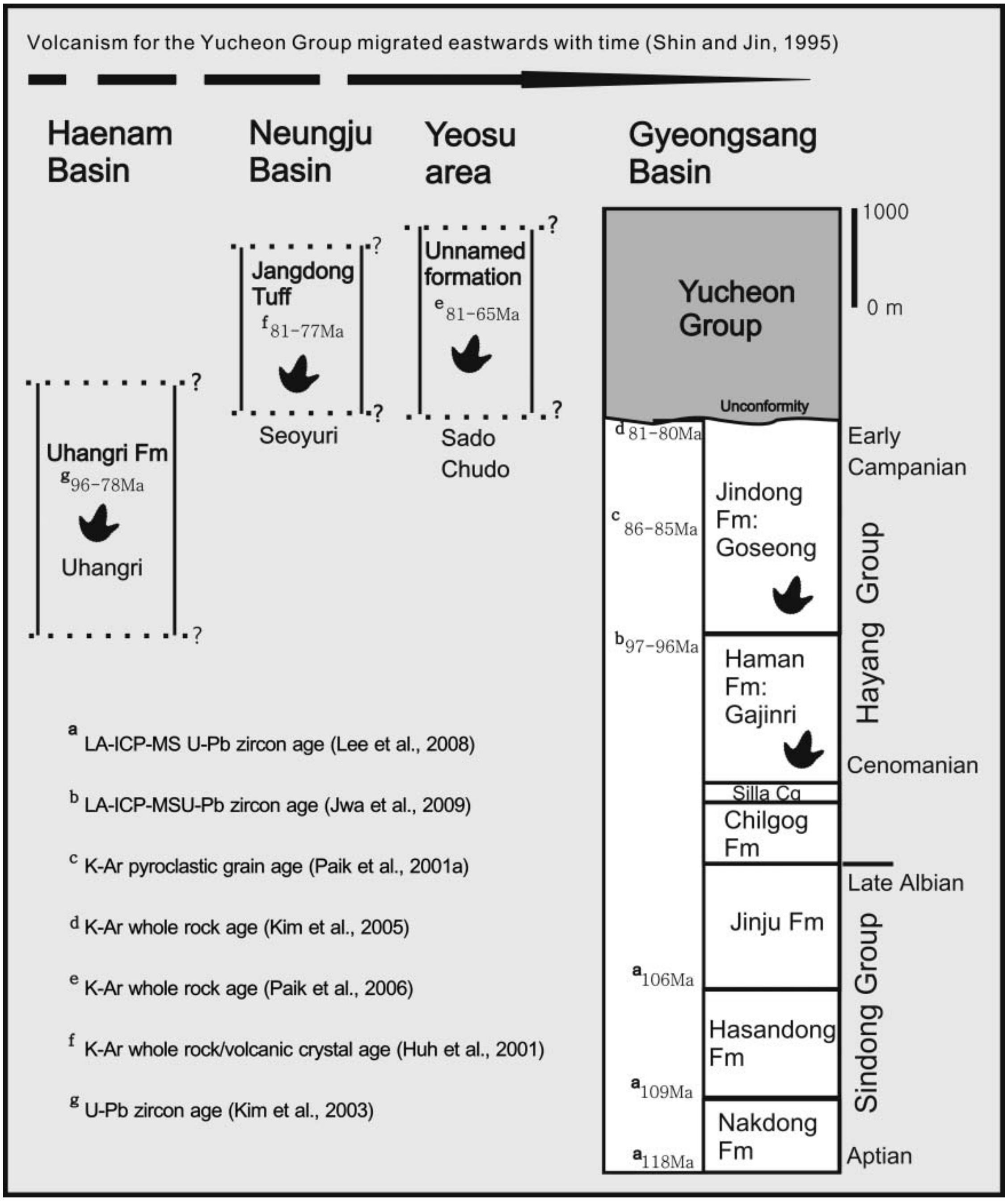

FIG. 2. Radiometric geological ages of the major dinosaur deposits on the KCDC.

sedimentary basins and covers about one-fourth of South Korea with a 9000-m-thick sequence of deposits assigned to the Gyeongsang Supergroup comprising, in ascending order, the Sindong, Hayang, and Yucheon groups and Bulguksa granites. The Gajinri and Goseong sites on the KCDC belong to the upper part of the Hayang Group (Baek and Yang, 1998) and the lowermost part of the Yucheon Group (Paik et al., 2006a), respectively (Fig. 2). The earliest development of the Gyeongsang Basin was interpreted to be of rift origin associated with plume-related magmatism (Okada, 1999, 2000; Chang, 2002). However, a recent study suggests that the Gyeongsang Basin was initiated by a N-S left-lateral, regional simple shear as a wrench tectonic system due to highly oblique subduction of the Izanagi Plate (B. H. Hwang et al., 2008).

The frequent intercalation of volcanic rocks in the pull-apart basins outside the Gyeongsang Basin and the absolute age measurement data for the dinosaur fossil-bearing deposits in these basins (Huh et al., 2001; Kim et al., 2003; Paik et al., 2006b) indicate that sediment fills in these basins are time-correlated with the upper part of the Hayang Group to Yucheon Group in the Gyeongsang Basin. The KCDC along the southwestern part of the peninsula, including the Haenam, Hwasun, Boseong and Yeosu sites, belongs to these subordinate small and isolated basins. Due to relatively small basin size, sediments in these basins are characterized by rapid vertical and lateral facies change over relatively short distances.

The spatial relationships and time-correlations between the basins on the KCDC have not been well-delineated due to the rare occurrence of index fossils for biostratigraphy, the absence of key beds for correlation, complicated lateral facies change, discontinuity by intrusive and extrusive rocks, and the shortage in absolute age measurement data. Even though detailed information is lacking, in this paper we attempt to synthesize the stratigraphy, geochronology, and paleoenvironments of the KCDC in order to understand the occurrence and diversity of the vertebrate fossils and track remains in time and space.

STRATIGRAPHY AND GENERAL LITHOLOGY

The stratigraphy of the KCDC deposits was established primarily on lithostratigraphy, as their biostratigraphy and chronostratigraphy are incomplete. The Gyeongsang Basin, the largest on the KCDC, has a well-understood lithostratigraphy (Chang, 1975), whereas the lithostratigraphy of subordinate small and isolated basins in the western part of the KCDC have not been completely established due to the discontinuity of the sequence by frequent interruptions of intrusive and extrusive rocks. It is therefore difficult to establish a unified stratigraphic correlation between the basins on the KCDC.

There are a number of dinosaur fossil sites, including the Goseong and Gajinri sites, located on the Gyeonsang Basin, which comprises three subbasins developed by syndepositional faults during the deposition of the Hayang Group: from north to south, the Yeongyang, Euiseong, and Milyang subbasins. The KCDC deposits belong to the Milyang subbasin (Chang, 1975), which is in unconformable contact with pre-Cretaceous granitic rocks and Precambrian gneiss (H. I. Choi, 1985). The basin fill in the Milyang subbasin comprises a full sequence of the Gyeongsang Supergroup, which is divided into four stratigraphic units based on the degree of volcanic and plutonic activity. They are, in ascending order, the Sindong (prevolcanic), Hayang (sporadic volcanic), and Yucheon (climactic volcanic) groups and the Bulguksa granites (Chang, 1975). The Sindong and Hayang groups are composed of sandstone, shale, and minor amounts of conglomerate and marlstone deposited in continental environments. After deposition of the Hayang Group, active volcanism dominated in and around the basin, and formed the Yucheon Group that comprises primarily volcanic rocks with subordinate volcaniclastic rocks. Upper Cretaceous to Lower Tertiary granitic rocks, which are interpreted to be co-magmatic with the Yucheon volcanic rocks (Lee et al., 1987), intruded into all of the preexisting sequences.

Dinosaur bones from the Gyeongsang Basin were mostly found in the Sindong Group, whereas most of the dinosaur eggs and trackways of the Gyeongsang Basin occur in the Hayang Group. The fluvial Hasandong Formation of the Sindong Group is the primary dinosaur bone-bearing deposit on the KCDC, and most of the dinosaur tracks are concentrated in the lacustrine Jindong Formation of the Hayang Group. The Goseong dinosaur tracksites on the KCDC occur in the Jindong Formation. Dinosaur eggs mostly occur in the fluvial Goseong Formation of the Yucheon Group, and some of the eggs were found in the fluvial Hasandong (Sindong Group), Haman (Hayang Group), and Dadaepo (Yucheon Group) formations. The Gajinri site bearing numerous bird footprints, with some dinosaur tracks, occurs in the fluvial Haman Formation (Kim et al., this volume; Lockley et al., this volume, a).

The Haenam site located in the southwesternmost area on the KCDC (Fig. 1) belongs to the Haenam Basin and is composed of various types of tuffaceous and epiclastic rocks. The strata in the Haenam Basin were classified into four lithostratigraphic units, in ascending order: andesitic tuff (informal name), Uhangri Formation, Hwangsan Tuff, and Jindo Rhyolite (Kim et al., 2003). These strata are lithostratigraphically correlated with the Yucheon Group of the Gyeongsang Basin (Kang et al., 1995). Dinosaur, pterosaur, and web-footed bird tracks are preserved in the fluvio-lacustrine Uhangri Formation, which is considered Late Cretaceous in age (Chun, 1990; K. G. Hwang et al., 2002, 2008; Lockley et al., this volume, a; Minter et al., this volume). It comprises approximately a 400-m-thick interlayered epiclastic sequence of conglomerates, sandstones, mudstones, shales, cherts, and felsic to intermediate tuffs and lavas (Kim et al., 2003). The vertebrate tracks are mostly concentrated in the cherty mudstones. Synsedimentary deformation structures and sedimentary dykes of paleoseismic origin are associated with the track-bearing deposits.

The Hwasun site is located in the Neungju Basin, which is filled by the Neungju Group (Fig. 1). The Neungju Group consists mainly of volcanic rocks including andesite and rhyolite, tuffs, and tuffaceous deposits that are lithostratigraphically correlated with the Yucheon Group (Kang et al., 1995). It is divided into five informal lithostratigraphic units, in ascending order of sedimentary deposits, lower andesitic deposits, upper andesitic deposits, lower rhyolitic deposits, and upper rhyolitic deposits, but some strata are formally classified with proper stratigraphic names. For example, the dinosaur track-bearing deposits at the Hwasun site (Huh et al., 2006; Lockley et al., this volume, b) are within the Jangdong Tuff, belonging to the lower rhyolitic deposits of the Neungju Group. The Jangdong Tuff is composed of approximately 800 m of interlayered tuff, tuffaceous sandstone and mudstone, and shale. Dinosaur tracks occur in shale-dominated lake margin deposits, and the tracks mostly occur in interlaminated fine-grained sandstone-siltstone-mudstone beds (Huh et al., 2006).

The Boseong site is located on the southern periphery of the Neungju Basin, outside the basin proper (Fig. 1), and the spatial distribution of the sedimentary sequence at the Boseong site is not connected with any other neighboring Cretaceous basins. The Boseong sequence is composed of acidic to intermediate volcanic rocks, tuffs, and tuffaceous and epiclastic deposits like that of the Neungju Group and is therefore lithostratigraphically correlated with the Yucheon Group of the Gyeongsang Basin (Kang et al., 1995). It is divided into, in ascending order, the Seonso Conglomerate, Seonso Formation, Pilbong Rhyolite, Gaeksanri Flow, Obongsan Brecciated Tuff, and Docheonri Rhyolite (Hwang and Cheong, 1968). Dinosaur eggs occur in the Seonso Conglomerate, which is primarily epiclastic, partially tuffaceous, and consists of conglomerates, sandstones, and mudstones. Lapilli tuffs occur in the lowermost part of the Seonso Conglomerate. Dinosaur eggs and bones are present in sandy mudstones with pedogenic calcretes (Paik et al., 2004).

The Yeosu site is located in the southwestern part outside the Gyeongsang Basin (Fig. 1). It consists of five islands (Jeokgeumdo, Nangdo, Mokdo, Chudo, and Sado), whose sedimentary sequence is part of an isolated basin fill. The Yeosu sequence is composed of sedimentary rocks such as conglomerates, sandstones, shales, and volcanic rocks and tuffs of a wide compositional range and is also lithostratigraphically correlated with the Yucheon Group of the Gyeongsang Basin (Kang et al., 1995). However, the sequence has not been classified into formal lithostratigraphic units. The sedimentary rocks are alluvial fan, fluvial, and lacustrine deposits, and dinosaur tracks occur in the lake margin deposits lying in the upper part of the sequence (Paik et al., 2006b). The track deposits (Huh et al., this volume; Lockley et al., this volume, c) are interlaminated to thinly interbedded, fine-grained sandstone-siltstone-mudstone; pyroclastic deposits including tuff, agglomerate, and lava flows are intercalated in places.

GEOCHRONOLOGY

Various geological ages of the Cretaceous deposits in the Gyeongsang Basin have been proposed, with the primary differences arising from the methods used, ranging from biostratigraphic correlation of nonmarine invertebrate fossils, fossil plants, and pollen, and by magnetostratigraphic correlation, radiometric, and fission track dating. The Nakdong Formation (the lowest unit of the Sindong Group) and the overlying Hasandong Formation were correlated with the Hauterivian to Barremian by charophytes (Seo, 1985); however, they are assigned to the Aptian to Albian by mollusks (Yang, 1978). The Jinju Formation (the uppermost unit of the Sindong Group) was also assigned to the Aptian to Albian based on fossil plants (Kimura, 1973) and the Aptian by mollusks (Yang, 1982), while it was bracketed within the Neocomian by pollen (D. K. Choi, 1985). The upper part of the Hayang Group was correlated with the Cenomanian to Turonian by mollusks (Yang, 1982) and correlated with the Aptian to Early Albian by pollen (D. K. Choi, 1985). Magnetostratigraphic correlation of the Sindong and Yucheon groups indicate an Aptian and Campanian age, respectively (Doh and Kim, 1994; Doh et al., 1994).

During the last decade, numerical age measurements have been obtained using various techniques and yielded new age data to correlate the Cretaceous deposits in Korea (Fig. 2). The LA-ICP-MS U-Pb zircon age ranges from 137.9 ± 7.1 Ma to 106.2 ± 3.7 Ma for the Sindong Group (Lee et al., 2008, 2010). The youngest detrital zircon age of three formations in the Sindong Group becomes progressively younger stratigraphically, as expected: 118 Ma for the Nakdong Formation, 109 Ma for the Hasandong Formation, and 106 Ma for the Jinju Formation. Accordingly, the depositional age of the Sindong Group ranges from late Aptian to late Albian, which is younger than indicated by biostratigraphic correlations. From a volcanic pebble of the Silla Conglomerate in the lower part of the overlying Hayang Group, Kim et al. (2005) obtained an $^{40}Ar/^{39}Ar$ hornblende age of 113.4 ± 2.4 Ma, indicating the depositional age of the Silla Conglomerate is younger than late Aptian. For the Gusandong Tuff, which occurs in the upper part of the Hayang Group, Jwa et al. (2009) reported a LA-ICP-MS U-Pb zircon age of 97–96 Ma. The K-Ar whole-rock age of pyroclastic clasts in the Jindong Formation was recovered at 86–85 Ma (Paik et al., 2001a). In addition, the boundary between the Hayang Group and the overlying Yucheon Group has been interpreted to be 81–80 Ma (Kim et al., 2005). Considering this data, the Hayang Group is interpreted to have been deposited during the late Albian to early Campanian (Lee et al., 2010).

The Cretaceous sequence of the KCDC in the western part of the Gyeongsang Basin is lithostratigraphically correlated with the Yucheon Group. The Yucheon Group is up to 2,000 m thick in places and consists mainly of extrusive rocks, including andesite, rhyolite, and various types of tuff, with subordinate volcaniclastics and nonvolcaniclastic sedimentary layers. Overall, the composition of the volcanic rocks changes from intermediate in the lower part to acidic upwards. Development or deposition of the group occurred in and around volcanic vents, forming volcanic complexes, including caldera complexes as indicated by the presence of many circular volcanic structures that are recognized on Landsat images. The sedimentary strata, including both volcaniclastic and epiclastic materials, are the deposits of small fluvial plains and lakes that were developed on topographic lows. Isotopic ages of volcanic rocks lithostratigraphically correlated with the Yucheon Group show a general trend of younging from west to east, being over 90 Ma in the Haenam area (SW part of the peninsula), about 80–74 Ma in the Gwangyang-Namhae area (central southern coast) and 77–58 Ma around the Milyang area (SE Gyeongsang Basin) (Shin and Jin, 1995). This may indicate that volcanism for the Yucheon Group migrated eastwards with time (Fig. 2).

Some of the Cretaceous sediments outside the Gyeongsang Basin were radiometrically dated. The Cretaceous sediments in the Haenam Basin were dated to be 96–78 Ma based on U-Pb zircon dating (Kim et al., 2003). K-Ar whole-rock ages of volcanic rocks and clasts at the Hwasun site were measured at 81–77 Ma (Huh et al., 2001). For the Yeosu dinosaur track-bearing deposits, Paik et al. (2006b) reported that the K-Ar whole-rock age of volcanic clasts and tuffs ranges from 81 to 65 Ma, implying a Campanian to Maastrichtian age. However, whole rock dates obtained from metamorphic rock are subject to error in favor of younger ages. Thus, additional alternate dating is needed to establish more reliable time-correlation for the Cretaceous deposits of the KCDC outside the Gyeongsang Basin.

PALEOENVIRONMENTS

The general paleoclimatic regime during the Cretaceous on the Korean Peninsula is interpreted to have been warm and dry (H. I. Choi, 1985; Paik and Kim, 1997). In contrast, paleoclimatic conditions during the Cretaceous from coastal areas of Japan and NE China adjacent to the Korean Peninsula have been inferred to be humid (Kimura, 1987). During the Cretaceous, the Korean Peninsula was situated inland of an active continental margin (H. I. Choi, 1985). Cretaceous paleomagnetic data from South Korea (Park et al., 2005) reveal that the Korean Peninsula was located at about 42°N during the middle to late Early Cretaceous and drifted southward to the present latitude (37°N) during the Late Cretaceous. The arid climatic conditions during the Cretaceous in the Korean Peninsula are thus compared to that of modern mid-latitudes due to an orographic effect. Topographic highs developed towards the west and east of the Gyeongsang Basin (H. I. Choi, 1985; Okada, 2000; Lee and Kim, 2005), which resulted in a rain-shadow environment for the Gyeongsang Basin. During the deposition of the Gyeongsang Basin, the location of topographic highs was changed from west to east with time. During the early stage, topographic highs were located along the western boundary of the basin, and sediments were derived from western and northwestern sources (Chang and Kim, 1968; Koh, 1986). In the late stage of basin filling, sediments were mostly derived from eastern and northeastern sources (Chang et al., 1990) where uplifting of Precambrian basement and the Mino accretionary complex occurred due to left-lateral strike-slip movements (Lee and Kim, 2005; Lee, 2009).

This orographic interpretation is supported by the abundant presence of calcretes and evaporite mineral casts in floodplain deposits of the Hasandong Formation of the Sindong Group (Paik and Lee, 1994, 1998; Lee, 1999; Paik and Kim, 2003) and in extensive evaporative mudflat deposits of the Jindong Formation of the Hayang Group (Paik et al., 2001a; Paik and Kim, 2006). (See Houck and Lockley, 2006, for alternate interpretations of the Jindong paleoenvironments.)

Paleoweathering conditions in the source areas for the Gyeongsang Basin have been estimated by geochemistry of fine-grained sediments. Chemical index of alteration (CIA; Nesbitt and Young, 1982) values of Sindong Group shales range from 58.3 to 75.6 with an average of 70.1, and Hayang Group shales from 51.9 to 73.1 with an average of 64.4 (Lee and Lee, 2003). CIA values for shales of the Hayang Group in the Yeongyang Subbasin also show a similar range from 64 to 76 with an average of 68 (Lee, 2009). These values indicate moderate weathering in the source area. Average CIA values of Sindong Group shales are higher than Haygang Group shales, suggesting a more intense degree of weathering in the source for the Sindong Group. In the Sindong Group, Nakdong shales show higher CIA values than Hasandong and Jinju shales. This is in agreement with the interpretation that the paleoclimate during the Nakdong Formation deposition is considered to have been more humid than during deposition of the Hasandong and Jinju formations (H. I. Choi, 1985). Lower CIA ranges of the Hayang Group shales were probably caused by drier conditions and/or shorter transport of volcanic detritus to the basin during Hayang Group deposition (Lee and Lee, 2000), which is in agreement with the results of detrital compositions of sandstones (Um et al., 1983). This interpretation is supported by the results of a paleoclimatic study of the Jindong Formation by Paik and Kim (2006), who reported the extensive development of dry to saline mudflat deposits, the presence of common evaporite mineral casts, complicated polygonal desiccation cracks and rainprints, and pedogenic carbonate development. Paik and Kim (2006) interpreted the Jindong Formation as playa lake and sheetflood sediments deposited under relatively dry climatic conditions, with flooding stages persisting much longer than evaporation and desiccation stages. Houck and Lockley (2006) suggested that much volcaniclastic sediment was redistributed as a result of such sheet flooding, which in turn may have been induced by volcanism. Drier conditions during the Hayang deposition than during the Sindong deposition might have been induced by enhanced orographic effects related to the uplifting of the accretionary complex located to the east and northeast of the basin.

All of the sedimentary basins on the KCDC were fault-bounded inland basins, and volcanic activity was associated with the basin boundaries, forming high lands. The depositional systems of the basins were composed of alluvial fan, fluvial, and lacustrine environments. The Gyeongsang Basin was a half-graben (H. I. Choi, 1985) or graben basin and had few cycles of basin filling and expansion. By contrast, small pull-apart basins in the western part of the KCDC are completely isolated and consist of only one cycle of basin filling. Although the complete paleoenvironmental settings including paleogeography, paleotopography, paleoclimatology, and paleoecology and their changes through the Cretaceous on the KCDC have not yet been delineated, some of the studies of the dinosaur deposits provided data to help better understand the paleoenvironments of the KCDC (Paik and Lee, 1998; Paik et al., 1998, 2001a, b, 2004, 2006b, 2007, 2009; Lee, 1999; Paik, 2000; Houck and Lockley, 2006; Kim et al., 2008).

The Lower Cretaceous dinosaur habitats in the Gyeongsang Basin were inferred based on dinosaur bone deposits of the fluvial Hasandong Formation to have been dry woodlands with a semi-arid climate and alternation of wet and dry periods (Paik, 1998; Paik and Lee, 1998; Paik et al., 1998, 2001b; Lee, 1999). In these dinosaur bone deposits, traces of scavenging by carrion beetles is preserved (Paik, 2000). The occurrences of dinosaur track deposits in the Upper Cretaceous lacustrine Jindong Formation suggests that dinosaurs inhabited a volcanic terrain under a semi-arid climate (Paik et al., 2001a; Houck and Lockley, 2006). The Jindong Lake was exploited by the dinosaurs for water sources during drought seasons (Paik et al., 2001b). The occurrences of bird footprint deposits in the Upper Cretaceous Haman and Jindong formations suggest that dinosaurs and birds congregated in the lake margin environment during Haman and Jindong deposition (Baek and Yang, 1998; Kim et al., 2008). The occurrences of dinosaur egg-bearing deposits in the Gyeongsang Basin indicate that the floodplain was used as a primary nesting site during the Cretaceous (Paik et al., 2004). The presence of calcic and vertic features in these egg deposits suggests that the nesting sites deposited in a semi-arid climate with alternating wet and dry periods (Paik et al., 2004).

The dinosaur track deposits in the Upper Cretaceous small isolated basins in the western part of the KCDC are similar to those of the Gyeongsang Basin in their development of lake-margin deposits, associated with tuffaceous deposits (Chun, 1990; Huh et al., 2006; Paik et al., 2006b; K. G. Hwang et al., 2008). This implies that the lake margins in these volcanic terrains were a major habitat for the dinosaurs on the Korean Peninsula during the Late Cretaceous. The common occurrence of pedogenic calcretes in the dinosaur track-bearing deposits of the Gyeongsang Basin (Paik et al., 2001b) contrasts with the track-bearing deposits in the western part of the KCDC that show rare development of pedogenic calcretes, suggesting that the habitat of dinosaurs in these small isolated basins may have experienced frequent flooding.

The dinosaur egg-bearing deposits in the western part of the KCDC (Boseong site) are also floodplain deposits, as in the Gyeongsang Basin. The preservation of the dinosaur egg clutches in calcic and vertic palaeosols indicates that the palaeoclimate of the nest area was also semi-arid seasonally with available water (Paik et al., 2004). The record of repeat dinosaur nesting or "site fidelity" (sensu Horner, 1982) in the Boseong egg-bearing deposits (Paik et al., 2004) suggests that the semi-arid floodplain was preferred by dinosaurs as nesting sites in the Late Cretaceous.

The paleoclimatic zonation based on the flora (Meyen, 1987; Vakhrameev, 1991; Chumakov et al., 1995) and model simulation of precipitation minus evaporation (Barron and Moore, 1994) identified the Korean Peninsula as a humid area with little seasonality during the Cretaceous. However, the common development of calcic and vertic paleosols in the Cretaceous continental deposits of the KCDC (Paik, 1998; Paik and Lee, 1998; Paik and Kim, 2003) suggests semi-arid and seasonal paleoclimatic conditions during the Cretaceous. The development of dry mudflats in the dinosaur track-bearing deposits of the KCDC (Paik and Kim, 2006; Paik et al., 2007) indicates that the Korean Peninsula was semi-arid during the Late Cretaceous. The Cretaceous flora in the southern part of Korea supports the development of an arid climate (Kimura and Ohana, 1990). The flora of conifer woods from the Cretaceous deposits in Korea also supports semi-arid paleoclimatic condition during the Cretaceous in Korean Peninsula (Oh et al., 2011). The development of the rhythmic deposits in the Haman Formation (So et al., 2007), Jindong Formation (Kim and Paik, 2001), and Yeosu site deposits (Paik et al., 2009) indicate seasonality, with alternating wet and dry periods. The occurrence of halite traces as sediment-infilled casts in the Jindong Formation (Goseong site) and the Jangdong Tuff (Hwasun site) support the existence of the seasonality (Paik et al., 2007).

Rare occurrences of invertebrate body fossils in the dinosaur track-bearing deposits of the KCDC provide little information to understand the paleoecology of the dinosaur habitats. Instead, the occurrence of dinosaur tracks in these lake margin deposits can provide data on dinosaur paleoecology. Dinosaurs are preserved in a number of habitats ranging from upland to lacustrine and coastal areas and from humid to arid climates (Dodson, 1997). The dinosaur behavior inferred from dinosaur tracks includes habitat, locomotion, swimming, herding, preying, and so forth (Lockley, 1991; Lockley and Conrad, 1994; Martin, 2001). The orientation of dinosaur trackways in the track deposits of the KCDC are variable but include examples that suggest directions both perpendicular and subparallel to the lake shorelines (Paik et al., 2001a, 2006b; Huh et al., 2006; Hwang et al., 2004; Lockley et al., 2006), suggesting that the dinosaurs visited lakes for water and moved along the lakeshores. Although many dinosaur tracks are found in the coastal deposits (Lockley and Conrad, 1989; Avanzini et al., 1997), it is not yet known whether dinosaurs drank saline water. It was interpreted that the Jindong (Goseong site) and the Jandong (Hwasun site) lakes were sometimes brackish by the presence of evaporite traces, suggesting that the Late Cretaceous dinosaurs inhabiting lakes on the Korean Peninsula might have drunk brackish waters (Paik et al., 2007).

SYNTHESIS

Dinosaur remains, including tracks, bones, and eggs, are common in the Cretaceous nonmarine deposits of South Korea, and their occurrences vary with stratigraphy and paleoenvironment. Dinosaur tracks, which are the most abundant, are preserved mostly in Upper Cretaceous lake margin deposits, whereas dinosaur bones occur mostly in Lower Cretaceous floodplain deposits. The bones are in localities associated with dinosaur eggs, but bones have not yet been found in the track-bearing deposits. Most dinosaur eggs are found in the Upper Cretaceous deposits, and they occur mostly in floodplain alluvial fan to meandering river deposits. Many dinosaur remains are preserved in arid paleosols (Paik et al., 2001a, b, 2004, 2006b; Paik and Kim, 2003), but a large number of tracks are

KCDC	Western part				Eastern part	
Basin	Haenam	Neungju	Unnamed	Unnamed	Gyeongsang	
Locality	*Uhangri Haenam County*	*Seoyuri Hwasun County*	*Bibongri Boseong County*	*Sado and Chudo Yeosu City*	*Deokmyeongri Goseong County*	*Gajinri Jinju City*
Fossil type	*Dinosaur tracks Pterosaur tracks Bird tracks*	*Dinosaur tracks Bird tracks*	*Dinosaur eggs Dinosaur bones*	*Dinosaur tracks Bird tracks*	*Dinosaur tracks Bird tracks*	*Dinosaur tracks Bird tracks*
Formation	*Uhangri Fm*	*Jangdong Tuff*	*Seonso Cg*	*Unnamed*	*Jindong Fm*	*Haman Fm*
Age	*Late Cretaceous*	*Late Cretaceous*	*Late Cretaceous*	*Late Cretaceous*	*Late Cretaceous*	*Late Cretaceous*
Depositional environment	*Lake margin*	*Lake margin*	*Floodplain*	*Lake margin*	*Lake margin*	*Alluvial plain*
Paleoclimatic condition	*Semi-arid*	*Semi-arid*	*Semi-arid*	*Semi-arid*	*Semi-arid*	*Semi-arid*
Volcanic activity	*Associated*	*Associated*	*Associated*	*Associated*	*Associated*	*Associated*
Paleosol development	—	—	*Calcic and vertic paleosol*	*Palustrine calcrete*	*Palustrine calcrete*	—

FIG. 3. Summarized occurrences of major dinosaur deposits on the KCDC.

associated with fine-grained lake shoreline paleoenvironments. We conclude that dinosaurs inhabited alluvial fan, fluvial plain, and lake margins on the Korean Peninsula throughout the Cretaceous under a semi-arid climate with strong seasonality. The rare occurrence of dinosaur tracks in the Lower Cretaceous deposits and in some basins might be attributed to the limited exposure of lake-margin deposits. The occurrences of dinosaur remains in the KCDC are summarized in Figures 3 and 4.

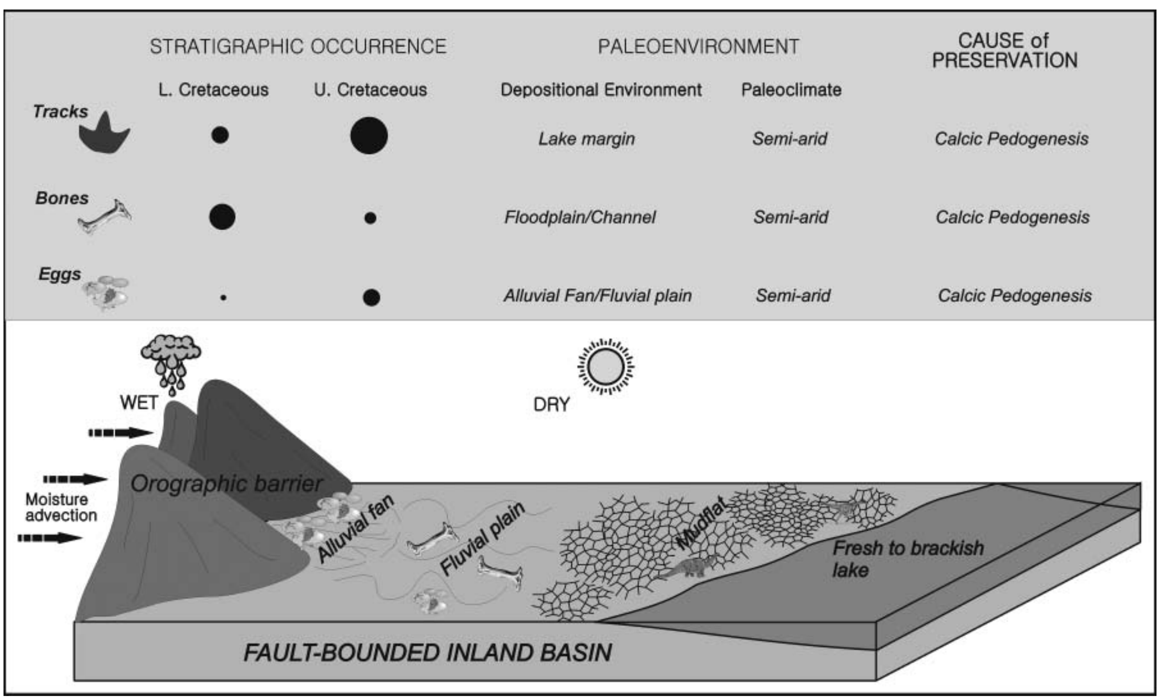

FIG. 4. Schematic diagram showing the occurrences of the dinosaur fossils in the Gyeongsang Basin.

It is odd that the occurrence of angiosperm fossil trees is so limited in the Upper Cretaceous track-bearing deposits in South Korea compared with the abundance of angiosperm trees in the Upper Cretaceous of Japan (Stopes and Fujii, 1910; Shimakura, 1937; Takahashi and Suzuki, 2003). The fossil wood from other Upper Cretaceous deposits in Korea are all gymnosperm trees, including *Cupressinoxylon* and *Taxodioxylon* (Kim et al., 2002). It is inferred that the southern part of the Korean Peninsula was primarily covered with mesic forests with taxodiaceous trees during the Late Cretaceous (Paik et al., 2006b). Thus, the presence of large lakes as water sources, rich vegetation of gymnosperm trees as food, and a semi-arid climate formed the general landscape and environmental settings suitable for dinosaurs and their preservation in the Cretaceous deposits in South Korea.

In conclusion, a number of paleontological and sedimentological studies of diverse dinosaur records in the Cretaceous deposits in the Korean Peninsula revealed that the KCDC is an important integrating concept to help us understand dinosaur evolution and paleoenvironments in space and time during the Cretaceous. However, more reliable time-correlation between the dinosaur fossil-bearing deposits is still needed to understand age relationships between different deposits and the evolutionary dynamics of dinosaurs and their habitats in East Asia.

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