Jeong Yul Kim
Min Huh

# Dinosaurs, Birds, and Pterosaurs of Korea

## A Paradise of Mesozoic Vertebrates

Springer

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# Preface

*Until I spoke her name, she had been no more than a mere gesture. When I spoke her name, she came to me and became a flower. Speak my name that fits this color and odor of mine. I may go to her and become her flower. We all wish to become something. You to me and I to you wish to become an unforgettable gaze. (Flower, Kim, Chunsu, 1922–2004).*

Like the world famous science fiction adventure films *Jurassic Park* and *Jurassic World*, the Gyeongnam Goseong Dinosaur World Expo and International Dinosaur Symposium has attracted a vast number of people. This Expo is held every three years at the world famous Goseong Dinosaur Track Site in Korea.

The Fourth Gyeongnam Goseong Dinosaur World Expo, held in 2016, attracted over 1.5 million visitors, including several tens of thousands of foreigners. In addition, millions of students have learned about the dinosaurs of Korea through their being introduced in elementary school, middle school, and high school science textbooks.

Furthermore, several hundreds of scientists, including dinosaur experts from around the world, visited the dinosaur, bird, and pterosaur track sites of Korea during the 2012 EleventhSymposium of the Mesozoic Terrestrial Ecosystems and the Haenam Uhangri International Dinosaur Symposiums held in Korea.

Since 1969—when *Koreanaornis hamanensis*, the second Mesozoic bird tracks to be formally named, were discovered in the Haman Formation, Korea—numerous and well-preserved dinosaur, bird, and pterosaur tracks have been reported. For example, a special issue of the journal *Ichnos* entitled *Tracking on the Korean Cretaceous Dinosaur Coast: 40 years of Vertebrate Ichnology in Korea* was published in 2012 (vol. 19, issue 1–2). The senior author and his colleagues presented a paper entitled "Dinosaur, Bird, and Pterosaur Tracks from the Cretaceous of Korea: The Paradise of Mesozoic Vertebrates" at the 2012 Symposium on Mesozoic Terrestrial Ecosystems (MTE) held in Korea. The symposium was organized by the junior author of this volume, and resulted in the title of this book.

However, unfortunately and surprisingly, to date no science book about the Mesozoic vertebrates of Korea has been published. Therefore, this book is the first science book on Mesozoic vertebrates written for young students, lay readers, and teachers, as well as for scientists who are interested in the dinosaurs, birds, and pterosaurs of Korea. Furthermore, this book can be enjoyed by visitors to the Goseong Dinosaur World Expo and International Dinosaur Symposium in Korea, and the 2024 International Geological Congress (IGC), which will be held in Busan, Korea.

This book consists of seven chapters. Chapter 1 briefly introduces the history of research and the scientific value of Korean dinosaurs, birds, and pterosaurs, and presents the geologic setting and Cretaceous sedimentary basins of Korea. Timelines of important research on vertebrates from the Cretaceous Period in Korea are shown in Chap. 1. Footprints, bones, eggs, teeth, skin and tail impressions of Korean dinosaurs are presented in Chap. 2. Important vertebrate tracks introduced are the smallest theropod tracks (*Minisauripus*), raptor tracks with two-toed impressions (*Dromaeosauripus*), large sauropod tracks with pentadactyl manus traces (*Brontopodus pentadactylus*), clover leaf-shaped ornithopod tracks (*Ornithopodichnus*), and quadrupedal ornithopod tracks (*Caririchnium kyoungsookimi* and *C. yeongdongensis*). Theropod egg clutches (*Macroelongatoolithus*) and dinosaur teeth, including a recently discovered tyrannosaurid tooth, are introduced in Chap. 2, Which also discusses recently discovered dinosaurs including *Koreanosaurus*, *Koreaceratops*, and *Pukyongosaurus*. Dinosaur tracks from North Korea's Cretaceous Period are also briefly introduced in Chap. 2.

Tracks of birds from the Cretaceous Period in Korea are introduced in Chap. 3. Diverse bird tracks named in Korea are explained. They are the second named bird tracks (*Koreanaornis*), web-footed bird tracks (*Hwangsanipes*, *Uhangrichnus*), the oldest bird tracks with web traces (*Ignotornis yangi*), the oldest web-footed bird tracks with feeding traces (*I. gajinensis*), and new semipalmate bird tracks (*Gyeongsangornipes*). Chapter 4 introduced pterosaurs from the Cretaceous Period in Korea. The largest pterosaur tracks (*Haenamichnus*), swimming traces of pterosaurs (*Ptraichnus* ichnosp.), the first bipedal tracks of pterosaurs (*H. gajinensis*), and the tracks of a new pterosaur (*Ptraichnus koreanensis*) are explained in Chap. 4. A pterosaur skeleton and teeth are also briefly discussed in Chap. 4. Turtle tracks and carapace, crocodile bones and teeth, and a new lizard (*Asprosaurus*) are also introduced in Chap. 4. Skeletal remains of birds (the so-called Korean *Archaeopteryx*) and pterosaurs discovered in the Lower Cretaceous area of North Korea are also briefly introduced in Chaps. 3 and 4.

Chapter 5 deals with diverse fossils associated with vertebrate tracks, such as molluscs, fish, arthropods, plants, stromatolites, and invertebrate trace fossils, which are also important for understanding the paleoenvironment during the Cretaceous Period in Korea. Chapter 6 introduces the Korean Cretaceous Dinosaur Coast (KCDC) as a candidate for a UNESCO World Heritage inscription including the Haenam, Hwasun, Boseong, Yeosu, Goseong, Gajinri, and Gainri sites. The new dinosaur track site of Yeongdong and the *Koreanaornis* bird track site of

Haman are also briefly introduced. Chapter 6 also discusses four well-known dinosaur eggshell sites: Boseong, Hwaseong, Hadong, and Tongyeong.

Chapter 7 presents a summary of research into Mesozoic vertebrates in Korea and discusses the prospects of further research. The total number of dinosaur, bird, and pterosaur tracks and trackways discovered in Cretaceous basins is shown in table and figure format. In addition, a geographic map is provided showing the distribution of vertebrate taxa and ichnotaxa described from the Cretaceous Period in Korea, together with a world geographic map showing the distribution of the Cretaceous bird and pterosaur ichnotaxa named in eight countries. Chapter 7 also discusses the present situation and problems for research into Cretaceous vertebrates to be resolved for the future development of Korean Mesozoic vertebrate paleontology. Finally, Fig. 7.7 presents a reconstruction of the Cretaceous Paradise, based on the diverse fossils from the Cretaceous Period in Korea.

References cited in the text are listed at the end of each chapter for readers who wish to learn about the topics in greater detail. An administrative district map showing the locations of vertebrate fossils from the Cretaceous Period in Korea is provided for readers who wish to visit the fossil locations presented in Appendix 1. Major museums and research centers for visitors who are interested in Mesozoic vertebrates in Korea are also introduced in Appendix 2. Finally, for readers an index of locations, strata, vertebrate and invertebrate taxa and ichnotaxa, and author names is provided for the reader.

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We specially thank Yang, S. Y., emeritus professor of Kyungbuk National University, who first discovered dinosaur eggshells and footprints and who has carried out extensive research into the paleontology and ichnology of invertebrates and vertebrates from the Cretaceous Period in Korea. He is regarded as a pioneer of study into the Mesozoic vertebrates of Korea. The research of Yang, S. Y. provided a cornerstone for the development of vertebrate ichnology in Korea. We particularly thank M. G. Lockley, emeritus professor of the University of Colorado, Denver. One of the most famous experts of vertebrate ichnology, he has provided scientific ways for development of vertebrate ichnology in Korea and has published many papers about vertebrate footprints from the Cretaceous Period in Korea with Korean colleagues, including the authors of this book, since the late 1990s.

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# Chapter 1
# Introduction

## 1.1 Korea: Land and Administrative Division

The Korean Peninsula (Fig. 1.1) extends southward from the eastern end of the Asian continent. It is roughly 1000 km (621 miles) long and 216 km (134 miles) wide at its narrowest point. Mountains cover 70% of the land mass, making Korea one of the most mountainous regions in the world. The mountain range that stretches along the east coast falls steeply into the East Sea; along the south and west coasts, the mountains descend gradually to the coastal plains that produce the bulk of Korea's agricultural crops, especially rice.

The peninsula is divided just slightly north of the 38th parallel. The Republic of Korea (ROK) in the south and the Democratic People's Republic of Korea (DPRK) in the north are separated by the Demilitarized Zone.

The ROK consists of the capital city of Seoul, the self-governing city of Sejong, eight provinces and one special self-governing province (do). There are six metropolitan cities: Busan, Daegu, Incheon, Gwangju, Daejeon and Ulsan, 74 cities (si), and 84 counties (gun).

An administrative district map showing the locations of Mesozoic vertebrate fossils is provided in Appendix A.

## 1.2 Brief History of Research into the Dinosaurs, Birds, and Pterosaurs of Korea

Research into the Mesozoic vertebrates of Korea began in 1969, when the bird tracks of *Koreanaornis hamanensis* were discovered in the Cretaceous Haman Formation, Haman, Korea (Fig. 1.2, Kim 1969). *K. hamanensis* represents the second formally named ichnotaxon of bird tracks following *Ignotornis mcconnelli* (Mehl 1931), of the Upper Cretaceous Period in Colorado, USA.

As shown in Tables 1.1 and 1.2, dinosaur eggshells were subsequently discovered in the Hasandong Formation in 1972 (Yang 1976). Dinosaur bones were



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**Fig. 1.1** Location of the Korean Peninsula in the Far East Asian continent

**Fig. 1.2** *Koreanaornis hamanensis* preserved on the rippled surface of a Cretaceous siltstone bed in the Haman Formation, Haman County, Korea

**Table 1.1** Timeline of important research into dinosaurs from the Cretaceous Period in Korea

| Year | Location | Formation | Type | Author(s) | Remarks |
|---|---|---|---|---|---|
| 1976 | Hadong | Hasandong Fm | Eggshells | Yang | 1st report |
| 1979<br>1981 | Uiseong<br>Uiseong | Gugyedong Fm<br>Gugyedong Fm | Bones<br>Bones | Kim<br>Kim | 1st report |
| 1982 | Goseong | Jindong Fm | Tracks | Yang | 1st paper |
| 1982 | Uiseong | Gugyedong Fm | Bone | Chang et al. | |
| 1983 | Uiseong | Gugyedong Fm | Bones | Kim | *Ultrasaurus tabriensis*, (*nomen dubium*, Lee et al. 1997; Upchurch et al. 2004) |
| 1986 | | Hayang Group | Tracks | Kim | *Goseongosauripus kimi*, *Hamanosauripus ungulatus*, *Koreanosauripus cheongi* (*nomen dubium*, Lockley et al. 1994) |
| 1989 | Goseong | Jindong Fm | Tracks | Lim et al. | |
| 1990 | Goseong | Jindong Fm | Tracks | Lim | |
| 1992 | Goseong<br>Uiseong | Jindong Fm<br>Sagok Fm | Tracks<br>Tracks | Kim and Seo | *Elephantosauripus metacarpus*, *Megalosauripus koreanensis* (*nomen dubium*) |
| 1993 | Haman<br>Goseong | Jindong Fm | Tracks | Kim | *Hamanosauripus ovalis*, *Ultrasauripus ungulates*, *Koseongosauripus onychion* (*nomen dubium*) |
| 1994 | Goseong | Jindong Fm | Tracks | Lim et al. | 516 trackways |
| 1996 | Phyongsan | Ponghwasan Series | Tracks | Pak and Kim | North Korean dinosaur tracks |
| 1997 | Hadong | Hasandong Fm | Eggshells | Yun and Yang | |
| 1997 | Haenam | Uhangri Fm | Tracks | Huh et al. | *Caririchnium* |
| 1997 | Jinju | Hasandong Fm | Teeth | Lee et al. | *Chiayüsaurus asianensis* (*nomen dubium*, Park et al. 2000) |
| 1998 | Goseong | Jindong Fm | Tracks | Baek and Seo | 132 trackways |

(continued)

**Table 1.1** (continued)

| Year | Location | Formation | Type | Author(s) | Remarks |
|---|---|---|---|---|---|
| 1999 | Boseong | Seonso Cg | Eggshells | Huh et al. | |
| 2000 | Hwaseong | Tando Fm | Eggshells | Lee et al. | |
| 2000 | Jinju | Hasandong Fm | Teeth | Park et al. | 1st paper, *Chiayüsaurus* sp. |
| 2001 | Yeosu | Unnamed strata | Tracks | Huh et al. | |
| 2001 | Hwasun | Jangdong Tuff | Tracks | Huh et al. | |
| 2001 | Hadong | Hasandong Fm | Bones | Dong et al. | *Pukyongosaurus millenniumi* (*nomina dubia*, Upchurch et al. 2004) |
| 2001 | | Gyeongsang Supergroup | | Lee et al. | Review of vertebrate fauna |
| 2002 | | Hasandong Fm | Teeth | Lim et al. | Megalosaurid, location unknown |
| 2002 | Boseong | Seonso Cg | Eggshells | Huh and Zelenisky | *Spheroolithus* sp., *Faveoloolithus* sp. |
| 2002 | Masan | Jindong Fm | Tracks | Hwang et al. | 7 sauropod trackways |
| 2003 | Masan | Jindong Fm | Tracks | Huh et al. | Review of dinosaur tracks |
| 2004 | Changnyeong | Jindong Fm | Tracks | Hwang et al. | 10 sauropod trackways |
| 2005 | Uiseong | Gugyedong Fm | Bones | Kim et al. | Maniraptoran theropod |
| 2006 | Hwasun | Jangdong Tuff | Tracks | Huh et al. | Theropod |
| 2006 | Goseong | Jindong Fm | Tracks | Lockley et al. | Synthesis, cf. *Caririchnium*, *Brontopodus* isp. |
| 2006 | Goseong | Jindong Fm | Eggs | Huh et al. | Synthesis of dinosaur eggs |
| 2007 | Hadong | Hasandong Fm | Teeth | Lee et al. | Theropod |
| 2008 | Namhae | Haman Fm | Tracks | Kim et al. | ***Dromaeosauripus hamanesis*** |
| 2008 | Namhae | Haman Fm | Tracks | Lockley et al. | *Minisauripus* |
| 2008 | Sacheon | Hasandong Fm | Teeth | Lee | Tyrannosaurid |
| 2009 | Masan | Jindong Fm | Tracks | Kim et al. | ***Ornithopodichnus masanensis*** |
| 2010 | Goseong, | Jindong Fm | Skin impressions | Kim et al. | 1st paper |

(continued)

**Table 1.1** (continued)

| Year | Location | Formation | Type | Author(s) | Remarks |
|---|---|---|---|---|---|
| | Namhae | Haman Fm | | | |
| 2010 | Sacheon | Haman Fm | Skin impressions | Paik et al. | |
| 2010 | Boseong | Seonso Cg | Bones | Huh et al. | ***Koreanosaurus boseongensis*** |
| 2011 | Hwaseong | Tando Fm | Bones | Lee et al. | ***Koreaceratops hwaseongensis*** |
| 2011 | Tongyeong | Goseong Fm | Eggshells | Kim et al. | ***Macroelongatoolithus goseongensis***, *Dictyoolithus neixiangensis* |
| 2012 | Hwasun | Jangdong Tuff | Tracks | Lockley et al. | ***Ornithopodichnus***, pes only sauropod trackways (cf. *Brontopodus*) |
| 2012 | Yeosu | Unnamed strata | Tracks | Lockley et al. | Multiple track sites with parallel trackways |
| 2012 | Jinju | Haman Fm | Tracks | Kim and Lockley | ***Brontopodus pentadactylus*** |
| 2012 | Namhae | Jinju Fm | Tracks | Kim et al. | ***Dromaeosauripus jinjuensis*** |
| 2012 | Namhae | Haman Fm | Tracks | Kim et al. | *Brontopodus birdi* |
| 2012 | Goseong | Jindong Fm | Tracks | Lim et al. | ***Caririchnium kyoungsookimi*** |
| 2012 | Namhae | Haman Fm | Tracks | Kim et al. | *Minisauripus* |
| 2013 | Yeongdong | Saniri Fm | Theropod tail traces | Kim and Lockley | 1st report |
| 2014 | Shinan | Unnamed strata | Egg clutch | Huh et al. | *Macroelongatoolithus xixiaensis* |
| 2016 | Yeongdong | Saniri Fm | tracks | Kim et al. | ***Caririchnium yeongdongensis*** |
| 2016 | Jinju | Haman | Tracks | Kim et al. | Display behavior |

*Notes* Fm = Formation, Cg = Conglomerate; valid taxa and ichnotaxa named in Korea are shown in bold

**Table 1.2** Timeline of important research into birds, pterosaurs, and other vertebrates from the Cretaceous of Korea

| Year | Location | Formation | Type | Author(s) | Remarks |
|---|---|---|---|---|---|
| 1969 | Haman | Haman Fm | Bird tracks | Kim | ***Koreanaornis hamanesis***, 1st report |
| 1990 | Haenam | Uhangri Fm | Bird tracks | Chun | 2nd report |
| 1992 | Goseong | Jindong Fm | Bird tracks | Lockley et al. | ***Jindongornipes kimi*** |
| 1995 | Haenam | Uhangri Fm | Bird tracks | Yang et al. | ***Hwangsanipes choughi***, ***Uhangrichnus chuni*** |
| 1996 | Haenam | Uhangri Fm | Pterosaur tracks | Huh et al. | 1st report |
| 1997 | Haenam | Uhangri Fm | Pterosaur tracks | Lockley et al. | 1st paper |
| 1998 | Jinju | Haman Fm | Bird tracks | Baek and Yang | *Koreanaornis hamanensis* |
| 2001 | Goryeong | Hasandong and Jinju Fm | Pterosaur teeth | Yun and Yang | 1st report |
| 2002 | Goryeong | Hasandong Fm | Pterosaur bone | Lim et al. | 1st report |
| 2002 | Haenam | Uhangri Fm | Pterosaur tracks | Hwang et al. | ***Haenamichnus uhangriensis*** |
| 2004 | Goryeong | Jinju Fm | Crocodile bone and tooth | Yun et al. | 1st report |
| 2004 | Hadong | Hasandong Fm | Crocodile skull | Lee et al. | 1st report |
| 2004 | Hadong | Hasandong Fm | Amphibian tracks | Lee et al. | 1st report, four trackways |
| 2006 | Namhae | Haman Fm | Pterosaur tracks<br>Bird tracks | Kim et al. | *Pteraichnus* ichnosp. (swimming traces)<br>***Ignotornis yangi*** (oldest web-footed bird tracks) |
| 2006 | Goseong | Jindong Fm | Bird tracks | Lockley et al. | ***Goseongornipes markjonesi*** |
| 2007 | Hadong | Hasandong Fm | Pterosaur tracks | Lee et al. | *Pteraichnus koreanensis* |
| 2007 | Jinju | Hasandong Fm | Crocodile teeth | Yun et al. | |
| 2009 | Gyeongsan | Geoncheonri Fm | Turtle carapaces | Lee et al. | *Kirgizemys* cf. *K. exaratus* |
| 2009 | Sinuiju | Sinuiju Series | Bird and pterosaur bones | Gao et al. | "Korean *Archaeopteryx*", pterosaur skull |
| 2012 | | | Bird tracks | Lockley et al. | Synthesis |
| 2012 | Jinju | Haman Fm | Bird tracks | Kim et al. | |

(continued)

**Table 1.2** (continued)

| Year | Location | Formation | Type | Author(s) | Remarks |
|---|---|---|---|---|---|
| | | | | | ***Ignotornis gajinensis***, a paradise of Mesozoic birds |
| 2012 | Namhae | Haman Fm | Pterosaur tracks | Kim et al. | ***Haenamichnus gainensis*** |
| 2012 | Yeosu | Unnamed strata | Bird tracks | Huh et al. | *Aquatilavipes* |
| 2013 | Goseong | Jindong Fm | Bird tracks | Kim et al. | ***Gyeongsangornipes lockleyi*** |
| 2015 | Boseong | Seonso Cg | Lizard bones | Park et al. | ***Asprosaurus bibongriensis*** |
| 2016 | Sacheon | Jinju Fm | Turtle tracks | Kim and Lockley | *Chelonipus*, 1st report |
| 2017 | Jinju | Jinju Fm | Mammaliform tracks | Kim et al. | Hopping tracks ***Koreasaltipes jinjuensis*** |

*Notes* Fm = Formation, Cg = Conglomerate; valid taxa and ichnotaxa named in Korea are shown in bold first discovered in 1973 in the Gugyedong Formation of Uiseong (Kim 1979, 1981). Interestingly, dinosaur bones were also discovered by Chang in 1977 at Tabri, Uiseong, which is the same site at which Kim discovered dinosaur bones in 1973. The Uiseong dinosaur bones excavated by Chang were first reported in an article in a journal (Chang et al. 1982). The following year, Kim (1983) also reported the Uiseong dinosaur bones and tentatively assigned them to *Ultrasaurus tabriensis*.

Dinosaur ichnology, the study of dinosaur tracks and traces, began in Korea in 1982, when Yang first described dinosaur tracks in the Jindong Formation of Goseong, on the southeastern coast of Korea (Yang 1982). Professor Yang is a pioneer of dinosaur ichnology as well as the paleontology of the Mesozoic molluscan fossils of Korea; he established a cornerstone for the development of dinosaur and bird ichnology in Korea. Subsequently, Kim (1986) introduced dinosaur tracks from the Lower Cretaceous Period of Korea at the First International Symposium on Dinosaur Tracks and Traces. Kim (1986) first named *Goseongosauripus kimi*, *Hamanosauripus ungulates* and *Koreanosauripus cheongi* from the Hayang Group in an abstract in which there were no illustrations or designated holotypes. These ichnotaxa were regarded to be *nomina dubia* due to the uncertainty of their validity (Lockley et al. 1994). Furthermore, dinosaur tracks named as being those of *Elephantosauripus metacarpus*, *Megalosauripus koreanensis*, *Hamanosauripus ovalis*, *Koseongosauripus onychion*, and *Ultrasauripus ungulatus* were reported (Kim and Seo 1992; Kim 1993). However, these ichnotaxa seem to be also *nomen dubia* due to incomplete descriptions.

Since the 1980s, Martin Lockley, a vertebrate track specialist at the University of Colorado, has been involved in cooperative research into the Mesozoic vertebrate tracks in Korea. Dinosaur tracks from the Jindong Formation, Goseong area, were reported by Lim et al. (1989), who later documented that the Goseong track site containing 516 dinosaur trackways revealed the highest density of dinosaur and bird track levels anywhere in the world (Lim et al. 1994). In 1993 in the *National Geographic* magazine, Gore introduced the Goseong gongyong balzaguk, dinosaur footprints from the Cretaceous strata exposed on the coastal area of Goseong area with a comment by Martin Lockley, “You could walk this beach all day and not run out of footprints”.

The second occurrence of bird tracks was from the Uhangri Formation, Haenam area (Chun 1990), though the ichnotaxonomy of these tracks was not treated. New bird tracks, *Jindongornis kimi*, were described in the Jindong Formation at the Goseong track site (Lockley et al. 1992). *Jindongornis kimi* represents the second named bird tracks following the first avian footprints named *K. hamanensis* in Korea. Two types of web-footed bird tracks, which were discovered in the Uhangri Formation, Haenam area, by Chun (1990), were later described as *Hwangsanipes choughi* and *Uhangrichnus chuni* (Yang et al. 1995).

A significant advance in the study of Mesozoic vertebrates in Korea was made in 1997, when the International Dinosaur Symposium for the Uhangri Dinosaur Center and Theme Park in Korea was held at the Uhangri dinosaur track site at Haenam. Many participants—including world famous vertebrate specialists such as M. G. Lockley, D. M. Unwin, L. L. Jacobs, P. J. Currie, C. A. Meyer, and

M. Matsukawa—had the opportunity to observe well-preserved dinosaur, bird, and pterosaur tracks at the Uhangri track site. At the symposium, Huh et al. (1997) reported preliminary research on the Uhangri dinosaur tracks. Particularly, during the symposium, Lockley et al. (1997) first reported large pterosaur tracks from the Uhangri Formation in the Haenam area. The Uhangri pterosaur tracks represent the first pterosaur tracks recorded in Asia.

In 1997, dinosaur eggshells were first described in the Hasandong Formation, Hadong area (Yun and Yang 1997). Subsequently, remarkably well-preserved and abundant dinosaur egg clutches and shells were recorded from the Seonso Conglomerate, Boseong area, and the Tando Formation, Hwaseong area (Huh et al. 1999; Lee et al. 2000a).

In addition, dinosaur teeth were also first described as *Chiayüsaurus asianensis* among others from the Hasandong Formation, Jinju area (Lee et al. 1997). In 2000, however, Park et al. (2000) described dinosaur teeth as *Chiayüsaurus* sp. and regarded that *Chiayüsaurus asianensis* (Lee et al. 1997) was *nomen dubium*. Dinosaur teeth attributable to tyrannosauroids and sauropods were also reported for the first time in the Hasandong Formation (Yun et al. 2007; Lee 2007; Lee et al. 2008).

Following the discovery of the Goseong and Uhangri track sites, several new dinosaur track sites have been discovered since the beginning of the 2000s. For instance, remarkably well-preserved and abundant dinosaur tracks were reported at the Yeosu, Hwasun, Masan, and Changnyeong track sites (Huh et al. 2001a, b, 2006a, b; Hwang et al. 2002a, b, 2004). It is noteworthy that 132 trackways of diverse dinosaurs were found at the Donghae track site, Goseong area (Baek and Seo 1998) and 10 trackways comprising approximately 560 sauropod tracks were described at the Changnyeong site (Hwang et al. 2004). The most abundant and diverse dinosaur tracks, which were first found in the Hai District, Goseong County (Yang 1982), as well as bird tracks, were reviewed and synthesized about 25 years later by Lockley et al. (2006). In addition, abundant dinosaur tracks found at the Hwasun and Yeosu sites in 2001 (Huh et al. 2001a, b) were also synthesized over ten years later (Huh et al. 2006a; Lockley et al. 2012a, b). Furthermore, new dinosaur tracks with only two-digit impressions were first described as *Dromaeosauripus hamanensis*, which is probably attributable to a theropod similar to the Dromaeosaur, in the Haman Formation, Namhae area (Kim et al. 2008b). In addition, the smallest theropod tracks, *Minisauripus*, about 2 cm in length, were discovered at the Haman Formation, Namhae area, (Lockley et al. 2008). It is also noteworthy that new ornithopod dinosaur tracks of a clover-leaf shape at the Jindong Formation, Masan area, were described as *Ornithopodichnus masanensis* (Kim et al. 2009).

In contrast to vertebrate tracks, dinosaur bone fossils reported from the Cretaceous Period have rarely been in Korea. Dinosaur bones were first described as *Pukyongsaurus millenniumi* at the Hasandong Formation, Hadong area (Dong et al. 2001). However, like *U. tabriensis* of Kim (1983), *Pukyongosaurus millenniumi* was regarded to be *nomina dubia* due to the uncertainty of its validity (Upchurch et al. 2004). In 2005, dinosaur bones discovered at the Gugyedong

Formation, Uiseong area, in 1973 were reinterpreted to be attributable to a maniraptoran theropod (Kim et al. 2005). It is extremely significant that new dinosaur bones were recently discovered from the Cretaceous Period in Korea. The first discovery was dinosaur bones described as *Koreanosaurus boseongensis* at the Seonso Conglomerate, Boseong area (Huh et al. 2010). The second discovery was dinosaur bones described as *Koreaceratops hwaseongensis* from the Tando Formation, Hwaseong area (Lee et al. 2011). In 2010, dinosaur skin impressions were first also reported at the Jindong and Haman Formations of the Goseong, Namhae, and Sacheon areas (Kim et al. 2010; Paik et al. 2010).

At the beginning of 2000, pterosaur teeth and bones were first reported at the Hasandong and Jinju Formations, Goryeong area (Yun and Yang 2001; Lim et al. 2002a, b, c). Pterosaur tracks previously reported at the Uhangri Formation (Huh et al. 1996; Lockley et al. 1997) were described as a new ichnogenus and ichnospecies, *Haenamichnus uhangriensis* (Hwang et al. 2002a). *Haenamichnus* represents the third named ichnogenus for pterosaur tracks following the first, *Pteraichnus* (Stokes 1957), and the second, *Purbeckopus* (Wright et al. 1997). In addition, two new pterosaur track sites have been discovered. The first is located at Namhae, where pterosaur tracks and trackways were described as *Pteraichnus* ichnosp. (Kim et al. 2006). It is noteworthy that *Pteraichnus* ichnosp., from Namhae area, probably shows the swimming behavior of the trackmaker. Subsequently, new pterosaur tracks were described as *Pteraichnus koreanensis* from the Hasandong Formation, Hadong area (Lee et al. 2008). Lee et al. (2009) also first described a turtle carapace as *Kirgizemys* cf. *K. exaratus* at the Geoncheonri Formation, Gyeongsan area.

Significant advances in the study of Korean Mesozoic vertebrates occurred from 2012, when the special volume entitled *Tracking on the Korean Cretaceous Dinosaur Coast: 40 years of Vertebrate Ichnology in Korea* was published in the journal *Ichnos*. In this special issue of *Ichnos*, Korean vertebrate and avian ichnology was synthesized and reviewed (Lockley et al. 2012d, f). Paik et al. (2012) reviewed and synthesized the stratigraphy, geochronology, and paleoenvironments of vertebrate fossil-bearing deposits which had been formed between the Aptian and Campanian Periods and which are volcanically influenced alluvial fan, fluvial plain, and lake margins. In addition, the Gajin track site, which shows the world's richest and most diverse array of bird tracks, was introduced with descriptions of *Ignotornis gajinensis*, *K. hamanensis*, *Goseongornipes markjonesi*, and cf. *Aquatilavipes* ichnosp. indet., and *Brontopodus pentadactylus* (Kim et al. 2012c). Furthermore, Kim et al. (2012b) reported enigmatic giant pterosaur tracks, *Haenamichnus gainensis*, which is highly significant to the understanding of the bipedal locomotion of pterosaurs. Bird tracks assigned to *Aquatilavipes* were first reported in the Yeosu Islands Archipelago (Huh et al. 2012). The new didactyl dinosaur tracks at the Jinju Formation, Namhae area, which represent the second ichnospecies of *Dromaeosauripus*, were described as *D. jinjuensis* (Kim et al. 2012d).

In addition, *Ornithopodichnus* and pes only sauropod trackways were first described at the Hwasun track site (Lockley et al. 2012b) and a new quadrupedal ornithopod trackway was described as *Caririchnium kyoungsookimi* at the Jindong Formation, Goseong area (Lim et al. 2012).

Recently, theropod dinosaur tail impressions were first reported at the Yeongdong track site by Kim and Lockley (2013), who reviewed 38 recorded dinosaur tracks with tail traces that had not previously been reported. New semi-palmate bird tracks at the Jindong Formation, Goseong area, were described as *Gyeongorinipes lockleyi* (Kim et al. 2013).

Kim et al. (2011) discovered new dinosaur egg sites at Tongyeong, where a new oospecies *Macroelongatoolithus goseongensis* and *Dictyoolithus neixiangensis* were described. A nearly complete dinosaur egg clutch was also reported on Aphae-do, Shinan County (Huh et al. 2014). New quadrupedal ornithopod tracks at the Saniri Formation of Yeongdong track site were recently described as *Caririchnium yeongdongensis* (Kim et al. 2016a). The first lizard bones found in Korea at the Seonso Conglomerate, Boseong area, were described as *Asprosaurus bibongriensis* (Park et al. 2015). The first turtle tracks at the Lower Cretaceous Jinju Formation, Sacheon area, assignable to *Chelonipus*, were also recently described (Kim and Lockley 2016). Recently, Kim et al. (2017) described hopping mammaliform tracks at the Jinju Formation, Jinju area, as *Koreasaltipes jinjuensis*.

## 1.3 Scientific Value of Korean Dinosaurs, Birds, and Pterosaurs

Korea is one of the best-known regions in the world for Cretaceous vertebrate ichnology. An abundance of diverse vertebrate tracks in an excellent state of preservation and the high density of the occurrence of tracks and track-bearing stratigraphic beds in the Cretaceous Period of Korea represent a Mesozoic paradise of vertebrates (Kim et al. 2012a). As such, the area is a candidate for UNESCO World Heritage status. As shown in Table 1.3, bird tracks named in Korea are considerably more diverse than those of any other country in the world. The smallest theropod tracks (*Minisauripus*), raptor tracks with only two-digit impressions (*Dromaeosauripus*), new clover leaf-shaped ornithopod tracks (*Ornithopodichnus*), a new ichnospecies of *Brontopodus* (*B. pentadactylus*), new quadrupedal ornithopod tracks (*C. kyoungsookimi* and *C. yeongdongensis*), the largest pterosaur tracks (*H. gainensis*), the second named bird tracks (*Koreanaornis*), the oldest web-footed bird tracks (*Ignotornis yangi*), and diverse dinosaur eggshells including *M. goseongensis*, as well as new dinosaur bones (*Koreanosaurus* and *Koreaceratops*) first named in the Cretaceous of Korea have highly significant scientific value to the understanding of the history of Mesozoic vertebrates.

**Table 1.3** Vertebrate taxa and ichnotaxa described from the Cretaceous Period in Korea

| Types | Vertebrate taxa and ichnotaxa | References |
|---|---|---|
| Dinosaur skeletons | ***Ultrasaurus tabriensis****<br>***Pukyongosaurus millenniumi****<br>***Koreanosaurus boseongensis***<br>***Koreaceratops hwaseongensis*** | Kim (1983)<br>Dong et al. (2001)<br>Huh et al. (2010)<br>Lee et al. (2011) |
| Dinosaur teeth | ***Chiayüsaurus asianensis****<br>*Chiayüsaurus* sp. | Lee et al. (1997)<br>Park et al. (2000) |
| Dinosaur eggs | *Dictyoolithus neixiangensis*<br>***Macroelongatoolithus goseongensis***<br>*Macroelongatoolithus xixiaensis*<br>*Spheroolithus* sp.<br>*Faveoloolithus* sp. | Kim et al. (2011)<br>Kim et al. (2011)<br>Huh et al. (2014)<br>Huh and Zelenitsky (2002)<br>Huh and Zelenitsky (2002) |
| Dinosaur tracks | ***Hamanosauripus ungulates****<br>***Koreanosauripus cheongi****<br>*Brontopodus* ichnosp.<br>***Dromaeosauripus hamanensis***<br>*Minisauripus zhenshounani*<br>***Ornithopodichnus masanensis***<br>*Brontopodus birdi*<br>*Ornithopodichnus*<br>***Caririchnium kyoungsookimi***<br>***Brontopodus pentadactylus***<br>***Dromaeosauripus jinjuensis***<br>***Caririchnium yeongdongensis*** | Kim (1986)<br>Kim (1986)<br>Lockley et al. (2006)<br>Kim et al. (2008b)<br>Lockley et al. (2008)<br>Kim et al. (2009)<br>Kim et al. (2012)<br>Lockley et al. (2012b)<br>Lim et al. (2012)<br>Kim and Lockley (2012)<br>Kim et al. (2012d)<br>Kim et al. (2016a) |
| Pterosaur tracks | ***Haenamichnus uhangriensis***<br>***Pteraichnus koreanensis***<br>*Pteraichnus* ichnosp.<br>***Haenamichnus gainensis*** | Hwang et al. (2002a)<br>Lee (2007)<br>Kim et al. (2006)<br>Kim et al. (2012b) |
| Bird tracks | ***Koreanaornis hamanensis***<br>***Jindongornipes kimi***<br>***Uhangrichnus chuni***<br>***Hwangsanipes choughi***<br>***Goseongornipes markjonesi***<br>***Ignotornis yangi***<br>***Ignotornis gajinensis***<br>***Gyeongsangornipes lockleyi***<br>*Aquatilavipes* ichnosp. | Kim (1969)<br>Lockley et al. (1992)<br>Yang et al. (1995)<br>Yang et al. (1995)<br>Lockley et al. (2006)<br>Kim et al. (2006)<br>Kim et al. (2012c)<br>Kim et al. (2013)<br>Kim et al. (2012c); Huh et al. (2012) |
| Pterosaur skeletons | *Dsungaripterus*? cf. *D. weii* | Lim et al. (2002c) |
| Turtle carapace | *Kirgizemys* cf. *K. exaratus* | Lee et al. (2009) |
| Lizard skeletons | ***Asprosaurus bibongriensis*** | Park et al. (2015) |
| Turtle tracks | *Chelonipus* ichnosp. | Kim and Lockley (2016) |
| Mammaliform tracks | ***Koreasaltipes jinjuensis*** | Kim et al. (2017) |

*Notes* Taxa and ichnotaxa marked with an asterisk (*) are regarded to be *nomen dubia* (Lockley et al. 1994; Lee et al. 1997; Park et al. 2000; Upchurch et al. 2004); taxa and ichnotaxa named in Korea are shown in bold

The abundance of vertebrate tracks in Korea can be estimated on the basis of comparison of counting the data of tracks and trackways, and track sites. The world's largest track site in terms of exposed surface was the Upper Cretaceous dinosaur track site at Cal Orckó, Bolivia. This track site was the most spectacular in the world, exposing more than 5000 tracks (Lockley et al. 2012a). However, unfortunately the track-bearing surface collapsed in 2010. Eleven track sites in Spain and Portugal nominated for World Heritage status contain about 13,640 tracks (Lockley et al. 2012a). A recent study (Kim and Kim 2016) showed that about 1370 dinosaur trackways and 14,280 dinosaur tracks have been reported from the Cretaceous Period at approximately 90 track sites in Korea. It is known that Spain has about 150 track sites and that the high plains of eastern Colorado and New Mexico have about 70 dinosaur track sites (Lockley 2007). Therefore, Korea is a region abundant with a high density occurrence of dinosaur tracks and trackways.

The excellent quality of preservation of vertebrate tracks in Korea is also unique. Most deposits bearing vertebrate fossils of the Early to Late Cretaceous Periods are distributed in the south and southeast of Korea. During the Early Cretaceous and Early Neogene Periods, the Bulgugsa Granite series intruded widely into the fossil-bearing deposits which were therefore thermally metamorphosed, resulting in relatively durable hard rocks such as hornfels. Therefore, even though the fossil-bearing deposits are exposed to the influences of tides and waves in coastal areas, diverse and abundant vertebrate tracks are remarkably well-preserved (Fig. 1.3). In fact, almost all vertebrate fossil sites are located along the south and

**Fig. 1.3** Well-preserved ornithopod trackway from the Cretaceous Period in the Jindong Formation, Goseong County, Korea

southeast coastal areas of Korea, where slightly inclined strata (around 15°) reveal the direct evidence of the Mesozoic history of vertebrates.

The most diverse and abundant bird tracks from the Cretaceous Period in Korea are remarkable when compared with those of any other country. To date, there are 26 Cretaceous avian ichnospecies assigned to 20 ichnogenera, if we interpret *Archaeornithipus meijida* (Fuentes Vidarte 1996) and *Magnoavipes lowei* (Lee 1997) as dinosaurian-like (Lockley and Harris 2010), and if we include *Moguiornis robusta* (Xing et al. 2011), *Dongyangornis sinensis* (Azuma et al. 2013), *I. gajinensis* (Kim et al. 2012c), *Gyeongsangornipes lockleyi* (Kim et al. 2013) and *Paxavipes babcockensis* (McCrea et al. 2015).

Thus, six ichnogenera among the 20 ichnogenera of Cretaceous avian tracks were formally named in Korea (Table 1.3). They are *Koreanaornis* (Kim 1969), *Jindongornipes* (Lockley et al. 1992), *Hwangsanipes* (Yang et al. 1995), *Uhangrichnus* (Yang et al. 1995), *Goseongornipes* (Lockley et al. 2006) and *Gyeongsangornipes* (Kim et al. 2013). Eight avian ichnospecies among 26 ichnospecies of the Cretaceous Period were also named in Korea, among which is *Ignotornis gajinensis* (Kim et al. 2012c). Therefore, about one third of Cretaceous avian ichnogenera and ichnospecies has been formally named in Korea, which means that not only does Korea have the most diverse record worldwide, it has far greater diversity than any other country (Table 1.4). In this regard, the Gajin track site is particularly notable. At the Gajin track site, more than 2500 well-preserved

**Table 1.4** Record of Mesozoic bird and pterosaur ichnotaxa named in eight countries

| | Ichnotaxa | Korea | China | USA | Canada | Argentina | Spain | Japan | UK |
|---|---|---|---|---|---|---|---|---|---|
| Birds | ● *Gyeongsangornipes lockleyi* | ● | | | | | | | |
| | ● *Goseongornipes markjonesi* | ● | | | | | | | |
| | ● *Hwangsanipes choughi* | ● | | | | | | | |
| | ● *Ignotornis gajinensis* | ● | | | | | | | |
| | ● *Ignotornis yangi* | ● | | | | | | | |
| | ● *Jindongornipes kimi* | ● | | | | | | | |
| | ● *Koreanaornis hamanensis* | ● | | | | | | | |
| | ● *Uhangrichnus chuni* | ● | | | | | | | |
| | ● *Aquatilavipes sinensis* | | ● | | | | | | |
| | ● *Dongyangornis sinensis* | | ● | | | | | | |
| | ● *Koreanaornis dodsoni* | | ● | | | | | | |
| | ● *Moguiornipes robusta* | | ● | | | | | | |
| | ● *Pullornipes aureus* | | ● | | | | | | |
| | ● *Shandongornipes muxiai* | | ● | | | | | | |
| | ● *Tatarornipes chabuensis* | | ● | | | | | | |
| | ● *Wupus agilis* | | ● | | | | | | |
| | ● *Ignotornis mcconnelli* | | | ● | | | | | |
| | ● *Sarjeantopodus semipalmatus* | | | ● | | | | | |
| | ● *Aquatilavipes swiboldae* | | | | ● | | | | |
| | ● *Aquatilavipes curriei* | | | | ● | | | | |
| | ● *Limiavipes curriei* | | | | ● | | | | |
| | ● *Paxavipes babcockensis* | | | | ● | | | | |
| | ● *Barrosopus slobodai* | | | | | ● | | | |
| | ● *Patagonichornis venetiorum* | | | | | ● | | | |
| | ● *Yacoriteichnus avis* | | | | | ● | | | |
| | ● *Aquatilavipes izumiensis* | | | | | | | ● | |
| Pterosaurs | ▲ *Haenamichnus gainensis* | ▲ | | | | | | | |
| | ▲ *Haenamichnus uhangriensis* | ▲ | | | | | | | |
| | ▲ *Pteraichnus saltwashensis* | | | ▲ | | | | | |
| | ▲ *Pteraichnus stokei* | | | ▲ | | | | | |
| | ▲ *Pteraichnus longipodus* | | | | | | ▲ | | |
| | ▲ *Pteraichnus palacieisaenzi* | | | | | | ▲ | | |
| | ▲ *Pteraichnus parvus* | | | | | | ▲ | | |
| | ▲ *Pteraichnus nipponensis* | | | | | | | ▲ | |
| | ▲ *Purbeckopus pentadactylus* | | | | | | | | ▲ |

● Bird ichnotaxa
▲ Pterosaur ichnotaxa

bird tracks associated with theropod and sauropod tracks were recorded from the Early Cretaceous Haman Formation of the Gajin area, Jinju, Korea (Kim et al. 2012c). Bird tracks were described as being *K. hamanensis*, *G. markjonesi,* ?*Aquatilavipes*, and *I. gajinensis*, which is a semipalmate bird track associated with arcuate to semi-circular, double-grooved impressions resulting from spoonbill-like feeding behavior. The Gajin track site represents a record of the world's richest and most diverse Cretaceous bird array, which has been dubbed "A paradise of Mesozoic birds" (Kim et al. 2012c).

Table 1.4 also shows a record of pterosaur ichnotaxa named in eight countries. Although the ichnotaxonomy of pterosaur tracks has been debated (e.g., Sánchez-Hernández et al. 2009; Pascual-Arribas et al. 2015), three ichnogenera—including *Haenamichnus*, *Pteraichnus*, and *Pubeckopus*—and nine ichnospecies are regarded as valid (Lockley and Harris, in press). Several Spanish ichnogenera and ichnospecies of pterosaurs as well as *P. koreanensis* (Lee et al. 2008) are regarded as invalid ichnotaxa (e.g., Sánchez-Hernández et al. 2009; Leckley and Harris, in press). If we follow these, *Haenamichnus*, one of three ichnogenera of pterosaurs, and *H. uhangriensis* (Hwang et al. 2002a, b) and *H. gainensis* (Kim et al. 2012b), two of nine ichnospecies of pterosaurs have been named from the Cretaceous Period in Korea.

The Korean bird track *Koreanaornis* (Kim 1969) was originally described as from the Early Cretaceous Period in Korea. To date, *Koreanaornis* has been reported from the Dakota Formation, Utah, USA (Anfinson et al. 2009), Xinjiang and Sichuan, China (Xing et al. 2011; Lockley et al. 2012e), the Zebbag Formation, Tunisia (Contessi and Fanti 2012), and La Rioja of Spain (Díaz-Martinez et al. 2015). *Koreanaornis*, attributable to small shorebirds, is significant to the understanding of paleoenvironments, paleoecology, and global ichnostratigraphic correlation of track-bearing deposits.

To date, nine valid ichnospecies belonging to three ichnogenera of pterosaur tracks have been known in the world (Lockley et al. 2008; Sánchez-Hernández et al. 2009; Pascual-Arribas et al. 2015; Lockley and Harris, in press). They are *Pteraichnus saltwashensis* (Stokes 1957), *P. stokesi* (Lockley et al. 1995), *P. longipodus* (Fuentes Vidarte et al. 2004). *P. parvus* (Meijide Calvo et al. 2001; Meijide Calvo and Fuentes Vidarte 2001), *P. nipponensis* (Lee et al. 2010), *P. palacieisaenzi* (Pascual-Arribas et al. 2015), *Purbeckopus pentadactylus* (Wright et al. 1997), *H. uhangriensis* (Hwang et al. 2002a), and *H. gainensis* (Kim et al. 2012b). Therefore, two of nine pterosaur ichnospecies and one of three ichnogenera of pterosaur tracks were formally named in Korea. Especially, *H. gainensis* shows the longest trackway (about 18 m in length, with 25 consecutive tracks) and is the largest pterosaur track (ranging from 27.5 to 39.0 cm in length). In addition, *H. gainensis* is the only pterosaur tracks attributable to bipedal, fully erect, and digitigrade stance and gait. The other six ichnospecies have generally been accepted as having been made by quadrupedal, semi-erect, and plantigrade pterosaurs (Unwin 1989; Lockley et al. 1995; Hwang et al. 2002a; Lee 2007). Therefore, *H. gainensis* supports Bennett (1990), who documented that at least some large pterodactyloids could have been primarily plantigrade bipeds.

Several new dinosaur tracks recently named in Korea are also important for the understanding of the gait, stance, and behavior of dinosaurs. They are *B. pentadactylus* (Kim and Lockley 2012), *C. kyoungsookimi* (Lim et al. 2012), *C. yeongdongensis* (Kim et al. 2016a), *D. hamanensis* (Kim et al. 2008b), *D. jinjuensis* (Kim et al. 2012d), *Minisauripus* (Kim et al. 2012a, b, c, d, e), and *O. masanensis* (Kim et al. 2009).

Compared with dinosaur tracks and eggshells, dinosaur bones have rarely been reported from the Cretaceous Period of Korea. In this regard, the first ceratopsian dinosaur, described as *K. hwaseongensis* (Lee et al. 2011), and a new basal ornithopod dinosaur, described as *Koreanosaurus boseongensis* (Huh et al. 2010), are paleontologically important.

Vertebrate fossils are also important as geological and natural heritages for research, education, and tourism. Sixteen Cretaceous vertebrate fossil sites have been designated as Natural Monuments of the Cultural Heritage Administration of Korea (Table 1.5). Table 1.5 also shows five Cretaceous vertebrate fossil sites including one dinosaur track site designated as a natural monument in North Korea. The Haenam track site (Natural Monument No. 394), the Goseong track site (Natural Monument No. 411), the Boseong Dinosaur egg site (Natural Monument No. 418), the Yeosu track site (Natural Monument No. 434), and the Hwasun track site (Natural Monument No. 487) were nominated for status as a serial UNESCO World Heritage site in 2008, because they have outstanding universal value. The other eleven sites include the Haman track site (Natural Monument No. 222), the Uiseong track site (Natural Monument No. 373), the Yusuri bone site of Jinju (Natural Monument No. 390), the Namhae track site (Natural Monument No. 395), the Hwaseong dinosaur egg site (Natural Monument No. 414), the dinosaur fossil site of Adu Island, Sacheon (Natural Monument No. 474), the fossil site of Janggu Island, Hadong (Natural Monument No. 477), the fossil site of Gainri, Namhae (Natural Monument No. 499), the Hotandong track site of Jinju (Natural Monument No. 534), the theropod dinosaur egg fossil site of Aphaedo, Shinan (Natural Monument No. 535), and the Gunsan track site (Natural Monument No. 548). In this regard, Korea is a pioneering nation in regard to global geoheritage (Lockley et al. 2012a), and has national, international, and universal value.

**Table 1.5** Natural monuments of the Cretaceous vertebrate fossil sites of Korea

| Natural monument name | Location | Formation | NM No. | Remarks |
|---|---|---|---|---|
| Bird track site, Yongsanri, Haman | Yongsanri, Haman | Haman Fm | 222 | Type location of *Koreanaornis* |
| Dinosaur tracks, Jeori, Uiseong | Jeori, Uiseong | Sagok Fm | 373 | 1st NM of dinosaur track site |
| Cretaceous paleoenvironment and dinosaur fossil site, Yusuri, Jinju | Yusuri, Jinju | Hasandong Fm | 390 | Over 100 dinosaur bone fragments |
| Dinosaur, pterosaur, and bird track site, Uhangri, Haenam[a] | Uhangri, Haenam | Uhangri Fm | 394 | Type location of *Haenamichnus*, *Hwangsanipes*, and *Uhangrichnus* |
| Bird and dinosaur track site, Gajinri, Jinju | Gajinri, Jinju | Haman Fm | 395 | Type location of *Ignotornis gajinensis* and *Brontopodus pentadactylus* |
| Dinosaur and bird track site, Dukmyeongri, Goseong[a] | Dukmyeongri, Goseong | Jindong Fm | 411 | Type location of *Jindongornis*, 1st dinosaur track site of Korea |
| Dinosaur egg fossil site, Gojeongri, Hwaseong | Gojeongri, Hwaseong | Tando Fm | 414 | Type location of *Koreaceratops*, approx. 300 dinosaur egg shells |
| Dinosaur egg fossil site, Bibongri, Boseong[a] | Bibongri, Boseong | Seonso Cg | 418 | Type location of *Koreanosaurus*, approx. 200 dinosaur egg shells |
| Dinosaur track site and sedimentary strata, Nangdori, Yeosu[a] | Nangdori, Yeosu | Unnamed strata | 434 | Over 3500 dinosaur tracks |
| Dinosaur fossil site, Adu Island, Sacheon | Adu Island, Sacheon | Haman Fm | 474 | Dinosaur tracks, eggs, and bones, pterosaur tracks (*Haenamichnus gainensis*) |
| Fossil site, Janggu Island, Hadong | Janggu Island, Hadong | Hasandong Fm | 477 | Crocodile, dinosaur teeth, turtle, bivalvia |
| Dinosaur track site, Seoyuri, Hwasun[a] | Seoyuri, Hwasun | Jangdong Tuff | 487 | Theropod tracks dominated, over 1800 tracks |
| Fossil site, Gainri, Namhae | Gainri, Namhae | Haman Fm | 499 | Type location of *Ignotornis yangi* and *Haenamichnus gainensis* |

(continued)

**Table 1.5** (continued)

| Natural monument name | Location | Formation | NM No. | Remarks |
|---|---|---|---|---|
| Pterosaur, bird, and dinosaur track site, Hotandong, Jinju | Hotandong, Jinju | Jinju Fm | 534 | 545 pterosaur tracks, 642 bird tracks and 67 theropod tracks |
| Theropod dinosaur egg fossil site, Aphaedo, Shinan | Aphaedo, Shinan | Unnamed strata | 535 | Well-preserved egg clutch of *Macroelongatoolithus xixiangensis* |
| Dinosaur and pterosaur track site, Sanbukdong, Gunsan | Sanbukdong, Gunsan | Sanbukdong Fm | 548 | 184 ornithopod tracks, 36 theropod tracks, and 17 pterosaur tracks |
| Animal fossils, Ryonggungri[b] | Ryonggungri, Phyongsan County, North Hwanghae Province | Ponghwasan Series | 191 | |
| Fish fossil site, Onsong[b] | Hyangdangri, Onsong County, North Hamgyong Province | Seson Series | 335 | |
| Dinosaur track site, Ryonggungri, Pyeongsan[b] | Ryonggungri, Pyeongsan County, North Hwanghae Province | Ponghwasan Series | 466 | 30 tracks and 2 trackways |
| Founder frog fossil[b] | Baektodong, Sinuiju City, North Pyongan Province | Sinuiju Series | 470 | |
| Higher animal fossils, Sambong[b] | Sambongri, Onsong County, North Hamgyong Province | Hanbongsan Series | 500 | |

*Notes* NM = natural monument; Fm = Formation, Cg = Conglomerate
[a]Sites for inscription as a serial UNESCO World Heritage in 2008 (Cultural Heritage Administration of Korea)
[b]North Korean sites

## 1.4 Geological Setting and Cretaceous Sedimentary Basins of Korea

The Korean Peninsula, located at the eastern margin of the Asian continent, is known to have been formed by tectonic processes related to the Sino-Korean Craton, South China (or Yangtz) Craton, and the (Proto)Pacific plate. As shown in the geological map of Korea (Fig. 1.4), the basement rocks of Korea are Proterozoic crystalline rocks composed mainly of gneiss, schist, and metasediments. The Cambro-Ordovician marine deposits known as the Joseon Supergroup unconformably overlie the Precambrian basement rocks. Marine invertebrate fossils including trilobites, graptolites, brachiopods, and conodont were reported in the Joseon Supergroup. The Carboniferous to Permian Pyeongan Supergroup, which is composed of marine and non-marine deposits yielding fusulina, conodonts, and plant fossils, unconformably rest on the Joseon Supergroup. The gap of about 140 million years between the Joseon and Pyeongan Supergroups has been called the Great Hiatus in the mid-Paleozoic Period of Korea.

The Triassic to Jurassic Bansong and Nampo groups are composed mainly of non-marine clastic deposits that unconformably cover the Pyeongan Supergroup. It is known that the small basins for the Triassic to Jurassic deposits were formed by the Triassic Songnim Orogeny (or Disturbance). The Jurassic Daebo Orogeny resulted in the wide distribution of granitoids and significantly deformed the older rocks in Korea. The Cretaceous non-marine Gyeongsang Supergroup unconformably rests on the older rocks and yields diverse fossils including molluscs, plants, and vertebrate tracks. The Late Cretaceous granitoids, known as the Bulgugsa Granite, intruded and, in places, thermally metamorphosed the Gyeongsang Supergroup resulting excellent conditions for the preservation of vertebrate tracks. Small patches of the Neogene marine and non-marine deposits containing mollusc, fish, foraminifera, and plant fossils are distributed along the eastern coast of the Korean Peninsula and on Jeju Island.

The Cretaceous sedimentary basins are widely located at the southeast of the Korean Peninsula and distributed along the NE–SW trending faults (Fig. 1.5). The Gyeongsang Basin, the largest Cretaceous basin in Korea, is known to have been formed as a back-arc basin by the subduction of the Protopacific (Izanagi) plate (Chough and Sohn 2010). Small isolated sedimentary basins with a NE–SW trend were known to have been formed as pull-apart basins by sinistral strike slip fault (Chough 2013).

Chang (1975, 1977, 1978, 1988, 2002), Chang et al. (1990, 2003), and Chang and Park (2008) have intensively studied the stratigraphy of the Gyeongsang Supergroup and lithostratigraphically divided the group into the Sindong, Hayang, and Yucheon groups in ascending order (Fig. 1.6). Paleontological studies on molluscs (Yang 1975, 1976, 1978, 1979), spores and pollen (Choi 1985a), and charophytes (Choi, 1987) suggest that the Sindong and Hayang groups were formed during the

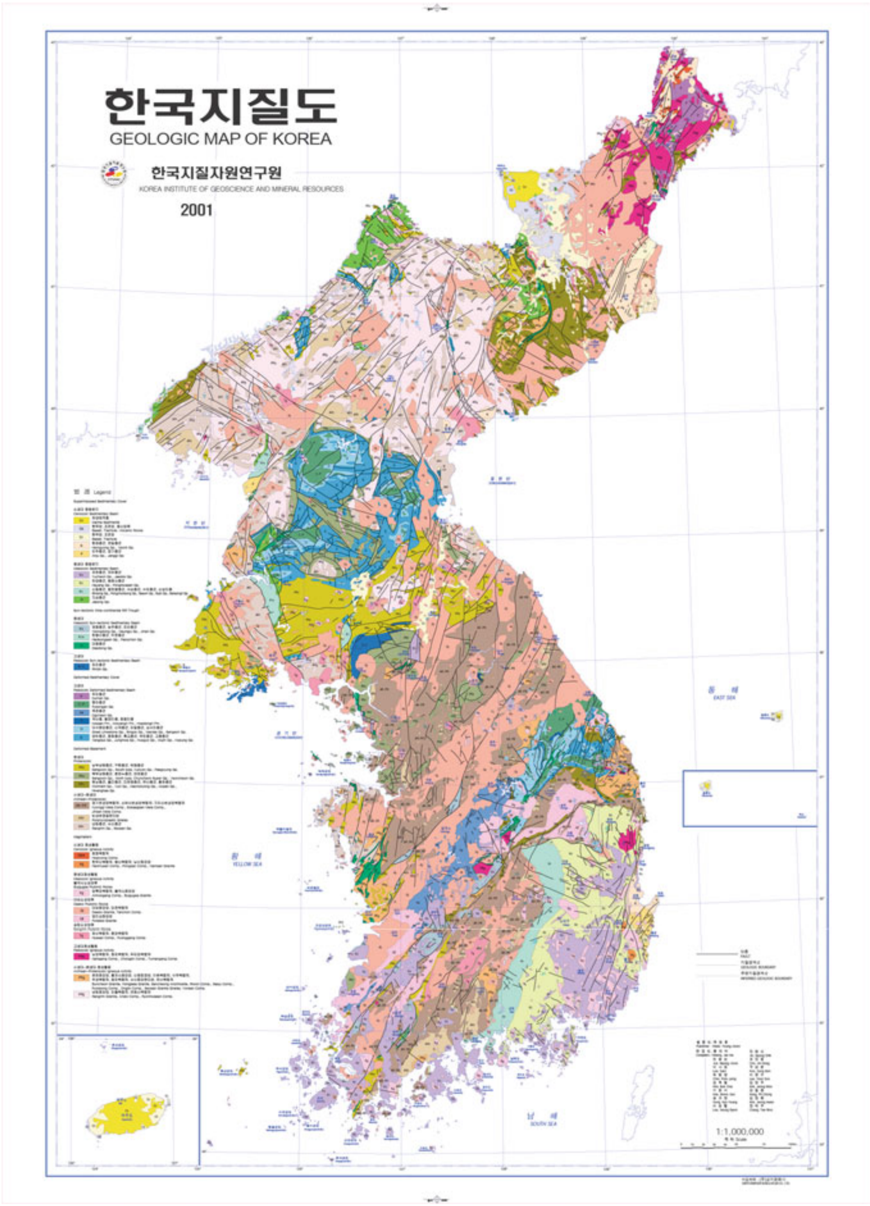


Fig. 1.4 Geological map of Korea. *Source* Korea Institute of Geoscience and Mineral Resources (2001)

Hauterivian and Campanian Periods. Sedimentological studies (Choi 1985b, 1986; Paik et al. 2012) indicate that the Cretaceous deposits were formed in the alluvial fan, floodplain, and lacustrine, warm and semi-arid paleoenvironments (Fig. 1.5).

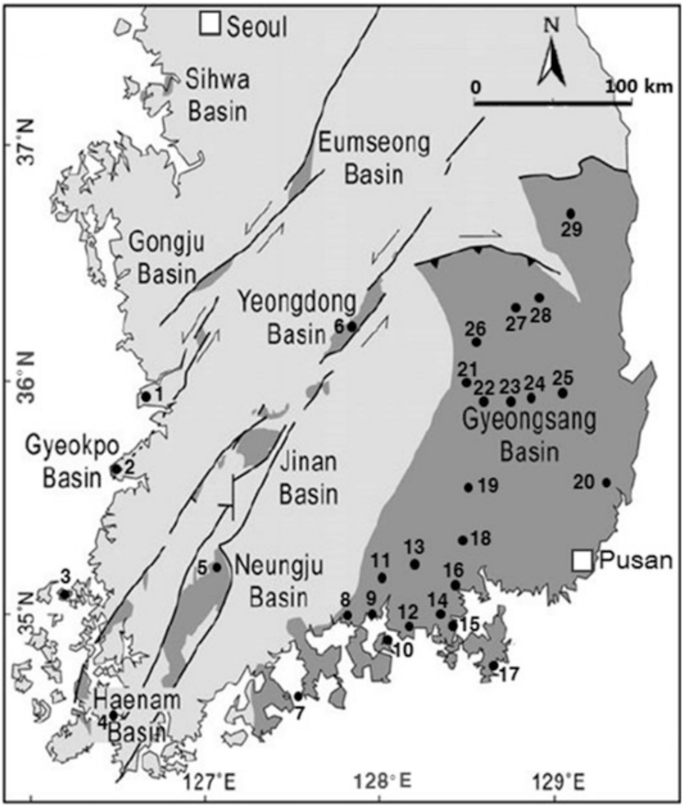


**Fig. 1.5** Distribution of Cretaceous sedimentary basins and vertebrate fossil sites in Korea.*Notes* The shaded areas represent the basin area. The lines across the Korean Peninsula in the NE–SW direction are major fault lines. 1: Gunsan track site; 2: Gyeokpo track site; 3: Sinan track site; 4: Uhangri, Haenam track site; 5: Seoyuri, Hwasun track site; 6: Yeongdong track site; 7: Nangdori, Yeosu track site; 8: Hadong track site; 9: Bito Island, Namhae track site; 10: Gainri and Sinsu Island, Namhae track site; 11: Sacheon track site; 12: Dukmyeongri, Goseong track site; 13: Gajinri, Jinju track site; 14: Duhori and Jukgyeri, Goseong track site; 15: Tongyeong track site; 16: Masan track site; 17: Geoje track site; 18: Haman track site; 19: Changnyeong track site; 20: Ulsan track site; 21: Chilgok track site; 22: Daegu track site; 23: Gyeongsan track site; 24: Yeongcheon track site; 25: Gyeongju track site; 26: Gunwi track site; 27: Uiseong track site; 28: Cheongsong track site; 29: Yeongyang track site (Kim and Kim 2016)

As shown in Fig. 1.5, almost all vertebrate fossil sites are located in the named Cretaceous basins. Exceptions are the Gunsan and Sinan sites, which are located at unnamed small basins. Over 20 vertebrate fossil sites are located at the largest Gyeongsang Basin. However, well-preserved major fossil sites—including the Goseong, Haenam, and Yeosu track sites—are located along the south coast of the Korean Peninsula (Fig. 1.5), though the Hwasun and Jinju track sites are located in an inland area.

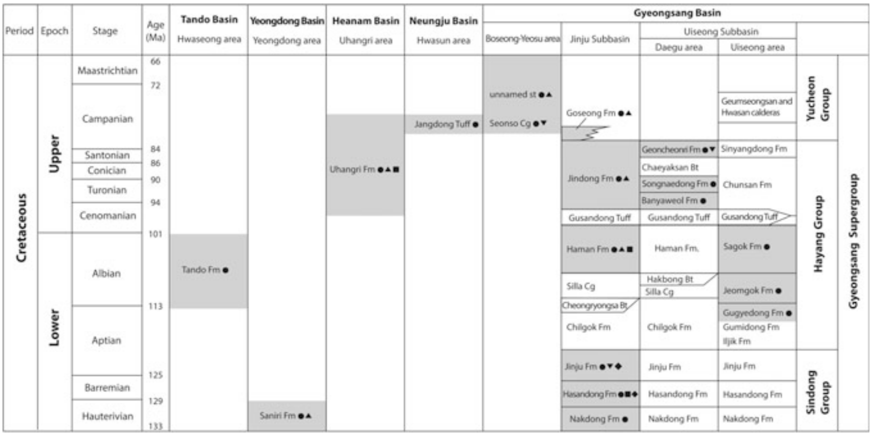


**Fig. 1.6** Stratigraphy of the Gyeongsang Supergroup.*Notes* The stratigraphy of the Gyeongsang Supergroup has been modified after Chang (1975, 1977), Choi (1986), Chang (1988), Chang et al. (1990, 2003), Mitsugi et al. (2001), Chough and Sohn (2010). The vertebrate fossil-bearing strata of the Cretaceous small basins have been modified after Huh et al. (2003, 2006a, b), Lee et al. (2001, 2011), Kim et al. (2003, 2008), Paik et al. (2006), Kim (2008), Kim et al. (2016a, b). Modification has also followed the stratigraphic distribution of Cretaceous vertebrates from Korea. Cg = conglomerate, Bt = basalt, Fm = Formation, st = strata. dot: dinosaur; triangle: bird; quadrangle: pterosaur; diamond: crocodile; inversed triangle: turtle or lizard

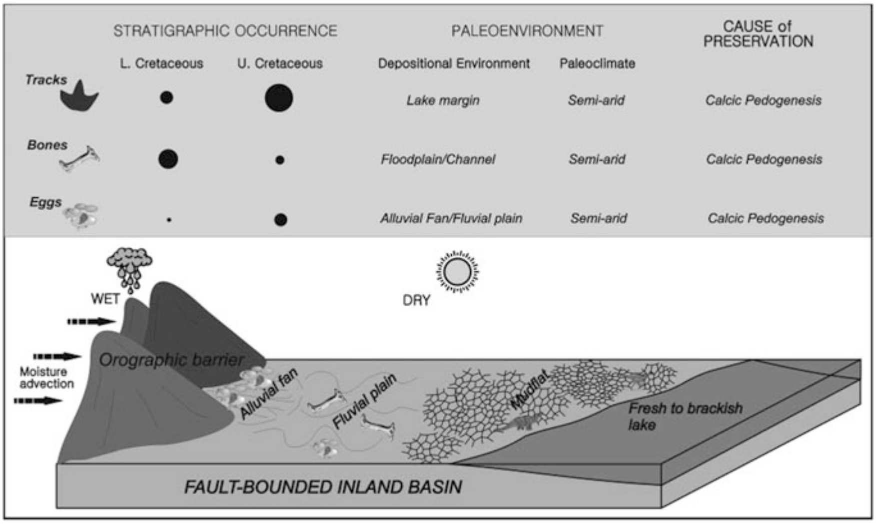


**Fig. 1.7** Schematic diagram showing the occurrence of dinosaur fossils in the Gyeongsang Basin (Paik et al. 2012)

Figure 1.6 shows the simplified stratigraphy of the Gyeongsang Supergroup, the vertebrate fossil-bearing strata of the Cretaceous small basins in Korea, and the stratigraphic distribution of Cretaceous vertebrates from Korea. An abundance of Cretaceous vertebrates including dinosaurs, birds, and pterosaurs has been recorded at the Uiseong and Milyang subbasins of the Gyeongsang Basin. As shown in Fig. 1.6, vertebrate tracks, bones, and eggs have been discovered in the Aptian to Albian Hayang Group. Vertebrates were also reported from the Hauterivian to Aptian Sindong Group, the Cenomanian to Maastrichtian strata of the Neungju and Haenam basins, and the Boseong-Yeosu area. The Hasandong, Jinju, Haman, Jindong, and Uhangri formations in particular yielded diverse, abundant, and well-preserved vertebrate fossils including the tracks, bones, teeth, and eggshells of diverse dinosaurs, birds, and pterosaurs. Like the Sanbukdong track site of the Gunsan area and the Aphaedo dinosaur egg clutch site in Shinan County which were recently discovered, more diverse vertebrate fossils can be expected to be found at the new sites of the Cretaceous basins in the Korean Peninsula in the future.

On the basis of sedimentology (Choi 1985a, b, 1986) and the abundant presence of calcretes, evaporate mineral casts, polygonal desiccation cracks, and rain drop impressions, the paleoenvironments of the vertebrate-bearing Cretaceous deposits of the Gyeongsang Basis are shown in Fig. 1.7 (Paik et al. 2012). The warm and dry paleoclimate and alluvial fan, floodplain, and lacustrine margin paleoenvironments of the Cretaceous in Korea were suitable for diverse vertebrates and for the excellent quality of their preservation in the Cretaceous of the Korean Peninsula.

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# Chapter 2
# Dinosaurs of Korea

## 2.1 Dinosaur Tracks

Numerous tracks of ornithopods, theropods, and sauropod dinosaurs have occurred in the Cretaceous basins mainly located in south east and south of the Korean Peninsula. In addition, diverse fossils of dinosaur bones, teeth, eggshells, skin impressions, and tail traces have been also discovered, though these are relatively uncommon compared with dinosaur tracks. This chapter presents visual images of well-preserved and paleontologically significant tracks, bones, teeth, and eggshells of dinosaurs.

The first discovery of dinosaur tracks at the Cretaceous Jindong Formation on the southern coastal area of Dukmyeongri, Hai District, Goseong County (Yang 1982) stimulated subsequent research into vertebrate ichnology in Korea. Although measured data of over 360 dinosaur tracks at Dukmyeongri were provided, Yang (1982) did not provide a systematic description of dinosaur tracks and trackways. In addition, Yang (1982) tentatively classified Dukmyeongri dinosaur tracks into seven types (Type 1, Type 2-1, 2, Type 3-1, 2, Type 4-1, 2) mainly based on track size, length/width of track, number of digits, and rotation of digits. He made no mention of the dinosaurs that could have made these tracks, such as theropods, sauropods, and ornithopods.

Subsequently, Lim (1990), who was a Ph.D. student supervised by Yang, extensively surveyed the evidence at Dukmyeongri and discovered numerous (around 5000) dinosaur tracks. Lim (1990) also made informal attempts to differentiate dinosaur tracks into two categories: Q type (quadrupedal, presumably all sauropods) and B type (bipedal ornithopods and theropods), and further subdivided these into several subcategories (Q1–Q4 and B1–B9). Some authors have used the Q and B types devised by Lim (1990) for the classification of dinosaur tracks (e.g., Seo 1992; Baek and Seo 1998). However, this scheme is not effective because there is too much disagreement among independent observers as to the category to which a particular dinosaur track belongs (Lockley et al. 2006).



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**Table 2.1** Statistics of identified trackways of dinosaurs from the Cretaceous Period in Korea

| Location | Basin | Theropod trackways | Sauropod trackways | Ornithopod trackways | Total trackways | References |
|---|---|---|---|---|---|---|
| Hai District, Goseong County | Gyeongsang Basin | 16 (4%) | 120 (31%) | 252 (65%) | 388 (100%) | Lim et al. (1994) |
| 8 districts, Goseong County | Gyeongsang Basin | 16 (5%) | 139 (34%) | 249 (61%) | 410 (100%) | Lee et al. (2000b) |
| 15 track sites | Gyeongsang Basin | 38 (7%) | 161 (29%) | 366 (64%) | 565 (100%) | Lee et al. (2001) |
| 25 track sites | Gyeongsang Basin | 28 (6%) | 148 (33%) | 269 (61%) | 445 (100%) | Huh et al. (2003)[a] |
| 85 track sites | Gyeongsang Basin | 106 (12%) | 295 (33%) | 502 (55%) | 903 (100%) | Kim and Kim (2016) |
| Uhangri, Haenam County | Haenam Basin | 1 (10%) | 2 (20%) | 7 (70%) | 10 (100%) | Huh et al. (2006a) |
| Seoyuri, Hwasun County | Neungju Basin | 66 (87%) | ?3 (4%) | 7 (9%) | 76 (100%) | Lockley et al. (2012a) |

[a]Track sites of the Yeosu area were included in the Neungju Basin instead of the Gyeongsang Basin

As shown in Table 2.1, statistics of identified trackways made by theropods, sauropods, and ornithopods was, for the first time, carried out in the Hai District of Goseong County by Lim et al. (1994). Among the 516 identified dinosaur trackways from the Cretaceous Jindong Formation at the Sangjok, Dukmyeongri, Bonghwagol, and Silbawi sites located on the southeastern coast of Hai District, southwest of Goseng County, proportions of theropod, sauropod, and ornithopod trackways are 16 (4%), 12 (31%), and 252 (65%), respectively (Lim et al. 1994). The remaining 128 trackways which are not attributable to any types of dinosaur are worthy of further research.

In addition, Lee et al. (2000b) reported 410 identified trackways from the Jindong Formation of eight districts including Donghae, Hoehwa (misspelled as Hoewha by Lee et al.), and other districts, as well as Hai District, Goseong County. According to Lee et al. (2000b), proportions of identified trackways of theropods, sauropods, and ornithopods are 16 (5%), 139 (34%), and 249 (61%), respectively. Lee et al. (2001) first reviewed vertebrate faunas from the Gyeongsang Supergroup distributed in the Gyeongsang Basin and reported 565 identified trackways of dinosaurs from the 15 track sites. Proportions of identified trackways of theropods, sauropods, and ornithopods are 38 (7%), 161 (29%), 366 (64%), respectively. Dinosaur tracks from the Cretaceous Period at 25 track sites including those at Hwasun, Yeonsu, Ulsan, and Geojae, which were not reported by Lee et al. (2001), were also reviewed by Huh et al. (2003).

Huh et al. (2003) reported that proportions of identified trackways of theropods, sauropods, and ornithopods are 28 (6%), 148 (33%), and 269 (61%), respectively. Huh et al. (2003) regarded that track sites in the Yeosu area, where only a number of tracks was shown, were included in the Neungju Basin instead of Gyeongsang Basin. However, it seems questionable that the number of new data (445 trackways) from many more track sites is much smaller than the number three years earlier (565 trackways), which may possibly be related to sources of indistinct trackways and data. Nonetheless, it is noteworthy that the proportions of identified trackways of theropods, sauropods, and ornithopods from the Goseong area and the Gyeongsang Basin are quite similar to each other: 4–7, 29–34, and 61–67%, respectively, though there are considerable difference in the number of identified trackways between them.

Recently, Kim and Kim (2016) compiled data about the Cretaceous vertebrate tracks from track sites previously reported in Korea. Their compiled data comprise identified tracks and trackways of vertebrates from 85 track sites, including the track sites at Hadong; Bito Island; Namhae; Duhori, Goseong; Tongyeong; Chilgok; Yeongcheon; Daegu; Gyeongsan; Gunwi; Cheongsong; and Yeongyang previously recorded in papers, reports, abstracts, and an unpublished thesis, as well as track sites reported by Lee et al. (2001) and Huh et al. (2003).

According to Kim and Kim (2016), there are 11,872 dinosaur tracks and 1058 dinosaur trackways from the Gyeongsang Basin, and 14,278 tracks and 1372 trackways from the Korean Peninsula. Among the dinosaur trackways from the Gyeongsang Basin, the proportions of identified trackways attributable to theropods, sauropods, and ornithopods are 106 (12%), 295 (33%), and 502 (55%), respectively (Kim and Kim 2016). The remaining trackways (255), which is about 23% of total dinosaur trackways (1158 trackways) from the Cretaceous of the Gyeongsang Basin, were not even assigned to theropods, sauropods, or ornithopods trackways. Instead, they were only assigned to dinosaur trackways, which means further systematic research on these tracks and trackways is necessary.

The Uhangri track site in the Haenam Basin is characteristically abundant with pterosaur and web-footed bird tracks, but there are relatively few identified trackways attributed to theropods (1), sauropods (2), and ornithopods (7) (Huh et al. 2003). However, the Seoyuri track site of the Neungju Basin, Hwasun County, reveals a predominant abundance of theropod trackways (66 = 87%) with a minor occurrence of identified trackways of sauropods (3 = 4%) and ornithopods (7 = 9%) (Huh et al. 2006a), which is very unusual compared with the proportions of dinosaur tracks from the Cretaceous Period at other track sites in Korea.

The proportions of different dinosaur groups represented by identified trackways at the Cretaceous Jindong Formation track sites of Hai District, Goseong County, where dinosaur tracks and trackways have been most abundantly recorded in Korea, are shown in Fig. 2.1 (Lim et al. 1994).

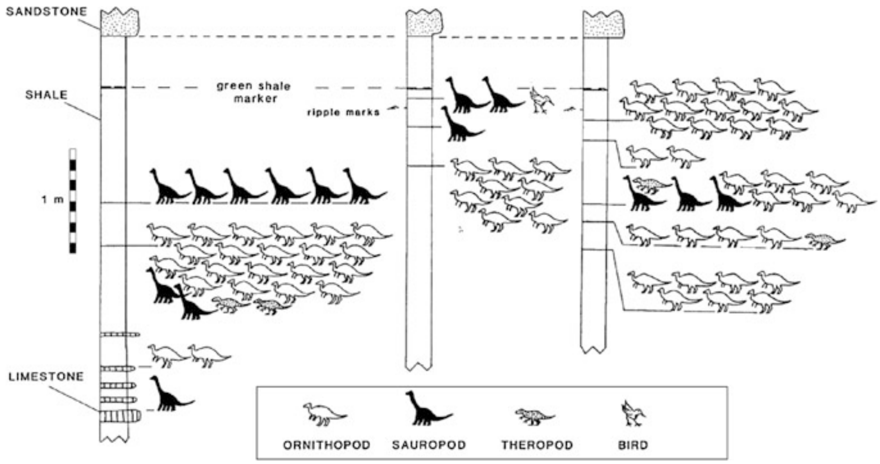



**Fig. 2.1** Proportions of different dinosaur groups represented by identified trackways at the Cretaceous Jindong Formation at track sites in the Hai District, Goseong County. *Source* Lim et al. (1994)

### 2.1.1 Ornithopod Tracks

Among 1072 trackways of dinosaurs previously recorded from the Cretaceous Period in Korea, ornithopod tracks and trackways are the most abundant (over 50%) (Kim and Kim 2016). In particular, an abundance of ornithopod tracks and trackways have been discovered at the Jindong Formation of the Gyeongsang Basin, the Uhangri Formation of the Haenam Basin, and the Jangdong Tuff of the Neungju Basin.

Figure 2.2 presents examples of ornithopod trackways from among the total of approximately 250 identified ornithopod trackways at the Jindong Formation, Goseong County (Lim 1990; Lim et al. 1994; Lockley 1994; Lee et al. 2000b). Figure 2.2a, e show the ornithopods that made the tracks as mostly moving to the northwest. Figure 2.2b–c, f–g show the ornithopods moving predominately southwest. Seven parallel to subparallel ornithopod trackways show movement to the southeast (Fig. 2.2d). A sauropod trackway in Fig. 2.1g shows an almost northward direction of movement. It is perhaps noteworthy that the main trackway trend (southwest) is more or less perpendicular to the wave ripple crest trends (Lockley et al. 2006). Parallel and subparallel ornithopod trackways in the Goseong area suggest that these ornithopods were gregarious in nature. As shown in Figs. 2.3 and 2.4, ornithopod tracks from the Jindong Formation, Goseong area, are mostly 25–35 cm in size and of a *Caririchnium*-like tridactyl morphology (Lockley 1994; Lockley et al. 2006, Figs. 2.3 and 2.4). The tracks are slightly wider than they are long. The digit impressions are mesaxonic, relatively thick and short, with rounded distal termination. Digit II and III impressions are almost parallel to slightly diverged at a low angle. The heel margin impressions are smoothly rounded or have a distinctively bilobate pattern (see Fig. 2.4). Impressions of manus and claw are not observed.

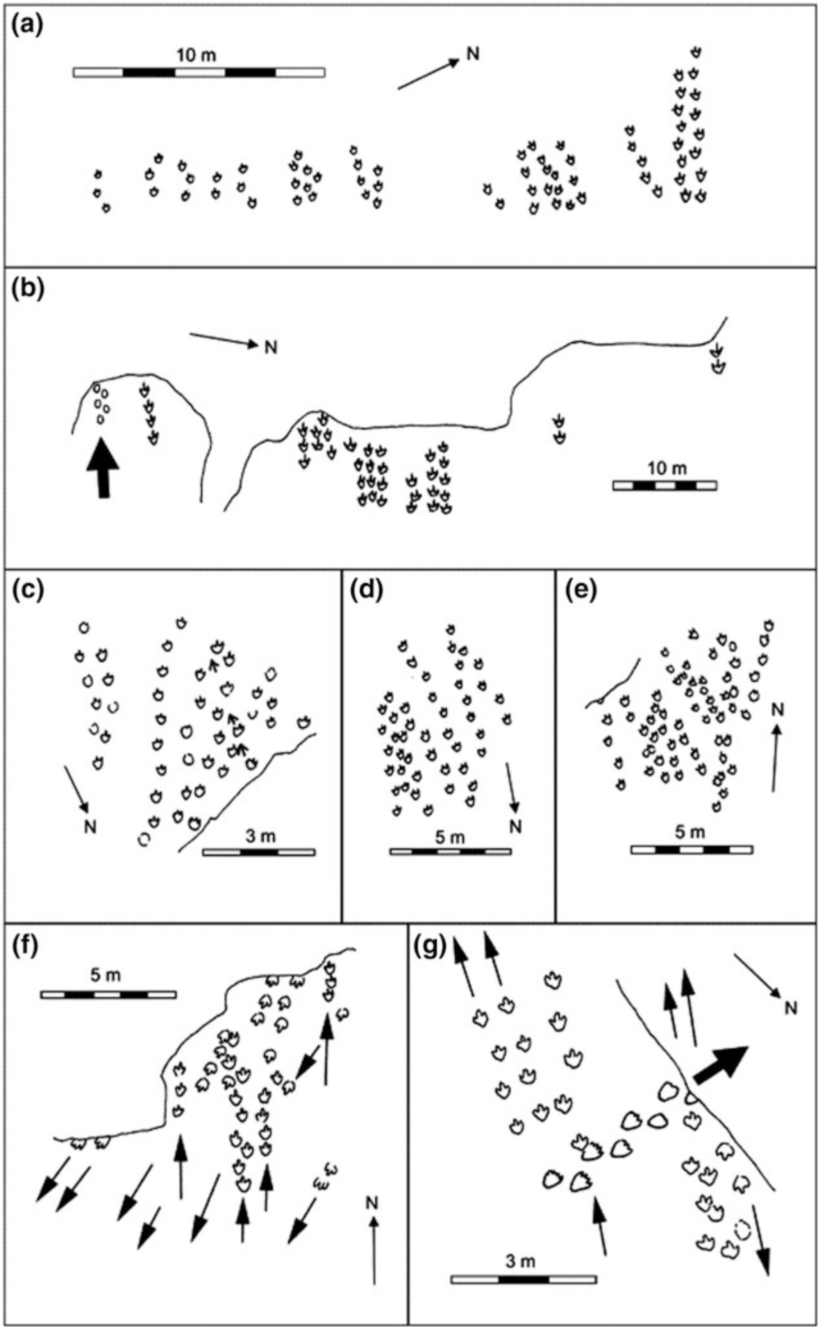
It is especially noteworthy that manus impressions in ornithopod trackways have never been observed at the Jindong Formation, Goseong area (Lockley et al. 2006). It is commonly known that small-sized early ornithopods are generally bipedal and large-sized late ornithopods are habitually quadrupedal and facultatively bipedal. Three probable explanations are possible for the absence of manus tracks. (1) There may have been overprinting of manus tracks with pes tracks. However, there is no double-printing that would provide evidence for this supposition (Lockley et al. 2006). (2) The facultative bipedalism of the ornithopod track makers may be relevant. However, it is probably unlikely that all ornithopod track makers only displayed facultative bipedal locomotion. (3) Shallow and very small (strong heteropody) manus impressions may have been unnoticed or overlooked in the field. The recent discovery of quadrupedal ornithopod trackways such as *Caririchnium kyoungsookimi* (Lim et al. 2012) and *Caririchnium yeongdongensis* (Kim et al. 2016), and several trackways personally observed in the field by the senior author, and *Caririchnium*-like probably quadrupedal tracks from the Uhangri Formation (Huh et al. 1997, Fig. 3) may partly indicate this possibility.

In this regard, it may be necessary to mention that all large ornithopods were quadrupedal, at least facultatively (Leonardi 1997) and manus track preservation bias is a key factor for identifying a trackmaker (Castanera et al. 2013). Absence of evidence is in no way evidence of absence! Further research and careful reexamination of “bipedal” ornithopod tracks and trackways from the Cretaceous Period in Korea is necessary.

Ornithopod trackways from the Chudo and Sado sites at the Yeosu area also show parallel to subparallel orientation (Lockley et al. 2012c, Fig. 2.5). Trackway directions are variable; northeast (five trackways at Chudo 5 and nine trackways at Chudo 4), southeast (four trackways at Chudo b2), southwest (five trackways at Chudo 6), west (seven trackways at Chudo 0), and south (eleven trackways at Chudo 3). However, deviation between trackways at the Chudo 6 site is minimal and inter-trackway spacing is extremely regular (Fig. 2.5). This regularity is strongly suggestive of gregarious behavior (Lockley et al. 2012b). The longest trackway from Chudo 6 (Fig. 2.6) measures 84 m and is currently the world’s longest confirmed ornithopod trackway.

Ornithopod trackways are well-known from the Cretaceous Period in Europe, the North and South Americas, and East Asia. Though the informed and taxonomically incorrect name ‘*Iguanodon* tracks’ was introduced as early as the 1860s (Sarjeant et al. 1998), the only six valid ichnogenera have been named from the Cretaceous Period: *Amblydactylus*, *Caririchnium*, *Hadrosauropodus*, *Iguanodontipus*, *Jiayinosauropus*, and *Ornithopodichnus*, which were recently reviewed by Lockley et al. (2014).

New ornithopod tracks from the Lower Cretaceous Jindong Formation, Masan area, were first described as *Ornithopodichnus masanensis* (Kim et al. 2009), which is recognized as a distinctive robust tridactyl track showing weak mesaxony slightly


(a)
10 m
N
(b)
N
10 m
(c)
N
3 m
(d)
5 m
N
(e)
N
5 m
(f)
5 m
N
(g)
N
3 m

◂**Fig. 2.2** Maps of parallel and subparallel ornithopod trackways from the Jindong Formation, Gosoeng area. *Notes* **a–e** Tracks from the Sangjok section showing 19, 11, 8, 7 and 10 individuals, respectively (after Lockley 1989; Fig. 3C; Lim 1990; Lim et al. 1989, Fig. 35.1). **f** trackways from the Dukmyeongri section (remapped by M. G. Lockley after Lim 1990, Fig. 16.49) showing seven trackways heading southwest and four to the north. **g** trackways from the Bonghwagol section (after Lim 1990, Fig. 16.89) showing five trackways heading southwest and one northeast, with a sauropod trackway heading west-northwest. However, the ornithopod trackways are much deeper than the sauropod trackways at this location (Lockley et al. 2006)

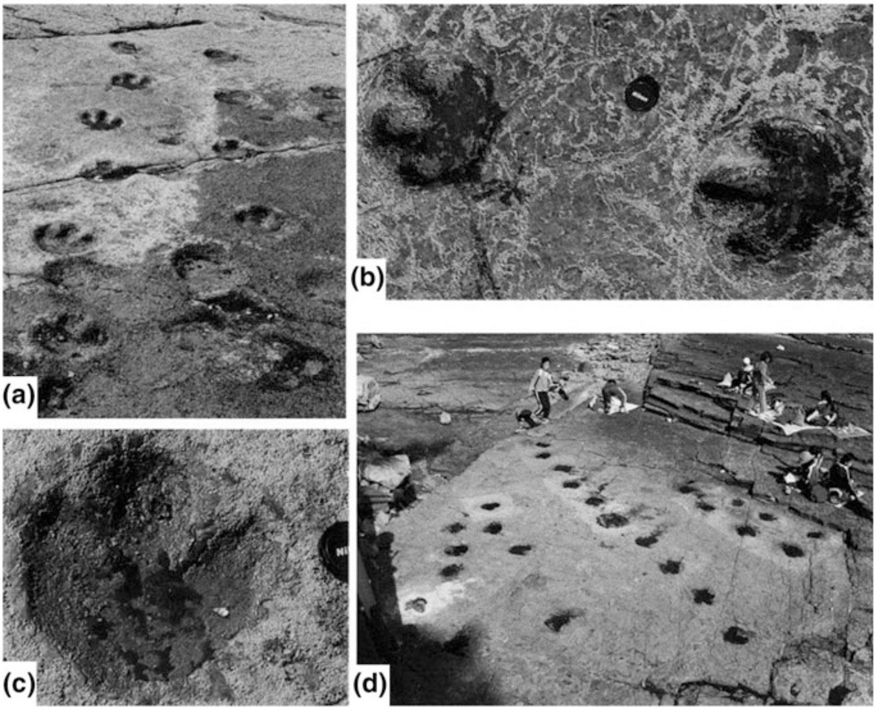



**Fig. 2.3** Photographs of ornithopod trackways from the Sangjok section, Goseong area. *Notes* **a** Parallel ornithopod trackways (after Lockley 1989); compare with two trackways at right side of map in Fig. 2.2a. **b** and **c** details from same trackways as A. **d** trackways corresponding to map in Fig. 2.2c. *Source* Lockley et al. (2006)

wider than it is long (l/w ratio = 0.91), with positive (inward) rotation. The toe prints are very thick, broad and U-shaped, resulting in a trefoil outline with a smoothly rounded hind margin. Digit III is short and projects anteriorly much less than digit II and IV (weak mesaxony). Divarication of digits II–IV is about 70° with an interdigital angle II–III larger than III–IV. The trackway width is narrow and the stride length/track length ratio is 4.2–4.6 (Table 2.2).

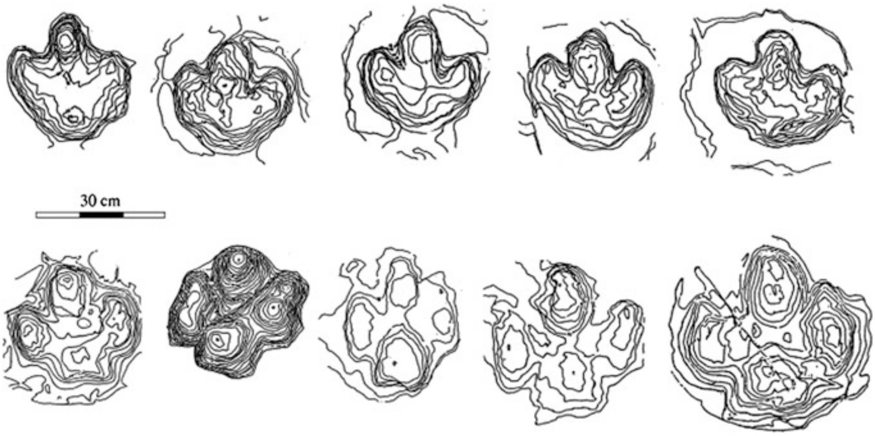



**Fig. 2.4** Contour maps of ornithopod tracks from the Jindong Formation at the Goseong dinosaur track site. *Source* Lockley et al. (2006)

The parallel to subparallel orientation of the *Ornithopodichnus* trackways evidently represents gregarious blunt-toed *Iguanodon*-like bipedal ornithopods, although poorly preserved manus traces are discerned in a few trackways (Figs. 2.7 and 2.8). *Ornithopodichnus* is distinct from other well-known iguanodontid tracks that display much stronger mesaxony and indicates a polarity in ornithopod foot morphology that can be verified by reference to known foot skeletons (Kim et al. 2009, Fig. 2.9).

Subsequently, the ichnogenus *Ornithopodichnus* was also reported at the Lower Cretaceous Tianjialow Formation, Shandong, China (Lockley 2009), the Upper Cretaceous Jangdong Tuff, Hwasun, Korea (Lockley et al. 2012b), the Lower Cretaceous Feitianshan Formation, Sichuan, China (Xing and Lockley 2014), and the Lower Cretaceous Jiguan Formation, Sichuan, China (Xing et al. 2015).

*Ornithopodichnus* trackways evidently represent gregarious blunt-toed *Iguanodon*-like bipedal ornithopods (Kim et al. 2009, Fig. 2.7). To date, the ichnogenus *Ornithopodichnus* has only been recorded from the Cretaceous Period in Korea and China, and thus appears to be related to ecological and biogeographical peculiarities (Xing and Lockley 2014). Small ornithopod tracks (approximately 12 cm in length and 15 cm in width) assigned to ichnogenus *Ornithopodichnus* from the Cretaceous Jangdong Tuff, Hwasun area (Lockley et al. 2012b) are shown in Fig. 2.10.

The ichnogenus *Caririchnium* is a quadrupedal trackway with a subsymmetric pes trace with quadripartite morphology, and the manus trace is irregular in size and shape (Leonardi 1984). Four ichnospecies of *Caririchnium* are known to be valid ichnotaxa (Lockley et al. 2014): *Caririchnium magnificum* (Leonardi 1984), *Caririchnium leonardi* (Lockley 1987), *Caririchnium protohadrosaurichnus* (Lee 1997), and *Caririchnium lotus* (Xing et al. 2007). Many ornithopod tracks and trackways from the Cretaceous Period in Korea have been simply labeled as

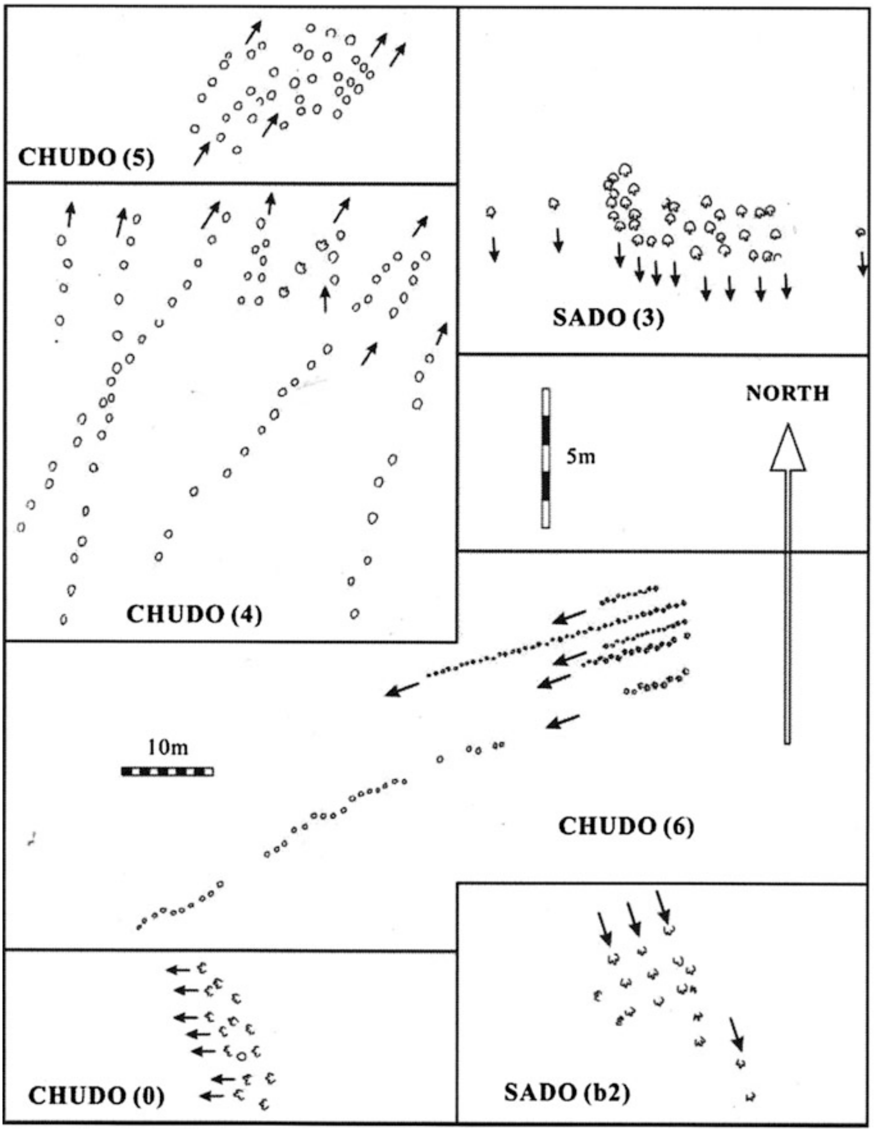



**Fig. 2.5** Maps showing the main sites with parallel ornithopod trackways on Chudo and Sado, Yeisu area. *Note* The 84 m trackway from the Chudo 6 site is the world's longest known ornithopod trackway. *Source* Lockley et al. (2012c)

*Iguanodon*-like tracks or *Caririchnium* without systematic ichnotaxonomical study (e.g., Huh et al. 1997, 2001a; Hwang et al. 2002b, 2004; Lockley et al. 2006). Furthermore, abundant ornithopod tracks occurred in the Cretaceous Period in Korea that have been regarded as having been formed by bipedal ornithopods.

**Fig. 2.6** Outcrop view of the 84 m trackway of ornithopod tracks at the Chudo site, Yeosu area

However, recent discovery of quadrupedal ornithopod trackways including *Caririchnium kyoungsookimi* (Lim et al. 2012) and *C. yeongdongensis* (Kim et al. 2016) may stimulate the reviewing of trackways previously considered as bipedal ornithopod trackways. Twenty years ago, Leonard (1997) suggested that many trackways of bipedal ornithopod dinosaurs may belong to facultative or obligate quadrupedal track makers. He suspected that all large ornithopods were quadrupedal, at least facultatively, and that they would produce very shallow and small manus tracks that would be highly susceptible to preservation bias, weathering and erosion after exposure, or oversight.

*C. kyoungsookimi* was first described at the Cretaceous Jindong Formation, Duhori, Goseong County (Lim et al. 2012). *C. kyoungsookimi* represents the first trackway of a quadrupedal ornithopod in Korea and consists of a tridactyl mesaxonic pes of quadripartite morphology and an elongatedly arcuate to gently subcrescentic manus. The pes impressions are approximately 40 cm in length and 32–35 cm in width (Lim et al. 2012, Fig. 2.11).

Recently, Kim et al. (2016) described new ornithopod tracks as *C. yeongdongensis* at the Lower Cretaceous Saniri Formation, Yeongdong area, central Korea. *C. yeongdongensis* is very unusual in having a large (approximately 15 cm in length and 15 cm in width) trefoil manus track situated anteromedial to the pes track with atypical negative (inward) rotation of 45° (Fig. 2.12). Ornithopod pes tracks are quadripartite with three separated, elongate-oval, nearly parallel sided,

**Table 2.2** Measurement of *Ornithopodichnus* trackways from the Cretaceous Jindong Formation, Masan City

| Trackway no. | Track no. | Length (cm) | Width (cm) | Pace (cm) | Stride (cm) | Pace angle (°) |
|---|---|---|---|---|---|---|
| TW 4′ | R1 | 34 | 34 | | | |
| | R2 | 36 | 32 | 70 | 160 | |
| | L2 | 36 | 36 | | 161 | |
| | L3 | 37 | 40 | | | |
| TW 4 | R1 | 34 | 39 | 75 | | |
| | L1 | 36 | 38 | 82 | 153 | 164 |
| | R2 | 38 | 40 | 80 | 159 | 173 |
| | L2 | 37 | 41 | 82 | 161 | 173 |
| | R3 | 36 | 38 | 84 | 166 | 175 |
| | L3 | 37 | 42 | | | |
| TW 2 | L1 | 40 | 46 | 97 | | |
| | R1 | 44 | 52 | 100 | 230 | 170 |
| | L2 | 44 | 48 | 94 | 197 | 174 |
| | R2 | 44 | 47 | 92 | 183 | 170 |
| | L3 | 40 | 49 | 97 | 183 | 168 |
| | R3 | 44 | 49 | 92 | 187 | 170 |
| | L4 | 44 | 47 | 96 | 186 | 167 |
| | R4 | 42 | 44 | | | |
| TW 3 | R1 | 44 | 35 | 93 | | |
| | L1 | 45 | 38 | 91 | 182 | 164 |
| | R2 | 41 | 36 | 91 | 183 | 166 |
| | L2 | 41 | 35 | 91 | 180 | 165 |
| | R3 | 45 | 38 | | | |
| TW 5 | R1 | 48 | 60 | 88 | | |
| | L1 | 40 | 58 | 92 | 177 | 160 |
| | R2 | 42 | 51 | 92 | 179 | 158 |
| | L2 | 37 | 58 | 92 | 177 | 165 |
| | R3 | 44 | 55 | | | |
| TW 1 | L1 | 30 | 54 | 77 | | |
| | R1 | (32) | (54) | 77 | 151 | 155 |
| | L2 | 39 | 63 | 78 | 153 | 160 |
| | R2 | 36 | 51 | 82 | 153 | 150 |
| | L3 | 36 | 55 | 83 | 162 | 155 |
| | R3 | 38 | 60 | 85 | 165 | 147 |
| | L4 | 40 | 55 | | | |

*Source* Kim et al. (2009)

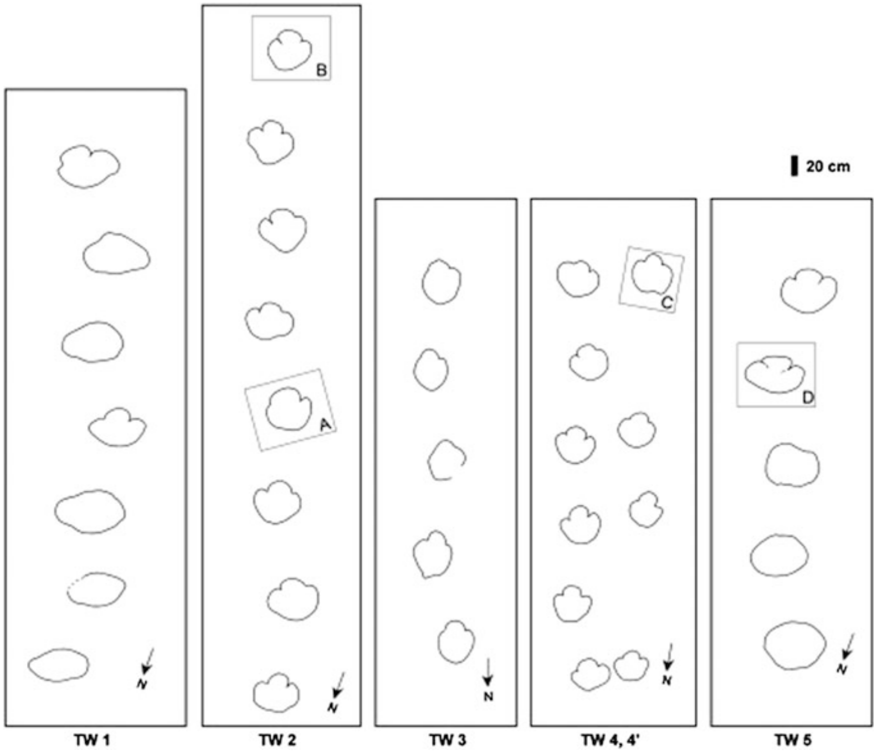



**Fig. 2.7** Line drawings of ornithopod trackways from the Jindong Formation, Masan area. *Note* **a–d** in trackways 2, 4′, and 5 correspond to individual tracks shown in II-8. These trackway sections are on display at the Natural Heritage Center, Daejeon. *Source* Kim et al. (2009)

wide digit impressions and a separate suboval heel impression (mean length and width about 41 and 36 cm, respectively: l/w ratio 1.13). Manus track morphotypes have a trefoil configuration, representing digits II–IV, in a triangular configuration and registered just in front of (anteromedial to) pes track digits II and III. The pes morphotype is typical of *Caririchnium*, but the manus morphotype is quite distinct from previously described ichnotaxa, thus justifying a new ichnotaxon (Kim et al. 2016). *C. yeongdongensis* is the sixth ichnospecies of *Caririchnium* and probably represents a facultatively quadrupedal *Iguanodon*-like ornithopod (Fig. 2.13).

Recently, Xing et al. (2016a) described a new ichnospecies of *Caririchnium*, *Caririchnium liucixini*, from the lower Cretaceous Jiguan Formation, Sichun, China. *C. liucixini* shows medium-sized, pes only *Caririchnium* tracks with quadripartite morphology including three digits with blunt claw or ungula marks and a triangular heel impressions (Xing et al. 2016a).

Measured data for the comparison of *Caririchnium* ichnospecies are shown in Table 2.3. Line drawings for the comparison of *Caririchnium* ichnospecies from the Cretaceous are shown in Fig. 2.14.

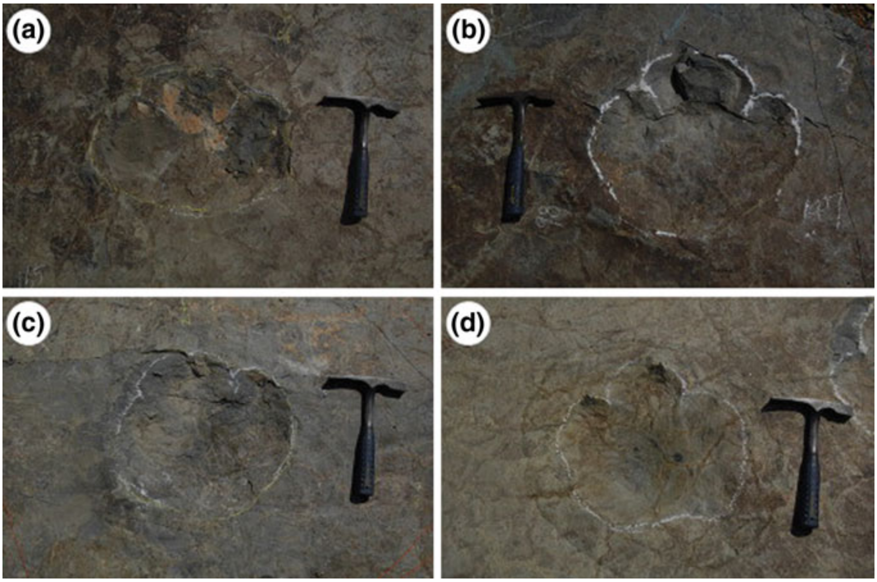



**Fig. 2.8** Examples of individual tracks of *Ornithopodichnus masanensis* at the Jindong Formation, Masan area. *Notes* **a** R2 of trackway 2; **b** R4 of trackway 2; **c** L3 of trackway 4′; **d** L2 of trackway 5. *Source* Kim et al. (2009)

### 2.1.2 Theropod Tracks

In comparison with tracks of herbivorous ornithopods and sauropods, theropod tracks were not abundantly recorded from the Cretaceous Period in Korea. In Goseong County, which has been known as one of the world's richest dinosaur track sites, containing 410 mapped trackways, only 5% (16 trackways) are attributed to theropods (Lee et al. 2000b). However, ichnotaxonomy based on a systematic description of theropod tracks from the Cretaceous Period in Korea has rarely been carried out, except for some theropod tracks and trackways assigned to *Minisauripus* (Lockley et al. 2008; Kim et al. 2012), *Dromaeosauripus hamanensis* (Kim et al. 2008a, b), and *Dromaeosauripus jinjuensis* (Kim et al. 2012b).

Examples of theropod tracks from the Jindong Formation, Goseong area, are shown in Fig. 2.15 (Lim 1990). The theropod tracks shown in Fig. 2.15 are tridactyl and mesaxonic. The three-digit impressions are relatively thick and tapered toward distal end. Digital pad impressions and sharp claw marks can be observed. Divarication between digits II and IV ranges between 60° and 80° (mostly

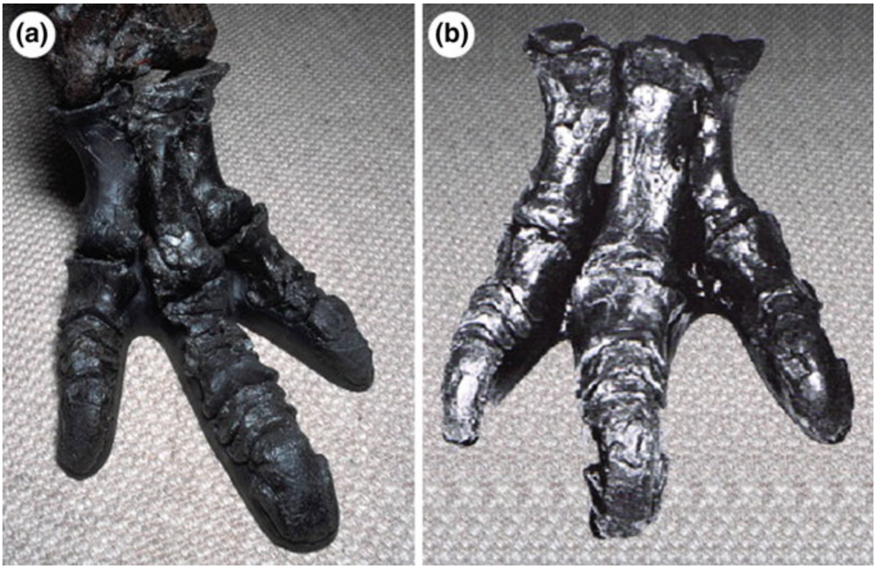



**Fig. 2.9** Photographs of the feet of *Iguanodon atherfieldensis* (**a**) and *Iguanodon bernissartensis* (**b**). *Note* These images show the polarity between robust, weakly-mesaxonic and gracile, strongly mesaxonic morphologies, respectively. Photographs courtesy of Pascal Godefroit and Casier (1978). *Source* Kim et al. (2009)

approximately 70°). Heel margin impressions are generally V-shaped. Tracks are 15–30 cm in length.

Kwak et al. (2007) synthesized theropod tracks from the Cretaceous Period at the Hwasun, Yeosu, Goseong, and Changnyeong track sites. They showed 96 identified trackways of theropods, which are mostly tridactyl and mesaxonic with slender, straight, and tapered digit impressions. Claw marks are commonly observed. Most theropod tracks are less than 25 cm in length, with a few large tracks up to 33 cm in length (Kwak et al. 2007). Divarication between digits II and IV appears to range from 60° to 90°.

However, theropod tracks uniquely dominate the Hwasun track site; more than 1500 dinosaur tracks were found here at five levels (Huh et al. 2001b, 2006a). Of these, theropod tracks comprise 87% of the total number of footprints. Theropod tracks are mostly small (15–30 cm in length), but a few tracks are large (up to over 50 cm in length). Diverse shapes of small and large theropod tracks and trackways from the LI level of the Hwasun track site are shown in Fig. 2.16 (Huh et al. 2006a). Figure 2.17 shows the distribution of seven small theropod trackways, and one large theropod trackway (H). Trackways indicate movement toward the northeast (trackways C–G), west (trackway B), and southwest (trackway A). A striking characteristic of trackway D, which is composed of six consecutive tracks with a length of 56 cm, is the alternation of long (L-R) and short (R-L) steps, suggesting an example of a limping dinosaur (Huh et al. 2006a).

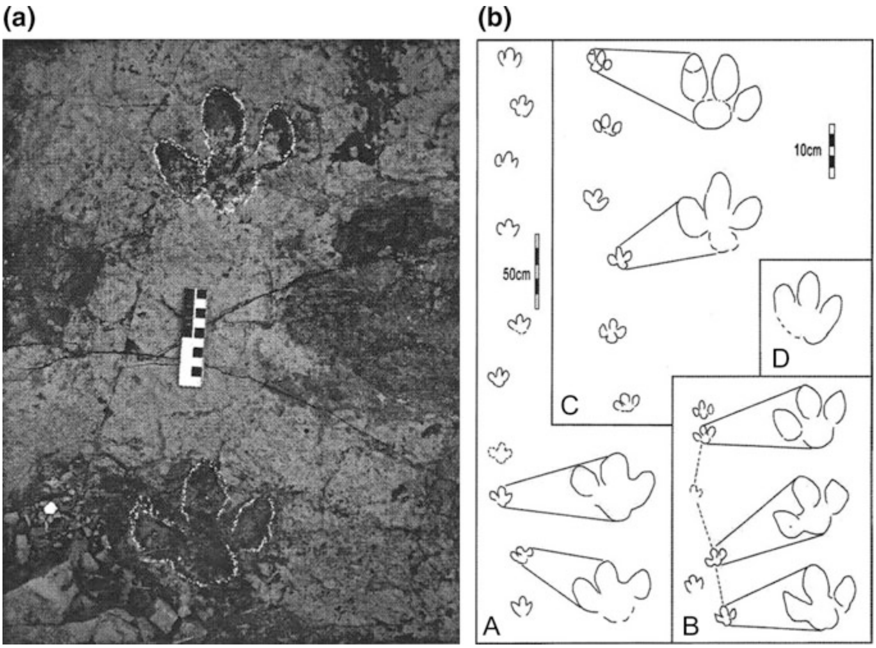



**Fig. 2.10** *Ornithopodichnus*, Hwasun area. *Notes* **a** Photograph of small *Ornithpodichus* tracks from level 2 at the Hwasun track site. Compare with sketch map on right. Scale bar = 10 cm. (Lockley et al. 2012b). **b** Sketch of small ornithopod trackways (*Ornithopodichnus*) from level 2. **a** O1 (with tracks inferred to be O1.t3 through O1.t13, but O1.t9 missing), **b** O2, **c** O5, **d** O6. All trackways are to the same scale with enlargements also drawn to same expanded scale. Note the reduced mesaxony in all tracks. (Lockley et al. 2012b)

Three types of theropod tracks were known from the Hwasun track sites (Huh et al. 2006a, Fig. 2.18). The first type, characterized by its small size, wide digit divarication, and thin digits, is comparable to *Magnoavipes* (Lee 1997). The second track type shows thick digits and relatively narrow divarication, and is similar to the tracks of *Ornithomimipus* and *Xianxipus*. The third type of track, characterized by its distinctive impressions of sharp claws, is larger, longer than 40 cm, with narrow digit divarication, and has been tentatively compared with theropod tracks from Canada and Japan (Huh et al. 2006a).

*Minisauripus*, originally regarded as an ornithopod track (Zhen et al. 1994), but later unequivocally recognized as a theropod track (Lockley et al. 2008), is the smallest known non-avian theropod ichnogenus. *Minisauripus* has been recorded only from the Lower Cretaceous Period in China and Korea (Zhen et al. 1994; Lockley et al. 2008; Kim et al. 2012; Xing et al. 2016b), All identified *Minisauripus* tracks from China (three sites) and Korea (five sites) are approximately 1.0–6.1 cm in length. The makers of these *Minisauripus* tracks have been interpreted to be approximately 5.0–23.0 cm high at the hip and to have bodies approximately 12.0–72.0 cm long (Xing et al. 2016b).

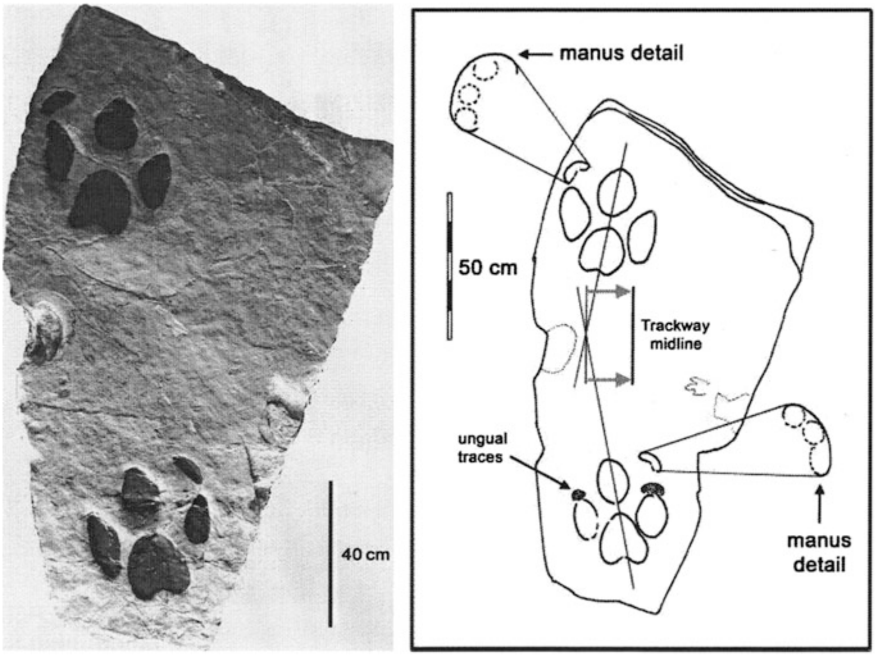



**Fig. 2.11** Photograph and sketch of specimen NHCG 10194 of *Caririchnium kyoungsookimi* showing details of manus impression. *Source* Lim et al. (2012)

Examples of *Minisauripus* tracks from the Cretaceous Haman Formation, Changseon and Sinsu island, are shown in Figs. 2.19 and 2.20 (Lockley et al. 2008; Kim et al. 2012).

As shown in Figs. 2.19 and 2.20, *Minisauripus* from the Early Cretaceous Haman Formation, Changseon Island, is very small, ranging from 1.1 to 1.8 cm in length. The maker of the *Minisauripus* track, which is the smallest theropod track ever known, appears to have been a theropod dinosaur the size of a chicken or a dove, with an estimated height at the hip of 5–8 cm high at the hip.

Most tracks of bipedal dinosaurs are tridactyl and didactyl; other reptiles are rare except for a few ichnogenera including *Velociraptorichnus* (Zhen et al. 1994), *Dromaeopodus* (Li et al. 2007), *Dromaeosauripus* (Kim et al. 2008a, b), and *Menglongipus* (Xing et al. 2009) (Table 2.4).

*Dromaeosauripus hamanesis*, first described from the Lower Cretaceous Haman Formation, Namhae area, shows didactyl theropod tracks approximately 15 cm in length and 9 cm in width, and consists only of impressions of digits III and IV, which show well-developed pad impressions (Table 2.5). Digit impressions are narrow (about 2 cm) and terminate in sharp claw traces. The trackway width is very narrow, about 10 cm, and four consecutive tracks are almost in a straight line. The tracks are thought to have been made by a dromaeosaurid characterized by a strongly recurved, pes digit II that did not register on the substrate. The

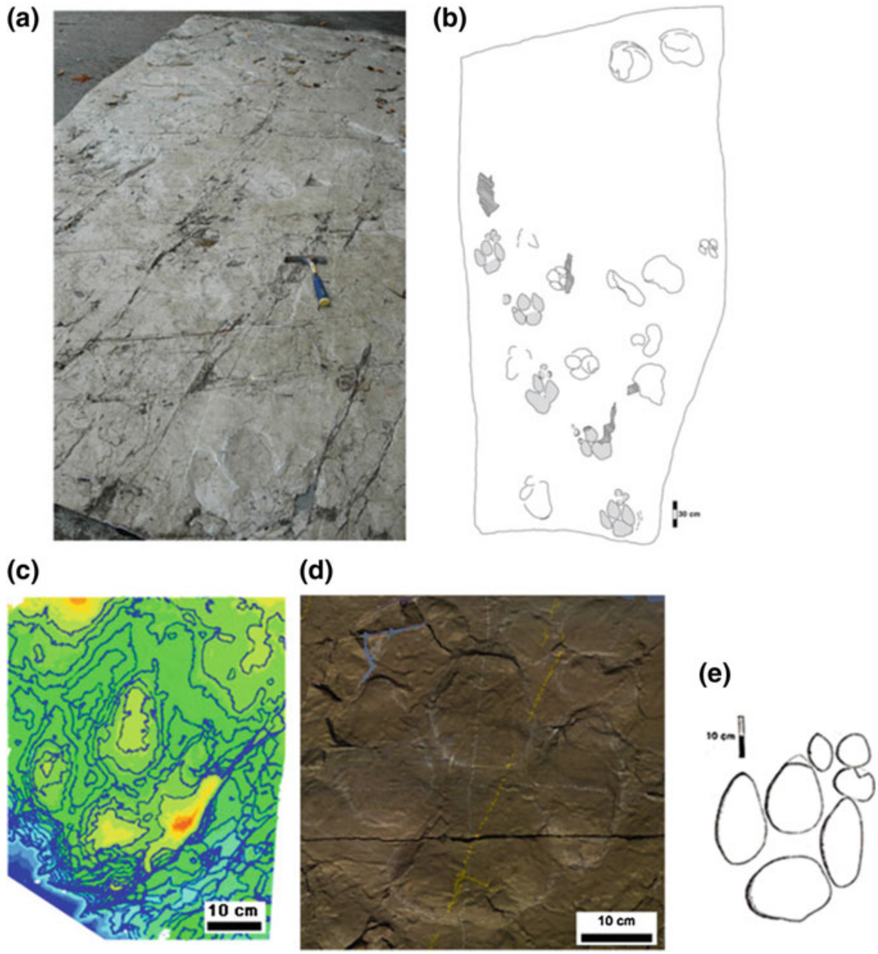



**Fig. 2.12** *Caririchnium yeongdongensis* from the Lower Cretaceous Period, Yeongdong area *Notes*: Photograph (**a**) and sketch (**b**) of trackway. 3D color contour map of right first (R1) track (**c**), 3D mesh image (**d**) and sketch (**e**) of left third (L3) track. *Source* Kim et al. (2016)

*D. hamanensis* trackway is attributed to a small Dromaeosaurid (Deinonychosauria) running bipedally at a speed of 17.5 km/h on a lake margin environment (Kim et al. 2008a, b, Fig. 2.21). The second ichnospecies of *Dromaeosauripus* was described as *D. jinjuensis* at the Jinju Formation, Namhae area, Korea (Kim et al. 2012b). *D. jinjuensis* is a small didactyl track (9.3 cm in length and 6.8 cm in width) characterized by slender impressions of digits III and IV, distinct digital pad impressions, very narrow divarication between digits III and IV, digit III slightly longer than digit IV, and sharp claw impressions (Table 2.6).

*D. jinjuensis* represents the oldest theropod dinosaur track described from the Cretaceous Period in Korea. *Dromaeosauripus* tracks suggest more diversity and a

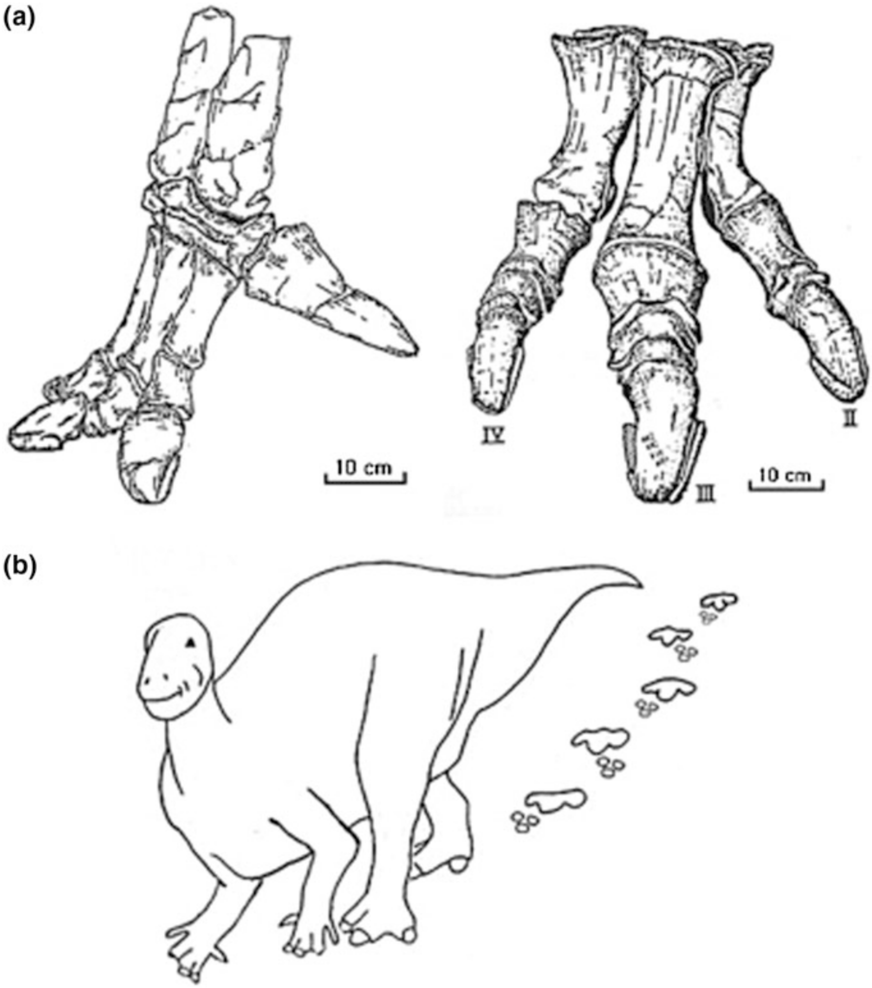



**Fig. 2.13** Manus in weight-bearing position and pes of *Iguanodon bernissartensis*. *Note* The *Iguanodon bernissartensis* is regarded to be one of the most likely track makers for *Caririchnium yeongdongensis*. Figure 2.13b is a reconstruction (Kim et al. 2016). *Sources* Fig. 2.13a, Norman (1980); Fig. 2.13b, Kim et al. (2016)

wider stratigraphic and paleogeographic distribution of dromaeosaurids. The track morphology of *Dromaeosauripus* may also indicate a more digitigrade gait (Kim et al. 2012b). A trackway about 4.3 m long composed of 12 consecutive tracks of *D. jinjuensis* is shown in Figs. 2.22 and 2.23 shows the line drawings of *D. hamanensis* and *D. jinjuensis* (Kim et al. 2012b). Recently, *Dromaeosauripus* tracks have been also reported at the Lower Cretaceous, Shandong Province, China (Xing et al. 2013). Table 2.7 shows measured data for comparison of *Dromaeosauripus* from Korea and *Velociraptorichnus* and didactyl tracks from

**Table 2.3** Measured data for comparison of *Caririchnium* ichnospecies

| *Caririchnium* ichnospecies | L/W | ΔL/W | RMPD | H | $M_s$ | $M_p$ | $P_s$ | II/IV | $H_s$ | $H_m$ | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Caririchnium magnificum* | 1.15[a] | 0.31[b] | 1.19[a] | 1:3.7[b] | I | A-AM[a] | Q | 35° -50° | ST | R | Leonardi (1984) |
| *Caririchnium leonardi* | 1.12[a] | 0.46[b] | 1.12[a] | 1:8.1 [b] | I | AL[a] | T | 90° | ? | SA | Currie et al. (1991) |
| *Caririchnium protohadrosaurichnos* | 1.10[a] | 0.39[b] | 0.83[a] | 1:14.6[b] | E | AL[a] | T | 56° | ? | L | Lee (1997) |
| *Caririchnium lotus* | 1.10[b] | 0.29[b] | 0.80[b] | 1:6.1[b] | SO-S | AL[a] | Q | 57°[b] | SC | SR | Xing et al. (2007, 2015) |
| *Caririchnium kyoungsookimi* | 1.16[a] | 0.45[a] | 0.59[a] | 1:42.6[a] | C | AL[a] | Q | 15° | ST | B | Lim et al. (2012) |
| *Caririchnium yeongdongensis* | 1.13[a] | 0.32[a] | 0.73[a] | 1:6.7[a] | CL | AM[a] | Q | 0° | SO | SR | Kim et al. (2016) |

*Source* Kim et al. (2016)

*Abbreviations* L/W: ratio of length and width of pes track; ΔL/W: ratio of length and width of anterior triangle of pes track; RMPD: relative manus-pes distance, ratio of manus-pes distance and pes track length; H: heteropody, ratio of manus track size and pes track size; Mp: positioning of manus track in relation to pes track; Ps: shape of pes track; Ms: shape of manus; II/IV: angle between digits II and IV; Hs: shape of heel impression; Hm: shape of heel margin impression; I: irregular; E: elongated; SO-S: suboval-semicircular; C: crescentic; CL: trefoil; A: anterior; AL: anterolateral; AM: anteromedial; Q: quadripartite; T: tripartite; ST: subtriangular; SC: subcircular; SO: suboval; R: rounded; SA: subangular; SR: subrounded; BL: bilobate

[a]Data calculated by present authors on the basis of corresponding papers

[b]Data from Xing et al. (2015)

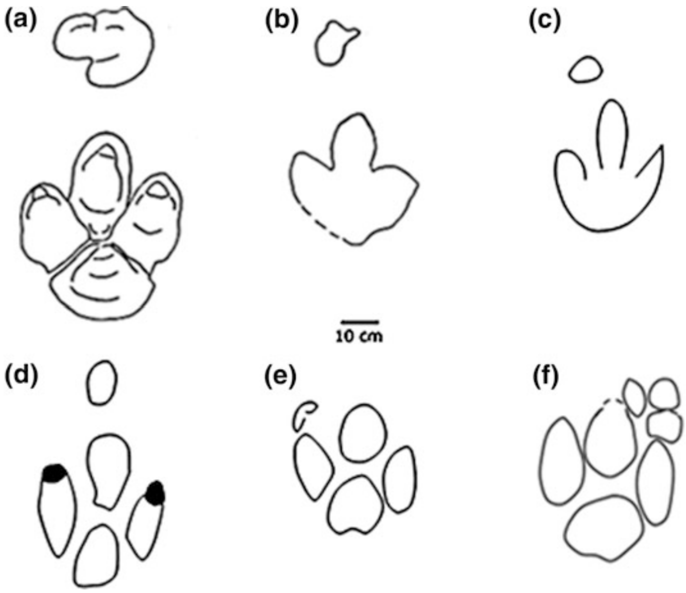



**Fig. 2.14** Scale line drawings of left manus-pes track set of *Caririchnium* ichnospecies. *Notes* **a** *Caririchnium magnificum* (Leonardi 1984); **b** *C. leonardi* (Currie et al. 1991); **c** *C. protohadrosaurichnos* (Lee 1997); **d** *C. lotus* (Xing et al. 2007, 2015); **e** *C. kyoungsookimi* (Lim et al. 2012); **f** *C. yeongdongensis* (Kim et al. 2016) (modified after Lockley et al. 2014). These illustrations have been drawn to the same scale

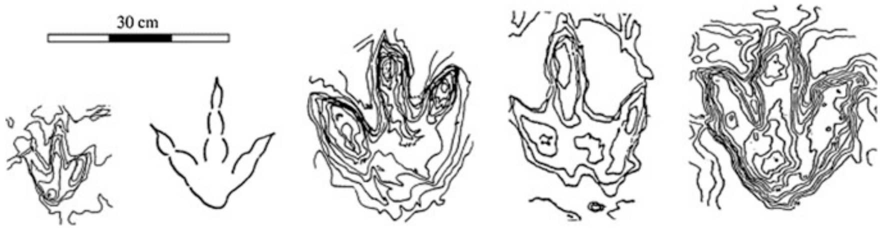



**Fig. 2.15** Theropod tracks from the Jindong Formation, Goseong area, arranged in order of increasing size. *Notes* From left to right, the specimens correspond to Figs. 18.25, 18.30, 18.24, 18.23, and 18.26 in Lim (1990), from the Sangjok, Bongwhagol, Sangjok, Sangjok and Dukmyeongri sections, respectively. *Source* Lockley et al. (2006)

China (Kim et al. 2012b). As shown in Table 2.7, *Dromaeosuripus* is distinguished from other didactyl tracks recorded in the morphology of footprint, the length/width ratio, divarication between digits III and IV, and the stride/track length ratio.

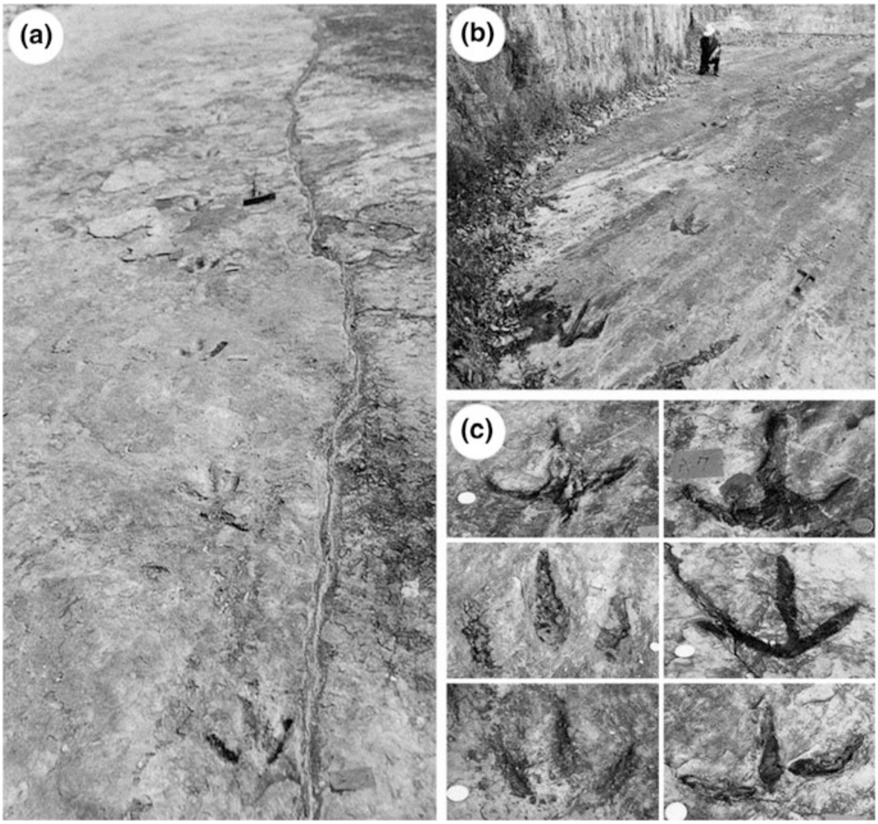



**Fig. 2.16** Photographs of theropod dinosaur tracks and trackways from level L1 at the Hwasun track site. *Notes* **a** Well-preserved, long theropod trackway from the Hwasun track site; **b** trackway of large-sized theropod; **c** diverse shapes of small theropod tracks. *Source* Huh et al. (2006a)

### *2.1.3 Sauropod Tracks*

Tracks of *Brontosaurs* (thunder lizards) are the largest among the most distinctive dinosaur tracks known. Despite a number of short reports in which various names have been assigned to sauropod ichnites, the general approach to sauropod ichnology has been almost entirely haphazard (Lockley et al. 1994). Therefore, a large number of existing sauropod ichnospecies including *Goseongosauripus kimi* (Kim 1986) and ornithopod tracks named *Koreanosauripus cheongi* (Kim 1986) are *nomen dubia* (Lockley et al. 1994). In addition, Kim and Seo (1992) and Kim (1993) described sauropod tracks named *Hamanosauripus ovalis*, *Ultrasauripus ungulatus*, and *Elephantosauripus metacarpus*, as well as *Caririchnium*-like ornithopod tracks named *Koseongosauripus onychion*, and theropod tracks named *Megalosauripus koreanensis* from the Cretaceous of the Gyeongsang Basin.

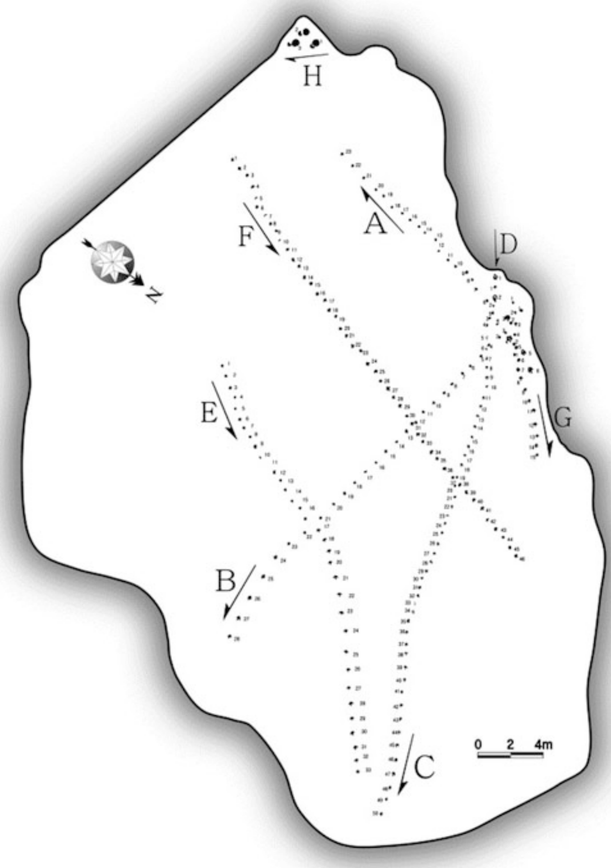



**Fig. 2.17** Map showing distribution of eight dinosaur trackways (A–H) at level L1 at the Hwasun track site. *Source* Huh et al. (2006a)

However, Kim and Seo (1992) and Kim (1993) did not show holotype, systematic description and ichnotaxonomic comparison. Their papers were published in a report instead of a peer-reviewed journal. Therefore, these ichnotaxa are regarded to be invalid.

Lockley et al. (1994) documented that trackway width, heteropody (manus/pes area ratios), and the morphology of pes claw impressions are useful for distinguishing thr ichnotaxa of sauropod tracks. To date, *Brontopodus birdi* (Farlow et al. 1989), *Brontopodus pentadactylus* (Kim and Lockley 2012), and *Parabrontopodus mcintoshi* (Lockley et al. 1994) have been named as sauropod tracks.

Following the most abundant ornithopod tracks, sauropod tracks have been also abundantly recorded in the Cretaceous of many track sites, including the Goseong,


**Fig. 2.18** Three types of theropod footprints from the Hwasun track site. *Notes* Scale bar represents 1 m **a** Small bird-like footprints with narrow digits and wide divarication; **b** medium-sized footprints with thick digits and a narrow toe impression; **c** large theropod footprints with distinct and sharp claw impressions. *Source* Huh et al. (2006a)

Hwasun, and Yeosu track sites. From the track sites of Goseong County, 139 identified trackways (34%) of a total of 410 dinosaur trackways are attributed to sauropods (Lee et al. 2000b). A sauropod trackway, one of the most familiar dinosaur trackways from the Goseong area, is shown in Fig. 2.24.

Sauropod tracks from the Jindong Formation, Goseong County, range from very small (9 cm in pes length) to very large (up to 105 cm in pes length) and the length of the pes track is predominately 20–40 cm (Lockley 1994; Lee et al. 2000b). Examples of sauropod trackways from the Jindong Formation, Goseong County, are shown in Fig. 2.25 (Lim 1990; Lockley et al. 1992, 2006; Lim et al. 1994; Lee et al. 2000b). Figures 2.25a, i show the smallest known sauropod trackway from the Hoehwa District (Lee et al. 2000b). The trackway consists of 30 consecutive tracks (13 manus and 17 pes impressions). The manus and pes tracks are 3 and 9 cm in length, respectively, which results in pronounced heteropody. The pes track is longer than it is wide, with a long axis slightly rotated outward. No pes claw impressions are observed (Lee et al. 2000b). Figure 2.25d–h show sauropod trackways with a wide gauge, which were described as *Brontopodus* ichnosp. (Lockley et al. 2006). Figure 2.25h shows the large sauropod trackway

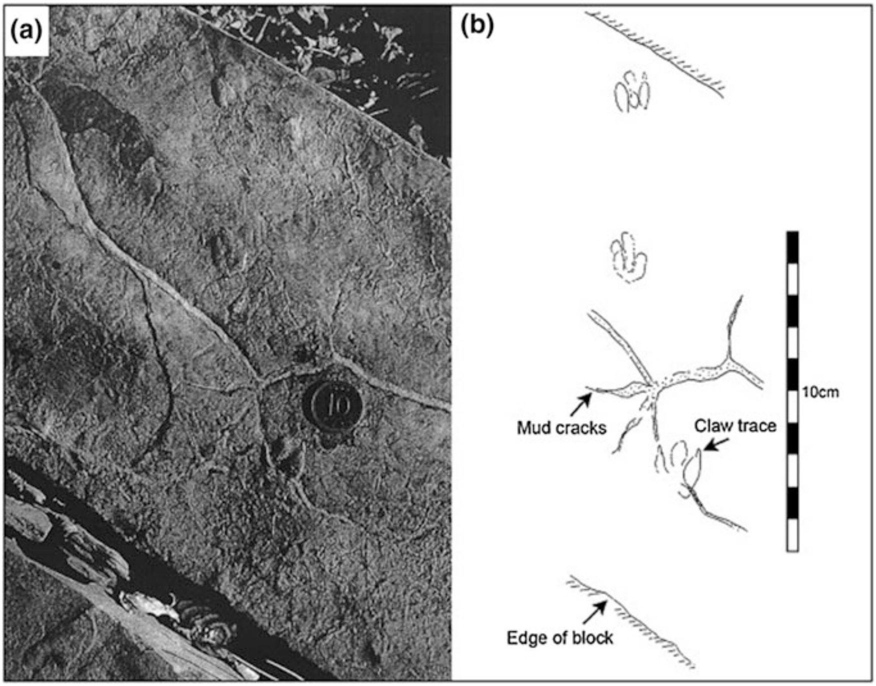



**Fig. 2.19** Photograph and drawing of first South Korean *Minisauripus* trackway discovered at the KML2 site, Haman Formation, Sinsu Island. *Source* Lockley et al. (2008)

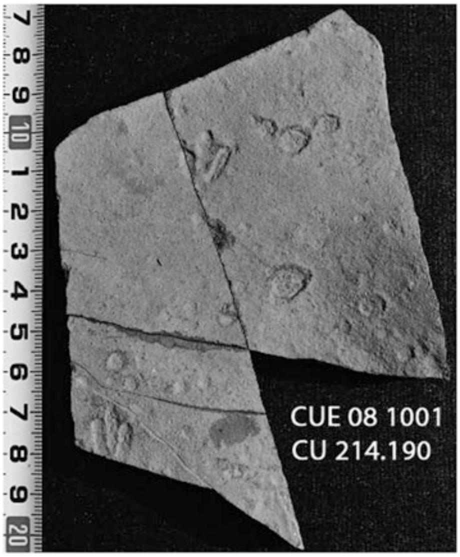



**Fig. 2.20** Photograph of replica of CUE 08 1001 (=CU 214.190) showing two consecutive *Minisauripus* tracks . *Notes* These tracks are 1.2–1.3 cm long, with a step of 7.1 cm. Note the raindrop imprints; specimen from Buyun, Changseon Island, Korea. *Source* Kim et al. (2012)

**Table 2.4** Record of Mesozoic didactyl dinosaur tracks described from literature

| Geological era | Formation | Location | Name | Track maker | Authors |
|---|---|---|---|---|---|
| Late Cretaceous (Maastrichtian) | | Mlynarka Mt. Poland | *Velociraptorichnus* sp. | Dromaeosaurid | Gierlinski (2007) |
| Early Cretaceous | Jiaguan Formation | Sichuan, China | *Velociraptorichnus sichuanensis* | *Velociraptor* | Zhen et al. (1994) |
| Early Cretaceous | Cedar Mt. Formation | Arches National Park, Utah | Didactyl tracks | *Utahraptor*-like dromaeosaurid | Lockley et al. (2004) |
| Early Cretaceous | Cedar Mt. Formation | Arches National Park, Utah | Didactyl tracks | *Utahraptor*-like dromaeosaurid | Cowan et al. (2010) |
| Early Cretaceous | Hekou Group | Gansu, China | Didactyl tracks | *Velociraptor* | Li et al. (2006), Xing et al. (2013) |
| Early Cretaceous (Barremian-Aptian) | Tianjialou Formation | Shandong, China | *Dromaeopodus shandongensis* | Deinonychosaur | Li et al. (2005, 2007) |
| Early Cretaceous | Haman Formation | Namhae, Korea | *Dromaeosauripus hamanensis* | Dromaeosaurid | Kim et al. (2008a, b) |
| Early Cretaceous | Buckeberg Formation | Obernkircken, Germany | Didactyl tracks | Troodontid | Lubbe et al. (2009) |
| Early Cretaceous | Jinju Formation | Namhae, Korea | *Dromaeosauripus jinjuensis* | Dromaeosaurid | Kim et al. (2012b) |
| Jurassic-Cretaceous | Tuchenzi Formation | Hebei, China | *Menglongipus sinensis* | Deinonychosaur | Xing et al. (2009) |
| Late Triassic | Chinle Group | Gateway, Colorado | *Pseudotetrasauropus*-like "didactyl" tracks | Saurischian archosaurs | Gaston et al. (2003) |
| Late Triassic | Chinle Group | Gateway, Colorado | *Evazoum*-like "didactyl" tracks | Saurischian archosaurs | Lockley et al. (2006) |

*Note* Not all tracks can be attributed to deinonychosaurs (*Dromaeosaurs* or Troodontids) (Kim et al. 2012b)

**Table 2.5** Measurement of trackway of *Dromaeosauripus hamanensis* at the early Cretaceous Haman Formation, Namhae area, Korea

| Track no. | L (cm) | W (cm) | $L_{III}$ (cm) | $L_{IV}$ (cm) | P (cm) | S (cm) | PA (°) | III/IV (°) | Or |
|---|---|---|---|---|---|---|---|---|---|
| R1 | (11.7) | 7.1 | 11.7 | 9.2 | 102 | | | 10 | N85° W |
| L1 | 15.5 | 7.1 | 11.7 | 9.2 | 102 | 204 | 180 | 13 | |
| R2 | 15.5 | 8.4 | 11.7 | 9.7 | 103 | 205 | 180 | 13 | |
| L2 | 15.5 | 8.4 | 11.4 | 9.7 | 102 | 204 | 180 | 15 | |
| R3 | 15.5 | | 11.6 | | | | | | |

*Note* Values in parenthesis are length of track without distal pad impression
*Source* Kim et al. (2008a, b)

composed of crescent-shaped manus tracks overprinted with large pes tracks, which is unusual in the sauropod trackways currently known.

The Jeori dinosaur track site, Uiseong County, first discovered in 1990 by Kim, was designated as the first Natural Monument (No. 373) related to dinosaur tracks in 1993. Compared with the Goseong track site located at the southern coastal area of Goseong County, where much more abundant and diverse dinosaur tracks are well-preserved, the Jeori track site, located inland, reveals dinosaur tracks that are relatively not well-preserved. Kim and Seo (1992) described the Jeori dinosaur tracks and assigned sauropod tracks to be *U. ungulatus*, and *E. metacarpus*. In addition, Kim (1993) assigned sauropod tracks from the Yongbawi site, Haman County, as *H. ovalis*. Figure 2.26 shows the outcrop view of the Jeori dinosaur track site and the sauropod tracks and trackways named *H. ovalis*, *U. ungulatus* and *E. metacarpus* (Kim and Seo 1992).

On the basis of brief description and measured data (Table 2.8) provided by Kim and Seo (1992) and Kim (1993), the narrow-gauge sauropod tracks named *U. ungulatus* and *E. metacarpus* appear to resemble *Parabrontopodus* (Farlow et al. 1989) and the wide-gauge sauropod tracks named *H. ovalis* seem to be *Brontopodus* (Lockley et al. 1994).

Although Kim (1986) already reported sauropod tracks tentatively named *H. ungulatus* and *K. cheongi* at the Lower Cretaceous, the Gyeongsang Basin, unfortunately *H. ovalis*, *U. ungulatus*, and *E. metacarpus* were not ichnotaxonomically compared even with his sauropod ichnotaxa. Despite the ichnotaxonomic problems, dinosaur tracks of the Jeori track site, which represent the first named Natural Monument (No. 373) for a dinosaur track site in Korea, are important for the understanding of dinosaur ichnology. Unfortunately, however, further research on the Jeori dinosaur tracks has not yet been carried out. It is very necessary to undertake systematic research on these tracks because the Jeori tracks have been seriously damaged due to weathering.

Following the Goseong track site, where dinosaur tracks were discovered for the first time in 1982, and the Jeori track site, the first natural monument designated for dinosaur tracks in 1993, the Uhangri track site, Haenam County, was first reported in 1997 by Huh et al. (1997) reported approximately 200 dinosaur tracks composed

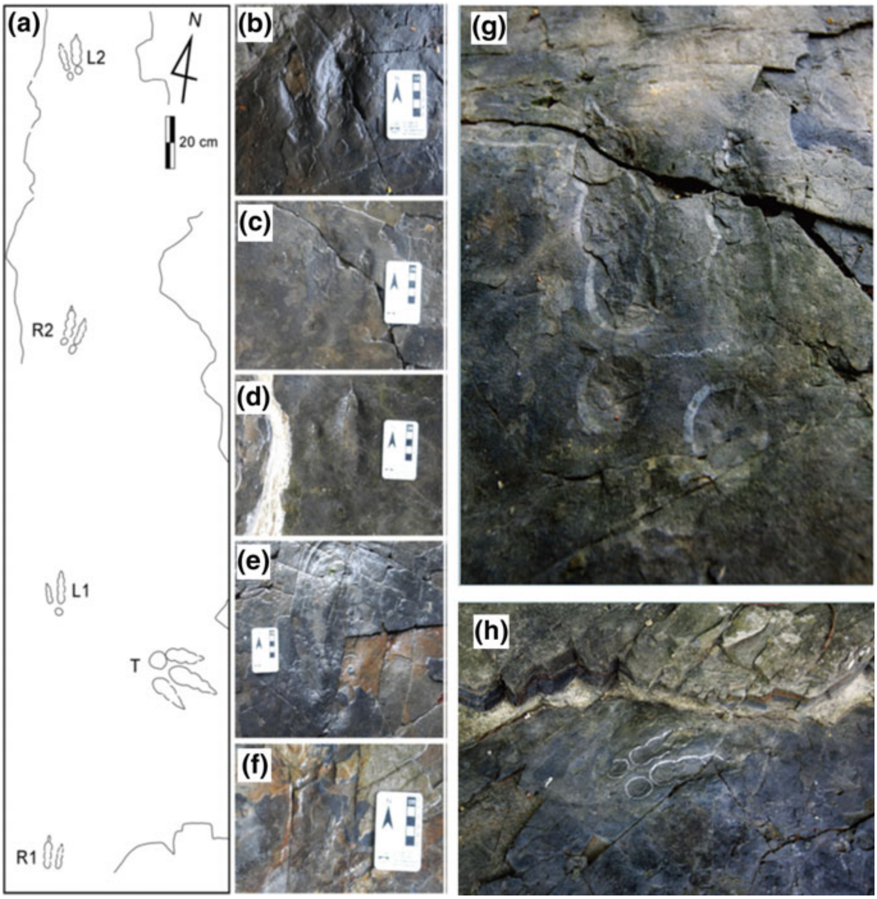



**Fig. 2.21** Dromaeosauripus hamanensis and a theropod track from the Lower Cretaceous Haman Formation, Namhae area. *Notes* **a** Sketch of trackway composed of consecutive *Dromaeosauripus* tracks R1, L1, R2, and L2, and theropod track T; **b** photograph of track L2; **c** photograph of track R2; **d** photograph of track L1; **e** photograph of a tridactyl theropod track T; **f** photograph of track R1, R3 is only partly preserved and not figured; **g** detail of R2; **h** detail of L2. *Source* Kim et al. (2008a, b)

of about 180 ornithopod tracks and a few sauropod trackways from the Upper Cretaceous Uhangri Formation.

Among the ornithopod tracks, a well-preserved track resembling *Caririchnium* is regarded to be the first record of a quadrupedal ornithopod track with strong heteropody, though the authors probably did not recognize it (Huh et al. 1997, Fig. 3). An identified sauropod trackway in a state of relatively good preservation was shown by Huh et al. (1997, Fig. 6). As shown in Fig. 2.27, the sauropod trackway was composed of three consecutive manus and pes tracks. The manus tracks are 21 cm in length and 65 cm in width. The pes impressions are large, up to 101 cm in

**Table 2.6** Measurement of trackway, *Dromaeosuripus jinjuensis* at the early Cretaceous Jinju Formation of Bito Island, Namhae area

| Track no. | Length L (cm) | Width W (cm) | Length of digit III | Length of digit IV | Angle III–IV (°) | Pace (P; cm) | Stride (S; cm) | Pace angle (PA; °) |
|---|---|---|---|---|---|---|---|---|
| R1 | 8.7 | 7 | 7.6 | 8 | 12 | – | | |
| L1 | 11 | 7 | 11.5 | 10 | 10 | 40 | 78 | 180 |
| R2 | 10.2 | 7 | 9.3 | 9.3 | 9 | 38 | 78 | 175 |
| L2 | 9.8 | 7 | 7.6 | 8 | 8 | 42 | 76 | 180 |
| R3 | 9 | 6.7 | 8.9 | 7.3 | 10 | 36 | 76 | 168 |
| L3 | 10.5 | 6.7 | 8.2 | 9 | 10 | 36 | 73 | 177 |
| R4 | 9.2 | 7 | 9.2 | 7.7 | 10 | 35 | 71 | 166 |
| L4 | 9 | 6 | 7.5 | 5.5 | 13 | 35 | 76 | 166 |
| R5 | – | – | 7.9 | – | – | 44 | 105 | 180 |
| L5 | 7 | 7.2 | 6.7 | 5.9 | 14 | 60 | 100 | 175 |
| R6 | 8.2 | 7 | 7.5 | 8 | 10 | 40 | 71 | 180 |
| L6 | – | 5.7 | – | – | 12 | 35 | | |
| Mean | 9.26 | 6.75 | 8.35 | 7.87 | 10.45 | 40.09 | 80.4 | 174.7 |

*Source* Kim et al. (2012b)

length and 74 cm in width, and the pace, stride, and pace angulation are 220 cm, 338 cm, and 114°, respectively. The manus tracks are elongated, generally shaped like a Fig. 2.28, and placed closely in front of the pes tracks. The pes tracks are longer than they are wide, subtriangular to subquadrangular, and outwardly (positively) rotated with angles of up to 45°. Digit impressions of pes tracks are not clearly observed, but the second pes track shows three short and thick digit impressions. The external trackway width is about 220 cm, and the trackway is narrow-gauged. Although the digit impressions are not clearly recognized and an ichnotaxonomic study on this trackway was not carried out (Huh et al. 1997), the overall features of this sauropod trackway resemble those of *Parabrontopodus* (Lockley et al. 1994).

In 1998, over 1300 dinosaur tracks and 132 identified trackways were reported from the new dinosaur track sites at Donghae District, southeast of Goseong County (Baek and Seo 1998). Of the 132 trackways, 98 trackways are bipedal (probably mostly ornithopod trackways) and 34 trackways are quadrupedal (probably mostly sauropod trackways). As shown in Fig. 2.28, most sauropod tracks are densely distributed and thus in many cases identified trackways are difficult to recognize.

In addition, most sauropod tracks are generally circular in outline without showing clear digit impressions. If they have a strong heteropody, sauropod trackways may appear to be bipedal because relatively small and shallow manus tracks may be overlooked or unrecognized. Furthermore, if they are overprinted or have very weak heteropody, some sauropod trackways may be regarded as bipedal because relatively similar sized manus tracks may be regarded as pes tracks. For example, Fig. 2.24 shows a symbolic and well-known dinosaur trackway in

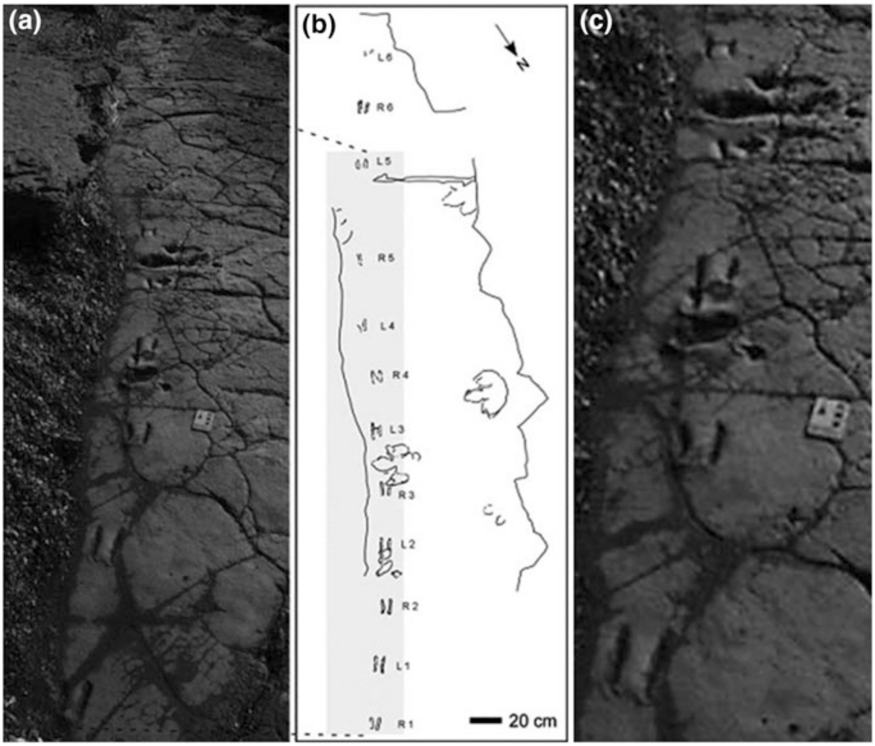



**Fig. 2.22** Photograph (**a**) and drawing (**b**) of didactyl theropod trackway of Dromaeosauripus jinjuensis from the Jinju Formation, Namhae area. *Notes* The scale bars in photographs **a** and **c** are 8 cm long; **c** detail of trackway composed of consecutive tracks (L1, R2, L2, and R3) crossing two ornithopod tracks. *Source* Kim et al. (2012b)

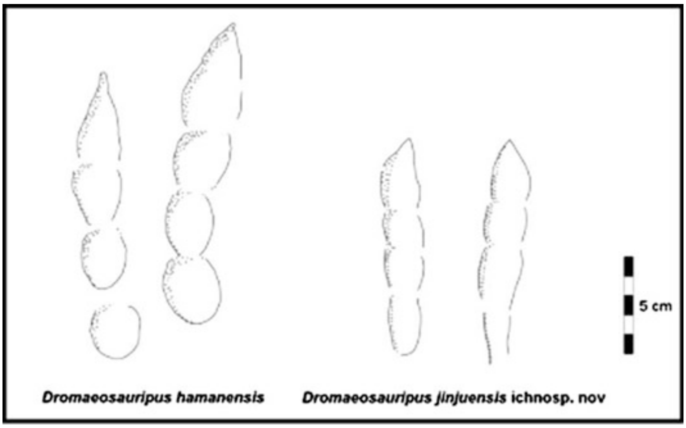



**Fig. 2.23** Line drawings of *Dromaeosauripus hamanensis* and *Dromaeosauripus jinjuensis* tracks. *Sources* The line drawing of the *Dromaeosauripus hamanensis* track is from Kim et al. (2008a, b) and that of *Dromaeosauripus jinjuensis* (L1 in Fig. 2.21) is from Kim et al. (2012b)

**Table 2.7** Comparison of *Dromaeosauripus* from Korea and *Velociraptorichnus* and didactyl tracks from China

| Types of tracks | L (cm) | W (cm) | L/W | $L_{III}$ | $L_{IV}$ | $W_{III}$ | $W_{IV}$ | III–I0V (°) | P (cm) | S (cm) | PA (°) | P/L | S/L | V (km/h) | Authors |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Velociraptorichnus* | 10.7–11.5 | 6.0–6.3 | (1.8) | 9–10.3 | 9.3–10 | 3–3.7 | 2.3–2.4 | 21–28 | 49 | | | 4.4 | | | Zhen et al. (1994) |
| Didactyl tracks | 13.5–15.3 | 5.3–8.2 | (2.1) | | | | | | (20–39) | (48–68) | (115–160) | 2.7 | | (1.9) | Li et al. (2006) |
| *Dromaeosauripus* | 15.5 | 8.4 | 1.91 | 11.7 | 9.2–9.7 | 3.6 | 2.4 | 10–15 | 102 | 204 | 180 | 6.6 | 13.2 | (17.5) | Kim et al. (2008a, b) |
| Shandong *Velociraptorichnus* | 10.0 | 4.5 | 2.22 | 6.5 | 5.5 | 1.5 | 1.0 | 20 | 55.5 | 111 | – | 5.55 | 11.0 | – | Li et al. (2007) |
| Large Shandong track | 28.5 | 12.5 | 2.28 | 16.0 | 16.0 | 3.5 | 3.5 | −5 | 92–103 | 186–206 | 180 | 3.6 | 7.2 | (5.9) | Li et al. (2007) |

*Note* Values in parenthesis are estimated and measured by authors from the figures of Zhen et al. (1994) and Li et al. (2006) who did not show these data in their papers
*Source* Kim et al. (2008a, b)

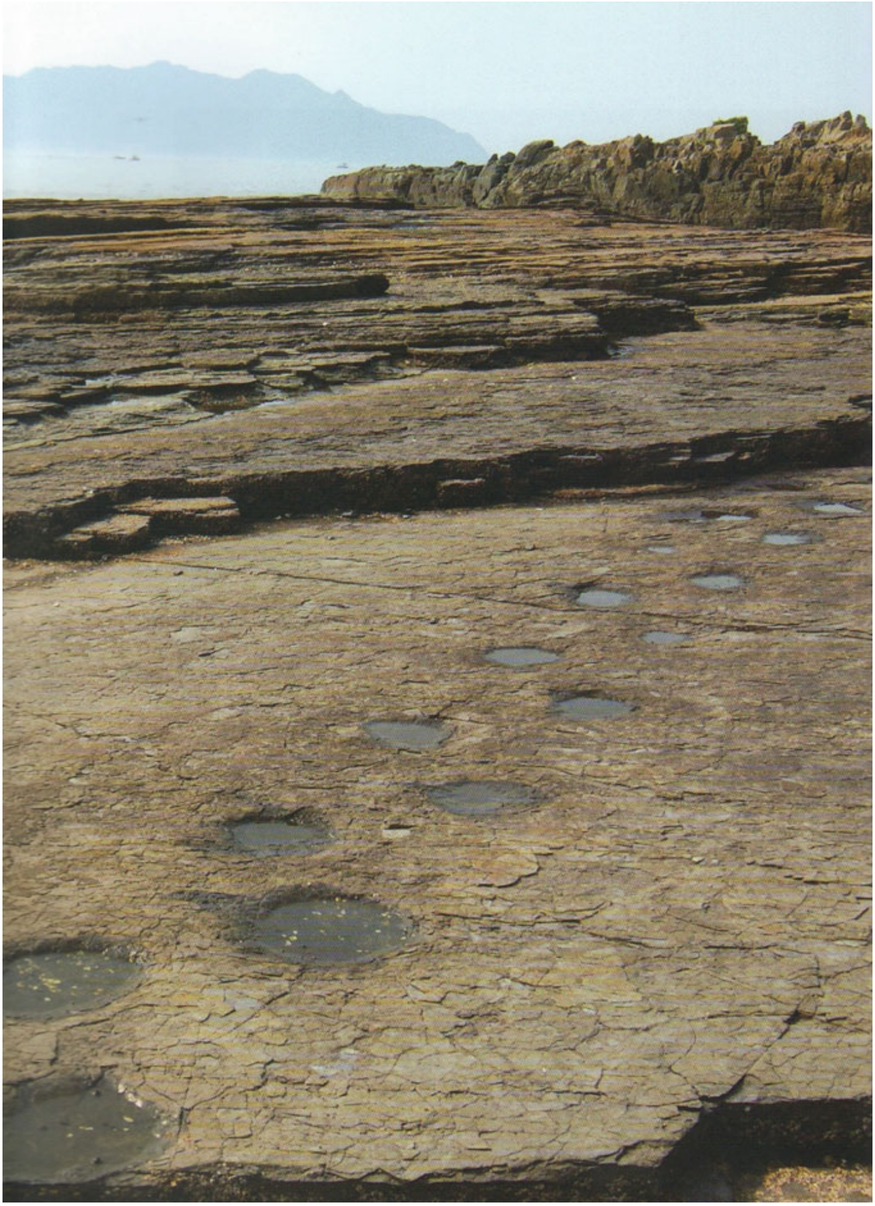


**Fig. 2.24** Sauropod trackway from the Jindong Formation, Goseong dinosaur track site

Goseong County. However, it is difficult to know whether this track is attributable to bipedal or quadrupedal sauropods, even whether individual tracks are manus or pes impressions. Furthermore, it is difficult to tell in which direction the sauropod track maker was moving.

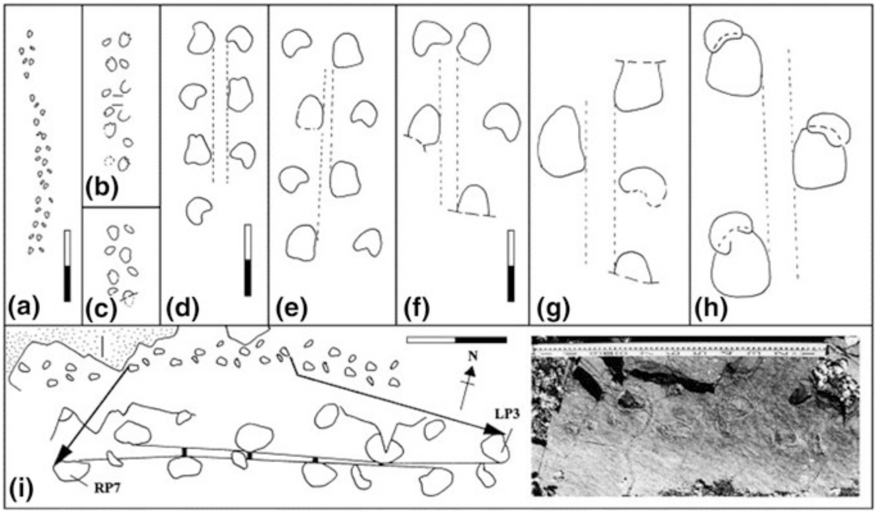



**Fig. 2.25** Sauropod tracks from the Jindong Formation, Goseong area. *Notes* Observe that all the larger examples (**d**–**g**) are wide gauge, as shown by dotted lines that indicate the inner, inter-pes trackway width (after Lim 1990, with his numerical designations). **a** smallest known sauropod trackway at Hoewha District, Goseong County (after Lee et al. 2000b, Fig. 8A; Yang et al. 2003, pl. 89); **b**–**g** tracks at the Samcheonpo track site, Hai District, Goseong County; **b** tracks at the Dukmyeongri section after Lim et al. (1994, Fig. 2); **c** tracks at the Dukmyeongri section after Lockley et al. (1992); **d** trackway 2-6-1 at the Sangjok section; **e** trackway 10-22-1 at the Silbawi section; **f** trackway 2-3-1 at Sangjok 2 section; **g** trackway 8-1-1 at the Dukmyeongri section; **h** trackway 8-9-1 at the Dukmyeongri section; **i** detail of small sauropod trackway shown in Fig. 25A (after Yang et al. 2003, pl. 89) with detail (enlarged × 3) of middle section showing left pes 3 (LP3) to right pes 7 (RP7), and margin of outcrop. Midlines and transverse black bars show variable trackway width. All scale bars represent 1 m (Lockley et al. 2006)

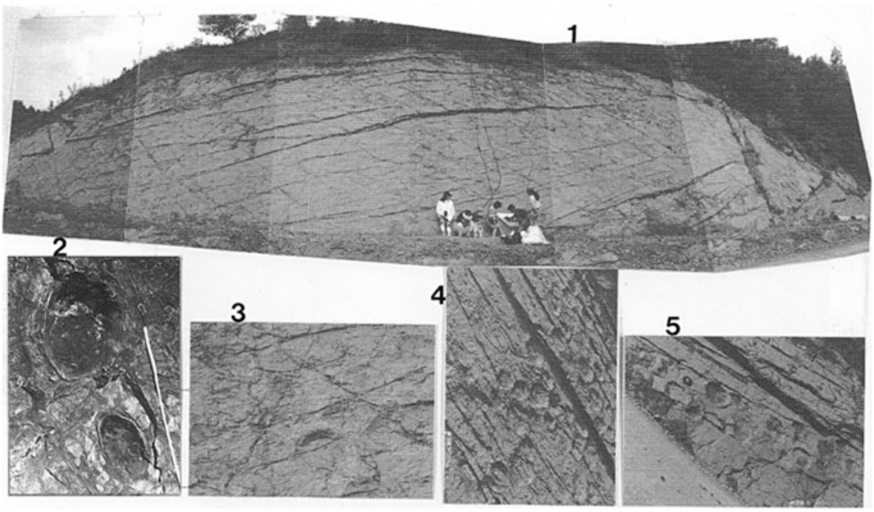



**Fig. 2.26** Jeori dinosaur track site, Uiseong County. *Notes* (1) Outcrop view of the track site; (2) sauropod tracks and trackways named *Hamanosauripus ovalis*; (3–4) *Ultrasauripus ungulates*; (5) *Elephantosauripus metacarpus*. *Source* Kim and Seo (1992)

**Table 2.8** Measurement of sauropod and ornithopod ichnotaxa named by Kim and Seo (1992) and Kim (1986, 1993)

| Ichnotaxa | Track length (Manus/Pes) (mm) | Track width (Manus/Pes) (mm) | Pace (Manus/Pes) (mm) | Stride (Manus/Pes) (mm) | Pace angle (Manus/Pes) | Trackway width (mm) | Remarks |
|---|---|---|---|---|---|---|---|
| *Hamanosauripus ovalis*, Kim and Seo, (1992), Kim (1993) | 260/330 | 190/260 | 1010–670 | 930–1200 | 70°/95° | 950–180 | |
| *Elephantosauripus metacarpus*, Kim and Seo (1992) | 110/530 | 360/470 | 1080/1010 | 1750/1700 | 100°/120° | 1010/960 | One trackway from Uiseong and another trackway from Gyeongsan, subcircular manus and elephant-like pes (Kim and Seo 1992) |
| *Ultrasauripus ungulatus*, Kim and Seo (1992), Kim (1993) | 230/805 | 450/805 | 1760/1840 | 980/870 | 107°/93° | 1450/1430 | One trackway, from Haman area, track maker is *Ultrasaurus* (Kim 1993) |
| *Koseongosauripus onychion*, Kim (1993) | 340 | 300 | 800 | 1600 | 180° | 320 | 11 trackways from Goseong area, tridactyl tracks, claw marks, no figure (Kim 1993) |
| *Hamanosauripus ungulatus*, Kim (1986) | | | | | | | Track maker is Iguanodont, no figure, no description and no diagnosis (Kim 1986) |
| *Koreanosauripus cheongi*, Kim (1986) | | | | | | | Track maker is sauropod, no figure, no description and no diagnosis (Kim 1986) |
| *Goseongosauripus kimi*, Kim (1986) | | | | | | | Track maker is elephantine sauropod, no figure, no description and no diagnosis (Kim 1986) |

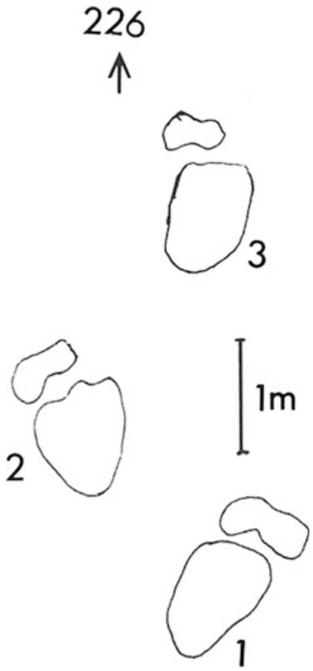



**Fig. 2.27** A sauropod trackway from the Upper Cretaceous Uhangri Formation, Haenam County. *Source* Huh et al. (1997)

**Fig. 2.28** Dense sauropod tracks from the Cretaceous Jindong Formation, Donghae District, Goseong County. *Photo* by author

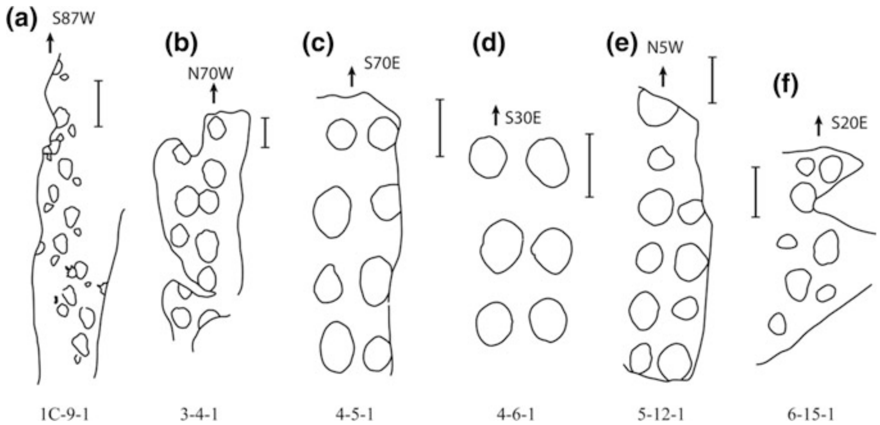



**Fig. 2.29** Sketch of quadrupedal sauropod trackways from the Cretaceous Jindong Formation, Donghae District, southeast of Goseong County. *Note* Scale bar = 1 m. *Source* After Baek and Seo (1998), Fig. 6

Nevertheless, Baek and Seo (1998) reported 34 quadrupedal (probably sauropod) trackways at the Donghae District. Six examples of relatively well-defined quadrupedal sauropod trackways are shown in Fig. 2.29.

The trackway IC-9-1 is a narrow-gauge, very large sauropod trackway composed of small elongated subtriagular manus tracks and elongated subtriangular to subcircular pes tracks. Digit impressions of pes tracks are not clearly observed; the manus tracks are 29 cm in length and the pes tracks are 44 cm in length. Sauropod trackway 3-4-1 is also narrow-gauge, and is composed of relatively large subcircular manus tracks and relatively large, elliptical to subcircular pes tracks. The manus impressions are approximately 80 cm in length and the pes tracks are 110–120 cm in length. The digit impressions of the pes tracks are not clearly recognized. Trackways 4-5-1 and 4-6-1 are medium- to wide-gauge, large quadrupedal sauropod trackways. The manus tracks are relatively large (60–65 cm in length) and subcircular, and the pes tracks are elliptical to subcircular and 75–85 cm in length, which results in very weak heteropody. Digit impressions and claw marks are not observed in the pes tracks.

Trackway 5-12-1 is a medium-gauge, quadrupedal sauropod trackway composed of regularly spaced consecutive manus and pes tracks. The manus tracks are relatively large and generally oval, and the long axis of the manus impressions is nearly perpendicular to the midline of the trackway. The pes tracks are subcircular to elliptical. The lengths of the manus and pes tracks are 56 and 72 cm, respectively, resulting in weak heteropody. The pace, stride, and pace angle of the pes tracks are 128 cm, 196 cm, and 80°, respectively. Trackway 6-15-1 is a partial narrow-gauge, quadrupedal sauropod trackway. The manus tracks are relatively small (22 cm long and 11 cm wide), and oval, subtriangular, and subcircular in outline. The pes tracks are 30 cm in length and 28 cm in width, and elliptical and subcircular in shape (Baek and Seo 1998).

In summary, sauropod trackways from the Cretaceous Jindong Formation in the Donghae District, Goseong County, are narrow-gauge like *Parabrontopodus* or wide-gauge like *Brontopodus* and are highly variable in size, ranging between 30 and 115 cm in length. In addition, dense parallel to subparallel trackways at several localities strongly suggest a gregarious herding behavior in the sauropods that made the tracks.

Seven small sauropod trackways composed of 105 tracks were discovered at the Cretaceous Jindong Formation of the Hogyeri track site of Masan City (Hwang et al. 2002b). As shown in Fig. 2.30, all trackways are narrow-gauge like *Parabrontopodus* (Lockley et al. 1994), and generally composed of small crescent-shaped manus and relatively large elliptical to subcircular pes tracks. Although the digit impressions of the pes tracks are not clear for the most part, a few pes tracks show four thick digit impressions (Fig. 2.30b). Some tracks of trackways B and C show that manus tracks were partly overprinted by pes tracks. Almost all the manus and pes tracks are outwardly (positive) rotated, but the manus tracks of trackways B and G are inwardly rotated. It is difficult to identify the manus and pes tracks in the trackway shown in Fig. 2.30e due to the absence of recognized digit impressions in pes tracks and due to the similarity in the size and shape of individual tracks with low mesaxony. Parallel to subparallel trackways suggest these sauropods exhibited gregarious behavior.

As shown in Table 2.9, the length of the manus track is 9.4–20 cm and that of the pes track is 19–57 cm. The Hogyeri tracks were attributed to small sauropods with an estimated hip height of approximately 2 m that walked slowly at a speed of 0.16–1.89 m/s on the lake margin environment in relatively dry conditions (Hwang et al. 2002b).

Two years later, Hwang et al. (2004) reported a new track site at Docheonri, Changnyeong County, where ten well-defined sauropod trackways composed of over 550 tracks are distributed. The Dochenri track site is exposed on an inclined area approximately 57 m in length and 25 m in height (Fig. 2.31). Ten trackways are parallel to subparallel in a N18°W-N37°W orientation, and are very narrow-gauged like *Parabrontopodus* (Lockley et al. 1994). The manus tracks range in shape from a crescent to a fan, and range in length from approximately 20 to 29 cm in length. The pes tracks are longer than they are wide and range from approximately 30 to 38 cm in length (Table 2.10).

Of the ten trackways, trackway E is the most well-preserved; it is 32.7 m in length and composed of approximately 100 consecutive tracks. The manus tracks are about 24 cm in length and the pes traces are about 34 cm in length, resulting in weak heteropody. The manus tracks show digits II, III, and IV impressions outwardly rotated (nearly perpendicular to the midline of the trackway) and digit I impressions inwardly (medially) rotated (Fig. 2.32).

It is generally known that manus tracks of sauropods are semicircular or horseshoe-shaped (convex forward) and, usually, they show no indication of separate digit impressions (Thulborn 1990). In this regard, the Docheonri sauropod trackways represent an unusual example as they show sauropod manus tracks with separate digit traces. Although Hwang et al. (2004) regarded four (I–IV) digit

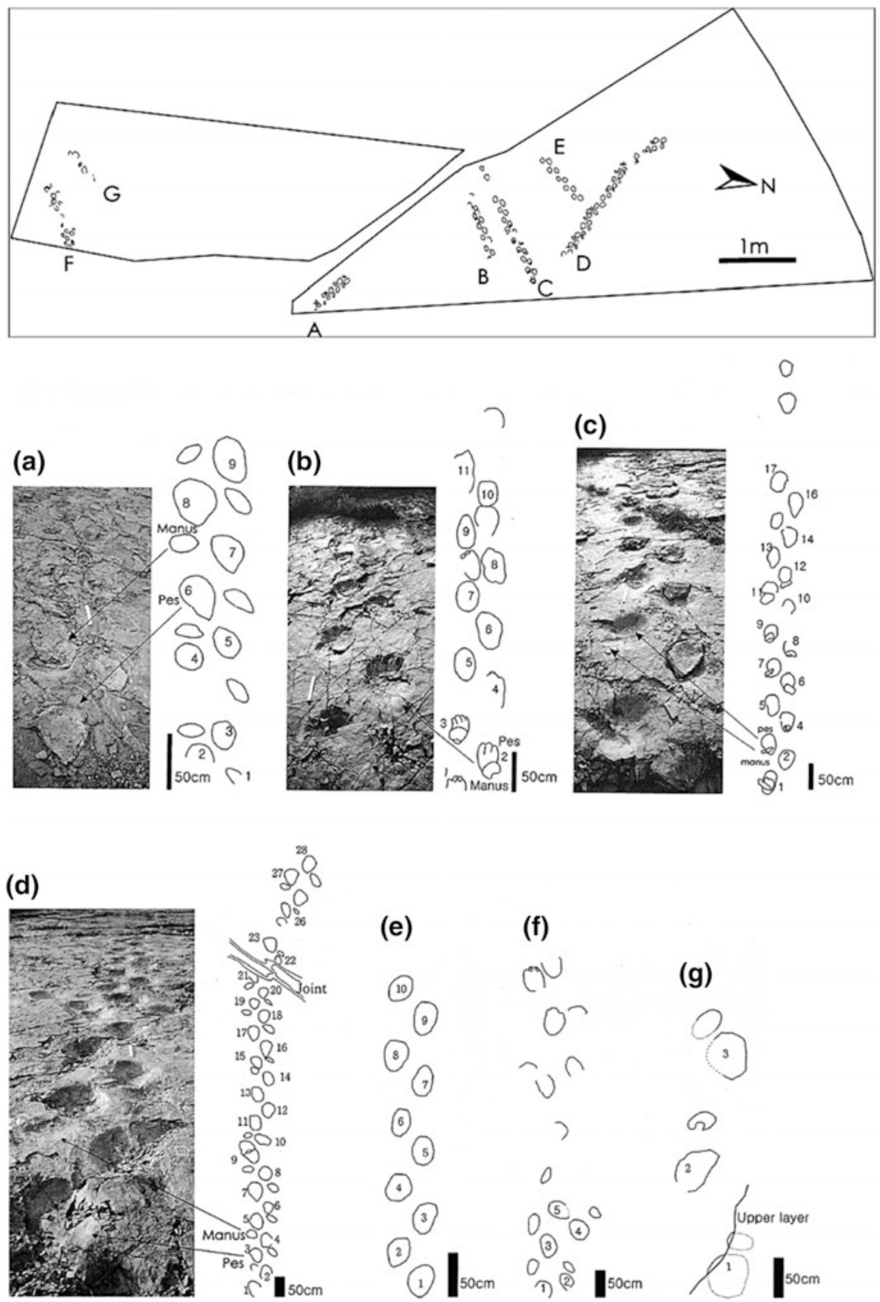



**Fig. 2.30** Map showing distribution of sauropod trackways at the Hogyeri track site, Masan City (top), and photographs and line drawings of sauropod trackways (middle and bottom). *Source* Hwang et al. (2002b)

**Table 2.9** Measurement of sauropod trackways from the Cretaceous Jindong Formation of Hogyeri, Masan City

| Track way | Manus/ pes | Trackway orientation | Track way width (cm) | Pace length | Stride length | Pace angulation | Track length | Track width | Track depth |
|---|---|---|---|---|---|---|---|---|---|
| A | Manus | N50W | 35.7 | 68.3 | 91.0 | 107.9 | 13.6 | 27.6 | 2.0 |
| | Pes | | | 38.7 | 50.0 | 106.4 | 37.0 | 20.6 | 3.4 |
| B | Manus | S68W | 36.0 | 65.7 | | | 11.0 | 16.0 | 5.4 |
| | Pes | | | 58.7 | 92.0 | 104.5 | 45.3 | 25.9 | 3.7 |
| C | Manus | S62W | 38.7 | 63.5 | 82.5 | 107.5 | 10.5 | 21.4 | 5.9 |
| | Pes | | | 60.8 | 87.3 | 101.5 | 38.6 | 25.9 | 5.1 |
| D | Manus | N64W | 33.8 | 69.2 | 96.8 | 77.5 | 18.7 | 29.2 | 1.3 |
| | Pes | N38W | | 56.0 | 95.4 | 111.5 | 42.3 | 30.6 | 4.7 |
| E | | S50W | 33.4 | 54.2 | 90.2 | 107.9 | 43.5 | 28.2 | |
| F | Manus | S60W | 42.5 | | | 51.7 | | | 2.5 |
| | Pes | | | 75.8 | 90.5 | | 27.0 | 28.2 | 2.9 |
| G | Manus | S32W | 29.0 | 120.5 | 272.6 | | 31.0 | 32.0 | 2.6 |
| | Pes | | | 140.1 | 283.5 | 145.0 | 52.0 | 37.0 | 4.3 |

*Source* Hwang et al. (2002b)

traces, the manus tracks appear to have five (I–V) digit impressions (Fig. 2.32). Recently, sauropod tracks assigned to *B. pentadactylus* characterized by five digit impressions of manus track (Kim and Lockley 2012) have been clearly distinguished in the Docheonri sauropod tracks in the morphology of manus tracks. The pes tracks of the Docheonri sauropod trackway E are elliptical to subcircular and composed of four digits I–IV impressions with claw marks and rounded heel margin impressions. However, the other trackways of the Docheonri track site are relatively poorly preserved and do not clearly show digit impressions.

It may be noteworthy that smaller manus tracks are deeper than those of the larger pes tracks of the Docheonri sauropod trackways A, D, F, and J (Hwang et al. 2004) and the Hogyeri sauropod trackways B and C (Hwang et al. 2002b). As shown in Tables 2.9 and 2.10, the difference between the depth of manus and pes tracks may not be related to the size (length) of a manus and pes track, heteropody, and the shape of the manus impressions. It is generally known that the depth of tracks is related to the substrate conditions, such as moisture content and the texture of sediments, and also to the variations in pressure in the fore and hind limbs of the track makers. In addition, it is generally known that the tracks of relatively larger hind feet are deeper than those of relatively smaller forefeet.

Nevertheless, the reason why smaller manus tracks are deeper than relatively larger pes tracks in some sauropod trackways from the Hogyeri and Docheonri track sites remains to be explained. It is clear that substrate conditions do not offer a reasonable explanation, because the trackways occur densely in a limited area and there is no distinct trend in the difference of track depth between the parallel to subparallel trackways. So, the difference in body weight pressure between manus

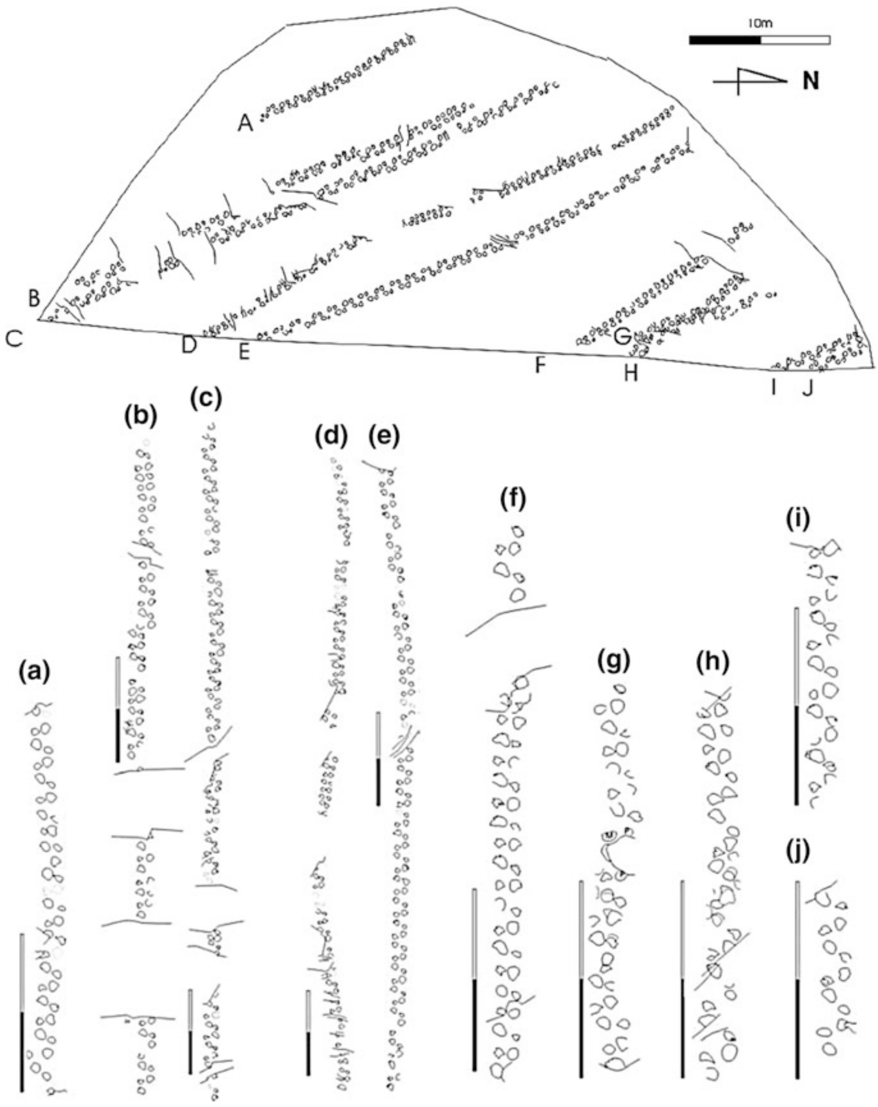



**Fig. 2.31** Map showing distribution of sauropod trackways from the Cretaceous Jindong Formation, Docheonri, Changnyeong County (top), and line drawing of sauropod trackways (bottom). *Source* Hwang et al. (2004)

and pes during locomotion of the track making individuals and species may be a possible explication for this. Another possibility may be the amount of time that a foot remains on the ground (Thulborn 1990), though it is known to be roughly equal for the forefeet and hindfeet in quadrupedal mammals (Alexander and Jayes 1983).

**Table 2.10** Measurement of sauropod trackways from the Cretaceous Jindong Formation of Docheonri, Changnyeong City (Hwang et al. 2004)

| Track-way | Pes/manus | Pace length | Stride length | Trackway width | Pace angulation | Track length | Track width | Track depth |
|---|---|---|---|---|---|---|---|---|
| A | Pes | 83.0 | 111.2 | | 88.1 | 29.9 | 31.0 | 25.4 |
| | Manus | 80.6 | 111.6 | | 88.2 | 28.9 | 30.9 | 27.5 |
| B | Pes | 82.7 | 115.4 | 12.0 | 89.7 | 35.1 | 30.0 | 31.9 |
| | Manus | 78.0 | 113.0 | | 93.1 | 22.9 | 30.4 | 20.1 |
| C | Pes | 70.4 | 119.6 | 8.0 | 100.0 | 35.7 | 29.8 | 27.4 |
| | Manus | 78.8 | 118.1 | | 94.9 | 22.1 | 33.5 | 24.4 |
| D | Pes | 56.9 | 101.0 | | 95.9 | 31.0 | 26.9 | 13.8 |
| | Manus | 62.0 | 101.6 | | 105.4 | 20.1 | 27.4 | 17.8 |
| E | Pes | 69.6 | 125.3 | 11.0 | 95.8 | 33.5 | 30.1 | 30.8 |
| | Manus | 77.2 | 123.7 | | 95.4 | 23.8 | 30.1 | 30.0 |
| F | Pes | 71.2 | 111.5 | 9.0 | 88.8 | 97.6 | 30.9 | 18.8 |
| | Manus | 79.3 | 115.4 | | 91.8 | 24.0 | 27.1 | 19.2 |
| G | Pes | 65.1 | 108.7 | | 101.3 | 35.6 | 29.9 | 19.8 |
| | Manus | 78.6 | 110.1 | | 87.1 | 22.7 | 31.4 | 16.3 |
| H | Pes | 75.5 | 115.0 | | 98.8 | 35.2 | 30.5 | 17.3 |
| | Manus | 79.9 | 126.4 | | 97.8 | 19.8 | 31.1 | 13.8 |
| I | Pes | 68.3 | 116.0 | | 116.6 | 38.2 | 32.0 | 25.8 |
| | Manus | 76.8 | 117.4 | | 102.7 | 21.4 | 28.9 | 20.1 |
| J | Pes | 74.7 | 128.4 | 8.0 | 112.2 | 33.7 | 27.6 | 13.5 |
| | Manus | 78.9 | 131.7 | | 105.0 | 20.2 | 31.5 | 18.2 |

Recently, a pes only sauropod trackway associated with ornithopod and theropod trackways was described at the Cretaceous Jangdong Tuff at the Hwasun track site (Lockley et al. 2012b). The sauropod trackway segment identified shows four consecutive pes tracks oriented towards the east. The trackway (Fig. 2.33) is distinctive because it shows no sign of manus tracks. Nevertheless, individual pes tracks are outwardly rotated, and well-preserved, with sediment rims and claw traces. The mean pes length and width is 72 and 52 cm, respectively ($N = 4$). The mean step is 135 cm ($N = 3$), and the mean stride is 217 cm ($N = 2$). The pace angulation is 108°, and the inner trackway width is approximately 30 cm. The lack of manus tracks suggests that they were overprinted by the pes. At least four isolated, crescent- to horseshoe-shaped (convex forward) manus tracks (M1–M4 in Fig. 2.32) are found scattered across the site at level 4. Their random distribution, without associated pes tracks, is difficult to interpret. It is tentatively inferred that they represent transmitted prints, or actual prints that penetrated randomly from a higher level as a result of differential substrate consistency (Lockely et al. 2012b).

A medium-gauge large sauropod trackway at the Haman Formation at the Gain track site, Namhae area, was first described as *B. birdi* (Kim et al. 2012a). The pes tracks, approximately 75 cm in length and 60 cm in width are composed of

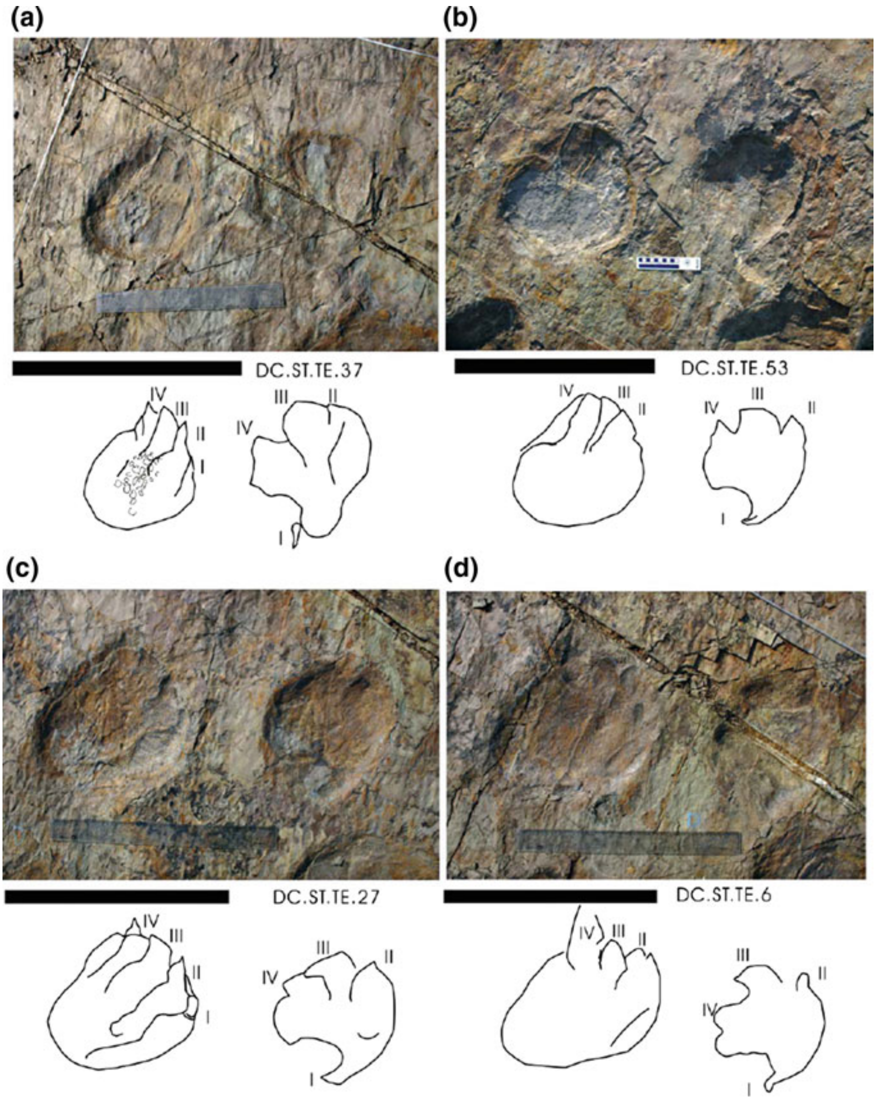



**Fig. 2.32** Photographs and line drawings of well-preserved manus-pes sets at the Docheonri sauropod trackway E. *Notes* **a–d** Show the 27th set, 37th set, 53th set, and 6th set, respectively. *Source* Hwang et al. (2004)

outwardly rotated pedal claw I, II, and III impressions. The digit impressions are outwardly curved. Digit I is about 18 cm long and 9 cm wide, digit II is 11 cm long and 8 cm wide, and digit III has only a faint impression. The manus tracks are nearly circular with diameters of about 55 cm. The heteropody, the ratio between the manus and pes area, ranges from 1: 1.5 to 1:2 (i.e., no pronounced heteropody).

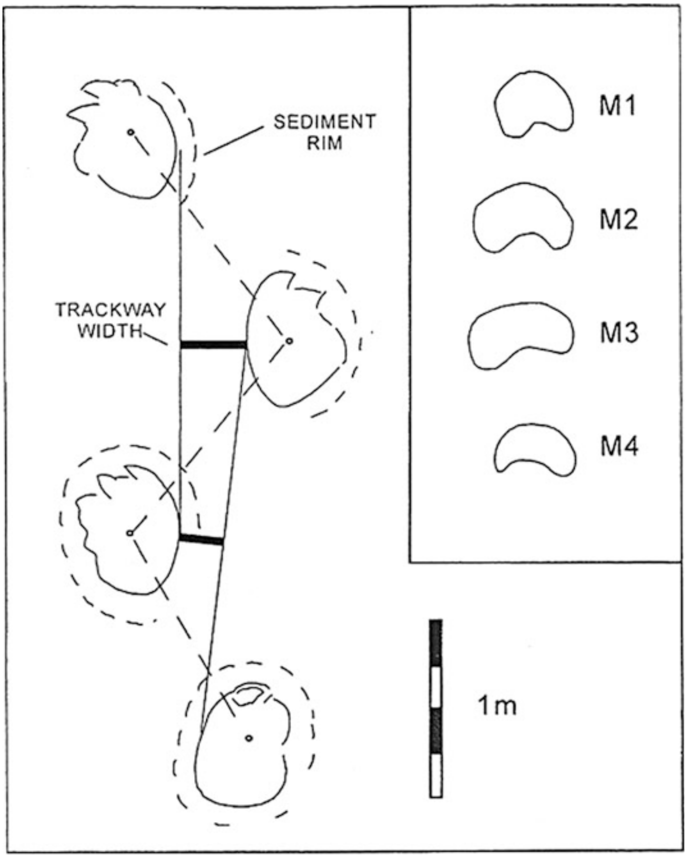



**Fig. 2.33** Pes only sauropod trackway from the Cretaceous Jangdong Tuff, Hwasun track site. *Notes* Inset (top right) shows isolated manus tracks. *Source* Lockely et al. (2012b)

The speed of the sauropod was estimated to be 0.87 m/s (approximately 3 km/h), indicative of slow walking. The Gain trackway closely resembles *B. birdi* described at the Lower Cretaceous, Texas (Farlow et al. 1989). The manus-pes area ratio of the Gain sauropod track is nearly identical (about 0.5) to that of the Texas *B. birdi* (Kim et al. 2012a, Fig. 2.34). The Gain sauropod tracks assigned to *B. birdi* represent the first record of this ichnospecies from the Cretaceous in Asia (Kim et al. 2012a).

Wide-gauged sauropod trackways with wide pentadactyl manus tracks revealing hitherto unreported morphology were first described as *B. pentadactylus* at the Lower Cretaceous Haman Formation, Jinju area (Kim and Lockley 2012). Sauropod trackway 1 is about 6 m long and composed of five left manus and five left pes tracks, and three right manus and three pes tracks. The manus tracks are wider than they are long, 31 cm long and 36.5 cm wide on average. They are typically composed of three to five blunt short digit impressions, and appear to

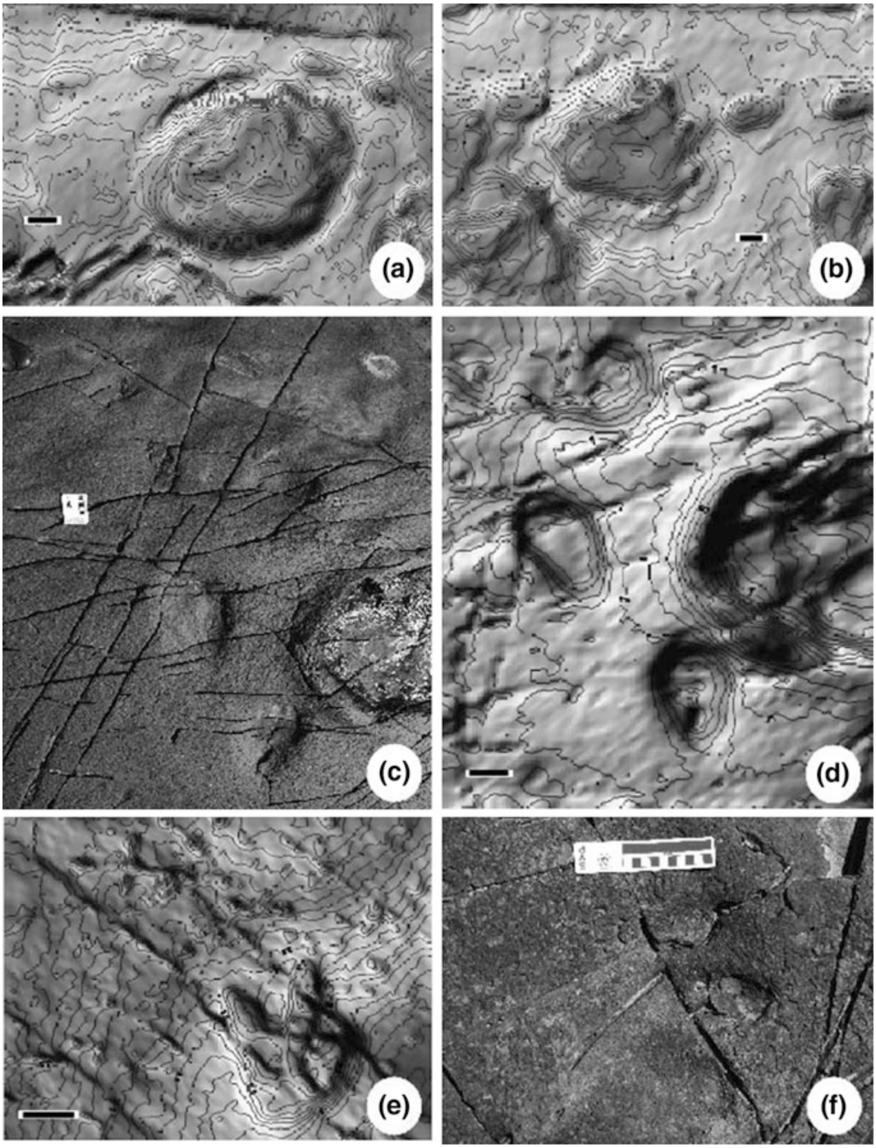



**Fig. 2.34** 3D scanning images showing the contours of tracks (**a**, **b**, **d**, **e**) and photographs of tracks (**c**, **f**) from the Haman Formation at the Gain track site. *Notes* **a** Left pes of a sauropod track with outwardly pointed digit impressions and a pterosaur trackway with five consecutive tracks (in upper part); **b** pterosaur trackway P1 and a sauropod pes showing outwardly curved digit impressions (note that the former is superimposed on the latter); **c**, **d** manus of a sauropod and pterosaur trackway P2; **e** a theropod track; **f** an ornithopod track from ornithopod trackway O1. Scale bars in **a**, **b**, **d** and **e** are 10 cm. *Source* Kim et al. (2012a)

rotate outward, with the axis of digit IV nearly at right angles to the midline of a trackway. The pes tracks are longer than they are wide, 50 cm long and 40 cm wide on average, and are outwardly rotated at about 35°. Digits I, II, and III have well-defined sharp claw traces (Figs. 2.35, 2.36 and 2.37; Table 2.11).

Trackway 2 is composed of ten consecutive manus and pes tracks. The manus tracks are wider than they are long, about 30 cm in length and 35 cm in width. The five-digit impressions of the manus track are blunt and show rounded terminations without claw impressions. The manus tracks are outwardly rotated at angles of 35°–40°. The pes tracks are longer than they are wide, about 40 cm in length and 30 cm in width. The four-digit impressions of pes tracks are short and blunt, and show rounded terminations without claw marks. The pes tracks are outwardly rotated at angles of 40°–50° (Figs. 2.35, 2.36 and 2.37).

All previously reported, well-preserved sauropod manus tracks have had a single semicircular outline. In most cases, discrete manus digit traces are not registered, although in some cases (e.g., type *Brontopodus*) impressions of digits I and V are visible, respectively, at the postero-medial and postero-lateral "corners" of the track's semicircular outline (Kim and Lockley 2012). Therefore, *B. pentadactylus* from the Gajin track site, Jinju area, provided new insight into the morphology of the fleshed-out manus of sauropods, unlike the sauropod tracks currently known. In

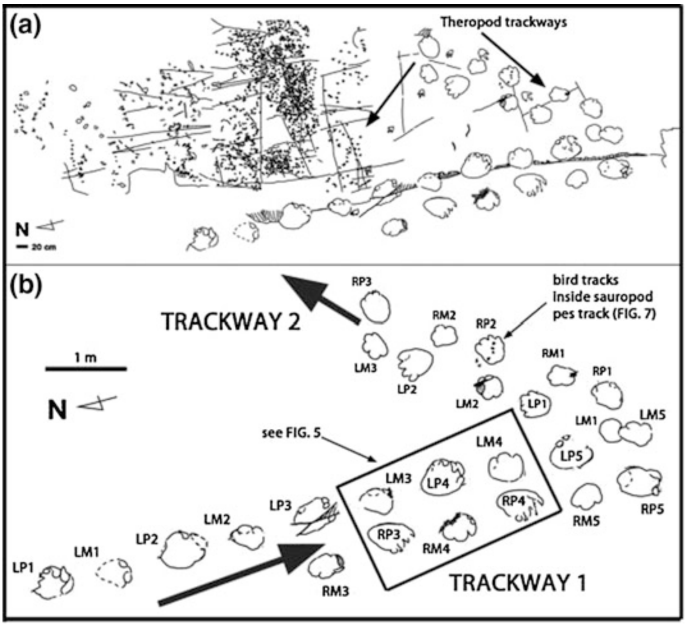



**Fig. 2.35** Distribution of dinosaur and bird tracks at the Gajin track site, Jinju area. *Notes* **a** Map of dinosaur and bird tracks preserved at Heritage Hall I in the Gajin track site, showing two theropod trackways; **b** detail of sauropod trackways 1, with key to details shown in Figs. 2.36 and 2.37. *Source* Kim and Lockley (2012)

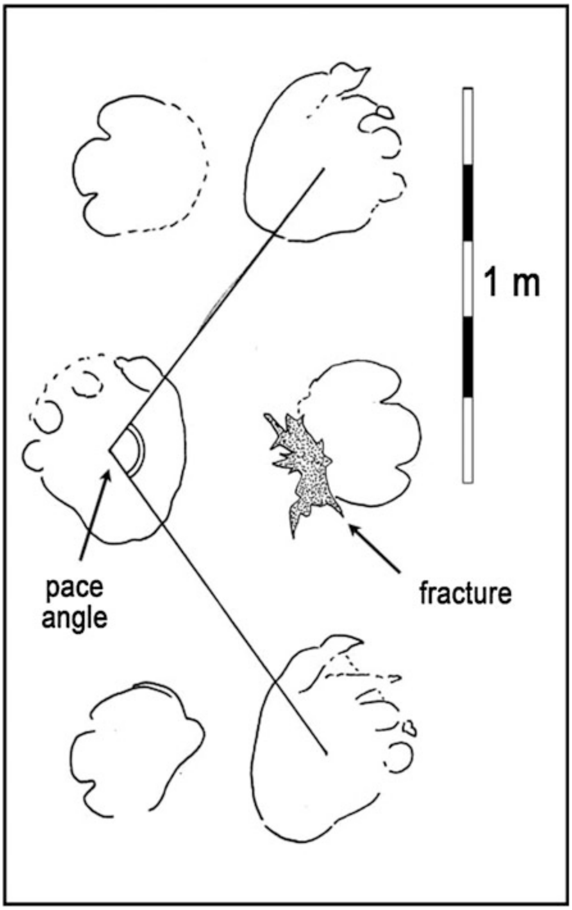



**Fig. 2.36** Detail of manus-pes sets of sauropod trackway 1 from the Gajin track site. *Notes* Compare with Figs. 2.35, 2.37 and 2.38. Note the difference between the pentadactyl manus track (bottom left) and the tridactyl manus tracks (right and top left). *Source* Kim and Lockley (2012)

addition, *B. pentadactylus* tracks are associated with thousands of diverse bird footprints in a lakeshore paleoenvironment (Fig. 2.38). *B. pentadactylus* from the Gajin track site represents the second ichnospecies of *Brontopodus* following *B. birdi*, which was described at the Glen Rose Limestone (Lower Cretaceous) and equivalents of Texas and Arkansas (Farlow et al. 1989).

### 2.1.4 Unusual Dinosaur Tracks with Internal Ridges

Very unusual dinosaur tracks with radial internal ridges at the upper Cretaceous Uhangri Formation, Haenam area, Korea, have been the subject of much controversy (Hwang et al. 2008). A total of 105 tracks with radial ridges were excavated in a 270 $m^2$ area (Lee and Huh 2002). The outlines of the tracks are circular in shape and

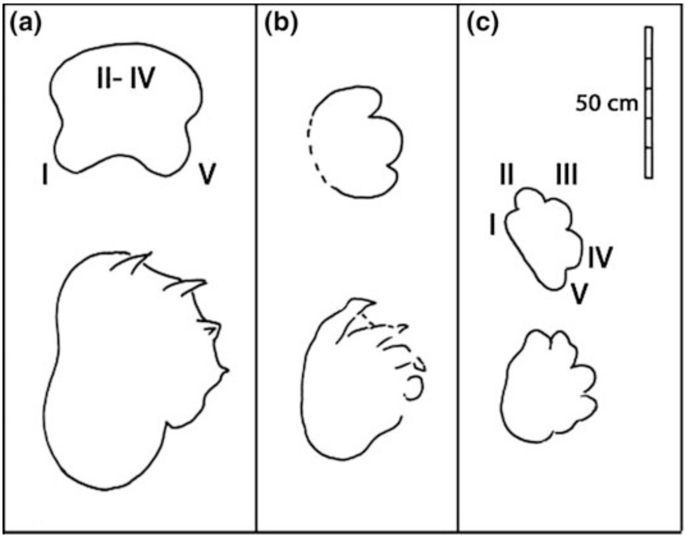



**Fig. 2.37** Comparison between *Brontopodus birdi* and Gajin trackways 1 and 2. *Notes Brontopodus birdi* (**a**), after Farlow et al. (1989); Gajin trackways 1 and 2 (**b** and **c**, respectively) at the same scale. Note the difference in shape, orientation of manus tracks, and digit designations between **a** and **c**. Compare **b** with Fig. 2.38. *Source* Kim and Lockley (2012)

range from approximately 73 to 83 cm in diameter. The tracks are large bowl-shaped impressions with depths ranging from 40 to 270 mm (Hwang et al. 2008, Fig. 2.39). The six radial internal ridges extend out from the counter of each footprint. The size and age of these tracks imply a dinosaurian track maker, but in morphology these peculiar tracks could not be readily compared or assigned to any other type of dinosaur track (Lee and Huh 2002; Thulborn 2004; Lee and Lee 2006). Accordingly, it has not yet been possible to determine clearly the type of track, type of track maker, or the direction of movement. To date, three possible scenarios or models have been reported for the interpretation of unusual dinosaur tracks with internal ridges (Lee and Huh 2002; Thulborn 2004; Hwang et al. 2008).

Lee and Huh (2002) first interpreted the peculiar tracks with radiating ridges as manus only sauropod tracks attributed to swimming sauropods (Fig. 2.40). However, the swimming scenario has been challenged by subsequent authors (Thulborn 2004; Hwang et al. 2008). Thulborn (2004) argued that the circular outlines of the large bowl-shaped impressions differ from the horseshoe shape typical of well-preserved manus sauropod tracks, and that the Uhangri tracks do not obviously match the hand or foot of any known group of dinosaurs (Thulborn 1990). Furthermore, Hwang et al. (2008) documented that no indicators of the swimming scenario such as "push up" ridges could be found at the Uhangri track site.

As an alternative to the swimming scenario, Thulborn (2004) proposed that the radial cracks are the result of the deformation of the upper layers of shale after the

**Table 2.11** Measurement of sauropod trackways 1 and 2 from the Gain track site

| Track No. | Length (cm) | Width (cm) | Pace (cm) | Stride (cm) | Pace angulation (°) | Rotation angle (°) | Relative stride length (SL/h) | Hip height (m) | Speed (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| *Trackway 1* | | | | | | | | | |
| LM1 | 30 | 38 | – | – | – | 90 | Manus 1.21 | Manus 1.24 | Manus 1.21 |
| | | | | | | | Pes 0.78 | Pes 1.89 | Pes 0.72 |
| LP1 | 45 | 38 | – | – | – | | | | |
| RM1 | – | – | – | – | – | 90 | | | |
| RP1 | – | – | – | – | – | | | | |
| LM2 | 32 | 36 | – | 155 | – | 90 | | | |
| LP2 | 48 | 42.7 | – | 151 | – | | | | |
| RM2 | – | – | – | – | – | – | | | |
| RP2 | 48 | 43 | – | – | – | | | | |
| LM3 | 33 | 35 | 96 | 147 | 107 | 90 | | | |
| LP3 | – | 36 | – | 152 | – | 37 | | | |
| RM3 | 30 | 39 | 93 | – | 105 | 90 | | | |
| RP3 | 48 | 36 | 91 | – | – | 35 | | | |
| LM4 | 35 | 38 | 86 | 147 | 104 | 90 | | | |
| LP4 | 49 | 42 | 95 | 150 | – | 35 | | | |
| RM4 | 32 | 37 | 97 | 154 | 104 | 90 | | | |
| RP4 | 45 | 40 | 93 | 153 | 114 | 38 | | | |
| LM5 | 26 | 35 | 92 | 153 | – | 90 | | | |
| LP5 | 46 | 39 | 85 | 149 | 110 | 37 | | | |
| RM5 | 30 | 34 | 98 | 148 | 102 | 90 | | | |
| RP5 | 49 | 33 | 83 | 135 | – | 35 | | | |
| *Trackway 2* | | | | | | | | | |
| LM1 | 24 | 27 | | | | | Manus 1.39 | Manus 1.06 | Manus 1.4 |
| | | | | | | | Pes 1.03 | Pes 1.46 | Pes 0.99 |
| RP1 | 36 | 29 | | | | | | | |
| RM1 | 22 | 30 | 85 | | 125 | | | | |

(continued)

**Table 2.11** (continued)

| Track No. | Length (cm) | Width (cm) | Pace (cm) | Stride (cm) | Pace angulation (°) | Rotation angle (°) | Relative stride length (SL/h) | Hip height (m) | Speed (m/s) |
|---|---|---|---|---|---|---|---|---|---|
| LP1 | 33 | 26 | 78 | | 135 | 28 | | | |
| LM2 | 24 | 30 | 84 | 148 | 125 | | | | |
| RP2 | 35 | 28 | 89 | 147 | 135 | 28 | | | |
| RM2 | 24 | 29 | 84 | 149 | 127 | | | | |
| LP2 | 37 | 31 | 89 | 156 | 135 | 30 | | | |
| LM3 | 23 | 30 | 80 | 146 | | | | | |
| RP3 | 41 | 28 | 83 | 148 | | 32 | | | |

*Source* Kim and Lockley (2012)

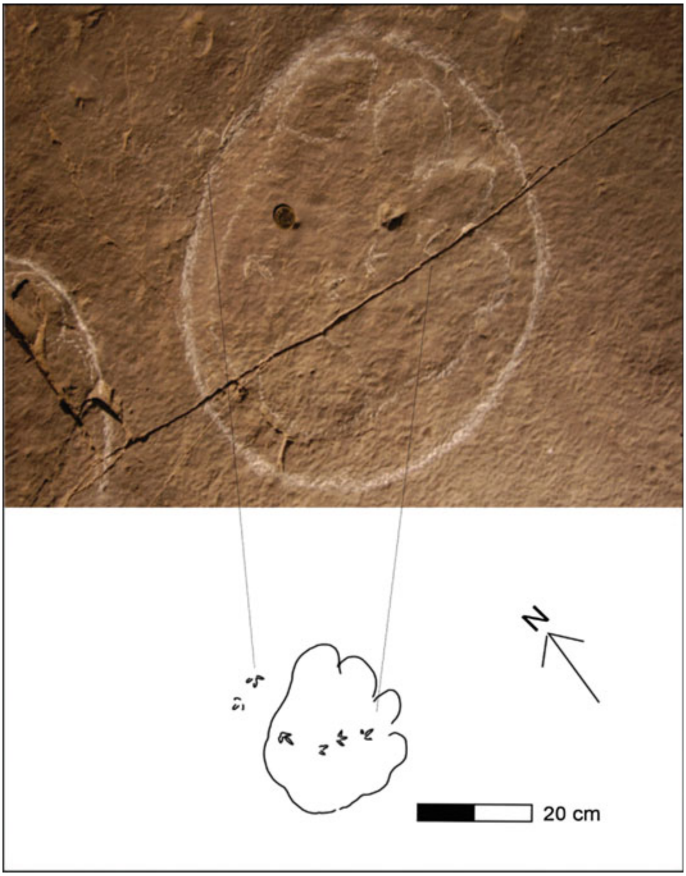



**Fig. 2.38** Photograph and sketch of bird tracks (*Koreanaornis hamanensis*) in the sauropod pes track (*Brontopodus pentadactylus*) from the Gain track site. *Source* Kim and Lockley (2012)

withdrawal of the dinosaur foot from the sediment. He proposed two possible mechanisms that might have caused the peculiar tracks with radial ridges. The first one was the adherence of mud to the dinosaur foot during withdrawal; the second was the formation of a blister-like dome as water, just displaced by the impact of the footfall, flowed back under the lifted laminae. The two models proposed by Thulborn (2004) for dinosaur tracks with internal ridges are shown in Fig. 2.41. Although he suggested that the two mechanisms could work in conjunction, the first requires very sticky, ductile mud to be directly impacted by the foot, whereas the second requires more cohesive laminae to lift up as a canopy (Hwang et al. 2008). However, there is no evidence supporting the delamination scenario of Thulborn (2004) at the track site at Uhangri (Hwang et al. 2008).

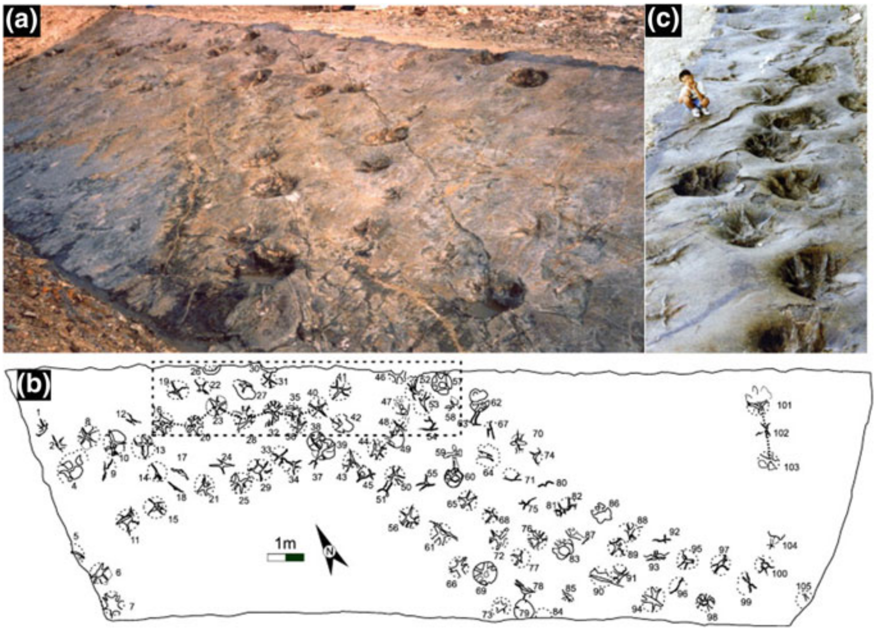



**Fig. 2.39** Track site III-1 (**a**) and detailed map (**b**) of the unusual dinosaur tracks with internal ridges at the Uhangri track site; photograph (**c**) shows the northern area of site III-1 at an early stage of excavation at the Uhangri track site. *Notes* There are two trackways here that proceed to northeast and east. Footprint numbers are listed on the detailed map (**b**). *Source* Hwang et al. (2008)

**Fig. 2.40** Reconstruction of a floating sauropod conjectured from the Uhangri sauropod manus tracks (after Lee and Huh 2002)

Hwang et al. (2008) proposed another new model for the interpretation of unusual tracks with internal ridges on the basis of tracks occurring at the Uhangri track site, Haenam area. They reviewed the swimming scenario (Lee and Huh 2002) and the delamination scenario (Thulborn 2004). Two important features newly observed at the track site are that, first, the footprints sometimes exhibit

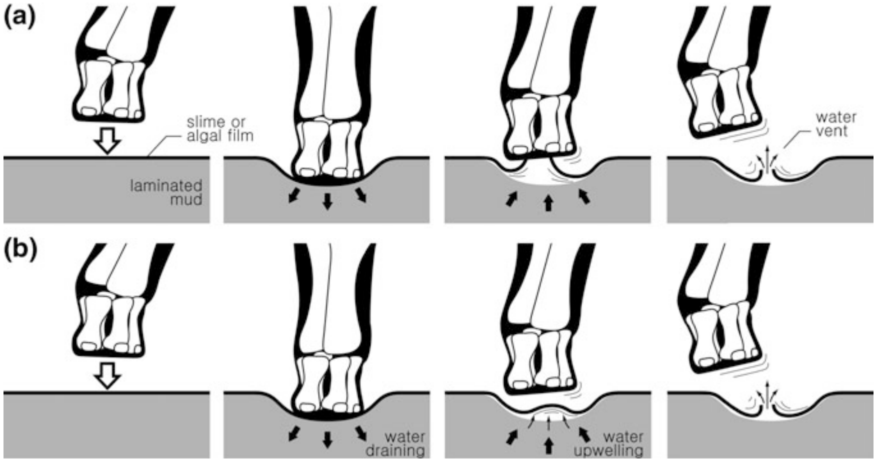



**Fig. 2.41** Two models proposed by Thulborn (2004) for Uhangri manus only tracks. *Notes* **a** "Milk skin" model; **b** "blister" model. *Source* Lee and Lee (2006)

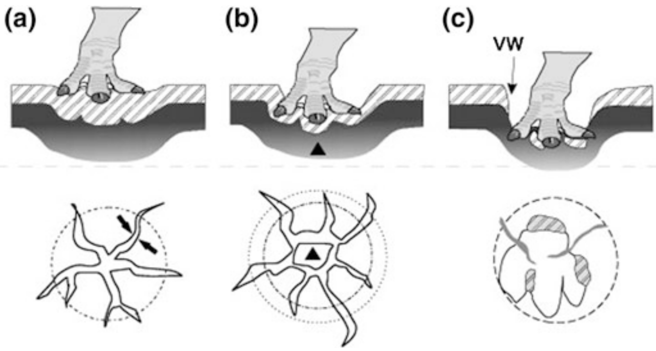



**Fig. 2.42** Differential formation of undertracks with ridges depending on depth. *Notes* **a** Relatively shallow undertracks lead to cracking of tuffaceous sand (diagonal lines) and molding of ridges in the underlying mud (grey). Arrows show that the angular change in the direction of the ridge margins is the same on both sides, supporting the evidence of cracking or a brittle fracture; **b** deeper impact, causing the sand layer to be more deeply impressed, especially in the center near the point of maximal impact force (filled triangle); **c** deepest penetration into the sand layer creates more complete, true footprints, with interference caused by distorted fragments of the sand layer. VW = vertical wall seen in deep footprints. *Source* Hwang et al. (2008)

characteristic features such as ungula, digit or heel impressions, suggesting that the mysterious traces are those of a tridactyl, bipedal dinosaur. Second, the unusual tracks are underprints, and the internal ridges are molds of radial cracks on the underside of a sand bed on which large bipeds were walking (Hwang et al. 2008). The formation of the unusual dinosaur tracks with radial ridges is shown in Fig. 2.42.

### *2.1.5 Dinosaur Tracks of North Korea*

Dinosaur tracks were also discovered at the Upper Cretaceous Ponghwasan Series of Ryonggungri, Phyongsan County, North Hwanghae Province (Pak and Kim 1996). The Ryonggungri dinosaur tracks discovered in 1989 were designated as Natural Monument No. 466 in North Korea in 1990. The Ryonggungri tracks are displayed at the Natural Museum of Kim Il Sung University, Pyongyang, North Korea (Pak and Kim 1996).

Unfortunately, a systematic description with measurement data of the dinosaur tracks was not provided. Only three photographs (unscaled) are shown in the book *Geology of Korea* (Paek et al. 1996), and these are presented in Fig. 2.43. Although the three trackways are shown as Anchisauripodidae (?), Tyrannosauridae, and Iguanodontidae, respectively, it is very difficult to recognize these in the photographs. However, their identification seems to be totally wrong, though they are ichnologically very important if they are proved to be ichnotaxonomically valid. Reexamination with careful observation, measurement, description, and comparison of dinosaur tracks from the Upper Cretaceous at Ryonggungri, Phyongsan County, North Korea, is necessary and should hopefully be undertaken in the future.

## 2.2 Dinosaur Bones

Compared with dinosaur tracks, skeletal dinosaur remains have rarely been reported from the Mesozoic in Korea. The first dinosaur skeletal remains were reported at the Gugyedong Formation of Tabri, Uiseong County, South Gyeogsang Province (Kim 1981). The dinosaur fossils were originally identified as a proximal end of right ulna belonging to the family Brachiosauridae (Kim 1981), and a part of sauropod femur or tibia (Chang et al. 1982). Kim (1983) described this dinosaur fossil as *Ulrtasaurus tabriensis* based mainly on its supposed huge size by simple comparisons with the ulna of *Supersaurus*.

However, Lee et al. (1997) reexamined the fossil specimen and described it as a proximal part of the left humerus of a sauropod, instead of a portion of the right ulna. This dinosaur fossil specimen deposited at the Department of Geology, Kyungbuk National University, Daegu, represents the first sauropod dinosaur fossil found in Korea (Fig. 2.44). A skeletal dinosaur remain discovered at the Tabri site, Uiseong area, was originally described as a hadrosaur femur (Kim 1983). However, the fossil was reexamined and redescribed as the left femur of a dinosaur belonging to a non-avian maniraptoran theropod of possible dromaeosaurid affinity (Kim et al. 2005). This fossil, which is housed at the Natural Heritage Center, National Research Institute of Cultural Properties in Taejeon, represents the second skeletal dinosaur fossil and the first non-avian theropod described in Korea.

In 2001, skeletal sauropod remains were described at the Hasandong Formation, Hadong County (Dong et al. 2001). The material is a fragmentary skeleton including seven incomplete cervical vertebrae, one dorsal vertebrae, one partial

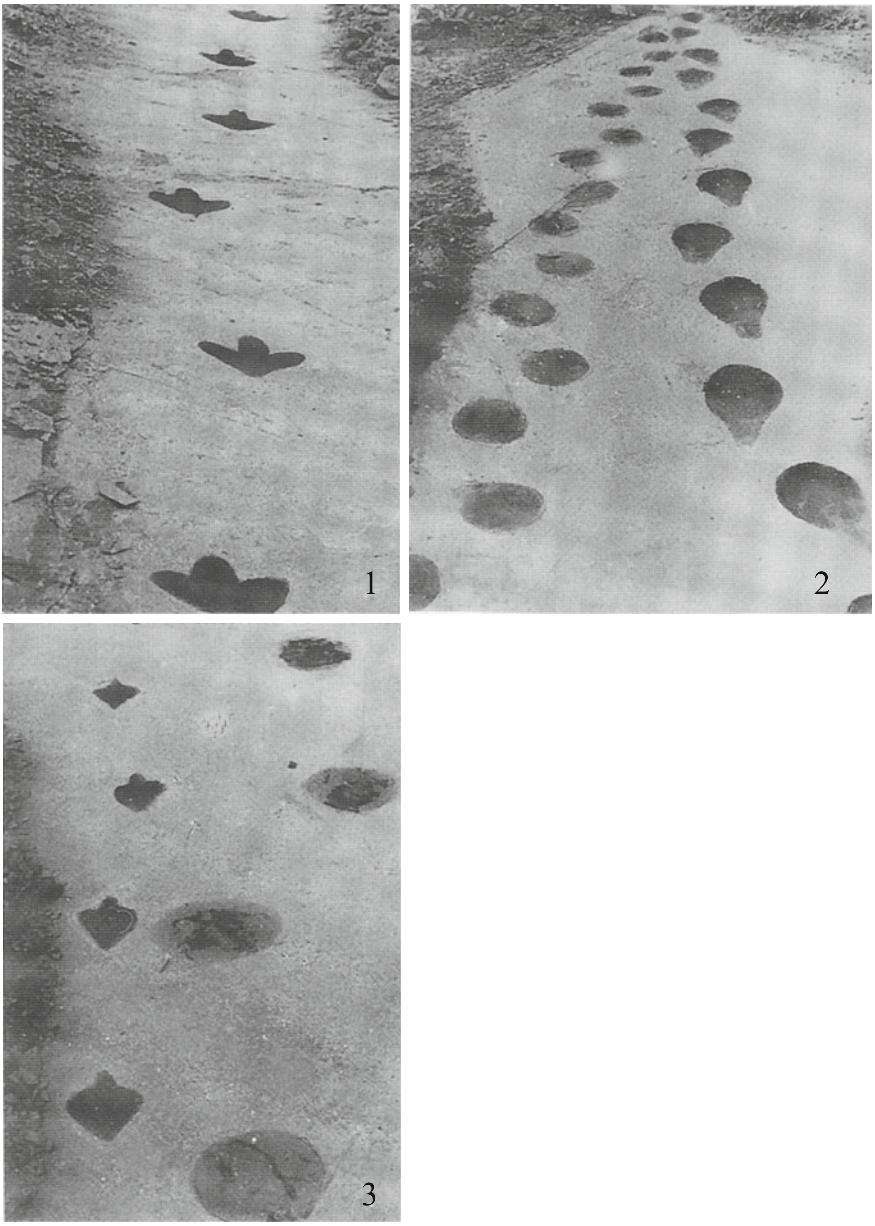



**Fig. 2.43** Dinosaur footprints from the Upper Cretaceous Ponghwasan Series, Ryonggungri, Phyongsan County, North Korea. *Notes* Tracks were originally regarded to be attributable to: (1) Anchisauripodidae (?); (2) Tyrranosauridae; (3) Iguanodontidae. The quality of the original figure is not good. *Source* Pak and Kim (1996)


**Fig. 2.44** The first dinosaur specimen discovered at the Cretaceous Gugyedong Formation at Tabri, Uiseong County. *Note* Length of specimen is 43 cm. *Sources* Chang et al. (1982); Kim (1983)

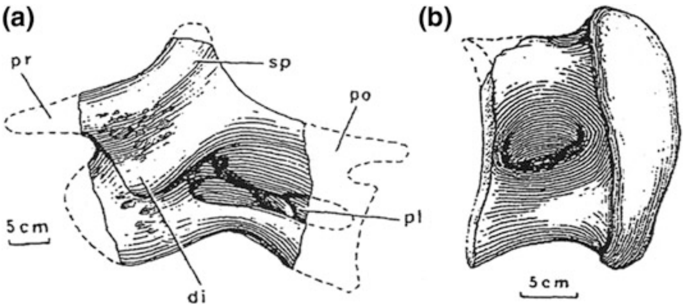



**Fig. 2.45** Skeletal remains assigned to *Pukyongosaurus millenniumi*. *Notes* **a** Cervical vertebra in lateral view; **b** lateral view of a dorsal vertebra. *Source* Dong et al. (2001)

clavicle (?), one chevron, and isolated bones. Although the skeletal remains are only fragmentary and incomplete, these fossils were named *Pukyongosaurus millenniumi* as the first named dinosaur, mainly on the basis of the cervical and dorsal vertebrae (Fig. 2.45). However, Upchurch et al. (2004) regarded it to be *nomen dubia* due to incomplete material.

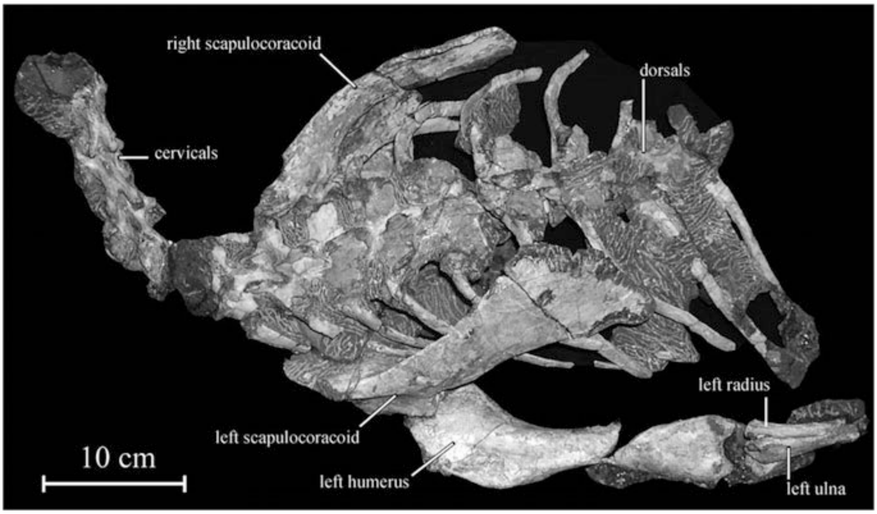



**Fig. 2.46** Holotype of *Koreanosaurus boseongensis* (KDRC-BB2) in dorsolateral view. *Source* Huh et al. (2010)

New basal ornithopod dinosaur fossil remains were first described at the Upper Cretaceous Seonso Conglomerate, Boseong County, where about 200 dinosaur eggshells were discovered (Huh et al. 2010). They are well-preserved and assigned to a new ornithopod taxon named *Koreanosaurus boseongensis*. This dinosaur is characterized by elongated neck vertebrae, very long and massive scapulocoracoid and humerus bones, proportionally short hindlimbs with a low hindlimb ratio for tibia/femur, and an anteroposteriorly elongated femoral shaft. According to the morphological, phylogenetic, sedimentological, and taphonomic data at hand, it was a burrowing dinosaur, like *Oryctodromeus* (Huh et al. 2010, Fig. 2.46).

Subsequently, a new basal neoceratopsian was first described at the Lower Cretaceous Tando Formation at the Sihwa site, Hwaseong County, where rich deposits of dinosaur eggshells were found (Lee et al. 2011). It represents the first ceratopsian dinosaur in the Korea Peninsula and was assigned to *Koreaceratops hwaseongensis*, which is characterized by very long caudal neural spines and a unique astragalus divided into two fossae by a prominent craniocaudal ridge on the proximal surface (Lee et al. 2011, Fig. 2.47). A phylogenetic analysis indicated that the *Koreaceratops* is positioned between *Archaeoceratops* and all derived neoceratopsians, and that the very tall caudal neural spines appear to be homoplasious, suggesting an independent adaptation, possibly for swimming (Lee et al. 2011).

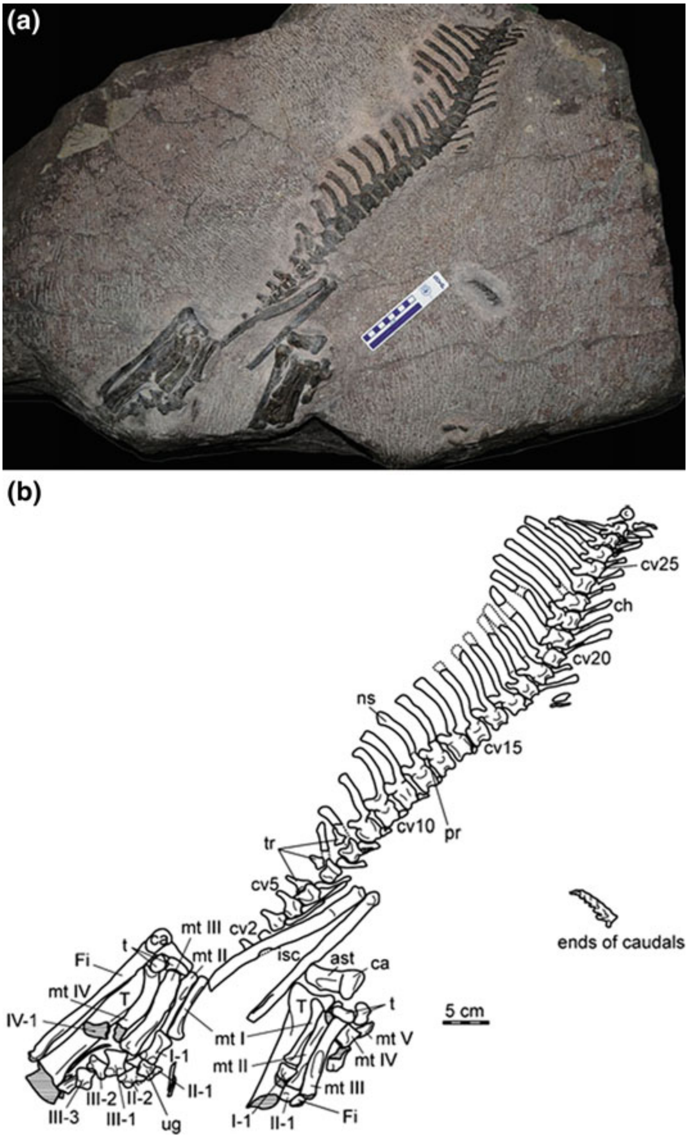



**Fig. 2.47** *Koreaceratops hwaseongenesis* from the Hwaseong area. *Notes* **a** Photograph of *Koreaceratops hwaseongensis* from the Tando beds (Albian) of Tando Basin in South Korea (KIGAM VP 200801, holotype) in ventral view. The proximal tibiae and fibulae are sharply cut off at the edge of the block. **b** Illustration of *K. hwaseongensis* with anatomical abbreviations: *ast* astragalus, *ca* calcaneum, *cv* caudal vertebra, *Fi* fibula, *isc* ischium, *mt* metatarsal, *ns* neural spine, *pr* prezygapophysis, *T* tibia, *t* tarsal, *tr* transverse process, *ug* ungula. The cross-hatch pattern indicates the broken edge of the bone, and the partial restoration of neural spines is shown with dotted lines. *Source* Lee et al. (2011)

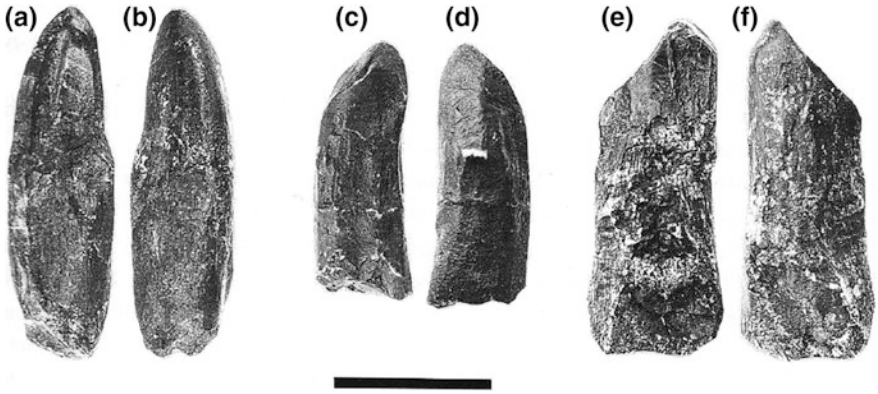



**Fig. 2.48** Holotype of *Chiayüsaurus asianensis* (KPE 8001) in lingual view (**a**) and labial view (**b**). Titanosaurid (?) tooth (KPE 8002) in lingual view (**c**) and labial view (**d**). Camarasaurid (?) tooth (KPE 8003) in lingual view (**e**) and labial view (**f**). *Note* Scale bar equals 2 cm. *Source* Lee et al. (1997)

## 2.3 Dinosaur Teeth

Dinosaur teeth were first described at the Lower Cretaceous Hasandong Formation at the Yusuri site, Jinju area (Lee et al. 1997). Three types of sauropod teeth were assigned to *Chiayüsaurus asianensis*, *Titanosauridae* (?), and *Camarasauridae* (?) (Fig. 2.48). The tooth assigned to *Chiayüsaurus asianensis* (Fig. 2.48a, b) is 46 mm in height as preserved. The root of the tooth is not preserved. The apical portion of the crown is slightly inclined lingually and distally. In lingual view, the slightly convex basal portion is high, occupying the proximal half of the height. The distal half is prominently concave in both vertical and horizontal directions. A narrow internal ridge runs in the middle part of the concavity from the apex. It bisects the spatulate depression asymmetrically, forming a smaller mesial portion than the distal. The well-developed wear surfaces produce a flat almost vertical facet cutting off the tip and extending downwards. It extends lingually to the half of the basal portion along the mesial margin, but does not reach the basal in the distal, forming a basally opening U-shaped border. Therefore, the border of the crown is entirely surrounded by the wear facet (1.8 mm in width) lingually. The labial side of the crown is uniformly convex without wear surfaces. There is a lateral groove on the mesio-labial side (Lee et al. 1997). Lee et al. (1997) regarded *Chiayüsaurus asianensis* as the first named dinosaurian fauna described from the Cretaceous in Korea. Park et al. (2000) also described dinosaur teeth but, however, regarded that *Chiayüsaurus asianensis* (Lee et al. 1997) should be considered as a *nomen dubium*.

Subsequently, a brachiosaurid tooth and megolosaurid tooth were first described at the Jinju and Hasandong formations, respectively (Lim et al. 2001, 2002). Yun et al. (2007) described theropod and sauropod teeth including specimens described by Lim et al. (2001, 2002) at the Lower Cretaceous Hasandong and Jinju formations. Of these, the tooth from the Hasandong Formation at Hapgari, Goryeong

County, was tentatively assigned to a tyrannosaurid tooth, which is characterized by well-developed multiple serrations (Figs. 2.49, 2.50 and 2.51).

Three new theropod teeth were discovered on Juji Island (Hasandong Formation), Daedori, Hadong County (Lee 2007). The crown height of one tooth is 81 mm, which is the largest theropod tooth ever found in Korea. The teeth are very similar to *Acrocanthosaurus* (Lee 2007). A tyrannosauroid premaxillary tooth was also described at the Hasandong Formation of the coastal area of Naeguri, Sacheon County (Lee 2008). Dinosaur teeth reported from the Cretaceous in Korea strongly indicate that a variety of theropod and sauropod dinosaurs, including tyrannosauroids, lived in the Korean Peninsula during the Cretaceous Period.

Interestingly, diverse theropod tooth marks were described on the caudal vertebra of an adult sauropod bone (*Pukyongosaurus*) from the Early Cretaceous (Paik et al. 2011). There, tooth marks provided new insight into the feeding behavior of theropods that scavenged the bodies of large sauropods.

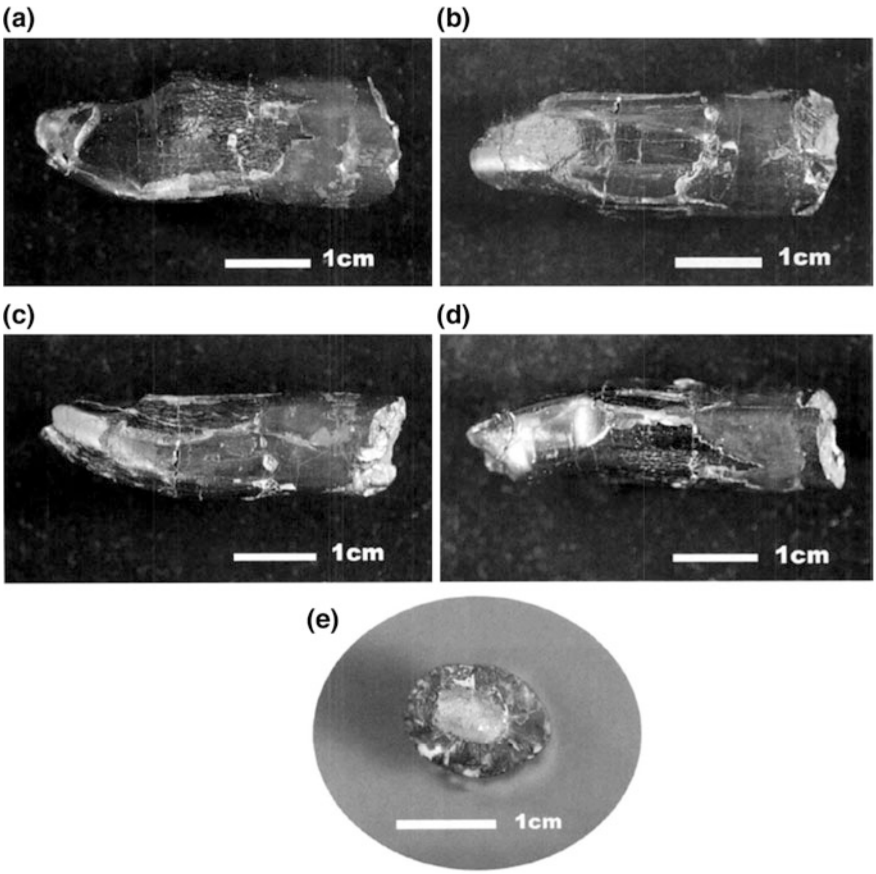



**Fig. 2.49** Sauropod (Brachiosauridae) teeth, KS7002 from the Jinju Formation, Sacheon area. *Notes* **a** Lingual view, **b** labial view, **c** anterior view, **d** posterior view, **e** elliptical cross section at base. *Source* Yun et al. (2007)

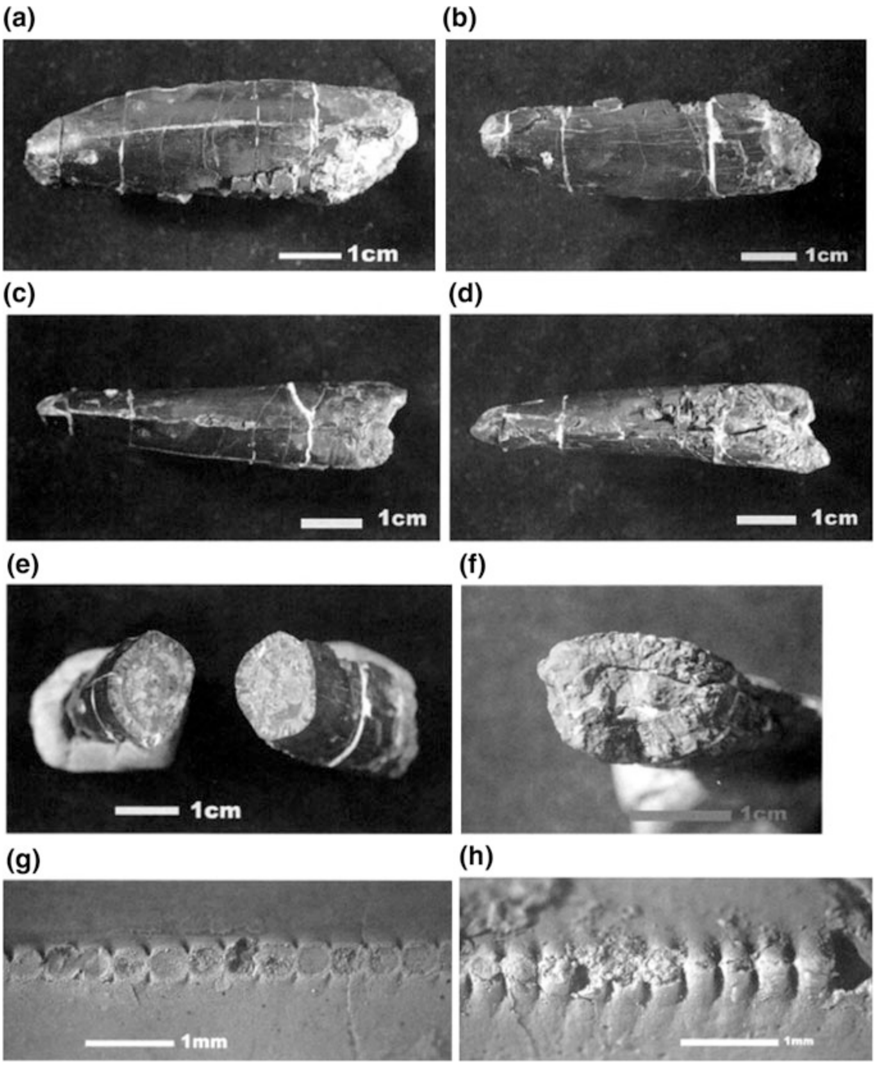
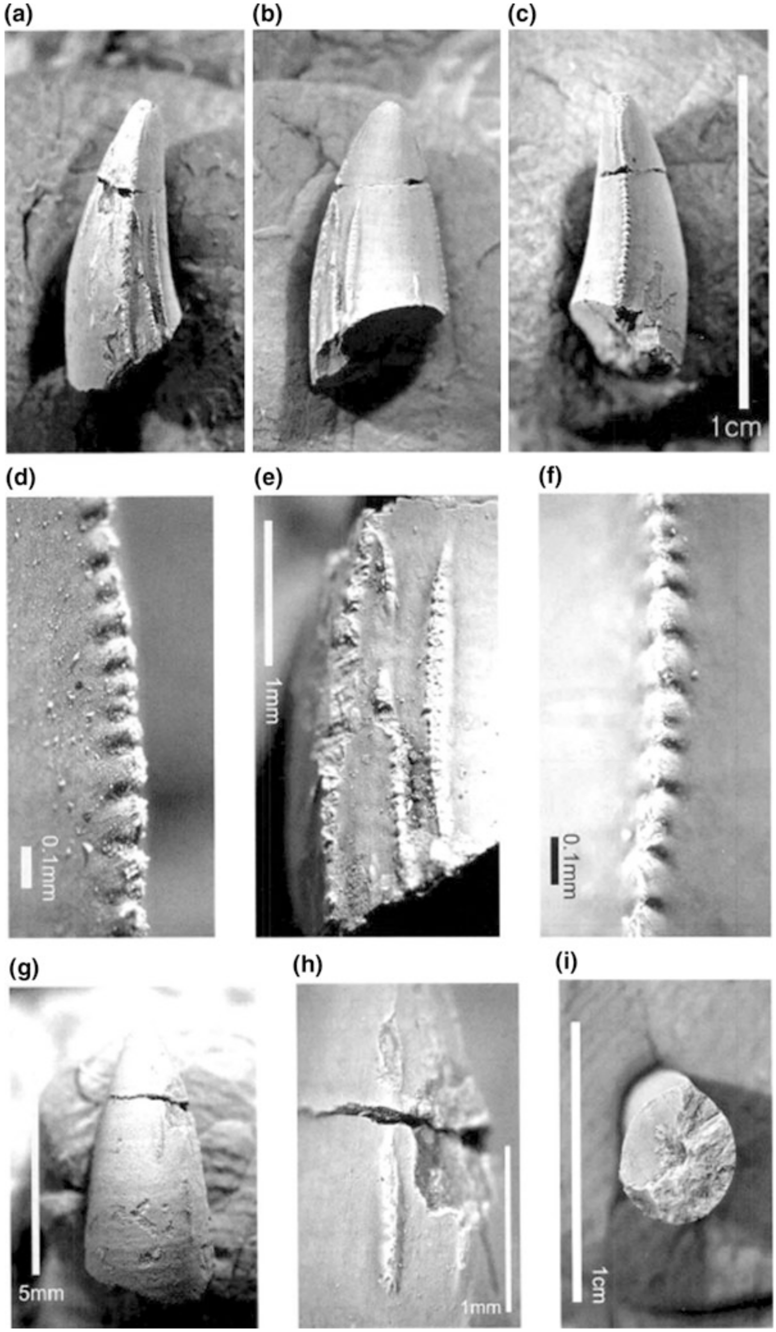



**Fig. 2.50** Theropod tooth, Megalosauridae, KS7001 from the Hasandong Formation, Hadong area. *Notes* **a** Labial view; **b** lingual view; **c** anterior view; **d** posterior view; **e** cross section at the middle part of the teeth; **f** eroded cross section at base; **g** anterior view of serrations, crown eroded out; **h** posterior view of serrations. *Source* Yun et al. (2007)

## 2.4 Dinosaur Eggs

Dinosaur egg fossils were first described at the Lower Cretaceous of the Hasandong Formation at the Sumunri site, Hadong County (Yun and Yang 1997, Fig. 2.52). On the basis of the microstructure of the eggshells, Sumunri dinosaur eggs are


(a)
(b)
(c)
1cm
(d)
0.1mm
(e)
1mm
(f)
0.1mm
(g)
5mm
(h)
1mm
(i)
1cm

◂**Fig. 2.51** Theropod tooth, Tyrannosauridae, YCS2002 from the Hasandong Formation, Goryeong area. *Notes* **a** Anterior view, **b** lingual view, **c** posterior view, **d** lingual view of serrations, **e** lingual view of multiple serrations, **f** posterior serrations, **g** labial view, **h** serrations on labial surface, about 1 mm, **i** elliptical cross section at base. *Source* Yun et al. (2007)

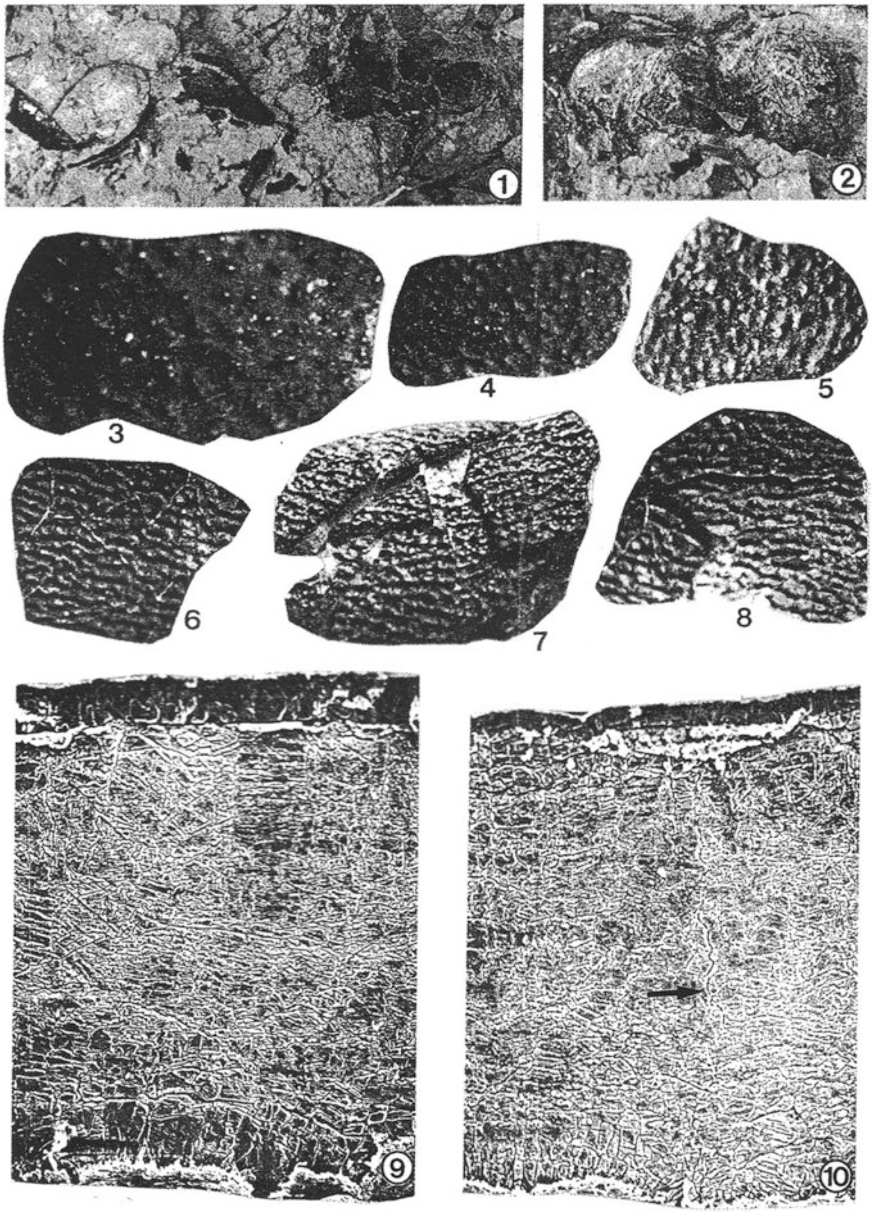



**Fig. 2.52** Dinosaur eggshells from the Hasandong Formation, Hadong area. *Notes* (1, 2) outcrop view, 3–8: surface ornamentation, 9–10: microscopic view. *Source* Yun and Yang (1997)

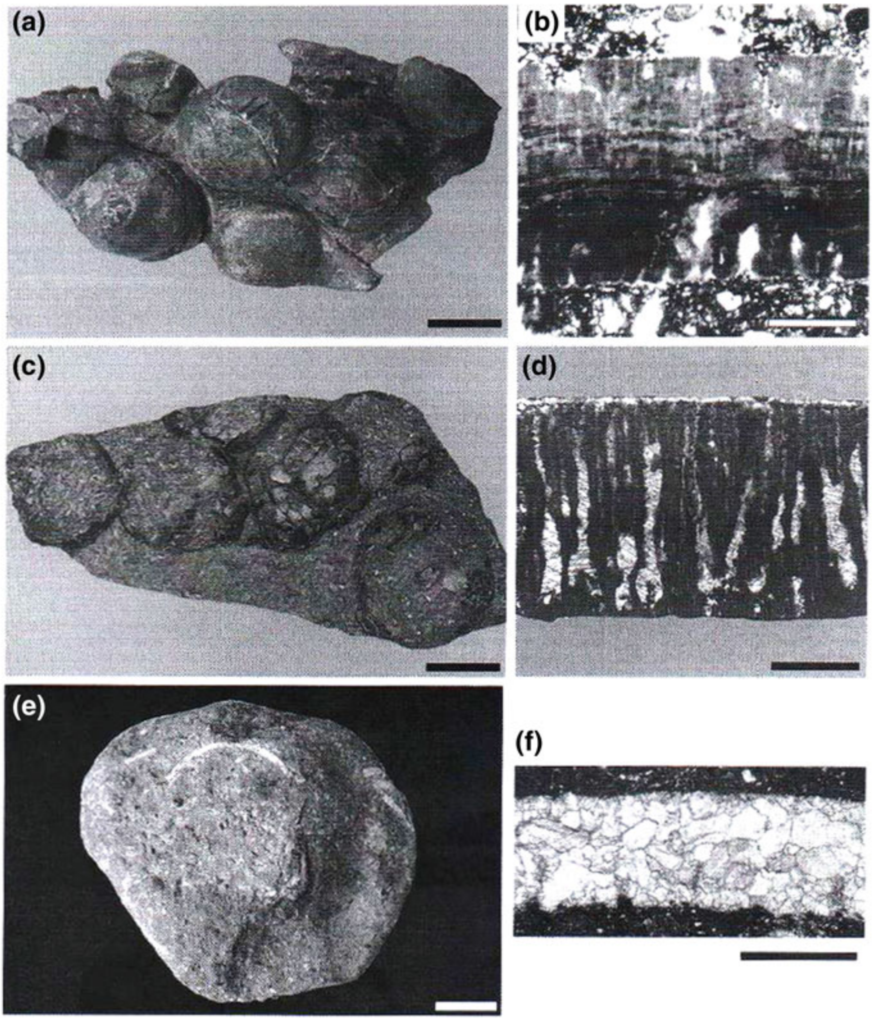



**Fig. 2.53** Dinosaur eggs from the Boseong dinosaur egg site. *Notes* **a** Top view of unhatched *Spheroolithus* egg clutch (DRCC-B106) from the Boseong dinosaur egg site; scale bar equals 5 cm. **b** radial thin section of eggshell from **a**; scale bar equals 1 mm. **c** top view of hatched *Faveoloolithus* egg clutch (cast, DRCC-B110); scale bar equals 10 cm. **d** radial thin section of eggshell from **c**; scale bar equals 1 mm. **e** partial fossil egg, possibly testudinate; scale bar equals 1 cm. **f** radial thin section of eggshell from **e**; scale bar equals 1 mm. *Source* Huh and Zelenisky (2002)

similar to those described as *Ovaloolithus laminadermus* and *Paraspheroolithus irenensis* from the Cretaceous in China (Yun and Yang 1997). Although the eggshells are poorly preserved, the Sumunri dinosaur eggs represent the first record of dinosaur egg fossils in Korea.

The second occurrence of dinosaur eggs was reported at the Seonso Conglomerate, Boseong site (Huh et al. 1999). Huh and Zelenitsky (2002) first described dinosaur eggshells as *Spheroolithus* sp. and *Faveoloolothus* sp. from the Boseong dinosaur egg site (Fig. 2.53). At the Boseong site, a total of 21 dinosaur clutches containing 195 eggs has been discovered (Huh et al. 2006b).

The eggs in both clutches assigned to *Spheroolithus* sp. are well-preserved and several have maintained their spherical shape. One clutch (DRCC-B106) contains four complete and four partial eggs; these eggs appear to be unhatched (Fig. 2.53a). A second clutch consists of six to eight eggs with their upper portions eroded. The eggs are tightly grouped in both clutches and occur randomly in a single layer. A vertical separation of 10–30 mm is visible among adjacent eggs in DRCC-B106.

Well-preserved eggs range from 75 to 84 mm ($N$ = 5) in diameter. The eggshell has a smooth outer surface and ranges in thickness from 1.83 to 2.52 mm ($N$ = 25). Examination of five thin sections indicates that the shell units are columnar to fan-shaped and tightly abutting (Fig. 2.53b). The units display a sweeping extinction pattern typical of the spherulitic morphotype. These eggs are similar in form and structure to spheroolithids described in Mongolia (Mikhailov 1994) and China (Zhao and Jiang 1974).

*Faveoloolithus* sp. is a partial clutch (DRCC-B110) collected from a block detached from a cliff face. This clutch contains six compressed eggs, three of which are complete and three of which are partial (Fig. 2.53c). Eggs within the clutch occur randomly in a single layer. The central portions of the upper halves of the eggs are missing, indicating that the eggs hatched prior to burial.

The clutched eggs range from 150 to 200 mm in diameter. The eggshell has a smooth outer surface and ranges in thickness from 1.33 to 2.10 mm ($N$ = 22). Examination of six thin sections indicates that the eggshell is somewhat recrystallized. In some thin sections, individual shell units are visible and contain pore canals (Fig. 2.53d). Pore canals are numerous, branching, and filled with secondary calcite. The porosity of the eggshell is high (25–30%), which is indicative of underground incubation. This porosity, however, may have been augmented somewhat by diagenesis. The egg morphology and eggshell structure are similar to those of Faveoloolithid eggs in China (Zhao and Ding 1976) and Mongolia (Mikhailov 1994). The Faveoloolithid eggs in Mongolia have been attributed to sauropod dinosaurs on the basis of their stratigraphic association with sauropod skeletal remains (Mikhailov 1994).

The third dinosaur egg site was discovered in the Sihwa area of Hwaseong County (Lee et al. 2000a, Fig. 2.54). Dinosaur eggshells were assigned to Faveoloolithids, Dendroolithids, and Elongatoolithids (Lee et al. 2000a; Lee 2004). At the Sihwa egg site, more than 20 clutches and 140 dinosaur eggs were found (Lee 2004).

A new dinosaur egg site was discovered in Tongyeong City, where at least six clutches including over 55 dinosaur eggs were found at the Upper Cretaceous Goseong Formation (Kim et al. 2011). Dinosaur eggs from the Tongyeong site were

**Fig. 2.54** Dinosaur eggshells from the Cretaceous Tando Formation at the Sihwa dinosaur egg site, Hwaseong area

first described as a new species, *Macroelongatoolithus goseongensis* and *Dictyoolithus neixiangensis* (Kim et al. 2011). The eggshells of *M. goseongensis* are large (39 cm in length) and elongated. The elongation index is 3.4 and the shell thickness is 2.3–3.1 mm. The continuous layer to mammillary layer ratio ranges up to 4.8:1 (Fig. 2.55). *M. goseongensis* differs from previously known oospecies of *Macroelongatoolthus*, *M. xixiaensis* and *M. zhangi* in China and *M. carlylei* in Utah in microscopic features (Kim et al. 2011). The occurrence of *M. goseongensis* suggests an oviraptosaur or oviraptosaur-like theropod, a possible maker of *M. goseongensis*, who lived in the Gyeongsang Basin during the Cretaceous Period.

*D. neixiangensis* is a spherical egg with a diameter of about 120 mm and a shell thickness of 1.5–1.7 mm. The outer surface of the egg is smooth with a grainy texture. It is characterized by the basic microstructure of an eggshell which displays irregular reticulate composed of two or three superimposed eggshell units

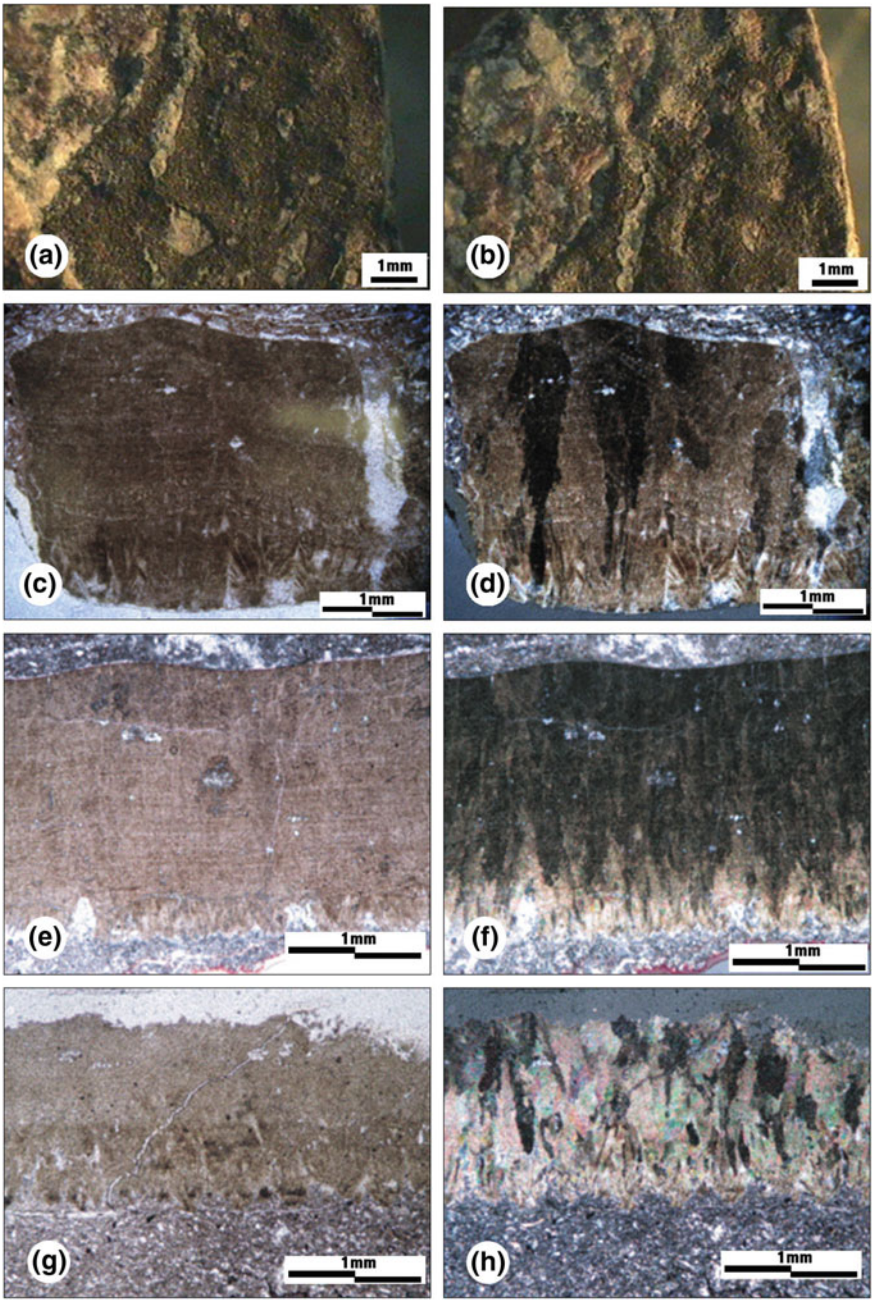



**Fig. 2.55** Microscopic features of giant theropod dinosaur eggs from the Goseong Formation, Tongyeong area. *Notes* **a**, **b** Outer surface of shell, **c**–**h** thin section view, **c**, **e**, **g** open nicol, **d**, **f**, **h** cross nicol. *Source* Kim et al. (2011)

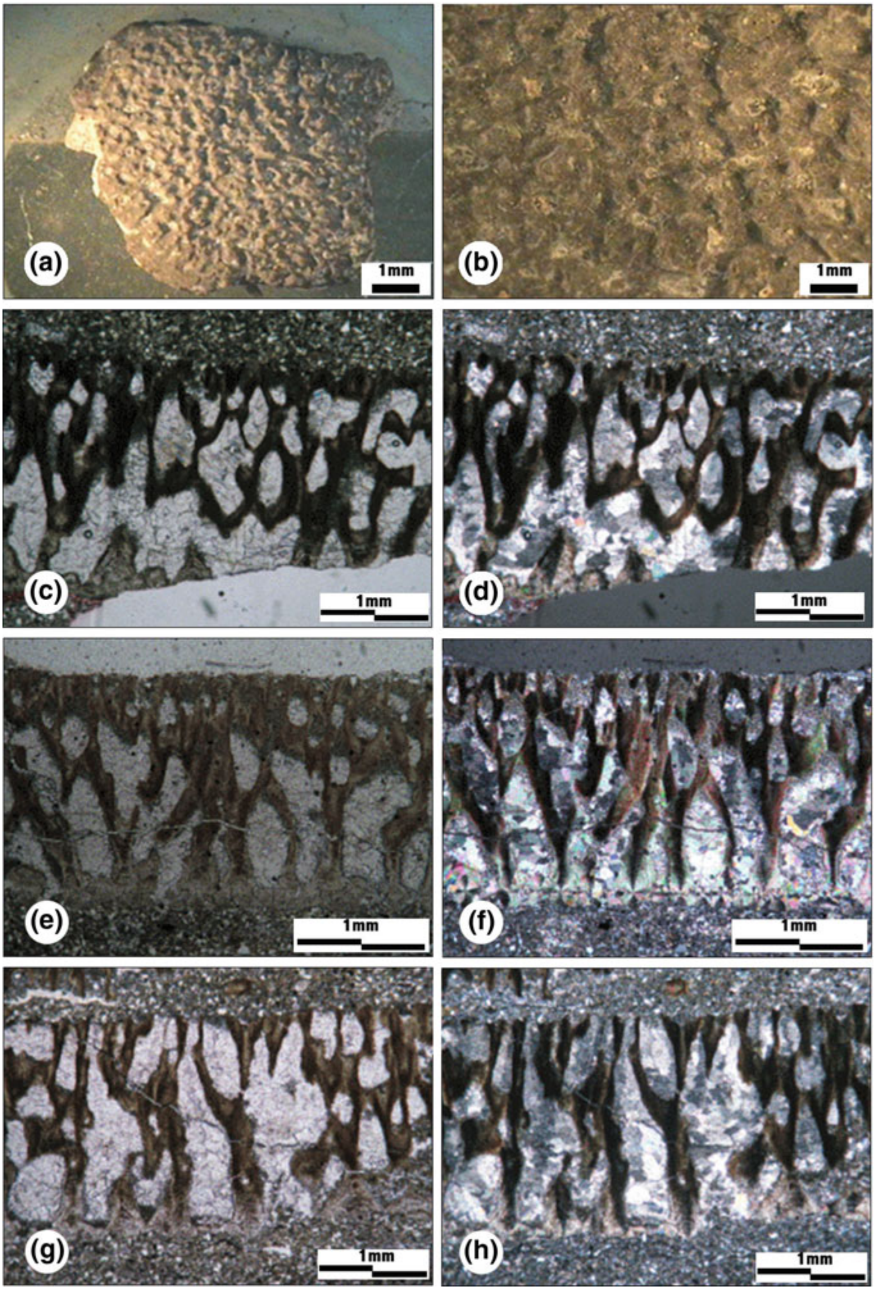



**Fig. 2.56** Microscopic features of sauropod dinosaur eggs from the Goseong Formation, Tongyeong area. *Notes* **a**, **b** Outer surface of shell; **c**–**h** thin section view; **c**, **e**, **g** open nicol; **d**, **f**, **h** cross nicol. *Source* Kim et al. (2011)

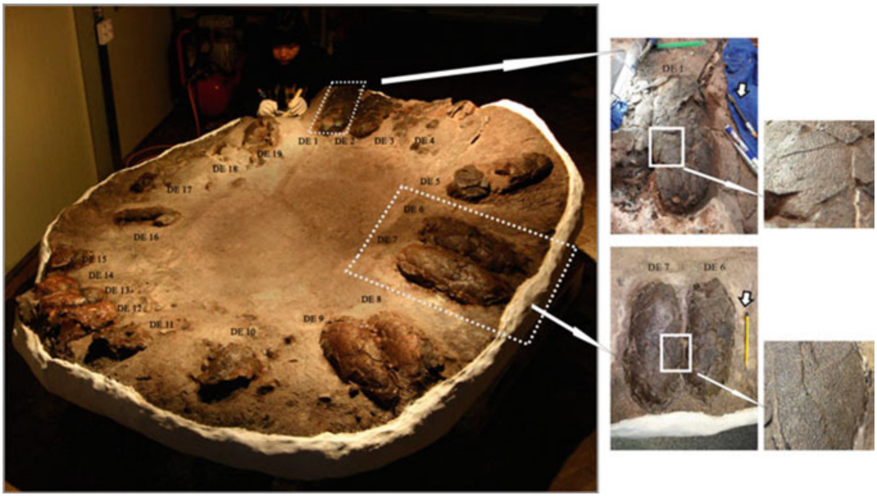


**Fig. 2.57** Aphae-do *Macroelongatoolithus xixiaensis* clutch, MNHN-nat201153. *Notes* Sets of well-preserved eggs indicating typical elongatoolithid ornamentation grading from ramotuberculate to lineartuberculate. *Source* Huh et al. (2014)

(Kim et al. 2011, Fig. 2.56). The occurrence of *D. neixiangensis* at the Upper Cretaceous Goseong Formation represents the first record of *Dictyoolithus* outside its typical location, Henan, China. It also provides evidence for widening the stratigraphic range from the Early Cretaceous Period to the Late Cretaceous Period, and its paleogeographic distribution from southeast China to Korea (Kim et al. 2011).

Recently, a complete giant theropod egg clutch was reported at the Upper Cretaceous of Aphaedo Island, Shinan County, southwest of Korea (Huh et al. 2014). The clutch of 19 dinosaur eggs is characterized by large, elongated, symmetrical eggs arranged in a single-layered ring-shaped clutch (Fig. 2.57). The eggs are inclined towards the center of the clutch which is 23 m in diameter, and an average of 41.2 cm long and 15.6 cm wide. The giant theropod eggshells were assigned to *Macroelongatoolithus xixiaensis* (Huh et al. 2014).

## 2.5 Dinosaur Skin Impressions and Tail Traces

Only fossilized skin impressions can provide tangible evidence to show what dinosaur integument and skin texture looked like in life (Horner 1984; Czerkas 1994). Although the first discovery of dinosaur skin impressions was made by Beckles in 1852, skin impressions of dinosaurs are rarely reported and have mostly been reported since the late 1990s. To date, no useful synthesis of the scattered

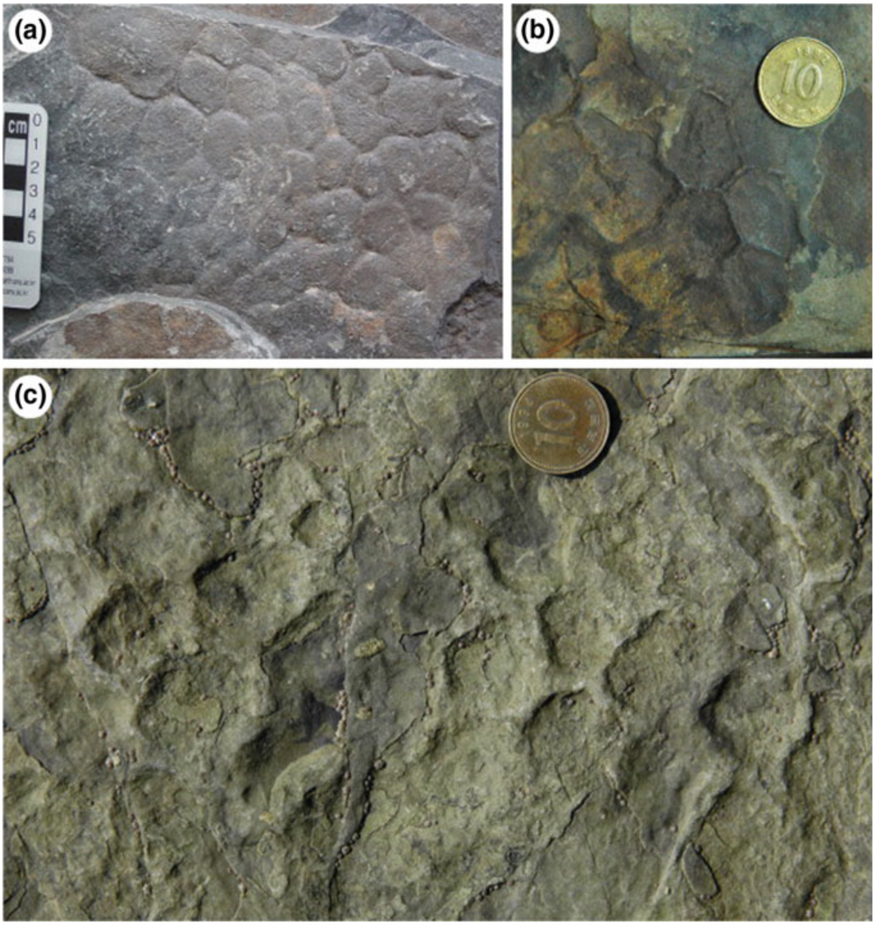



**Fig. 2.58** Skin impressions of dinosaurs from the Jindong and Haman formations. *Notes* **a** Jindong Formation, Dukmyeongri area; **b** Haman Formation, Gainri area; **c** Haman Formation, Sinsu Island. Coins in **b** and **c** are approximately 22.9 mm in diameter. *Source* Kim et al. (2010)

reports and specimens of dinosaur skin impressions is yet available (Kim et al. 2010).

Kim et al. (2010) first described dinosaur skin impressions at the Cretaceous Jindong and Haman formations in the Goseong and Namhae areas. Two specimens from the Haman Formation at Gainri and Sinsu Island reveal large polygonal to heptagonal scale impressions (2.0–2.5 cm). Another specimen from the Jindong Formation at Dukmyeongri, Goseong area, is an extremely well-preserved, honeycomb-like pattern of hexagonal scale impressions (Fig. 2.58). Kim et al. (2010) also provided criteria useful for distinguishing dinosaur skin impressions from the similar-shaped invertebrate trace fossils, such as glypogryptids, and

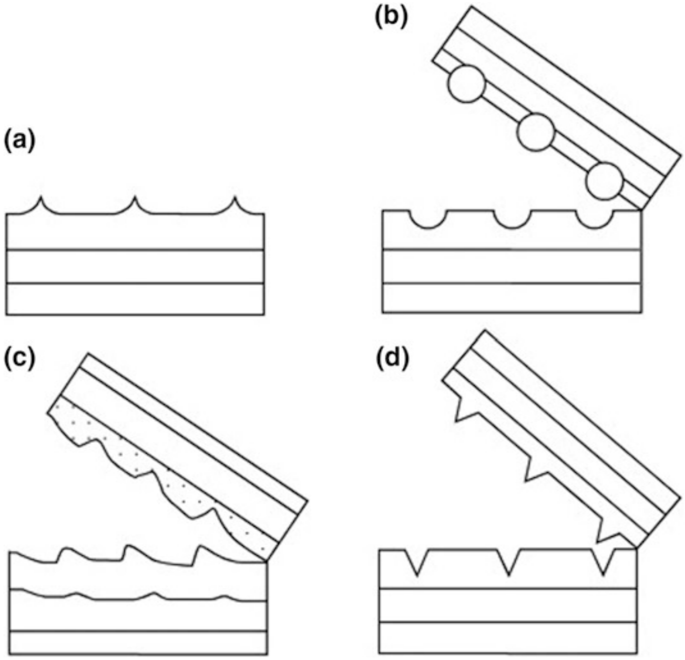



**Fig. 2.59** Schematic diagram for comparison of skin impressions (**a**), glypogryptids (**b**), load casts (**c**), and desiccation cracks (**d**). *Source* Kim et al. (2010)

inorganic sedimentary structures, such as load casts and desiccation cracks (Fig. 2.59).

In the same year, two specimens of dinosaur skin impressions were described from the Haman Formation, Sacheon area (Paik et al. 2010). The state of preservation of the Haman skin fossils suggests that sheet flood deposits on a floodplain to mudflat environment under only climatic conditions are potential candidates for dinosaur skin impressions to be found (Paik et al. 2010, Fig. 2.60).

Most dinosaurs seem to have walked with the tail lifted well clear of the ground; therefore, traces of a dragged tail are relatively uncommon (Bakker 1971, 1975; Thulborn 1990; Lockley 1991). Although more than 150 years have passed since Hitchcock first reported dinosaur tail traces from the Jurassic in Massachusetts (Hitchcock 1858) and subsequent discussion of the tail-dragging concept in relation to sauropods by Bird (1941, 1944), Bakker (1971), and others, dinosaur tail traces have rarely been reported (Irby and Albright 2002), and they are poorly understood (Platt and Hasiotis 2008), as are their functions. Tails of some dinosaurs, such as *Ankylosaurus* and *Euoplocephalus*, may have served as powerful weapons (Thulborn 1993). In other cases, dynamic stabilizing (Gauthier 1986) and counterbalancing (Ostrom 1969; Dixon 1989; Clark and Lindsay 2003; Norman 2005) functions have been proposed, especially for many dinosaurs with long necks and tails, and those with robust tail ligaments. Kim and Lockley (2013) reviewed 38

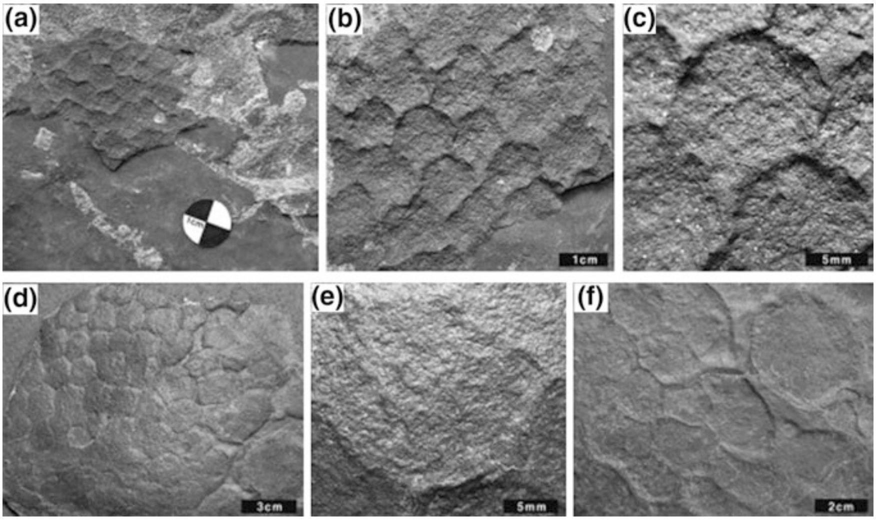


**Fig. 2.60** Dinosaur skin fossils from the Cretaceous floodplain (**a**–**c**) and lake margin (**d**–**e**) deposits. *Notes* **a** Skin impression on sandy mudstone with interlocking polygons (mostly hexagonal) in a honeycomb-like pattern. Invertebrate traces are associated; **b** closer view of (**a**). Diamond-shaped micropolygons are observed within the hexagonal polygons; **c** closer view of (**b**); **d** skin impression in positive relief on mudstone with interlocking hexagonal polygons; **e** closer view of (**d**). Micropolygonal texture is also observed within the polygons; **f** counterpart of (**d**). *Source* Paik et al. (2010)

previously reported records of dinosaur tail traces associated with tracks, to assess their geographic, stratigraphic, and taxonomic significance.

Recently, a theropod trackway with tail traces was described for the first time at the Lower Cretaceous Saniri Formation, Yeongdong area, central Korea (Kim et al. 2016). Theropod tracks are composed of three tapered pes digit impressions with narrow interdigital angles between digits II and IV (45°). The length and width of tracks are 22.8 and 15.5 cm, respectively. Theropod tracks are characteristically associated with a nearly continuous tail track, which is up to 360 cm in length, 4.5–6 cm in width, and a broad "U" shape in cross section (Kim et al. 2016, Fig. 2.61). The Yeongdong theropod tail traces represent the second instance of theropod tail traces from the Cretaceous Period to be found anywhere in the world (Kim and Lockley, 2013; Kim et al. 2016).

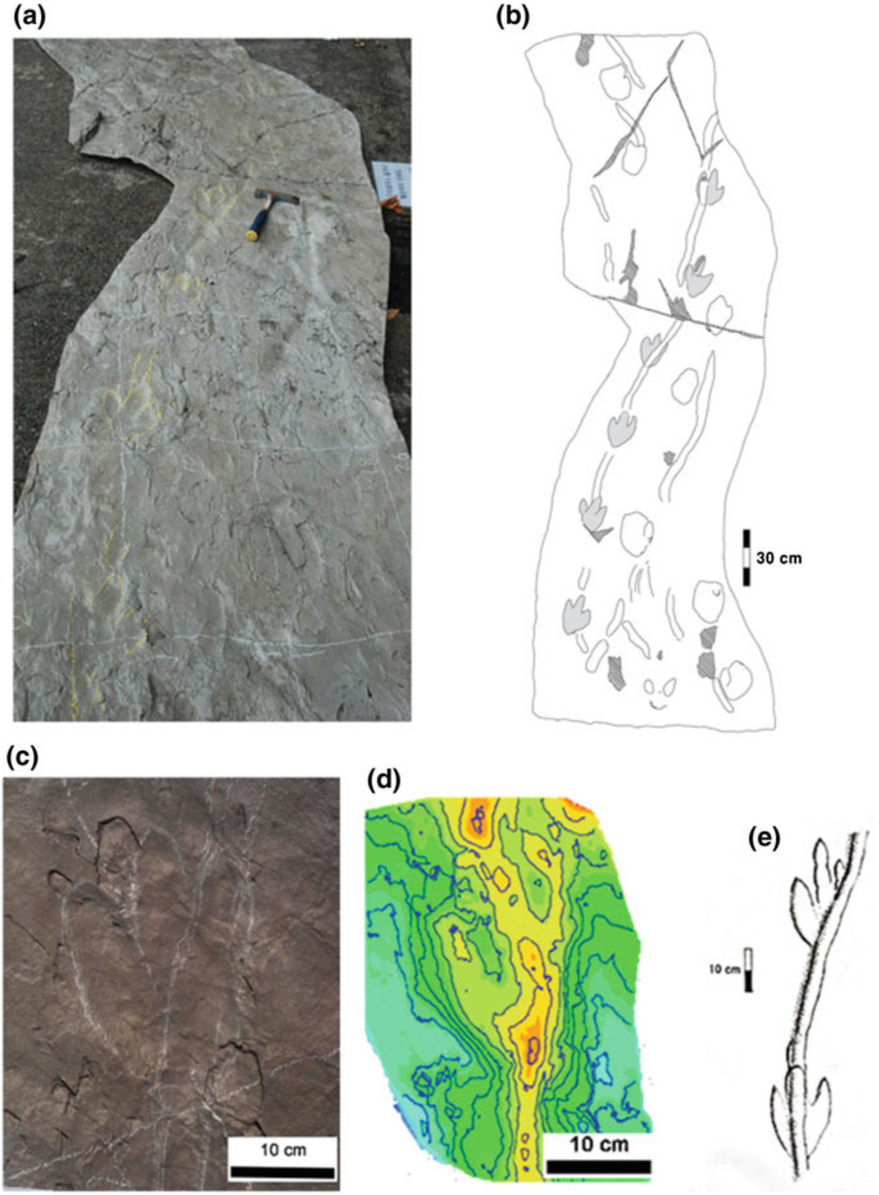



**Fig. 2.61** Theropod trackway with tail traces from the Lower Cretaceous Period, Yeongdong area. *Notes* Photograph (**a**) and sketch (**b**) of trackway. 3D mesh image (**c**) and 3D color contour map (**d**) of right second (R2) track. Sketch of two consequent tracks (R2 and L2) crossed by continuous tail drag impression (**e**). *Source* Kim et al. (2016)

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# Chapter 3
# Birds from the Cretaceous of Korea

## 3.1 Bird Tracks

In 1859, when Darwin's *On the Origin of Species* was published and two years before *Archaeopteryx* was discovered, fossil bird tracks were described for the first time at the Eocene deposits in France (Desnoyers 1859). However, the first bird track formally named *Ignotornis* was described at the Cretaceous in Colorado (Mehl 1931). The second bird track formally named was *Koreanaornis* described at the Cretaceous Haman Formation, Korea (Kim 1969). Lockley et al. (1992) first reviewed the Mesozoic bird tracks including *Ignotornis*, *Koreanaornis*, *Aguatilavipes*, and *Trisauropdiscus*.

Recently, Lockley and Harris (2010) reviewed bird tracks in the Mesozoic to Cenozoic deposits of the world and listed 19 ichnospecies accommodated in 15 ichnogenera of Cretaceous bird tracks and 45 ichnospecies accommodated in 23 ichnogenera of Cenozoic bird tracks. Since that time, the rapid increasing in number of discovery of new bird tracks from the Cretaceous has continued. Therefore, as shown in Table 3.1, 26 ichnospecies belonging to 20 ichnogenera of Cretaceous bird tracks have been discovered to date, if we add new ichnotaxa of bird tracks including *Koreanaornis dodsoni* (Xing et al. 2011), *Moguiornipes robusta* (Xing et al. 2011), *Tataornipes chabuensis* (Lockley et al. 2012), *Ignotornis gajinensis* (Kim et al. 2012), *Gyeongsangornipes lockleyi* (Kim et al. 2013), *Dongyangornis sinensis* (Azuma et al. 2013), *Limiavipes curriei* (McCrea et al. 2014), *Paxavipes babcockensis* (McCrea et al. 2015), and *Wupes agilis* (Xing et al. 2015). *Gruipeda vegrandiunus*, described at the Upper Cretaceous Cantwell Formation, Alaska (Fiorillo et al. 2011), is regarded to be *nomina dubia* because the specimen is incomplete (the first track incomplete and the second track being of web impressions) and description provides no diagnosis and offers inadequate comparison (only with *Trisaurodiscus*).

To date, there are eight ichnospecies of avian ichnotaxa formally named from the Cretaceous Period in Korea accommodated in six ichnogenera, which represent



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**Table 3.1** Purported Cretaceous avian ichnotaxa in order of naming

| Cretaceous avian ichnotaxa | Location | References |
|---|---|---|
| *Ignotornis mcconnelli* | Colorado, USA | Mehl (1931) |
| ***Koreanaornis hamanensis*** | Korea | Kim (1969) |
| *Aquatilavipes swiboldae* | Alberta, Canada | Currie (1981) |
| *Yacoriteichnus avis* | Argentina | Alonso and Marquillas (1986) |
| ***Jindongornipes kimi*** | Korea | Lockley et al. (1992) |
| *Patagonichornis venetiorum* | Argentina | Leonardi (1994) |
| *Aquatilavipes sinensis* | Sichuan, China | Zhen et al. (1994) |
| ***Hwangsanipes choughi*** | Korea | Yang et al. (1995) |
| ***Uhangrichnus chuni*** | Korea | Yang et al. (1995) |
| *Archaeornithipus meijidei*[a] | Spain | Fuentes Vidarte et al. (1996) |
| *Magnoavipes lowei*[a] | Texas, USA | Lee (1997) |
| *Aquatilavipes curriei* | Alberta, Canada | McCrea and Sarjeant (2001) |
| *Aquatilavipes izumiensis* | Japan | Azuma et al. (2002) |
| *Barrosopus slobodai* | Argentina | Coria et al. (2002) |
| *Sarjeantopodus semipalmatus* | Wyoming, USA | Lockley et al. (2004) |
| *Shandongornipes muxiai* | Shandong, China | Li et al. (2005) |
| ***Ignotornis yangi*** | Korea | Kim et al. (2006) |
| ***Goseongornipes markjonesi*** | Korea | Lockley et al. (2006a) |
| *Pullornipes aureus* | Laioning, China | Lockley et al. (2006b) |
| *Koreanaornis dodsoni* | Xinjiang, China | Xing et al. (2011) |
| *Moguiornipes robusta* | Xinjiang, China | Xing et al. (2011) |
| *Gruipeda vegrandiunusa*[b] | Alaska, USA | Fiorillo et al. (2011) |
| ***Ignotornis gajinensis*** | Korea | Kim et al. (2012) |
| *Tatarornipes chabuensis* | Nei Mongol, China | Lockley et al. (2012) |
| ***Gyeongsangornipes lockleyi*** | Korea | Kim et al. (2013) |
| *Dongyangornis sinensis* | Zhejiang, China | Azuma et al. (2013) |
| *Limiavipes curriei* | Alberta, Canada | McCrea et al. (2014) |
| *Wupus agilis* | Chongqing, China | Xing et al. (2007, 2015) |
| *Paxavipes babcockensis* | British Columbia, Canada | McCrea et al. (2015) |

*Notes* Ichnotaxa named in Korea are shown in bold. Ichnospecies marked with an ([a]) were interpreted as dinosaurian by Lockley and Harris (2010). An avian taxon with ([b]) are regarded to be *nomina dubia*
*Source* Modified after Lockley and Harris (2010)

about one third of the total avian ichnotaxa previously described from the Cretaceous deposits around the world. In this regard, the Korean Peninsula contains the most diverse avian ichnotaxa formally named, and it is the center of avian ichnology for understanding the morphological and behavioral evolution of early birds. Recently, the Gajin bird track site, Jinju area, Korea, was dubbed “A paradise of Mesozoic birds: the world’s richest and most diverse Cretaceous bird track

**Fig. 3.1** *Koreanaornis* from the Cretaceous Haman Formation at the Yongsanri bird track site, Haman area. *Source* Lockley et al. (1992)

assemblage" from the Early Cretaceous Haman Formation (Kim et al. 2012). Lockley et al. (2012) mentioned that Korea is the global epicenter for the study of Cretaceous bird tracks.

In 1969, Kim first reported bird tracks at the Lower Cretaceous Haman Formation, Haman area. Kim (1969) proposed the new ichnotaxon *Koreanaornis hamanensis*, but he did not provide a diagnosis and did not compare the tracks with *Ignotornis mcconnelli* described in Colorado by Mehl (1931). An emended description of *K. hamanensis* on the basis of topotype material was later provided by Lockley et al. (1992).

The *K. hamanensis* at the Haman track site (Fig. 3.1) is small tetradactyl bird track with a faint hallux impression, but often appearing tridactyl. The digit impressions are slender and often separated. Claw traces are variable, slender, and obscure. Tracks are wider than long except when the hallux is preserved and they range from about 2.5–4.4 cm in width. Divarication between digits II and IV average about 120° (range 105°–125°) (Lockley et al. 1992).

Bird tracks assigned to ichnogenus *Koreanaornis* have been described from the Cretaceous in Korea by some authors (Kim 1969; Lockley et al. 1992; Baek and Yang 1998); however, they did not offer diagnoses. For this reason, Kim et al. (2012) gave a revised diagnosis of *Koreanaornis*. Although Kim (1969) provided measurement data of ten tracks from the Haman Formation at the Yongsanri track site, Haman area, Lockley et al. (2012) provided a map showing at least 440 complete or partial tracks of *Koreanaornis* at Haman.

At the Gajin bird track site, Jinju, where Baek and Yang (1998) briefly described bird tracks including *K. hamanensis*, Kim et al. (2012) provided a map showing over 2000 bird tracks of *K. hamanensis* as well as *I. gajinensis*, *Goseongornipes markjonesi*, and *Aquatiavipes* isp. (see Figs. 3.9 and 3.10). The Gajin track site is now exposed at Heritage Halls I and II at the Gyeongnam Institute of Science Education, Jinju.

*K. hamanensis* from the Gajin track site is a small tridactyl bird track, much wider than it is long except in instances where the hallux is preserved. Hallux impressions are very small and rare. The digit impressions are slender, mostly connected. The track length ranges from 23 to 29 mm and its width from 31 to 34 mm. The length of the tracks cannot always be easily measured because traces of digits II–IV are not always connected in the metatarsal area and hallux traces are only sporadically preserved. The interdigital angle between digits II and III is 50°–60°, smaller than that of digits III and IV (60°–65°), indicating slight asymmetry. The divarication angle between digits II and IV ranges from 110° to 120° (Table 3.2). The measurement data of five trackways of *K. hamanensis* show tha thet pace, stride, and pace angle are 51–130 mm, 92–212 mm, and 145°–180°, respectively. A trackway composed of at least five consecutive tracks shows inward (positive) rotation reminiscent of modern shorebirds (Kim et al. 2012).

Bird tracks from the Gajin track site are too dense over most of the area to recognize discrete trackways. Approximately 2000 tracks of *Koreanaornis* occur on the single bedding plane within a small area 3 m × 1 m. This density of approximately 600 tracks per $m^2$ is denser than previously reported for any other bird track site (e.g., Lockley et al. 1992). As a result, discrete trackways are not easily recognized. This scenario suggests that the track makers were probably repeatedly active in a lake-margin environment, producing intense bioturbation.

*K. hamanensis* was also described at the Cretaceous Jindong Formation, Goseong area (Lockley et al. 1992) and is shown in Figs. 3.2 and 3.3.

*Koreanaornis* is clearly distinguished from *T. chabuensis* recently described at the Lower Cretaceous, Nei Mongol (Lockley et al. 2012), having a slender digit and being small. Small bird tracks described as *G. vegrandiunus* from the Upper Cretaceous Cantwell Formation, Alaska (Fiorillo et al. 2011), appear to resemble *K. hamanensis*, though the ichnotaxon is regarded as invalid due to an incomplete description and inadequate ichnotaxomic comparison.

*Koreanaornis* has been also reported from Shandong, Sichuan, and Xinjiang, China (Xing et al. 2011), Utah, USA (Anfinson et al. 2009), Tunisia (Contessi and Fanti 2012), and Spain (Díaz-Martinez et al. 2015). These reports potentially suggest the global distribution of *Koreanaornis* during the Cretaceous Period.

The second named bird track is *Jindongornipes kimi* which was described at the Lower Cretaceous Jindong Formation, Goseong area (Lockley et al. 1992). *J. kimi* is a moderately large bird track with well-developed hallux impressions. Up to four phalangeal pad traces are observed in the digit III impression. The divarication between digits II and IV ranges from 125° to 150°. The digit IV impressions are

**Table 3.2** Measurement of *Koreanaornis hamanensis* trackways at the Early Cretaceous Haman Formation, Gajin area, Jinju

| Trackway no. | Track no. | Track length (mm) | Track width (mm) | II–III (°) | III–IV (°) | II–IV (°) | Pace (mm) | Pace angle (°) | Stride (mm) | Trackway width (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| Trackway I | L1 | 22.6 | 30.2 | 50 | 75 | 125 | 82.9 | | | |
| | R1 | 24.5 | 38.8 | 65 | 70 | 135 | 56.6 | 160 | 139.5 | 52.8 |
| | L2 | 26.4 | 37.0 | | | | 84.8 | 145 | 156.5 | 60.3 |
| | R2 | 34.7 | 37.7 | 80 | 90 | 170 | 77.3 | 177 | 165.9 | 45.2 |
| | L3 | 264 | 37.7 | 50 | 80 | 130 | 71.6 | 177 | 147.0 | 43.4 |
| | R3 | 22.6 | 37.7 | 70 | 80 | 150 | 82.9 | 160 | 152.7 | 52.8 |
| | L4 | 18.9 | 33.2 | 40 | 85 | 125 | | | | |
| Trackway II | L1 | 38.0 | 38.0 | 68 | 74 | 142 | 130.3 | | | |
| | R1 | 27.2 | 38.0 | 75 | 60 | 135 | 86.9 | 146 | 211.8 | 65.2 |
| | L2 | 27.2 | 35.3 | 65 | 50 | 115 | 114.0 | 180 | 200.9 | 38.0 |
| | R2 | 32.6 | 40.7 | 65 | 45 | 110 | | | | |
| Trackway III | L1 | 20.4 | 29.6 | 70 | 50 | 120 | 45.9 | | | |
| | R1 | 20.4 | 25.5 | 70 | 60 | 130 | 51 | 145 | 91.8 | 43.4 |
| | L2 | 20.4 | 30.6 | 70 | 50 | 120 | 76.5 | 145 | 122.4 | 51.0 |
| | R2 | 20.4 | 30.6 | 70 | 60 | 130 | | | | |
| Trackway IV | L1 | 28.5 | 33.1 | 50 | 60 | 110 | 62.7 | | | |
| | R1 | 29.1 | 32.5 | 50 | 60 | 110 | 79.8 | 180 | 142.5 | 34.2 |
| | L2 | 25.1 | 34.2 | 60 | 60 | 120 | 51.3 | 170 | 142.5 | 45.6 |
| | R2 | 25.1 | 33.6 | 55 | 60 | 115 | 77.0 | 167 | 142.5 | 45.6 |
| | L3 | 22.8 | 34.2 | 50 | 65 | 115 | | | | |

*Source* Kim et al. (2012)

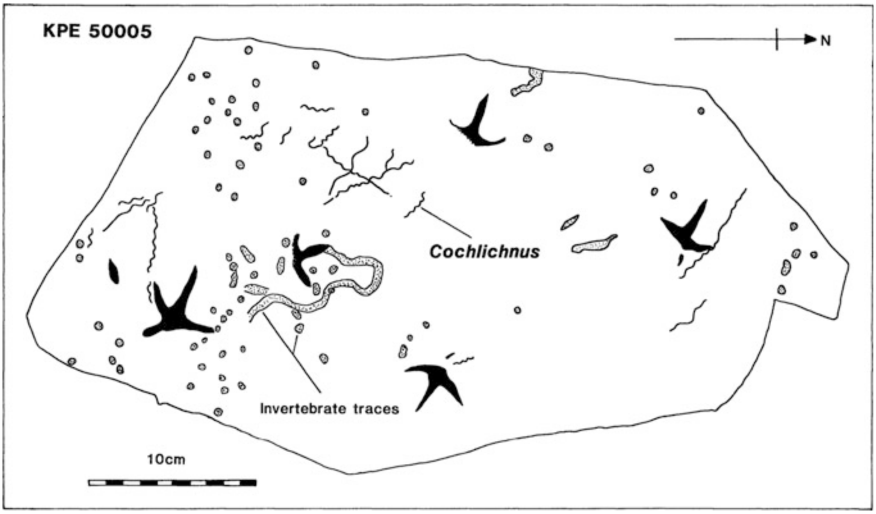


**Fig. 3.2** Bird tracks of *Koreanaornis hamanensis* from the Jindong Formation, Goseong area (Silbawi section; upper bird track horizon: KPE 50005). *Source* Lockley et al. (1992)

often wide proximally with a posteriorly directed heel that gives the track a pronounced asymmetry. The track length with the hallux is up to 80 mm and the track width ranges between 65 and 75 mm (Lockley et al. 1992). A holotype specimen and well-preserved bird tracks of *J. kimi* are shown in Fig. 3.3.

*J. kimi* is different from larger bird tracks recently assigned to *L. curriei* from Canada (McCrea et al. 2014) and *W. agilis* from China (Xing et al. 2015) in prominent hallux impressions and asymmetrical morphology.

Bird tracks with web traces were first discovered at the Upper Cretaceous Uhangri Formation, Haenam Basin, where dinosaur and pterosaur tracks are discovered in abundance, in the southwestern part of Korea (Chun 1990). In 1995, Yang et al. (1995) described these new bird tracks as *Uhangriensis chuni* and *Hwangsanipes choughi*, and the Eocene bird tracks with web trace as *Presbyorniformis feduccii*.

*U. chuni* is tridactyl small bird track with prominent web impressions between digits II–IV. The tracks are 37 mm in length and 45 mm in width (Table 3.3). The total average divarication between digits II–IV is about 110°. Digits II and IV are slightly curved inward. The anterior margin of the web impressions is slightly concave. *Uhangrichnus* was made by a web-footed water bird or shorebird of relatively small size (Yang et al. 1995). Although *U. chuni* was originally described without an example of a clear trackway and without evidence of a hallux trace, Lockley and Harris (2010, Fig. 9C) illustrated a topotype trackway (Fig. 3.4) which shows both features, as well as the characteristic inward rotation. Thus, the description of *U. chuni* can be emended as follows (Lockley et al. 2012):

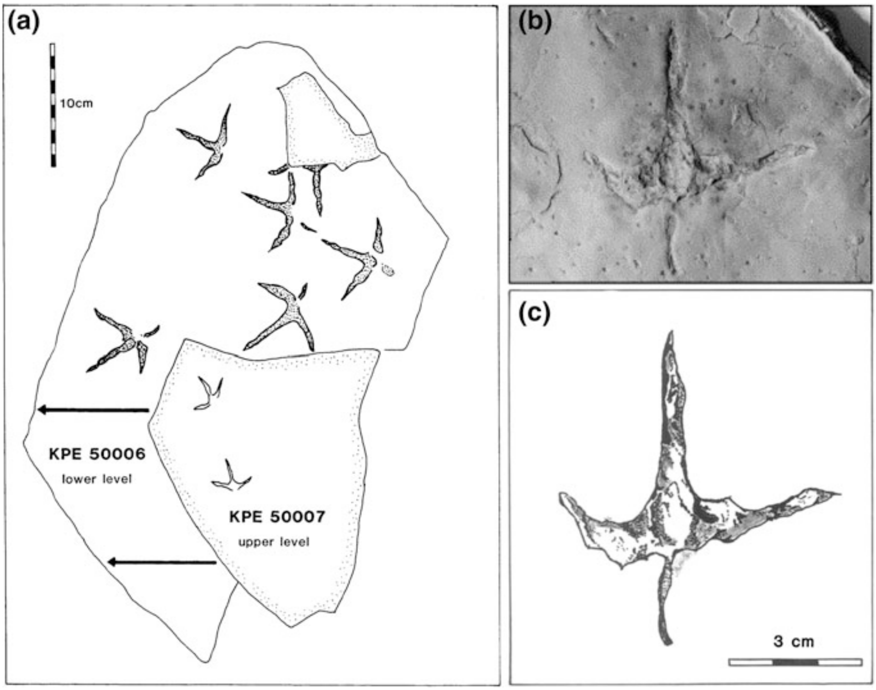


**Fig. 3.3** Bird tracks from the Jindong Formation, Goseong area. *Notes* **a** well-preserved *Jindongornipes* tracks (KPE 50006) and well-preserved *Koreanaornis hamanensis* tracks (KPE 50007); **b** photograph of type of material of *Jindongornipes kimi* (Lockley et al. 1992); **c** sketch of *Jindongornipes kimi* from holotype specimen KPE 50006 (Lockley et al. 2006a)

**Table 3.3** Measurements of an *Uhangrichnus* topotype trackway with hallux traces

| Trackway no. | Length + hallux (cm) | Length (cm) | Width (cm) | Step (cm) | Stride (cm) | Rotation (°) |
|---|---|---|---|---|---|---|
| T1 | – | 3.6 | – | – | | |
| T2 | – | 3.5 | 4.3 | 7.7 | 15.5 | 30 |
| T3 | 5.1 | 3.8 | 4.5 | 7.7 | 15.9 | 12 |
| T4 | 4.9 | 4.0 | 4.8 | 8.1 | | 18 |
| Mean | 5.0 | 3.7 | 4.5 | 7.8 | 15.7 | 20 |

*Source* Lockley et al. (2012)

A small, functionally tridactyl track of a web-footed bird with small, postero-medially directed hallux trace sporadically preserved. Web configuration palmate (i.e., well-developed) and equally developed in hypicies between digits II and III, and III and IV. Footprint, excluding hallux, wider (w) than long (l), averaging 3.70 and 4.58 cm, respectively (l/w = 0.81), but footprint length with hallux slightly longer than wide (l/w = 1.1; see Table 3.3). Trackway narrow with short step and stride (7.8 and 15.7 cm, respectively) and strong inward rotation (mean 20°) of digit III relative to trackway midline (Fig. 3.4).

*U. chuni* is distinguished from *G. markjonesi* (Lockley et al. 2006a), *Ignotornis mcconelli* (Mehl 1931), *Ignotornis yangi* (Kim et al. 2006), and *H. choughi* (Yang et al. 1995) in the absence of a hallux impression and a fully developed web trace. A small tridactyl bird track without a hallux impression recently described as *D. sinensis* at the Late Cretaceous, Zhejiang, China (Azuma et al. 2013) is also different from *U. chuni* in its slightly smaller size of track, slightly narrower divarication, and the asymmetry of web development and morphology.

Holotype and well-preserved of specimens of *Uhangrichnus* at the Uhangri Formation, Uhangri, Haenam area are shown in Figs. 3.4 and 3.5.

*H. choughi* is a tetradactyl relatively large bird tracks showing full webbing between digits II and IV. Hallux impressions are prominent and posteriorly directed. Web impressions are anteriorly concave. Tracks, not including the hallux, are 49 mm in length and 63 mm in width. The average divarication between digits II and IV is 112° (Yang et al. 1995). A holotype of *H. choughi* from the Cretaceous Uhangri Formation, Uhangri, Haenam area, is shown in Fig. 3.6.

Two web-footed bird tracks, *Uhangrichnus* and *Hwangsanipes*, from the Uhangri Formation, Haenam, represented the oldest web-footed bird tracks at the time of their discovery and provided evidence of web-footed shorebirds in the Late Cretaceous (Yang et al. 1995).

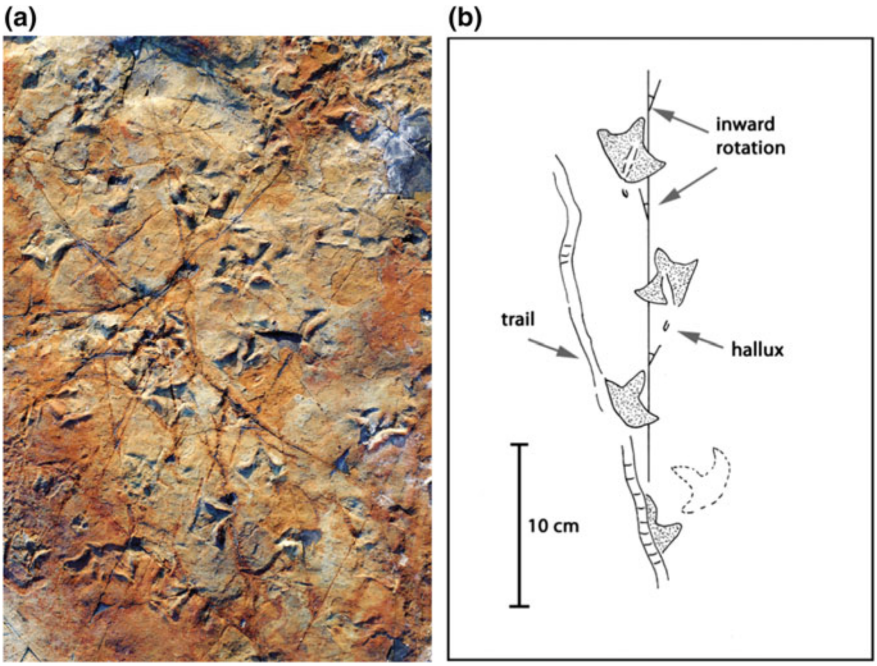


**Fig. 3.4** Web-footed bird track, *Uhangrichnus chuni*, from the upper Cretaceous Uhangri Formation, Uhangri track site, Haenam area. *Notes* **a** web-footed bird track, *Uhangrichnus chuni*; **b** topotype trackway of *Uhangrichnus chuni* [modified after Lockley and Harris (2010)]

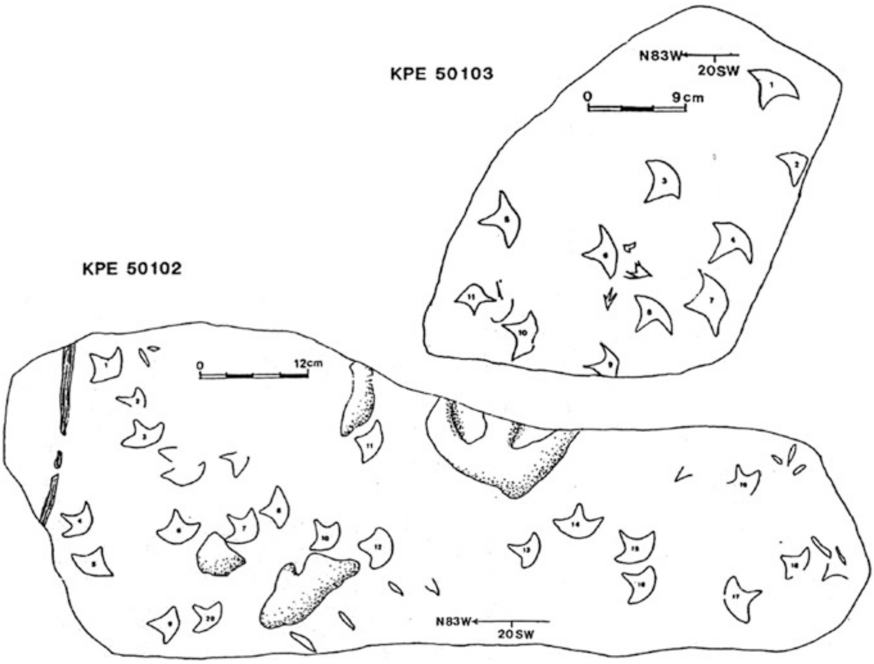


**Fig. 3.5** Detailed maps of specimens KPE 50102 and KPE 50103 of *Uhangrichnus chuni* from the Late Cretaceous Uhangri Formation, South Korea *Source* Yang et al. (1995)

Lockley et al. (2006a) synthesized dinosaur-dominated arrays from the Cretaceous Jindong Formation, Goseong County, and proposed a new avian ichnotaxon, *G. markjonesi*. *G. markjonesi* is a shorebird-like track with wide divarication between digits II and IV (140°–150°). The length of the track, including the hallux, track ranges from 41 to 45 mm; the length without the hallux ranges between 30 and 35 mm, and the width of track varies from 42 to 45 mm in holotype specimens. Digit II is shorter than IV. The hallux length ranges between 22 and 25% of the track length. Slightly semipalmate web impressions are developed between digits III and IV. The angle between the hallux and digit II is about 75° (Lockley et al. 2006a).

Five trackways assigned to *G. markjonesi* were also described at the Haman Formation, Gajin area, Jinju (Kim et al. 2012). These five trackways are composed of three to nine consecutive tracks. Measured specimens include KNUE 081002, KS 002, and KS 041-043 from the Gyeongsangnamdo Institute of Science Education collections (Table 3.4). KNUE 081002 represents an in situ trackway of at least nine consecutive footprints from Heritage Hall II. The trackways are variable in step, stride, and footprint rotation, and track 5 in the sequence is apparently missing. KS 002 and KS 041-043 represent clear examples of trackways from the Gyeongsangnamdo Institute of Science Education collections.

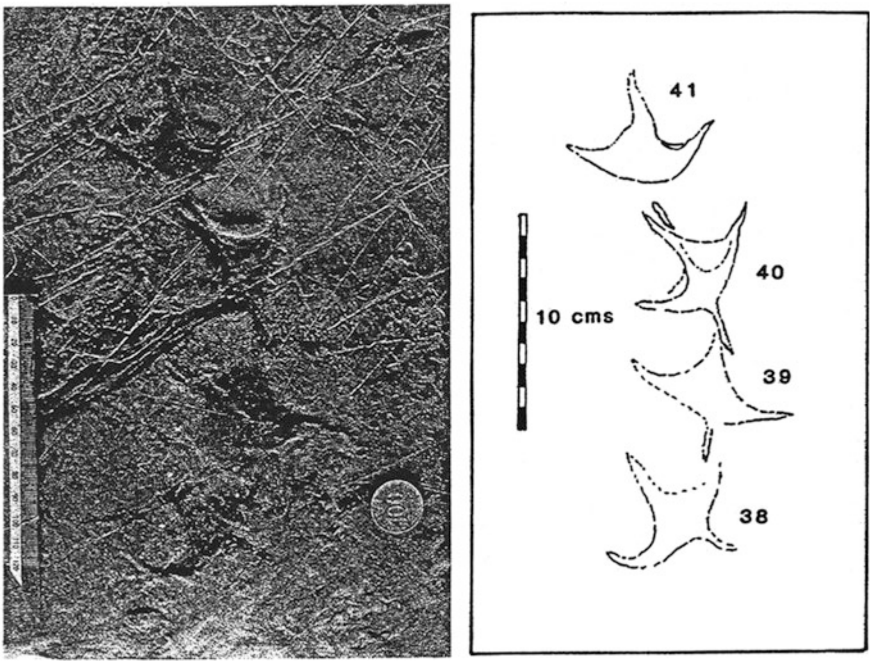


**Fig. 3.6** Photograph and line drawing of holotype of *Hwangsanipes choughi* KPE50101. *Source* Yang et al. (1995)

*G. markjonesi* was originally described by Lockley et al. (2006a) at the Cretaceous Jindong Formation, Goseong area, based on only two tracks 4.2 and 4.5 cm in length (with hallux) and 4.1–4.2 cm in width. The sample from the Gajin track site is much larger and permits a more detailed description of trackway parameters. KNUE 081002 is similar in size to the holotype, but specimens KS 002 and KS 041-043 are slightly smaller (see Table 3.4). The descriptions given below confirm that *Goseongornipes* is a slightly semipalmate bird track with wide divarication angles between digits II and IV, and a small posteriorly directed hallux. The newly described material also confirms that *Goseongornipes* belongs in the family Ignotornidae (Kim et al. 2006; Lockley et al. 2006a).

Many Gajin bird tracks compare well with *G. markjonesi* in track size and morphology. Hallux impressions are variably preserved in the Gajin tracks, and there is a significant range of divarication angles (approximately 115°–150°). As shown in Fig. 3.7, *G. markjonesi* from the Gajin track site is quite distinct from *Koreanaornis* in having a moderately well-developed hallux and slight semipalmate webbing impressions. *G. markjonesi* is also distinct from other well-documented Korean bird tracks such as *Jindongornipes* and *Uhangrichnus*. However, as noted, *G. markjonesi* is similar to *Hwangsanipes* and *Ignotornis* in features such as the hallux and semipalmate morphology. However, it is considerably smaller than these

**Table 3.4** Measurement of five trackways of *Goseongornipes markjonesi* at the Gajin bird track site, Jinju

| Trackway no. | Length (cm) | Length plus hallux (cm) | Width (mm) | Pace (cm) | Stride (cm) | Pace angle (°) | Inward rotation angle (°) | II–III | III–IV | II–IV | Number of tracks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| KNUE | 3.06 | 4.6 | 4.3 | 6.4 | 12.9 | 149.5 | 8.9 | 70.6 | 65.1 | 137 | 8 |
| KS 041 | 2.6 | 3.8 | 3.7 | 6.7 | 13.3 | 170 | 15 | 70 | 55 | 125 | 3 |
| KS 042 | 2.7 | 3.6 | 3.6 | 7.1 | 12.8 | 130 | 28 | 72 | 54 | 126 | 3 |
| KS 043 | 2.6 | 3.5 | 3.3 | 7.4 | 14.2 | 174 | 22 | 61 | 59 | 120 | 3 |
| KS 002 | 2.7 | 3.8 | 3.8 | 6.0 | 11.1 | 166 | 16 | 75 | 63 | 138 | 5 |
| **Mean** | **2.65** | **3.68** | **3.6** | **6.8** | **12.85** | **160** | **20.3** | **69.5** | **57.8** | **127.3** | **4** |

*Notes* All data are mean values measured from trackways. KNUE is an in situ trackway from the Heritage Hall II that consists of eight tracks in a nine-track sequence (with track 5 missing). Track specimens with the KS prefix are blocks in the Gyeongsangnamdo Institute of Science Education collection. Mean values (bold row) represent the grand mean average for all four KS trackways

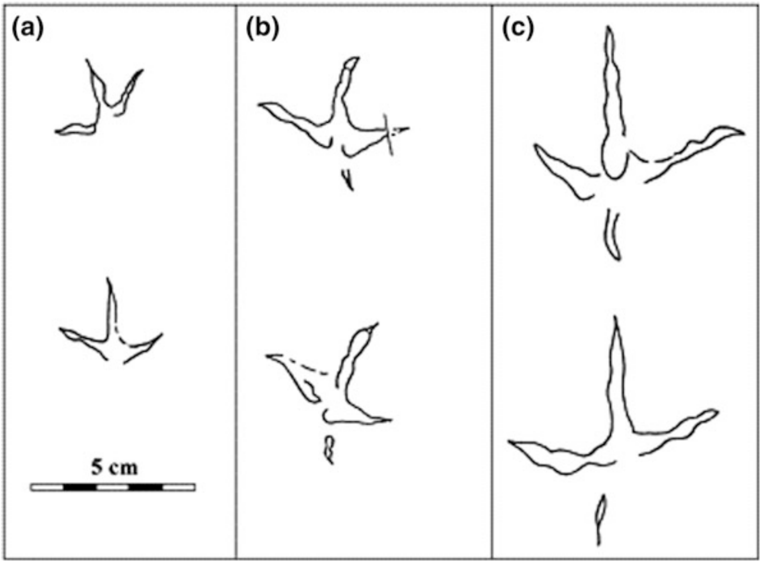


**Fig. 3.7** Comparison of bird track types from the Jindong Formation, Goseong area. *Notes* **a** *Koreanaornis hamanensis*, two tracks in sequence without hallux; **b** two apparently consecutive tracks of *Goseongornipes markjonesi*; **c** two separate tracks of *Jindonornipes kimi* (redrawn with modifications after Lockley et al. 1992, Fig. 19). *Source* Lockley et al. (2006a)

ichnogenera, and the development of the hallux and interdigital web traces (between III and IV) is less pronounced.

The Gajin track is a slightly semipalmated tetradactyl bird track with three widely splayed digits (II–IV) and a posteriorly directed hallux. The web traces are subtle, confined to the proximal hypex between digits III and IV (Lockley et al. 2006a). There are tetradactyl and, sometimes, tridactyl bird tracks with wide divarication angles between digits II and IV, averaging between 120° and 140°. Interdigital angles between digits II and III are larger (approximately 70°) than those between digits III and IV (approximately 58°), indicating asymmetry of tracks. The hallux is directed postero-medially. Some trackways, notably KS042, show a pronounced antero-medially directed indentation that separates the proximal traces of digits III and IV: this gives digit II the appearance of having a convex U- or V- shaped posterior margin. The mean track length, excluding the hallux, is about 2.7 cm; the mean track length including the hallux is about 3.7 cm; the mean track width is about 3.6 cm. The mean pace and stride of the five trackways are 6.8 and 12.9 cm, respectively. The mean pace angulation is 160°, and the mean inward rotation of digit III is 20.3° (Kim et al. 2012).

Figure 3.7 shows sketches for the comparison of bird track types including *K. hamanensis*, *J. kimi*, and *G. markjonesi* (Lockley et al. 2006a). As shown in Fig. 3.7, *Goseongornipes* is different from *Koreanaornis* in having a moderately well-developed hallux impression and slight semipalmate web impressions between digits III and IV. *J. kimi* is also distinguished from *G. markjonesi* by its much larger size, well-developed hallux impressions, phalangeal pad traces, and pronounced asymmetrical morphology.

The oldest record of web-footed bird tracks was reported at the Lower Cretaceous (Aptian-Albian) Haman Formation, Changseon Island, Korea (Kim et al. 2006). Eleven trackways composed of 80 tracks, which are assigned to *I. yangi*, are tetradactyl and anisodactyl bird footprints with postero-medially directed hallux impressions and fine acuminate claw traces on all four digits, displaying semipalmate web impressions between digits II and IV. The web traces are asymmetric; that is, more developed in hypex between digits III and IV than between digits II and III. As shown in Table 3.5, the average width of the tracks is approximately 45 mm; the average length of the tracks excluding the hallux is about 33 mm, and with the hallux is about 51 mm. Thus, the hallux is long and comprises an average of 35% of the track length. Divarications between digits II and III, III and IV, and II and IV are 64°, 59°, and 123°, respectively. Digit IV is slightly longer than digit II. As shown in Table 3.5, on the basis of the eleven identified trackways, the pace, stride, and pace angulation measured are 75–115 mm, 158–229 mm, and 139°–161°, respectively (Kim et al. 2006).

*I. yangi* represents the second ichnospecies of *Ignotornis* following *I. mcconelli* which was described at the Cretaceous of Colorado (Mehl 1931). *I. yangi* is similar in general morphology to *I. mcconelli* (Mehl 1931), but the former is different from the latter in its slightly small size, more developed web impressions, wider divarication between digits II and IV, and postero-medially directed hallux trace (Kim et al. 2006). In addition, *I. yangi* appears to be similar in morphology to *H. choughi*. However, *H. choughi* is distinctively distinguished from *I. yangi* by its much larger size, and the strong asymmetry in web traces between digits II and III and between digits III and IV (Kim et al. 2006). *I. yangi* is also clearly distinguished from the *D. sinensis* recently described in Zhejiang, China (Azuma et al. 2013) as the latter shows no hallux impressions. To date, *I. yangi* described at the Lower Cretaceous Haman Formation, Changseon Island, represents the oldest webbed bird tracks and the first Asian report of a named bird track similar to the material type of *Ignotornis* from North America (Kim et al. 2006). The webbed bird tracks and trackways assigned to *I. yangi* from the Haman Formation, Changseon Island, are shown in Fig. 3.8.

More than 2500 well-preserved bird tracks associated with unusual sauropod and theropod tracks were recorded from a dense array in lacustrine deposits at the Early Cretaceous Haman Formation of the Gajin track site, Jinju, Korea (Kim et al. 2012). The Gajin track site represents the world's most dense array of bird tracks (up to approximately 600 per $m^2$) at a single location and provides striking evidence of the diversity of avian ichnotaxa during the Cretaceous Period. The Gajin track site was therefore dubbed "A paradise of Mesozoic birds" (Kim et al. 2012). Bird tracks of the Gajin site were attributed to *K. hamanensis*, *G. markjonesi*, *Aquatilavipes*, and *I. gajinensis*. Sketch maps of bird tracks at the Gajin site are shown in Figs. 3.9 and 3.10.

**Table 3.5** Measurement (in mm) of bird tracks *Ignotornis yangi* at the Cretaceous Haman Formation, Changseon Island

| T | N | Wp | Lp | L/W | $L_{+p}$ | I | II | IV | La | Ra | $D_{II\text{-}IV}$ | $D_{I\text{-}II}$ | P | S | Pa | Pw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_I$ | 1L | 51 | 34 | 0.67 | 56 | 16 | 28 | 33 | 59 | 63 | 122 | 83 | 127 | 238 | 149 | 29 |
| | 2R | ? | 34 | ? | ? | 26 | ? | ? | 60 | ? | ? | ? | 117 | 230 | 142 | 32 |
| | 3L | 48 | 35 | 0.73 | 55 | 10 | 22 | 32 | 59 | 60 | 116 | 97 | 122 | 219 | 142 | 37 |
| | 4R | 46 | 34 | 0.74 | 56 | 18 | 24 | 30 | 66 | 56 | 122 | 90 | 101 | 200 | 145 | 31 |
| | 5L | 47 | 33 | 0.70 | 55 | 12 | 23 | 30 | 60 | 60 | 120 | 93 | 102 | 172 | 118 | 50 |
| | 6R | 46 | 32 | 0.70 | 52 | 11 | 22 | 30 | 61 | 59 | 120 | 82 | 98 | | | |
| | 7L | 48 | 33 | 0.69 | 58 | 13 | 23 | 31 | 60 | 58 | 118 | 92 | | | | |
| $T_{II}$ | 8R | 48 | 35 | 0.73 | 59 | 19 | 26 | 29 | 72 | 54 | 126 | 76 | 112 | 217 | 163 | 17 |
| | 9L | 49 | 37 | 0.76 | 58 | 17 | 24 | 32 | 77 | 52 | 129 | 80 | 107 | 214 | 180 | 4 |
| | 10R | 45 | 35 | 0.78 | | | 23 | 30 | 67 | 65 | 132 | | 104 | 213 | 161 | 19 |
| | 11L | 51 | 36 | 0.71 | 54 | 17 | 23 | 31 | 75 | 53 | 128 | 80 | 115 | 232 | 180 | 6 |
| | 12R | 47 | 36 | 0.77 | 60 | 15 | 24 | 30 | 62 | 60 | 122 | 112 | 119 | 180 | 137 | 34 |
| | 13L | 38 | 28 | 0.74 | | | 22 | 22 | 60 | 70 | 130 | | 75 | 150 | 125 | 36 |
| | 14R | 38 | 29 | 0.76 | | | 23 | 20 | 67 | 60 | 127 | | 93 | 155 | 135 | 25 |
| | 15L | 40 | 19 | 0.73 | | | 24 | 25 | 68 | 65 | 133 | | 75 | 152 | 130 | 25 |
| | 16R | 40 | 31 | 0.78 | | | 24 | 23 | 60 | 65 | 125 | | 92 | | | |
| | 17L | 40 | 28 | 0.70 | | | 22 | 25 | 60 | 65 | 125 | | | | | |
| $T_{III}$ | 18L | 43 | 31 | 0.72 | 38 | 10 | 23 | 28 | 66 | 56 | 122 | 50 | 47 | 94 | 102 | 36 |
| | 19R | 45 | 34 | 0.76 | 44 | 4 | 25 | 28 | 57 | 63 | 120 | 92 | 77 | 157 | 150 | 22 |
| | 20L | 47 | 34 | 0.72 | 47 | 8 | 25 | 32 | 73 | 55 | 128 | 65 | 85 | 193 | 172 | 8 |
| | 21R | 45 | 34 | 0.76 | | | 26 | 29 | 53 | 62 | 115 | | 109 | 200 | 170 | 7 |
| | 22L | 48 | 35 | 0.73 | 45 | 13 | 27 | 27 | 57 | 68 | 125 | 73 | 94 | 185 | 132 | 43 |
| | 23R | 45 | 34 | 0.76 | | | 26 | 30 | 60 | 57 | 117 | | 110 | 230 | 155 | 24 |
| | 24L | 45 | 35 | 0.78 | | | 23 | 32 | 67 | 55 | 122 | | 125 | 183 | 120 | 51 |
| | 25R | 42 | 32 | 0.76 | | | 27 | 30 | 60 | 58 | 118 | | 85 | | | |
| | 26L | 43 | 31 | 0.72 | | | 25 | 26 | 65 | 55 | 120 | | | | | |
| | 27L | 41 | 30 | 0.73 | | | 25 | 22 | 61 | 70 | 131 | | 91 | 187 | 173 | 3 |
| | 28R | 42 | 31 | 0.74 | | | 22 | 27 | 55 | 60 | 115 | | 98 | | | |
| | 29L | 43 | 31 | 0.72 | 48 | 8 | 24 | 30 | 55 | 50 | 105 | 77 | | | | |

(continued)

**Table 3.5** (continued)

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{IV}$ | 30R | 46 | 35 | 0.76 | 45 | 9 | 22 | 30 | 60 | 59 | 119 | 90 | 106 | 210 | 133 | 40 |
| | 31L | 47 | 32 | 0.68 | | | 25 | 32 | 60 | 58 | 118 | | 124 | 220 | 151 | 30 |
| | 32R | 47 | 35 | 0.75 | 56 | 15 | 26 | 28 | 64 | 56 | 120 | 85 | 106 | 220 | 168 | 13 |
| | 33L | 45 | 35 | 0.78 | | | 23 | 30 | 63 | 52 | 115 | | 115 | | | |
| | 34R | 45 | ? | ? | 63 | 16 | 24 | 28 | 76 | 54 | 130 | 85 | | | | |
| $T_{V}$ | 35L | 47 | 35 | 0.74 | 48 | 13 | 23 | 33 | 62 | 55 | 117 | 80 | 142 | 270 | 150 | 37 |
| | 36R | 47 | 30 | 0.64 | 48 | 13 | 20 | 30 | 76 | 61 | 137 | 79 | 138 | 205 | 140 | 35 |
| | 37L | 46 | 35 | 0.76 | 55 | 12 | 21 | 29 | 79 | 56 | 135 | 87 | 79 | 165 | 145 | 27 |
| | 38R | 44 | 32 | 0.73 | | | 22 | 30 | 59 | 60 | 119 | | 98 | 165 | 120 | 48 |
| | 39L | 47 | 33 | 0.70 | 63 | 16 | 23 | 34 | 59 | 62 | 121 | 120 | 95 | 156 | 167 | 9 |
| | 40R | ? | ? | ? | ? | 13 | ? | ? | ? | ? | ? | ? | 64 | 175 | 159 | 15 |
| | 41L | 41 | 30 | 0.73 | 48 | 13 | 22 | 23 | 60 | 68 | 128 | 52 | 113 | 193 | 132 | 42 |
| | 42R | 45 | 35 | 0.78 | 62 | 18 | 22 | 31 | 50 | 64 | 114 | 100 | 97 | | | |
| | 43L | 45 | 30 | 0.67 | 48 | 9 | 23 | 25 | 75 | 55 | 130 | 85 | | | | |
| $T_{VI}$ | 44L | 47 | 35 | 0.75 | 45 | 8 | 25 | 29 | 58 | 62 | 120 | 78 | 74 | 182 | 148 | 25 |
| | 45R | 46 | 35 | 0.76 | | | 23 | 30 | 70 | 56 | 126 | | 115 | 184 | 138 | 33 |
| | 46L | 45 | 32 | 0.71 | 48 | 15 | 25 | 25 | 73 | 66 | 139 | 78 | 51 | | | |
| | 47R | 47 | 36 | 0.77 | | | 30 | 27 | 70 | 55 | 125 | | | | | |
| $T_{VII}$ | 48L | 41 | 30 | 0.73 | | | 27 | 28 | 55 | 63 | 118 | | 90 | 136 | 137 | 27 |
| | 49R | 42 | 31 | 0.76 | 47 | 5 | 23 | 27 | 57 | 68 | 125 | 95 | 55 | 142 | 147 | 19 |
| | 50L | 41 | 32 | 0.78 | | | 25 | 22 | 66 | 58 | 124 | | 93 | 176 | 155 | 19 |
| | 51R | 42 | 30 | 0.71 | 48 | 6 | 22 | 30 | 55 | 68 | 123 | 113 | 93 | 176 | 148 | 25 |
| | 52L | 42 | 32 | 0.76 | 50 | 12 | 23 | 30 | 70 | 59 | 129 | 90 | 94 | | | |
| | 53R | 42 | 30 | 0.71 | 47 | 10 | 23 | 25 | 57 | 63 | 120 | 79 | | | | |

(continued)

**Table 3.5** (continued)

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{VIII}$ | 54R | 48 | 35 | 0.73 | | | 26 | 30 | 68 | 63 | 131 | | 120 | 243 | 150 | 32 |
| | 55L | 47 | 34 | 0.72 | 53 | 12 | 26 | 29 | 77 | 45 | 122 | 90 | 130 | 234 | 180 | 13 |
| | 56R | 43 | 30 | 0.70 | | | 20 | 27 | 70 | 54 | 124 | | 99 | 225 | 175 | 12 |
| | 57L | 47 | 33 | 0.70 | 46 | 6 | 22 | 30 | 60 | 47 | 107 | 110 | 126 | 223 | 164 | 14 |
| | 58R | 45 | 34 | 0.76 | | | 25 | 23 | 68 | 56 | 124 | | 100 | 203 | 150 | 23 |
| | 59L | 45 | 34 | 0.76 | | | 23 | 30 | 59 | 56 | 115 | | 111 | 215 | 150 | 28 |
| | 60R | 41 | 30 | 0.73 | 52 | 8 | 26 | 30 | 64 | 56 | 120 | 110 | 104 | 225 | 157 | 23 |
| | 61L | 45 | 35 | 0.78 | 46 | 12 | ? | ? | 67 | 62 | 129 | 92 | 127 | | | |
| | 62R | 45 | 33 | 0.73 | | | 23 | 30 | 68 | 59 | 127 | | | | | |
| $T_{IX}$ | 63L | 47 | 35 | 0.75 | | | 22 | 30 | 65 | 55 | 120 | | 96 | 195 | 156 | 20 |
| | 64R | 44 | 59 | 0.66 | 46 | 7 | 24 | 28 | 64 | 62 | 126 | 60 | 103 | 190 | 151 | 24 |
| | 65L | 48 | 33 | 0.69 | 62 | 9 | 23 | 30 | 69 | 52 | 121 | 91 | 94 | | | |
| | 66R | 45 | 32 | 0.71 | 48 | 12 | 23 | 27 | 63 | 63 | 126 | 88 | | | | |
| $T_X$ | 67L | 44 | 31 | 0.71 | | | 25 | 25 | 65 | 60 | 125 | | 100 | 204 | 155 | 23 |
| | 68R | ? | 30 | ? | | | ? | 24 | ? | 65 | ? | | 110 | 225 | 156 | 25 |
| | 69L | 48 | 33 | 0.69 | 51 | 8 | 23 | 33 | 68 | 55 | 123 | 90 | 122 | 240 | 148 | 33 |
| | 70R | 42 | 31 | 0.74 | | | 25 | 23 | 61 | 59 | 120 | | 130 | 245 | 164 | 19 |
| | 71L | 43 | 32 | 0.74 | | | 26 | 25 | 68 | 58 | 126 | | 119 | | | |
| | 72R | 43 | 31 | 0.72 | | | 27 | 25 | 69 | 54 | 123 | | | | | |
| $T_{XI}$ | 73L | 43 | 30 | 0.70 | | | 26 | 26 | 60 | 60 | 120 | | 75 | | | |
| | 74R | 40 | 31 | 0.78 | 43 | 8 | 23 | 29 | 68 | 58 | 126 | 92 | | | | |
| | 75 | 48 | 35 | 0.73 | | | 25 | 30 | 56 | 64 | 120 | | | | | |
| | 76 | 47 | 33 | 0.70 | 47 | 8 | 23 | 30 | 73 | 51 | 124 | 90 | | | | |
| | 77 | 47 | 35 | 0.75 | | | 24 | 34 | 72 | 50 | 122 | | | | | |
| | 78 | 48 | 33 | 0.69 | | | 22 | 32 | 74 | 51 | 125 | | | | | |
| | 79 | 40 | 30 | 0.75 | 48 | 12 | 23 | 27 | 52 | 68 | 120 | 85 | | | | |
| | 80 | 38 | 27 | 0.71 | | | 18 | 25 | 70 | 60 | 130 | | | | | |
| | M | 45 | 33 | 0.73 | 51 | 12 | 24 | 28 | 64 | 59 | 13 | 86 | 102 | 197 | 150 | 25 |

*Notes* T: Trackways; N: Number of measurement; Lp: Length of pes; Wp: Width of pes; L/W: Ratio of Lp/Wp; L + p: Length of pes including hallux; I, II, IV: Length of digits I, II, IV; La: digital angle between left side digit and III; Ra: digital angle between right side digit and III; $D_{II–IV}$: Divarication between digits II and IV; $D_{I–II}$: Divarication between digits I and II; P: Pace; S: Stride; Pa: Pace angle; Pw: Pace width; T: trackways I, II, IV, V and VI; L: left pes; R: right pes

*Source* Kim et al. (2006)

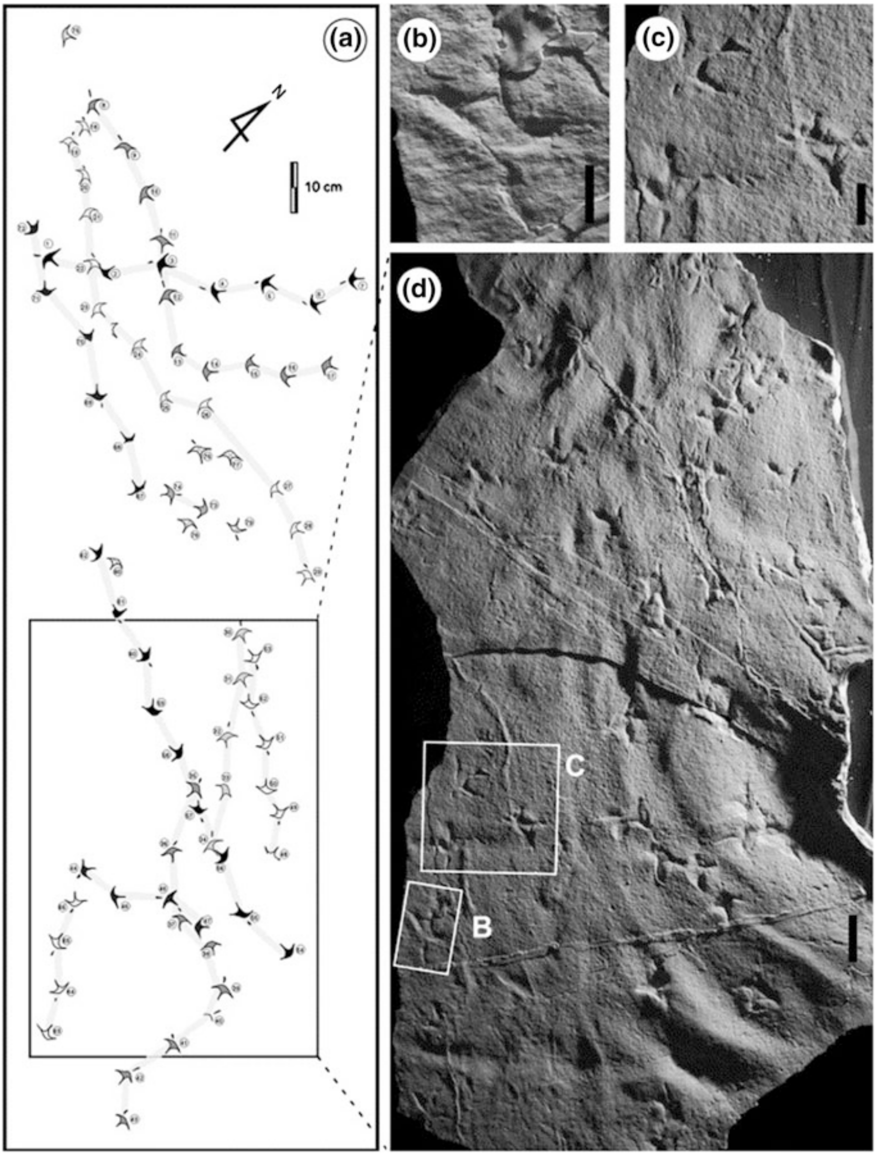


**Fig. 3.8** Web-footed bird tracks from the Haman Formation, Changseon Island. *Notes* **a** map of *Ignotornis yangi* trackways; eleven trackways recognized shown in white, gray, and black are preserved as specimen number KNUE 040417; **b**–**d** detailed photographs of *Ignotornis yangi* shown in **a**. Track number 66 shown in frame **b** is the holotype (compare with Lim et al. 2002, Fig. 3). The scale bars in **b** and **c** represent 20 mm; the scale bar in **d** represents 50 mm. *Source* Kim et al. (2006)


**Fig. 3.9** Sketch of bird tracks distributed at Heritage Hall I, the Gajin track site. *Note* Area A corresponds to the detailed map shown in Fig. 3.10. *Source* Kim et al. (2012)

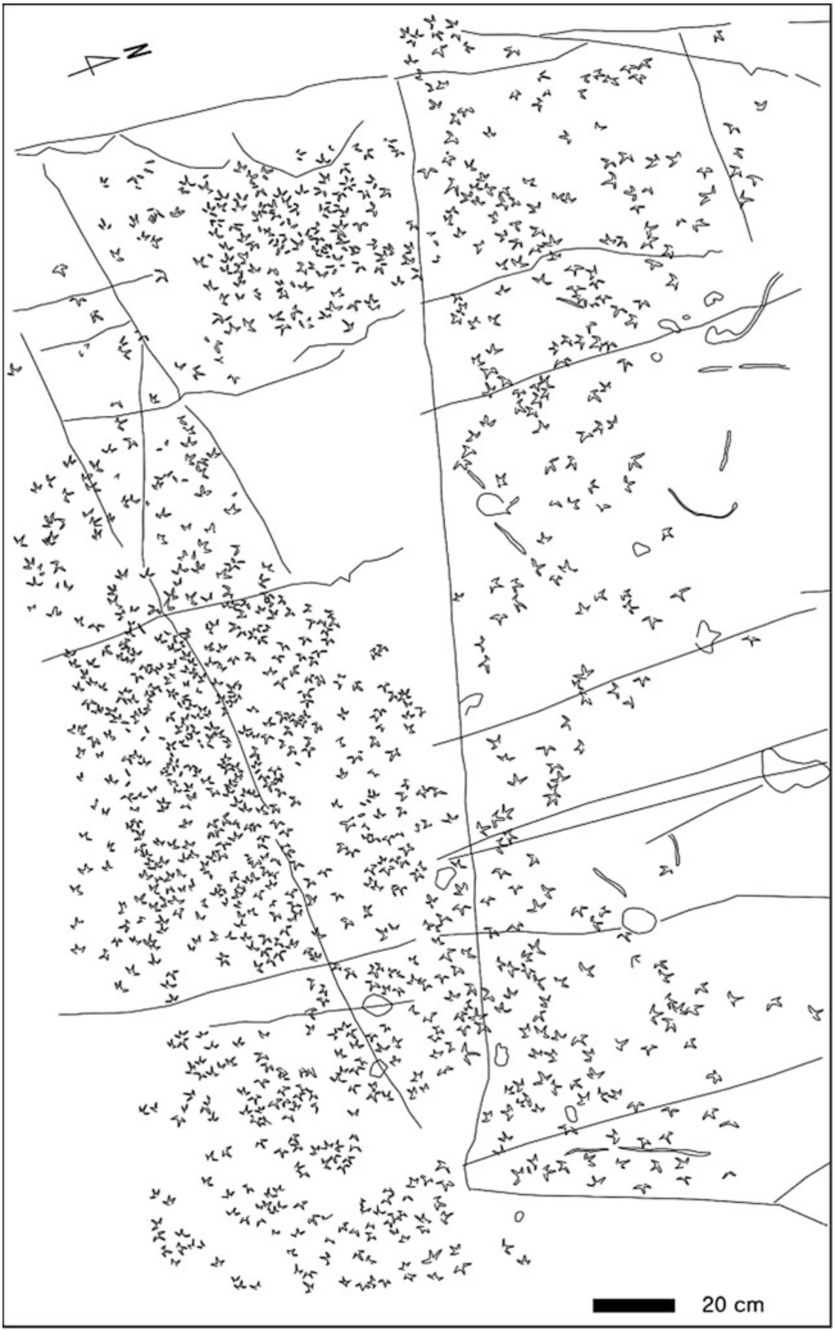


**Fig. 3.10** Detail of region of high bird track density from the Lower Cretaceous Haman Formation, Gajin track site. *Note* Compare with (Fig. 3.9a). *Source* Kim et al. (2012)

**Table 3.6** Measurement of bird trackways *Ignotornis gajinensis* at the Cretaceous Haman Formation of the Gajin area, Jinju

| Track no. | Track length (cm) | Track width (cm) | Pace (cm) | Stride (cm) | II-III | III-IV | II-IV | Pace angle | Trackway width (cm) |
|---|---|---|---|---|---|---|---|---|---|
| L1 | (6.3) | 5.3 | 10.6 | | 70 | 60 | 130 | | |
| R1 | (4.3) | 5.4 | 10.4 | 20.7 | 73 | 67 | 140 | 160 | 7.2 |
| L2 | (5.8) | 5.1 | 8.7 | 17.3 | 80 | 60 | 140 | 130 | 9.2 |
| R2 | (4.8) | 5.3 | 14.0 | 22.6 | | | | 172 | 6.3 |
| L3 | (6.3) | 5.3 | 10.4 | 22.6 | 75 | 70 | 145 | 145 | 5.8 |
| R3 | (6.8) | 5.5 | 20.7 | 31.1 | 70 | 60 | 130 | 165 | 5.8 |
| L4 | (6.4) | 5.8 | 14.4 | 34.2 | 75 | 65 | 140 | 155 | |
| Mean | (6.1) | (5.4) | 12.7 | 26.5 | 73.8 | 63.7 | 137.5 | 154.5 | 6.9 |

*Source* Kim et al. (2012)

Following the first ichnospecies of *Ignotornis*, *I. mcconelli* (Mehl 1931) and the second ichnospecies *I. yangi* (Kim et al. 2006), a third new ichnospecies, *Ignotornis*, *I. gajinensis*, was also described at the Gajin track site (Kim et al. 2012).

*I. gajinensis* is a tetradactyl semipalmate web-footed bird track with length, including the prominent posteriorly directed hallux impressions, of about 67.5 mm and a width of about 55.4 mm. Divarication between digits II and IV is about 130°. Interdigital angles between digits II and III, and III and IV are approximately 70° and 60°, respectively, resulting in slight asymmetry. The pace and stride length are highly variable, 87–207 mm and 173–342 mm, respectively (Table 3.6).

Arcuate and parallel double grooves frequently occur with tracks of this *Ignotorinis* morphotype. These are the most striking feature of *I. gajinensis* and thought be attributed to sweeping the opened bill from side to side to catch invertebrates in the substrate under the water. Arcuate double-grooved impressions of *I. gajinensis* have never been discovered in any other palmate bird tracks. This distinctive morphological "feeding" trace is characteristic of modern spoonbills (Order Ciconiiformes), a group not yet reported from the Lower Cretaceous Period. This is the first unequivocal example of extensive bill trace from the Cretaceous Period, and quite distinct from the dabble marks reported in association with the trackway named *Presbyorniformipes* at the Eocene in North America (Yang et al. 1995). Figure 3.11 shows a specimen of the type *I. gajinensi*s at the Lower Cretaceous Haenam Formation at the Gajin track site.

Cretaceous bird tracks assigned to *Aquatilavipes* as well as *Koreanaornis* were described for the first time at the Yeosu track site, Korea (Huh et al. 2012). The Yeosu *Aquatilavipes* is a small tridactyl bird track with no hallux impression. The average length and width of the tracks are 36 and 42.5 mm, respectively. The mean value of divarication between digits II and IV is 105.5° (Huh et al. 2012). Most of the complete bird tracks are oriented northward. At the southernmost end of the site, there are two sediment rims interpreted as the borders of non-avian dinosaur tracks.

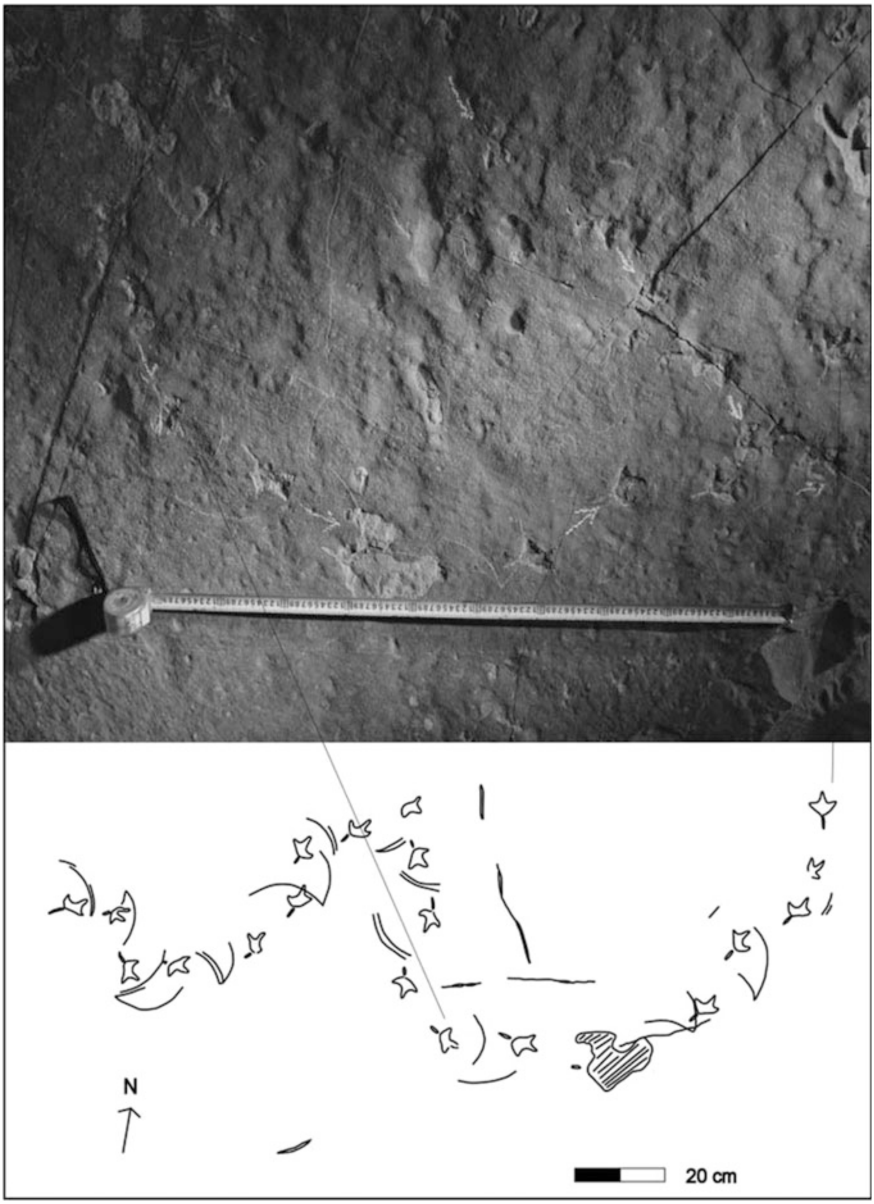


**Fig. 3.11** Photograph and map of *Ignotornis gajinensis* from the Lower Cretaceous Haman Formation at the Heritage Hall I area of the Gajin track site. *Source* Kim et al. (2012)

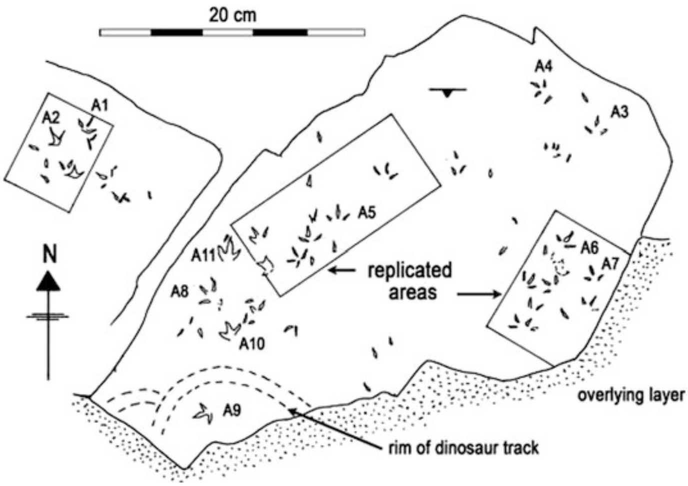


**Fig. 3.12** Bird tracks from the Aquatilavipes array on Sado Island, Yeosu area. *Notes* This array shows recognizable tridactyl tracks A1–A11 from which measurements were derived (compare the numbers with Fig. 3.13). Note the bird track inside a possible dinosaur track in the southern sector of the outcrop. Rectangular areas represent the approximate outlines of latex molds and replicas now in the Korea Dinosaur Research Center, Chonnam National University, and the University of Colorado Denver Dinosaur Tracks Museum (CU 214.214, 214.215, and 214.216). *Source* Huh et al. (2012)

Bird track A9 was found within one of these obscure tracks. Bird tracks assigned to *Aquatilavipes* from Sado Island, Yeosu, are shown in Figs. 3.12 and 3.13.

Tridactyl bird tracks similar to *Koreanaornis*, in that they also lack hallux traces, which are considerably larger (length and width of approximately 5.0 cm), were also described as *Aquatilavipes* at the Haman Formation of the Gajin track site (Kim et al. 2012).

Recently, a new semipalmate bird track was described as *G. lockleyi* at the Lower Cretaceous Jindong Formation, Donghae District, Goseong County, Korea (Kim et al. 2013). *G. lockleyi* is a small asymmetrical, strong mesaxonic bird track, about 31–32 mm long and 40–41 mm wide, with no clear hallux impression. The divarication between digits II and III (69°–71°) is larger than that between digits III and IV (56°–58°). The divarication between digits II and IV ranges from 125° to 130°. Semipalmate web impressions are clearly preserved, and the web between digits II and III is smaller than that between digits III and IV, resulting in strong asymmetry in web development. The length of digit III is 31–32 mm, and digits II and IV are 23 and 25 mm, respectively, which shows strong mesaxony (Kim et al. 2013).

*G. lockleyi* is distinctly distinguished from *Goseongornipes*, *Hwangsanipes*, *Ignotornis*, and *Sarjeantopodus*, which are web-footed bird tracks with prominent hallux impressions. *G. lockleyi* is different from *U. chuni*, which is also a web-footed bird track lacking a hallux trace, in its smaller size, larger divarication

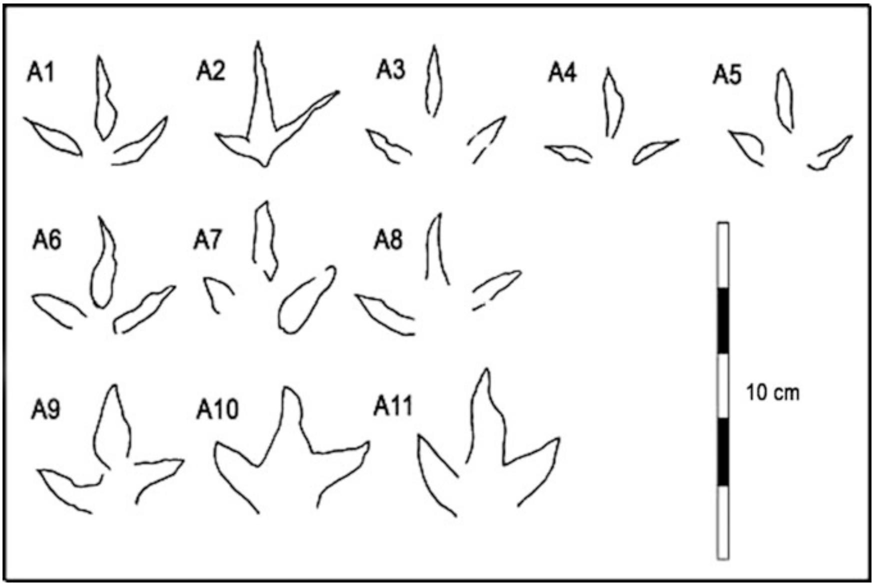


**Fig. 3.13** Bird tracks A1–A11 from the *Aquatilavipes* array on Sado Island, Yeosu area. *Source* Huh et al. (2012)

between digits II and IV, strong asymmetry of web development, and sharply pointed digital end (Fig. 3.14). On the basis of three tracks that are not well-preserved on a slab of red shale, new web-footed bird tracks with no hallux impression were recently described as *D. sinensis* at the Upper Cretaceous, Dongyang City, China (Azuma et al. 2013). *D. sinensis* appears to resemble *G. lockleyi*. However, *G. lockleyi* is distinguished from *D. sinensis* by its larger size, lower length/width ratio (0.77), and much larger divarication between digits II and IV. Table 3.7 shows measured data for comparison of named bird tracks with web traces from the Cretaceous Period.

## 3.2 Bird Bones

Like dinosaurs, Cretaceous bird skeletons are very rare in Korea. However, it is known that bird skeletons dubbed "*Archaeopteryx* of Choseon (Korea)" were discovered from the Lower Cretaceous in North Korea (Lee et al. 2001; Gao et al. 2009).

The only information we have regarding bird fossils from the Lower Cretaceous in North Korea is based on the book *Geology of Korea* published in Pyongyang, North Korea (Institute of Geology, State Academy of Sciences, DPRK). In this book, Pak and Kim (1996) described the Sinuiju Series of the Upper Jurassic Jasong

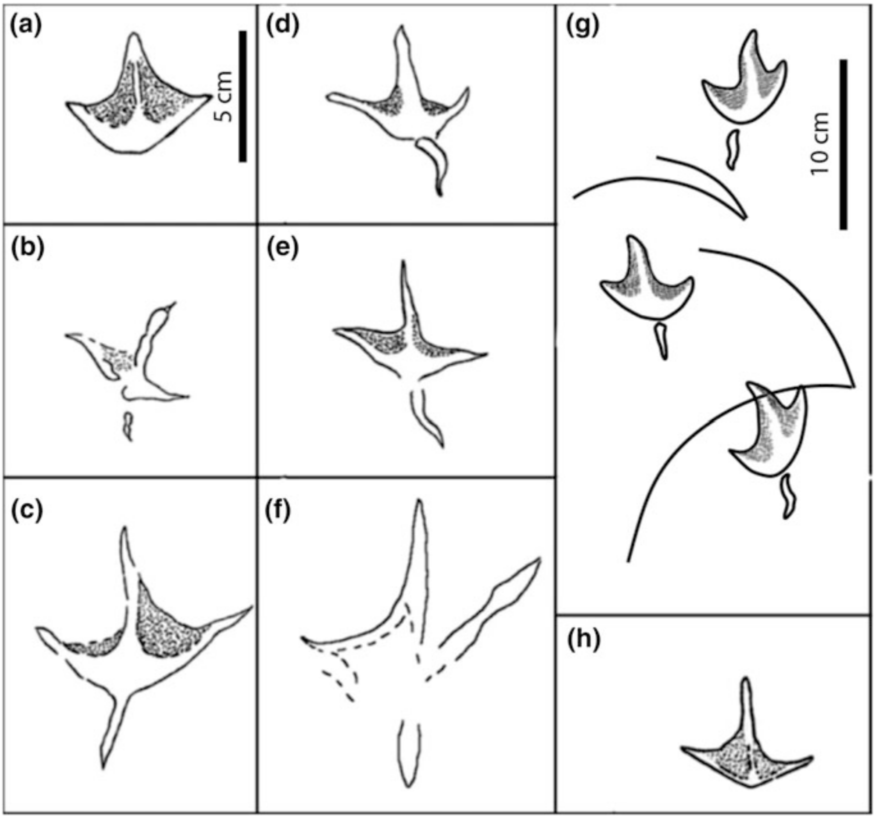


**Fig. 3.14** Comparison of named bird tracks with web traces from the Cretaceous Period. *Notes* **a** *Uhangrichnus chuni*; **b** *Goseongornipes markjonesi*; **c** *Hwangsanipes choughi*; **d** *Ignotornis mcconelli*; **e** *Ignotornis yangi*; **f** *Sarjeantopodus semipalmatus*; **g** a trackway of *Ignotornis gajinensis* from the Haman Formation; **h** holotype of *Gyeongsangornipes lockleyi* from the Jindong Formation, Hai District (KNUE 090204). Figures are shown at the same scale. *Source* Kim et al. (2013)

System, at which bird fossils were discovered in 1993. Interestingly, Pak and Kim (1996) reported that the Leader Kim Il Sung ordered that the bird fossils discovered in the third bed of the Sinuiju Series be called the founder birds ("*Archaeopteryx*") of Korea (*Proornis coreae* Lim). This bird fossil was designated as Natural Monument No. 464 of North Korea and housed at the Natural Museum of Kim Il Sung University, Pyongyang, North Korea (Fig. 3.15). Unfortunately, however, this bird fossil from the Lower Cretaceous of North Korea has not yet been formally described in a peer reviewed journal.

Gao et al. (2009) briefly reported these bird fossils at the Lower Cretaceous of North Korea. The first specimen (Fig. 3.15) shown in a stamp and *Geology of Korea* consists of a nearly complete wing-supporting skeleton, and the second

**Table 3.7** Data for comparison of named bird tracks with web traces from the Cretaceous Period

| Bird tracks | Length | Width | LII | LIII | LIV | II/III | III/IV | II/IV | References |
|---|---|---|---|---|---|---|---|---|---|
| *Uhangrichnus chuni* | 37 | 46 | | | | 53–58 | 51–59 | 110–111 | Yang et al. (1995) |
| *Goseongornipes markjonesi* | 30–35 (41–45) | 42–45 | | | | | | 140–150 | Lockely et al. (2006a) |
| *Hwangsanipes choughi* | (49) | 63 | | | | | | 112 | Yang et al. (1995) |
| *Ignotornis mcconnelli* | (56) | 50 | | | | | | 90–115 | Mehl (1931) |
| *Ignotornis yangi* | 33 (51) | 45 | 24 | | 28 | 64 | 59 | 123 | Kim et al. (2006) |
| *Ignotornis gajinensis* | (67.5) | 55.4 | | | | 70 | 60 | 130 | Kim et al. (2012) |
| *Sarjeantopodus semipalmatus* | (90) | 76 | 37 | | 59 | 67 | 42 | 109 | Lockley et al. (1994) |
| *Gyeongsangornipes lockleyi* | 31–32 | 40–41 | 23 | 31–32 | 25 | 69–71 | 56–58 | 125–130 | Kim et al. (2013) |

*Notes* Length and Width: track length and width (mm); LII, LIII, LIV: length of digits II, III and IV (mm); II/III, III/IV, II/IV: digit divarication angles (°) between digits II and III, III and IV, and II and IV, respectively. Length data in parentheses are values including the hallux
Source Kim et al. (2013)

specimen is a partial wing skeleton (Fig. 3.16). These bird fossils are characterized by having a strongly widened and subquadrangular deltopectoral crest of the humerus, a phalangeal formula of 2-3-4-x-x, the major and minor metacarpals equal in length, an extremely short proximal phalanx of the minor digit (III), and a semilunate bone free from the major metacarpal (Gao et al. 2009; Fig. 3.16). All of these are diagnostic features of the family Confuciusornithidae (Chiappe 2002). Several specimens of other bird skeletons from the Sinuiju Series indicate enantiornithine, which is a diverse group of extinct birds primitively retaining teeth that existed with Confuciusornithidae in the Korean Peninsula during the Cretaceous (Gao et al. 2009). In addition, the occurrence of the Cretaceous fossil birds extended the biogeographical distribution of the Jehol Biota, one of the most important Mesozoic largerstäten (Zhou and Wang 2010), into the Korean Peninsula.


**Fig. 3.15** A commemorative stamp produced in North Korea showing a fossil of "the Korean Archaeopteryx" . *Notes* Although the geological age of the fossil-bearing formation was regarded as Upper Jurassic (150 Ma shown in the stamp), Lee et al. (2001) and Gao et al. (2009) thought that it may be Lower Cretaceous

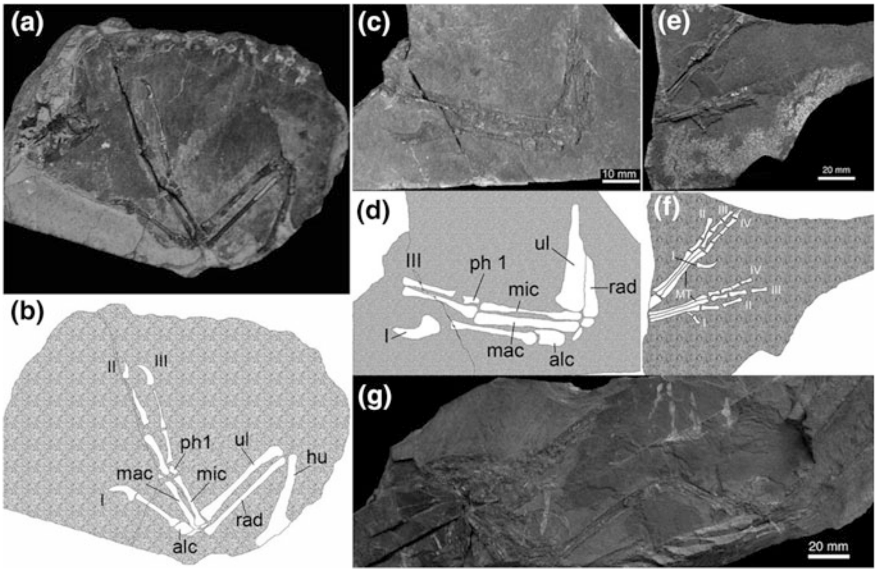


**Fig. 3.16** Representative bird fossils from Sinuiju, North Korea. *Notes* **a**–**b** wing skeleton and claws of a confuciusornithid (specimen of "the *Archaeopteryx* of Korea"); **c**–**d** partial forelimb of a confuciusornithid; **e**–**f** feet and the claws of an enantiornitine; **g** a large specimen with a long pygostyle. Abbreviations used in this figure are: alc = alular metacarpal; hu = humerus; mac = major metacarpal; mic = minor metacarpal; MT = metatarsal; ph = phalanx; rad = radius; ul = ulna. *Source* Gao et al. (2009)

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# Chapter 4
# Pterosaurs and Other Reptiles of Korea

## 4.1 Pterosaur Tracks

Unlike dinosaurs and birds which were discovered in abundance from the Cretaceous in Korea, pterosaur and other reptile fossils are comparatively rare. Nevertheless, tracks, teeth, and skeletons of pterosaurs have been reported, and they are highly significant for paleontological understanding not only about pterosaurs, but also about the dinosaurs and birds that flourished in east Asia during the Cretaceous Period.

Pterosaur tracks have attracted considerable attention in the debate over pterosaurian locomotion; bipedal or quadrupedal, digitigrade or plantigrade, fully erect or semi-erect (Padian 1983; Lockley et al. 1995; Bennett 1997; Unwin 1997). Three ichnogenera of purported pterosaur tracks have been described: *Pteraichnus* (Stokes 1957); *Purbeckopus* (Delair 1963), and *Haenamichnus* (Hwang et al. 2002). Up until the year 2000, only two ichnospecies of *Pteraichnus* were known: *Pteraichnus saltwashensis* Stokes (1957) and *Pteraichnus stokesi* Lockley et al. (1995). In 2000–2001, five new ichnospecies of *Pteraichnus* were described from the Berriasian Period in Spain. The Spanish ichnospecies of *Pteraichnus* have been reviewed by Billon-Bruyat and Mazin (2003), Lockley et al. (2008), and Sánchez-Hernández et al. (2009).

To date, four ichnospecies of pterosaurs have been described from the Cretaceous in Korea: *Haenamichnus uhangriensis* (Hwang et al. 2002), *Pteraichnus* ichnosp. (Kim et al. 2006), *Pteraichnus koreanensis* (Lee et al. 2008), and *Haenamichnus gainensis* (Kim et al. 2012).

Discovery of pterosaur tracks from the Upper Cretaceous Uhangri Formation in theat Haenam area was briefly noted by Huh et al. in (1996). The Uhangri pterosaur tracks represent the first recorded in Asia, and the largest pterosaur tracks ever discovered (Huh et al. 1996). Lockley et al. (1997) were the first to describe the Uhangri pterosaur tracks. They provided a map of the main concentration of pterosaur tracks from the Uhangri Formation at the Uhangri site (Fig. 4.1). As shown in Fig. 4.1, pterosaur tracks co-occur with web-footed bird tracks,

 
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*Uhangrichnus* and *Hwangsanipes* on a single bedding surface of well-laminated black shale deposited in a lake environment (Chun and Chough 1995). The co-occurrence of bird and pterosaur tracks is the second to be recorded and suggests that both groups may have shared the same food resources (Lockley et al. 1997).

At least thirty pterosaur tracks and two inferred trackways of pterosaur can be observed (Lockley et al. 1997, Fig. 4.2). One inferred trackway segment consists of one right manus track and two right and left pes tracks. The pes tracks are outwardly rotated at an angle about 3°–35°. The manus track is also outwardly rotated but at a much wider angle than that of the pes track. The other trackway segment is composed of two right manus, one left manus, and one left pes track (Fig. 4.2). The external trackway widths of the two trackway segments are 80 and 50 cm, respectively.

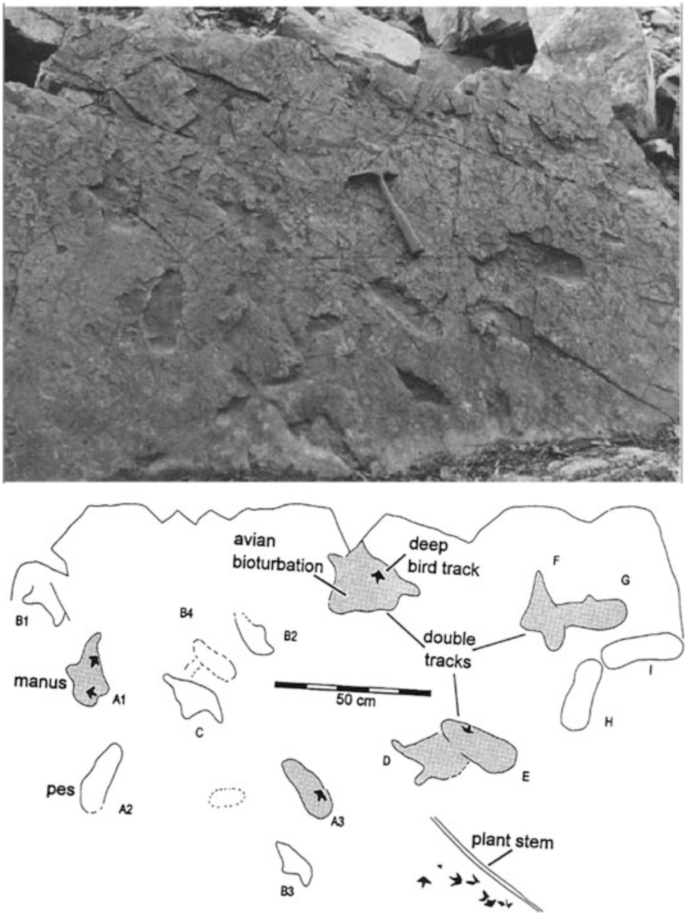



**Fig. 4.1** Photograph and map of the main concentration of pterosaur tracks at the Uhangri Formation, Haenam area. *Notes* Probable trackway segments A1–A3 and B1–B4 are redrawn in Fig. 4.2. Other tracks at the main site are labeled C–I. *Source* Lockley et al. (1997)

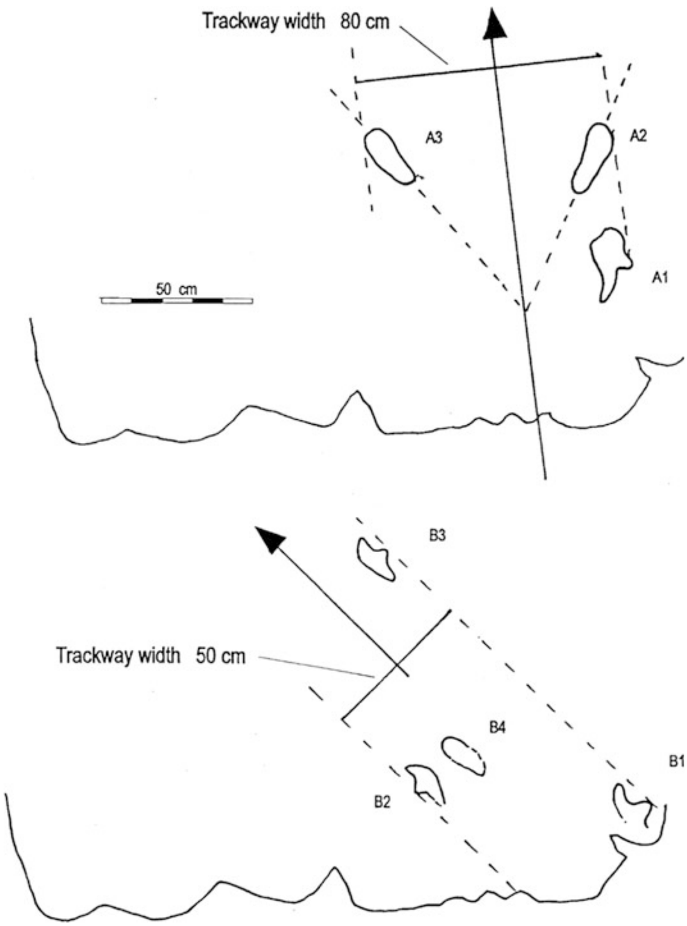



**Fig. 4.2** Individual pterosaur trackway segments (A1–3 and B1–4) interpreted from the main mapped area (cf. Fig. 4.1) of the Uhangri track site. *Source* Lockley et al. (1997)

In addition to the outward rotation of the manus and pes tracks, and to the trackway parameters, well-preserved and isolated manus and pes tracks show features diagnostic of pterosaurian affinity (Lockley et al. 1997). Figure 4.2 shows isolated tracks and a manus-pes set. Manus tracks are asymmetrical, tridactyl with digit III longer than digits I and II, and 20–30 cm in length. The pes track is elongated and characterized by having an impression of digit V and at least two pairs of semispherical digital pad impressions (Fig. 4.2).

All features of the Uhangri tracks indicate pterosaurian origin and conform to typical *Pteraichnus* morphology. Although a systematic description of the pterosaurian tracks was not carried out, the Uhangri tracks are significant in that: (1) they indicate the probable identity of the track maker, (2) they afford an improved understanding of Cretaceous pterosaur tracks, (3) they indicate pterosaur locomotion in large pterodactyloids, (4) they show pterosaur habitats and paleoecology, and (5) they denote the relationships between pterosaurs and birds (Lockley et al. 1997).

The first detailed systematic description of the Uhangri pterosaur tracks was reported in Hwang et al. (2002). As a result of two-year of excavation, 443 pterosaur tracks and thousands of footprints of web-footed birds were discovered in the upper part of the Uhangri track site (Yang et al. 1995; Huh et al. 1996; Lockley et al. 1997). The Uhangri pterosaur tracks represent the stratigraphically youngest record, the first to be reported from Asia (Lockley et al. 1997; Hwang et al. 2002). One pterosaur trackway composed of 14 pairs of tracks is 7.3 m long and the longest pterosaur trackway yet discovered (Hwang et al. 2002, Fig. 4.3).

The newly named *H. uhangriensis* represents the third ichnogenus and the fourth ichnospecies of pterosaur tracks following *P. saltwashensis* (Stokes 1957), *P. stokei* (Lockley et al. 1995), and *Purbeckopus pentadactylus* (Wright et al. 1997). *H. uhangriensis* is a quadrupedal and large pterosaur track. The front part of the elongated pes track is broadly triangular, with no separation of the digit impressions, while the heel region is narrower and rounded. Thick and short impressions of digit V of the pes track and impressions of large interphalangeal pads on pes digits II and III are distinct. The pes track is up to 350 mm in length, and 105 mm in width. The manus tracks are tridactyl, strongly asymmetric, and outwardly rotated at almost a right angle to the long axis of the trackway. The digit III trace is much longer than digits II and III. The manus track is up to about 235 mm in length, and 110 mm in width (Hwang et al. 2002, Table 4.1).

Although Hwang et al. (2002) described *H. uhangriensis* with the pes print being up to 350 mm in length and 105 mm in width, which was probably based on the holotype, they did not provide the measured data of the trackway including the holotype. According to the measured data of trackways A–F, the length of the pes tracks ranges from 170 to 235 mm (with a typical footprint size ranging from 200 to 220 mm (Hwang et al. 2002).

The second record of pterosaur tracks in Korea was described as *Pteraichnus* ichnosp. at the Lower Cretaceous (Aptian-Albian) Haman Formation, Sinsu Island, Namhae County (Kim et al. 2006, Fig. 4.4). The pterosaur tracks of Sinsu Island consist predominantly of tridactyl manus tracks characterized by strongly asymmetric digit impressions that outnumber elongated pes traces, which are less clear, by a ratio of about 10 to 1. The manus tracks are approximately 10–12 cm in length and 3–4 cm in width. The digit I impression is the shortest and is outwardly rotated at an angle of about 86° relative to the trackway axis, the digit II trace is intermediate and outwardly rotated at an angle of about 139°, and the digit III impression is the longest, slightly curved, and outwardly rotated at an angle of 165°–180° (Kim et al. 2006). The elongated pes tracks show short digit traces. Clusters of two, three or more short digit impressions or striations are characteristic features. The length and width of the elongated pes traces are up to 13.8 and 4.1 cm, respectively. The distal extremities are often marked by fine triangular claw impressions that terminate sharply (Kim et al. 2006).

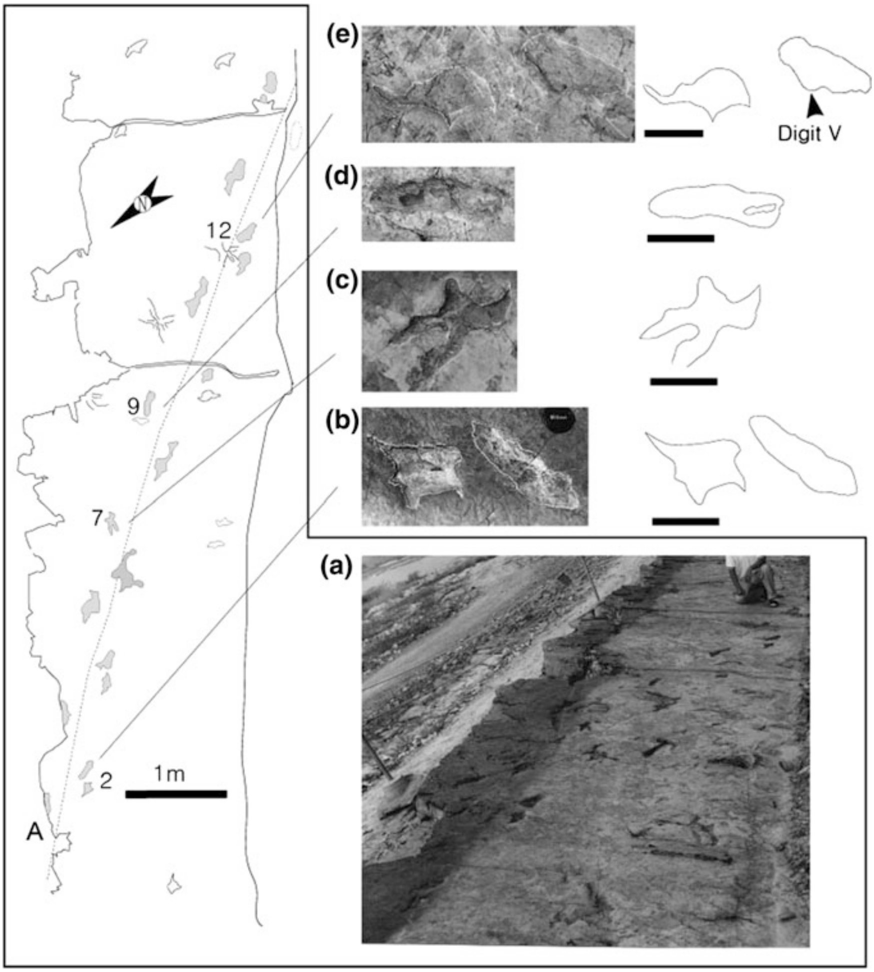



**Fig. 4.3** Pterosaur tracks and trackways from the Uhangri Formation of Haenam area. *Notes* **a** Photograph and map of site P9 (CNUPH.P9) showing the longest pterosaur trackway at the Uhangri Formation (A: length 7.3 m), which is also the longest known so far anywhere in the world. The dashed line indicates the trackway midline; **b** Impression of 2nd right manus-pes pair; **c** 7th left manus impression; **d** 9th left pes impression; **e** impression of 12th right manus-pes pair. The scale bar in (**b**–**e**) represents 100 mm. *Source* Hwang et al. (2002)

The characteristic shape of manus impressions allow the pterosaur tracks of Sinsu Island to be assigned to *Pteraichnus*. The elongated pes impressions and clusters of short digit impressions were interpreted to have been made by swimming pterosaurs (Kim et al. 2006). Pterosaur swim tracks have rarely been discovered, except for those from the Late Jurassic Summerville and Sundance formations of western North America (Lockley and Wright 2003). Like the cases of the Sinsu

**Table 4.1** Measurement of pterosaur trackways, *Haenamichnus uhangriensis* at the Uhangri Formation, Haenam area

| Trackway no. | Track no. | L/R | Track length (mm) | Track width (mm) | Track depth (mm) | FO (degrees) | Pace length (mm) | Stride length (mm) | Site |
|---|---|---|---|---|---|---|---|---|---|
| A | 1 | P-L | 245 | 70 | 11 | S57E | 515 | 877 | P9 |
| | 2 | M-R | 193 | 126 | 11 | S37E | | | |
| | | P-R | 217 | 69 | 10 | S29E | 646 | 1046 | |
| | 3 | P-L | 231 | 28 | 9 | S64E | 646 | 1092 | |
| | 4 | M-R | 214 | 88 | 10 | S51E | | | |
| | | P-R | 215 | 110 | 10 | S40E | 600 | 892 | |
| | 5 | M-L | 230 | 100 | 9 | S42E | | | |
| | | P-L | 235 | 110 | 11 | S60E | 338 | | |
| | 6 | M-R | 234 | 96 | 11 | S42E | | | |
| | | P-R | 231 | 53 | 10 | S29E | | | |
| | 7 | M-L | 214 | 94 | 11 | S55E | | | |
| | 8 | M-R | 250 | 123 | 11 | S37E | | | |
| | 9 | P-L | 224 | 65 | 11 | S46E | 862 | 1123 | |
| | 10 | M-R | 168 | 115 | 10 | S28E | | | |
| | 11 | M-L | 210 | 120 | 11 | S38E | | | |
| | | P-L | 215 | 90 | 11 | S38E | 691 | 1169 | |
| | 12 | M-R | 254 | 127 | 11 | S36E | | | |
| | | P-R | 235 | 108 | 11 | S18E | 631 | 1446 | |
| | 13 | M-L | 235 | 92 | 11 | S37E | | | |
| | | P-L | 202 | 109 | 11 | S42E | | 869 | |
| | 15 | M-L | | 55 | 11 | | | | |
| | | P-L | 254 | 122 | 11 | S56E | | | |
| Average | | Manus | 220 | 103 | 11 | | | | |
| | | Pes | 228 | 85 | 11 | | 616 | 1064 | |
| B | 1 | M-L | 240 | 150 | 18 | S42W | | | P4 |
| | | P-L | 242 | 102 | 14 | S62W | | | |
| | 2 | P-R | 227 | 99 | 13 | S8E | | | |

(continued)

**Table 4.1** (continued)

| Trackway no. | Track no. | L/R | Track length (mm) | Track width (mm) | Track depth (mm) | FO (degrees) | Pace length (mm) | Stride length (mm) | Site |
|---|---|---|---|---|---|---|---|---|---|
| Average | | Manus | 240 | 150 | 18 | | | | |
| | | Pes | 235 | 101 | 14 | | | | |
| C | 1 | M-R | | | | S11E | | | |
| | 2 | M-L | 170 | 80 | 9 | S17E | | | |
| | | P-L | 170 | 65 | 9 | S22E | | | |
| | 3 | M-R | 170 | 80 | 13 | S12E | | | |
| Average | | Manus | 170 | 80 | 11 | | | | |
| | | Pes | 170 | 65 | 9 | | | | |
| D | 1 | M-R | 159 | 54 | 13 | S23E | 710 | | P1 |
| | 2 | M-L | 202 | 67 | 13 | S2E | | | |
| E | 1 | M-R | 194 | 60 | 16 | N18E | 638 | 877 | |
| | 2 | M-L | 140 | 72 | 16 | N8W | 708 | | |
| | 3 | M-R | 194 | 91 | 10 | N31W | | | |
| F | 1 | M-L | 201 | 64 | 19 | S65W | 654 | 1362 | |
| | 2 | M-R | 165 | 54 | 9 | | 977 | | |
| | 3 | M-L | 178 | 38 | 14 | N62W | | | |
| Average | | Manus | 181 | 52 | 14 | | 816 | 1362 | |

*Note* FO: Footprint long axis orientation
*Source* Hwang et al. (2002)

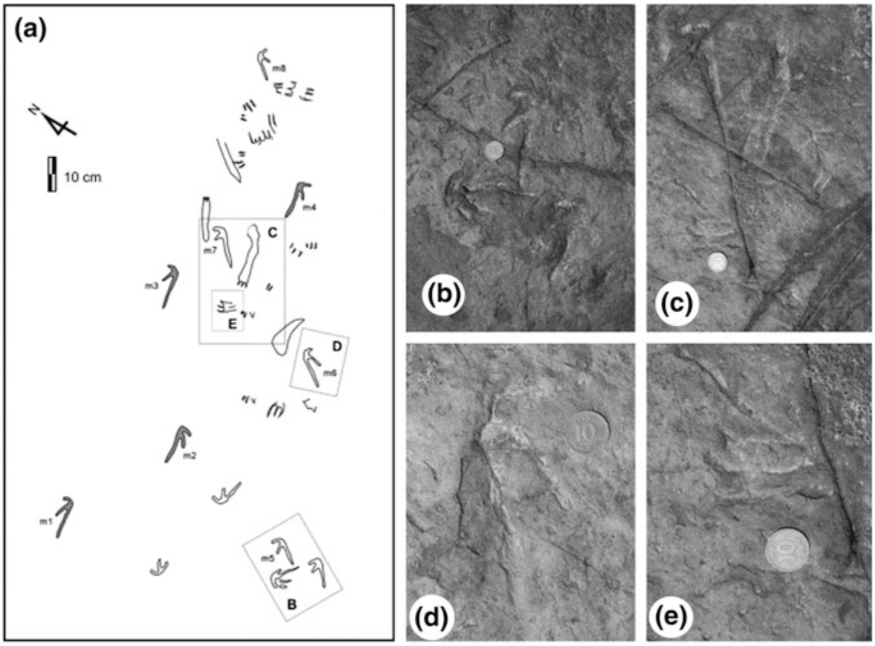



**Fig. 4.4** The pterosaur tracks from the Haman Formation, Sinsu Island. *Notes* **a** Map of *Pteraichnus*; two trackways recognized are shown in black (m 1 to m 4) and gray (m 5 to m 8); **b**–**e** detailed photographs of *Pteraichnus* shown in **a**. The coin in **b**–**e** is 23 mm in diameter. Note that additional manus tracks and incomplete pes "swim" tracks indicate one or more trackways of other individuals. *Source* Kim et al. (2006)

tracks, the manus-dominated array is also typical of pterosaur track assemblages (Lockley et al. 1995; Mickelson et al. 2004).

The fifty new pterosaur tracks were reported from the Lower Cretaceous Hasandong Formation, Hadong County, Korea (Lee et al. 2008). These new pterosaur tracks were named *P. koreanensis* (Lee et al. 2008, Figs. 4.5 and 4.6).

*P. koreanensis* is small quadrupedal track composed of asymmetrical and tridactyl manus impressions and a triangular, elongated, fully plantigrade, and tetradactyl pes track (Lee et al. 2008). The average manus length and width are 25.6 and 12.3 mm, respectively. The digit I trace is anterolaterally oriented and the shortest (average length 10.7 mm). Digits II and III are oriented posterolaterally. The digit II impression is intermediate in length (12.8 mm) and the digit III trace is the longest (18.5 mm). Divarications between digits I–II, II–III, and I–III are 68.5°, 47.6°, and 116.2°, respectively (Lee et al. 2008, Table 4.2).

The pes track is an average of 25.7 mm in length and 12.8 mm in width. The four digit imprints are roughly subequal in length. The metatarsals are long and elongated, and always longer (average length 17.5 mm) than the digit (Lee et al. 2008). *P. koreanensis* represents the stratigraphically oldest pterosaur tracks in Korea, and the first named ichnospecies of *Pteraichnus* in Asia.

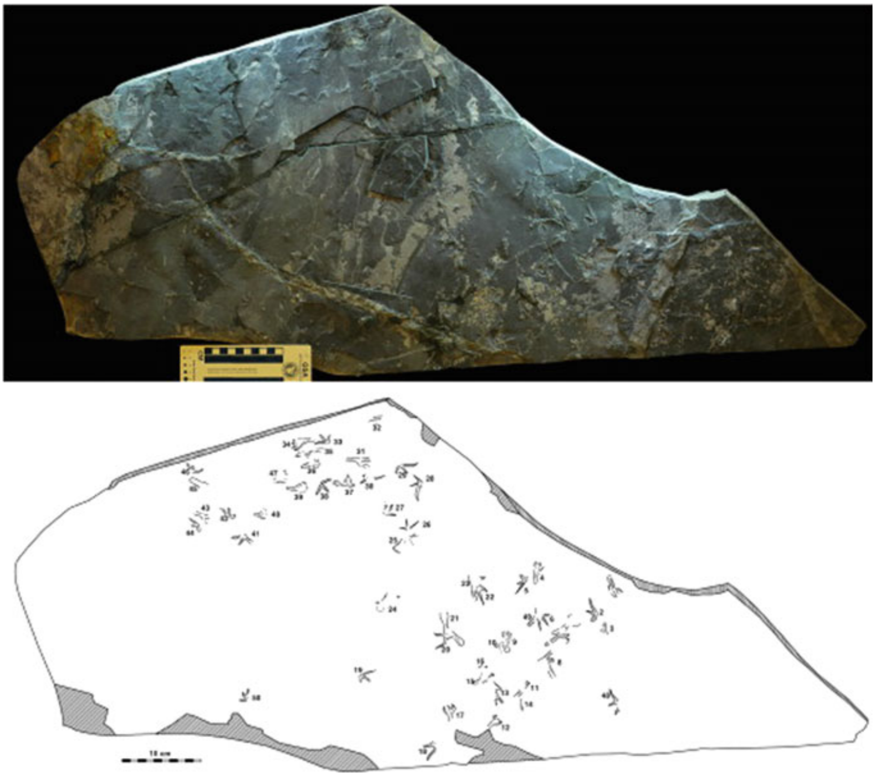


**Fig. 4.5** Photograph and drawing of *Pteraichnus koreanensis* from the Lower Cretaceous Hasandong Formation, Hadong area. *Source* Lee et al. (2008)

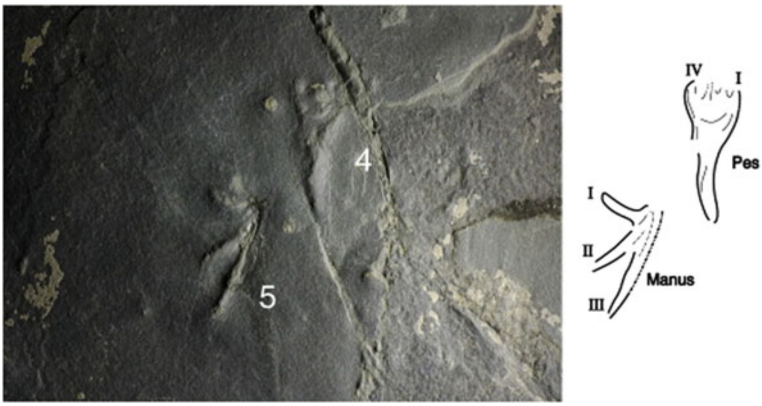



**Fig. 4.6** Enlarged photograph and drawing of a complete right manus-pes set (number 4, 5) of the Hadong pterosaur tracks. *Source* Lee et al. (2008)

**Table 4.2** Measurement (in mm) of *Ptraichnus koreanensis* at the Hasandong Formation at the Hadong site

| $T_{\#}$ | M/p | L/R | L | W | L/W | I | II | III | IV | MT | $D_{I–II}$ | $D_{II–III}$ | $D_{I–III}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | P | R | 21.4 | 12.5 | 1.7 | | | | 7.4 | 12.9 | | | |
| 2 | M | L | 27.9 | 12.1 | 2.3 | 9.3 | 13.5 | 22.9 | | | 75 | 50 | 125 |
| 3 | P | L | | | | | | | | 16.3 | | | |
| 4 | P | R | 23.6 | 10.9 | 2.2 | 9.5 | | | 10.8 | 15.2 | | | |
| 5 | M | R | 22.4 | 10.1 | 2.2 | 7.3 | 12.7 | 20.7 | | | 50 | 30 | 80 |
| 6 | M | L | 25.5 | 12.2 | 2.1 | 10.7 | 17.1 | 20.7 | | | 45 | 45 | 90 |
| 7 | P | ? | 30.1 | 13.9 | 2.2 | | | 8.5 | 9.3 | 20.5 | | | |
| 8 | P | ? | 28.7 | | | | | | | 22.7 | | | |
| 9 | P | R | 21.7 | 11.0 | 2.0 | 9.6 | 9.4 | 10.5 | 8.1 | 16.2 | | | |
| 10 | M | R | | 12.3 | 0.0 | 8.7 | 9.6 | | | | | | |
| 11 | P | ? | 25.8 | 10.8 | 2.4 | | | 9.6 | | 16.6 | | | |
| 12 | P | ? | 25.0 | 12.8 | 2.0 | 8.2 | 8.3 | | 9.7 | 17.9 | | | |
| 13 | M | L | 32.6 | | | 12.3 | 12.6 | 19.1 | | | | | |
| 14 | M | ? | | | | 5.9 | | | | | | | |
| 15 | M | ? | | | | | 8.5 | | | | | | |
| 16 | P | ? | 25.9 | 14.7 | 1.8 | 8.1 | 8.7 | 11.8 | 14.7 | 20.6 | | | |
| 17 | P | ? | 26.8 | 16. | 1.6 | 10.7 | 11.2 | 10.0 | 12.4 | 20.6 | | | |
| 18 | M | R | | 16.8 | | | 13.4 | 18.1 | | | | | |
| 19 | M | R | 23.1 | 10.9 | 2.1 | 9.7 | 10.9 | 14.5 | | | 60 | 55 | 115 |
| 20 | M | R | 26.2 | 16.8 | 1.6 | 10.0 | 18.0 | 14.1 | | | | | |
| 21 | P | R | 24.9 | 8.9 | 2.8 | 7.8 | 7.9 | 8.2 | 10.0 | 15.6 | | | |
| 22 | M | L | 28.1 | 12.6 | 2.2 | 14.8 | 15.3 | 23.4 | | | 70 | 35 | 105 |
| 23 | P | L | 32.8 | 16.7 | 2.0 | 10.6 | | 13.4 | 14.7 | 19.3 | | | |
| 24 | P | ? | 30.4 | 14.6 | 2.1 | 9.9 | | 12.4 | | 19.2 | | | |
| 25 | M | ? | 23.8 | 10.4 | 2.3 | 11.3 | 13.1 | 21.3 | | | | | |
| 26 | M | L | 27.9 | 15.1 | 1.8 | 11.7 | 17.0 | 20.2 | | | 70 | 65 | 135 |
| 27 | M | R | 24.1 | 13.9 | 1.7 | 12.0 | 14.5 | 16.0 | | | 65 | 35 | 100 |

(continued)

**Table 4.2** (continued)

| $T_{\#}$ | M/p | L/R | L | W | L/W | I | II | III | IV | MT | $D_{I–II}$ | $D_{II–III}$ | $D_{I–III}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | M | R | 29.7 | 16.6 | 1.8 | 15.2 | 16.6 | 23.0 | | | 65 | 65 | 130 |
| 29 | M | R | 29.2 | 13.7 | 2.1 | 13.8 | 14.0 | 19.9 | | | 70 | 50 | 120 |
| 30 | P | ? | 32.3 | 16.2 | 2.0 | 8.4 | | 12.2 | | 21.2 | | | |
| 31 | P | ? | 30.1 | 12.7 | 2.4 | 10.3 | 12.2 | 13.9 | 13.6 | 19.5 | | | |
| 32 | P | ? | | | | | | 14.4 | 12.4 | | | | |
| 33 | M | R | 21.2 | 14.0 | 1.5 | 9.2 | 12.8 | 16.5 | | | 55 | 45 | 100 |
| 34 | P | ? | 25.0 | 13.8 | 1.8 | 8.1 | 8.9 | 9.8 | 8.7 | 15.4 | | | |
| 35 | M | ? | 29.1 | | | 13.9 | 12.5 | 20.0 | | | | | |
| 36 | P | ? | 22.6 | 10.5 | 2.2 | 8.0 | | 8.9 | 7.7 | 12.0 | | | |
| 37 | P | ? | 25.0 | 13.1 | 1.9 | 8.5 | 8.1 | 10.0 | 7.0 | 16.7 | | | |
| 38 | M | L | 26.3 | 12.3 | 2.1 | 11.1 | 11.3 | 17.4 | | | 70 | 65 | 135 |
| 39 | P | ? | 23.1 | 11.1 | 2.1 | 8.5 | 9.1 | 10.6 | 9.0 | 17.0 | | | |
| 40 | P | ? | | 11.2 | 0.0 | 8.3 | 8.7 | 9.1 | 8.6 | | | | |
| 41 | M | L | 26.2 | 13.5 | 1.9 | 11.9 | 11.3 | 16.2 | | | 80 | 50 | 130 |
| 42 | M | R | 22.7 | 8.5 | 2.7 | 9.4 | 8.7 | 16.6 | | | 75 | 55 | 130 |
| 43 | P | ? | 20.8 | 12.0 | 1.7 | | 7.3 | | 9.2 | 16.3 | | | |
| 44 | M | L | 19.2 | 11.1 | 1.7 | 7.9 | 7.2 | 11.5 | | | 100 | 40 | 140 |
| 45 | P | ? | 20.7 | 10.1 | 2.0 | | 7.9 | | 8.9 | 14.4 | | | |
| 46 | M | L | 22.6 | 10.3 | 2.2 | 9.3 | 8.8 | 14.4 | | | 85 | 30 | 115 |
| 47 | P | ? | 23.2 | 13.0 | 1.8 | 8.1 | 8.9 | 10.2 | | 17.6 | | | |
| 48 | M | L | 27.9 | 11.7 | 2.4 | 11.8 | 14.3 | 21.9 | | | 60 | 55 | 115 |
| 49 | P | L | 25.5 | 14.1 | 1.8 | 8.7 | | | 11.1 | 19.5 | 70 | 40 | 110 |
| 50 | M | L | 21.2 | 11.6 | 1.8 | 10.0 | 12.5 | 18.3 | | | | | |
| Manus in average | | | 25.6 | 12.3 | 2.2 | 10.7 | 12.8 | 18.5 | | | 68.5 | 47.6 | 116.2 |
| Pes in average | | | 25.7 | 12.8 | 2.0 | 8.9 | 9.0 | 10.8 | 10.2 | 17.5 | | | |

*Notes* Abbreviations: $T_{\#}$, track number; M/P, manus/pes; L/R, left/right; L, length; W, width; L/W, ratio of length/width; I, II, III, IV, length of digits I, II, III, IV; MT, metatarsals length; $D_{I–II}$, divarication between digits I and II; $D_{II–III}$, divarication between digits II and III; $D_{I–III}$, divarication between digits I and III
*Source* Lee et al. (2008)

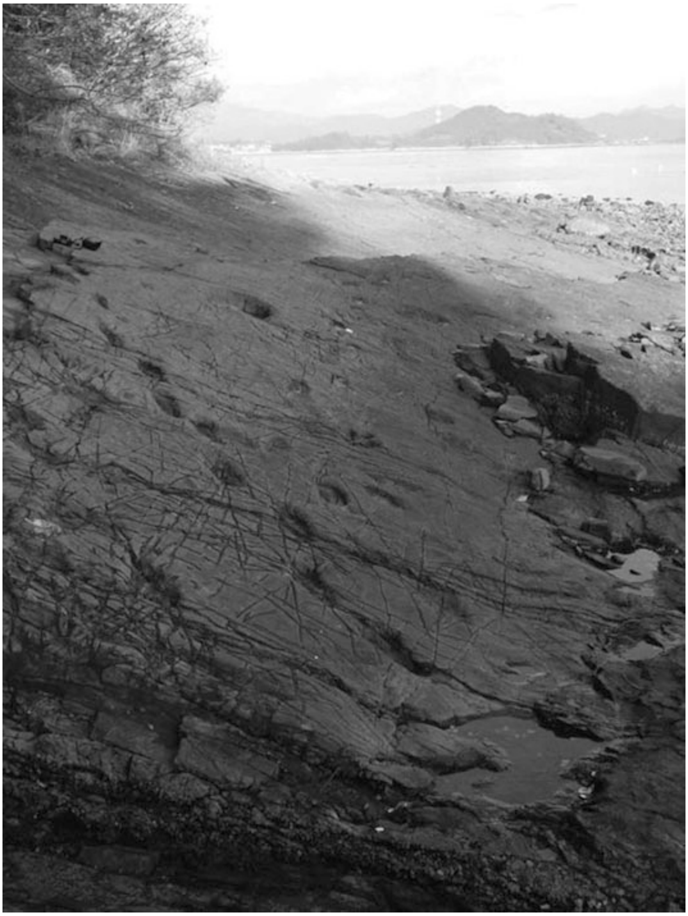


**Fig. 4.7** Outcrop view of the Gain track site on Changseon Island. *Notes* The top is to the east. This image shows the bipedal trackway of elongated pterosaur tracks (from lower right to upper left) and the quadrupedal trackway of large sauropod tracks (from center to upper right) which are preserved on the gently inclined bedding surface of the Haman Formation. The individual pterosaur tracks are up to 35 cm in length. *Source* Kim et al. (2012)

Enigmatic giant pterosaur tracks and associated dinosaur tracks were described at the Lower Cretaceous Haman Formation at the Gain site, Changseon Island—where the oldest web-footed bird tracks, *Ignotornis yangi*, and the first *Minisauripus* were found (Kim et al. 2006; Lockley et al. 2008)—and Adu Island, which is located about 2 km west of the swimming pterosaur track site in Sinsu Island (Kim et al. 2006).

The Gain track site, Changseon Island, Namhae County (Fig. 4.7) has been known for more than twenty years and was designated as Natural Monument No. 499 of Korea. It yields enigmatic tracks vaguely resembling modern human footprints associated with sauropod, ornithopod, and theropod tracks on the same bedding surface.

Many tourists, including several creationists, have visited the Gain track site, which has ironically been thought to provide evidence that humans and dinosaurs coexisted. In this regard, the Gain track site is a case similar to that of the Paluxy River "human" footprint story in Texas (Kuban 1989). Seo (1997) interpreted the tracks as possibly pterosaurian but provided no conclusions pending further research. An interpretative sign introducing the Gain tracks to tourists explains that the human footprint-like tracks were originally interpreted as pterosaur tracks at the time of their discovery, but could be unknown dinosaur tracks.

There are at least five pterosaur trackways at the Gain track site, with one sauropod trackway assigned to *Brontopodus birdi*, two ornithopod trackways, and one theropod trackway (Fig. 4.8). As shown in Fig. 4.8, the longest pterosaur trackway (P1) is about 18 m long and composed of 25 consecutive tracks. This trackway represents the longest pterosaur trackway yet documented; the previous record-holder was the trackway of *H. uhangriensis* (7.3 m in length; Hwang et al. 2002). Trackways P2, P3, P4, and P5 are composed of nine, six, ten, and five consecutive tracks, respectively. At the Adu track site, one trackway composed of five consecutive tracks is preserved (Fig. 4.9).

The Gain and Adu tracks assigned to a new ichnospecies, *H. gainensis* (Kim et al. 2012), are large, pes only tracks in narrow trackways, indicating an erect, bipedal track maker with outwardly rotated, subsymetric, plantigrade pes impressions. The external trackway width ranges from 20 to 32 cm, about three times the pes width. The pace angulation ranges from 136° to 154° and the stride length changes between 77 and 100 cm (2.8–3.3 times the track length) at the Gain track site. The pes tracks are 27.5–35.0 cm in length and 14.2–14.4 cm in width at the Gain site (Table 4.3).

The pes tracks are plantigrade and subtriangular with a narrow, tapering heel impression, and are weakly rotated outward at an angle of about 10°–20° relative to the trackway axis at the Gain site. The Adu tracks, however, show weakly inward rotation (Fig. 4.9). The holotype track bears impressions of four separate pedal digits

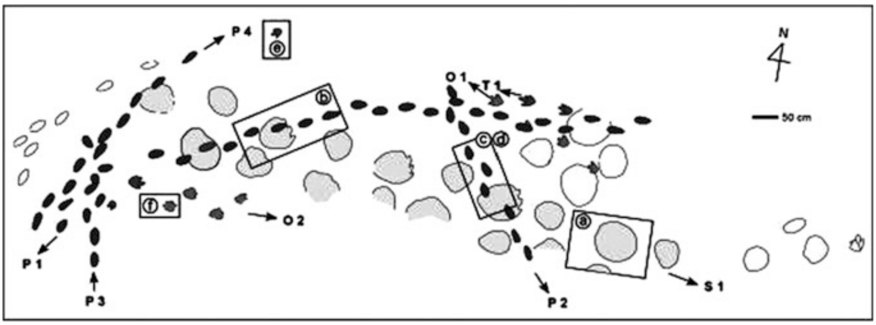



**Fig. 4.8** Map showing track distribution at the Gain track site. *Notes* Arrows indicate trackway direction. The boxes lettered a–f correspond to tracks and trackway portions shown close up in Fig. 2.34. Note that many tracks overlap. *Source* Kim et al. (2012)

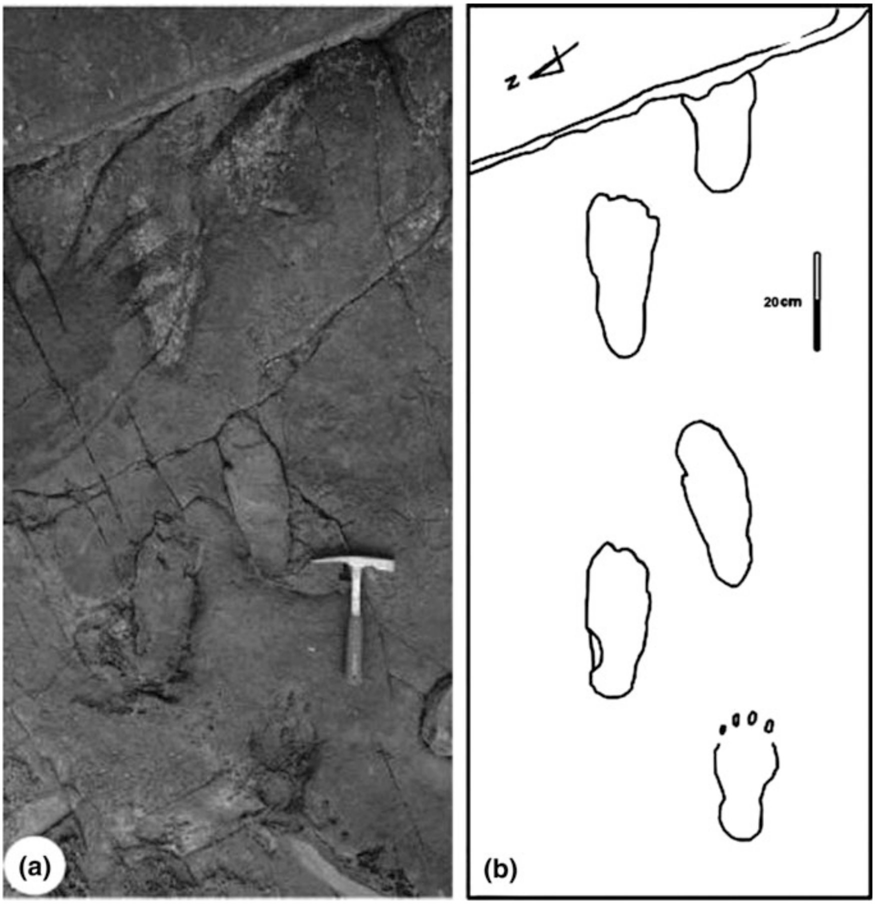



**Fig. 4.9** Photograph and sketch of pterosaur trackway on Adu Island. *Source* Kim et al. (2012)

(each about 2.5 cm thick) with short claw marks and relatively large, deep heel impressions with the posterior margin subtending an acute angle (Fig. 4.10a, b).

The Adu tracks are very large, elongated, and subtriangular, and occur in a narrow trackway (Figs. 4.9 and 4.10c, d). The Adu tracks are 39 cm in length and 16 cm in width. The trackway width is 21–32 cm and less than the track length (width: length ratio 0.6–1.0).

To date, three ichnogenera of pterosaur tracks have been described: *Pteraichnus* (Stokes 1957), *Purbeckopus* (Delair 1963), and *Haenamichnus* (Hwang et al. 2002). Although only a single ichnospecies of *Purbeckopus*—*P. pentadactylus* (Wright et al. 1997)—and two ichnospecies of *Haenamichnus*—*H. uhangriensis* (Hwang et al. 2002), and *H. gainensis* (Kim et al. 2012)—were previously known, thirteen ichnospecies of *Pteraichnus* have been reported. Billon-Bruyat and Mazin (2003) reviewed ichnospecies of purported pterosaur tracks from Spain (Calvo and Moratalla

**Table 4.3** Measurement of pterosaur tracks, *Haenamichnus gainensis* at the Cretaceous Haman Formation at the Gain track site

| Track no. | Length (cm) | Width (cm) | Pace (cm) | Stride (cm) | Pace angle (°) |
|---|---|---|---|---|---|
| P1-1 | 31 | 13 | – | – | – |
| P1-2 | 31 | 13 | 56 | 97 | 133 |
| P1-3 | 30 | 12 | 51 | 100 | 130 |
| P1-4 | 29 | 14 | 56 | 96 | 135 |
| P1-5 | 30 | 14 | 49 | 83 | 145 |
| P1-6 | 33 | 14 | 54 | 83 | 143 |
| P1-7 | 29 | 14 | 54 | 97 | 160 |
| P1-8 | 29 | 16 | 46 | 91 | 160 |
| P1-9 | 27 | 14 | 43 | 91 | 138 |
| P1-10 | 29 | 14 | 51 | 97 | 160 |
| P1-11 | 31 | 16 | 49 | 100 | 158 |
| P1-12 | 29 | 14 | 54 | 97 | 157 |
| P1-13 | 31 | 17 | 45 | 97 | 145 |
| P1-14 | 34 | 14 | 57 | 111 | 180 |
| P1-15 | 29 | 14 | 54 | 106 | 169 |
| P1-16 | 29 | 11 | 51 | 108 | 179 |
| P1-17 | 30 | 14 | 53 | 103 | 155 |
| P1-18 | 27 | 14 | 51 | 89 | 147 |
| P1-19 | 31 | 14 | 41 | 97 | 152 |
| P1-20 | 29 | 16 | 57 | 104 | 138 |
| P1-21 | 30 | 16 | 54 | ? | ? |
| P1-22 | ? | ? | ? | 106 | ? |
| P1-23 | 27 | 14 | ? | ? | ? |
| P1-24 | 29 | 14 | 49 | 120 | 144 |
| P1-25 | 31 | 11 | 60 | 91 | 130 |
| P1-26 | 29 | 14 | 43 | – | – |
| Mean | 29.6 | 14.2 | 51 | 98.4 | 152.4 |
| P2-1 | 27 | 13 | – | – | – |
| P2-2 | 31 | 15 | 48 | 77 | 130 |
| P2-3 | 29 | 17 | 39 | 88 | 145 |
| P2-4 | 27 | 14 | 50 | 97 | 148 |
| P2-5 | 29 | 15 | 50 | 81 | 130 |
| P2-6 | 27 | 15 | 40 | 100 | 130 |
| P2-7 | 31 | 15 | 67 | 120 | 150 |
| P2-8 | 29 | 13 | 62 | 81 | 150 |
| P2-9 | 31 | 13 | 39 | – | – |
| Mean | 29 | 14.4 | 49.4 | 92 | 140.4 |
| P3-1 | 29 | 15 | – | – | – |
| P3-2 | 32 | 17 | 45 | 90 | 158 |

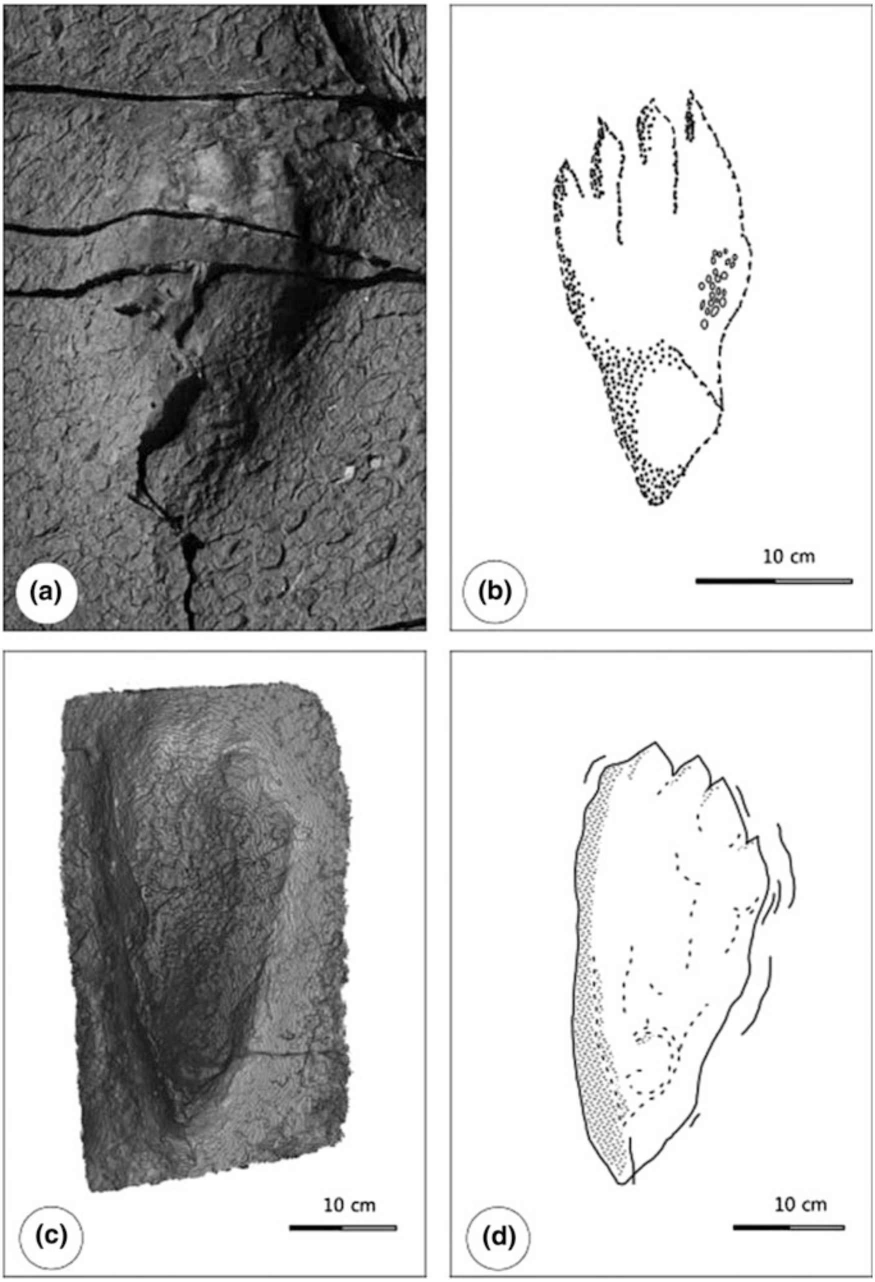
(continued)

**Table 4.3** (continued)

| Track no. | Length (cm) | Width (cm) | Pace (cm) | Stride (cm) | Pace angle (°) |
|---|---|---|---|---|---|
| P3-3 | 28 | 12 | 48 | 72 | 121 |
| P3-4 | 26 | 12 | 40 | 69 | 129 |
| P3-5 | 22 | 15 | 43 | ? | ? |
| P3-6 | ? | ? | ? | 77 | ? |
| P3-7 | 28 | 15 | ? | – | – |
| Mean | 27.5 | 14.3 | 44 | 77 | 136 |
| P4- | 35 | 12 | – | – | – |
| P4- | 33 | 12 | 48 | 100 | 140 |
| P4- | 35 | 16 | 46 | 100 | 150 |
| P4- | 33 | 16 | 50 | 100 | 150 |
| P4- | 39 | 16 | 50 | 80 | 140 |
| P4- | 35 | 16 | 34 | 80 | 150 |
| P4- | 35 | 16 | 48 | 96 | 160 |
| P4- | 35 | 12 | 50 | 106 | 160 |
| P4- | 33 | 14 | 60 | 139 | 178 |
| P4- | 37 | 12 | 82 | – | – |
| Mean | 35 | 14.2 | 52 | 100.1 | 153.5 |

*Note* ?: unattainable
*Source* Kim et al. (2012)

1998; Pascual-Arribas and Sanz Pérez 2000; Fuentes Vidarte 2001; Meijide Calvo 2001; Meijide Calvo and Fuentes Vidarte 2001; Meijide Calvo et al. 2001; Meijide Fuentes 2001; Fuentes Vidarte et al. 2004a, b). Billon-Bruyat and Mazin (2003) suggested that five ichnospecies (*P. palaciei-saenzi*, *P. vetusitior*, *P. manueli*, *P. cidacoi*, and *P. parvus*) were all *nomina dubia*. Later, a new ichnospecies, *P. longipodus*, was reported from Spain (Fuentes Vidarte et al. 2004a). Lockley et al. (2008) reported that six ichnospecies of *Pteraichnus* from Spain were based on insufficiently described, isolated footprints, not trackways, and several of these ichnospecies are probably *nomina dubia*. Subsequently, Sánchez-Hernández et al. (2009) reviewed the *Pteraichnus* ichnospecies from the Early Cretaceous in Soria, Spain and suggested that six Spanish ichnospecies must be restudied and their validity reassessed with respect to all named purported pterosaurian ichnotaxa. In addition, Sáchez-Hernández et al. (2009) regarded that, of the six ichnospecies of purported pterosaur tracks from Spain, only *Pteraichnus longipodus* (Fuentes Vidarte et al. 2004a) and *P. parvus* (Meijide Calvo et al. 2001) are probably valid taxa. Recently, Lockley and Harris (in press) also reviewed pterosaur trace fossils and argued once more that there are only five valid ichnospecies within *Pteraichnus* (*P. saltwashensis*, *P. stokesi*, *P. longipodus*, *P. parvus*, and *P. nipponensis*). Recently, Pascual-Arribas et al. (2015) redescribed the ichnospecies *P. palacieisaenzi* based on the qualified tracks in greater detail and compared it with other pterosaur ichnospecies for the validity of *P. palacieisaenzi*.


(a)
10 cm
(b)
10 cm
(c)
10 cm
(d)

◂**Fig. 4.10** Photograph, 3D scanning image with contour lines, and sketches of *H. gainensis* at the Gain and Adu track sites. *Notes* **a** Photograph; **c** 3D scanning image with contour lines; **b**, **d** sketches of *H. gainensis* from the Gain and Adu tracksites. **a**, **b** Holotype, the second right pes of pterosaur trackway P2 from the Gain track site; **c**, **d** Adu track, showing an elongated, subtriangular outline with impressions of four digits and a subangular heel margin. Note the probable skin impressions in the middle right of the track **b**. *Source* Kim et al. (2012)

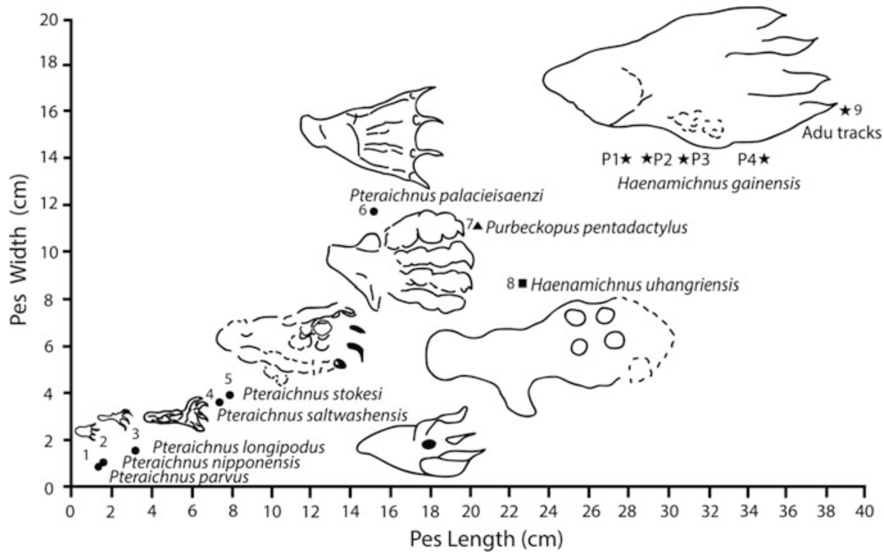



**Fig. 4.11** Comparison of track length and width of well-known pterosaur tracks. *Notes* Observe that the length/width ratio of *H. gainensis* (Kim et al. 2012) is virtually the same as that of *Ptraichnus*. P1–P4 correspond to the pterosaur trackway numbers shown in Fig. 4.8; all other data are from *P. saltwashensis* (Stokes 1957), *P. stokesi* (Lockley et al. 1995), *P. parvus* (Meijide Calvo et al. 2001), *P. longipodus* (Fuentes Vidarte et al. 2004a), *P. nipponensis* (Lee et al. 2010), *P. palacieisaenzi* (Pascual Arribas et al. 2015), *Purbeckopus pentadactylus* (Wright et al. 1997), and *Haenamichnus uhangriensis* (Hwang et al. 2002). Other ichnospecies of *Pteraichnus* are not shown here due to being regarded as invalid (Bruyat and Mazin 2003; Lockley et al. 2008; Sánchez-Hernández et al. 2009; Lockley et al., in press). *Source* Modified from Kim et al. (2012)

Comparison of pes track length and width of valid and probably valid ichnotaxa of pterosaur tracks is shown in Fig. 4.11. As shown in Fig. 4.11, *H. gainensis* is extremely large in length (up to 39 cm) and represents the largest pterosaur tracks hitherto reported. Before the discovery of *H. gainensis, H. uhangriensis*, which is up to 23.5 cm in length, afforded the largest pterosaur tracks (Hwang et al. 2002). The pes track of *H. uhangriensis* is nearly similar in length to that of *Purbeckopus pentadactylus* (206 mm in length and 111 mm in width), which is larger than *Pteraichnus palacieisaenzi* (153.4 mm in length and 119 mm in width), the largest ichnospecies of *Pteraichnus* recently reported (Pascual-Arribas et al. 2015).

In addition, the Gain and Adu trackways of pterosaurs are characteristically composed of pes only tracks with a narrow trackway width (the ratio of trackway width and pes track width is about 3.1) and wide pace angulation (136°–154°). All pterosaur tracks currently known are quadrupedal, the only exception being *H. gainensis*, which is a pes only pterosaur track strongly suggesting bipedal locomotion of the track maker. The narrow trackway of *H. gainensis*, which shows wide pace angulation, may suggest the track maker had an erect stance. The morphology of the pes track, which is characterized by a elongated subtriangular shape with four short digit impressions and a subtriangular heel trace, suggests a plantigrade stance rather thandigitigrade (Kim et al. 2012).

Early in the nineteenth century, Cuvier (1809) first proposed a bipedal mode of terrestrial locomotion for his reptilian "pterodactyls." However, narrow pterosaur trackways, composed only of pes prints and indicative of a fully erect, bipedal pterosaur with a digitigrade stance and gait had not been found (Padian and Olsen 1984) prior to the discovery of the Gain tracks. Furthermore, Unwin (1997) mentioned that some, perhaps all, pterosaurs were plantigrade and quadrupedal with a semi-erect stance and gait. In addition, however, Bennett (1990, 1997) argued for upright bipedal locomotion in large pterodactyloids and proposed that future discoveries of large pterodactyloid trackways would serve to test this posture. Therefore, the large and pes only trackways with a narrow trackway width of *H. gainensis* have provided a intriguing new insight into the subject of a 200-year-long controversy about the locomotory posture of pterosaurs (Kim et al. 2012).

Do human footprints coexist with dinosaur tracks? Like the well-publicized but false argument that human footprints coexist with dinosaur tracks in the Cretaceous limestones exposed in the Paluxy riverbed near Glen Rose, Texas (Kuban 1989), some creationists in Korea believe that human footprints co-occur with dinosaur tracks at the Gain site.

The following is a part of a report by Cheong (2004; translated by J. Y. Kim; comments in brackets by J. Y. Kim), a member of the Earth Science Division of the Publication Committee, Korea Association for Creation Research:

> World famous dinosaur tracksites in Korea. Unfortunately, the site is a place where Earth's past history was not correctly known to us because interpretation as the work about Creator God was not carried out… In the morning, we prayed briefly. We were completely taken by surprise [at the Gain tracksite]. We observed amazing fossils of human footprint-like tracks co-occurring with dinosaur tracks. We believed that our Creator God led us to them.

It is not necessary to argue here the story of the coexistence of humans and dinosaurs. However, for the general public, students, and children, it seems necessary to point out that the supposed human footprints are *not*, in fact, human footprints; rather, they are the pes tracks of pterosaurs that resemble human footprints only in size and general elongated shape. The following reasons detail the argument against the footprints being human but, rather, being pterosaur tracks (Kim et al. 2012):

1. *Age differs tremendously*. The age of footprint-bearing strata is Albian-Aptian (late Early Cretaceous) about 125–100 Ma. However, the oldest record of hominid fossils, *Sahelanthropus tchadensis*, dates to the late Miocene, about 6.5–7.0 Ma (Brunet et al. 2002). It is not scientifically accepted that pterosaurs lived until the Miocene or that hominids lived during the Cretaceous Period.

**Fig. 4.12** Paleoecology restoration of the track-bearing environment based on the co-occurrence of pterosaur, sauropod, ornithopod, and theropod tracks, and plant fossils at the Lower Cretaceous Haman Formation at the Gain track site. *Source* Kim et al. (2012)

2. *Morphology differs.* Elongate, subtriangular tracks with impressions of four digits and claws cannot be made by human feet, which are instead characterized by impressions of a medial arch, ball, heel, and five toes with a pronounced digit I.
3. *Size and locomotion pattern differ.* The Gain and Adu pterosaur tracks measure 27.5–39 cm in length, too large to be attributed to average humans. Also, stride lengths of the Gain pterosaur tracks measure 77–100 cm, which is also too large to be made by a human walking on a muddy substrate with high water content.

Figure 4.12 shows the paleoecology restoration of the track-bearing environment based on the co-occurrence of pterosaur, sauropod, ornithopod, and theropod tracks, and plant fossils at the Lower Cretaceous Haman Formation of the Gain and Adu sites (Kim et al. 2012).

## 4.2 Pterosaur Bones

Compared with pterosaur tracks, pterosaur skeletons have rarely been reported from the Cretaceous Period of the Korea Peninsula. To date, two reports of pterosaur skeletons have been found; one in South Korea and the other in North Korea.

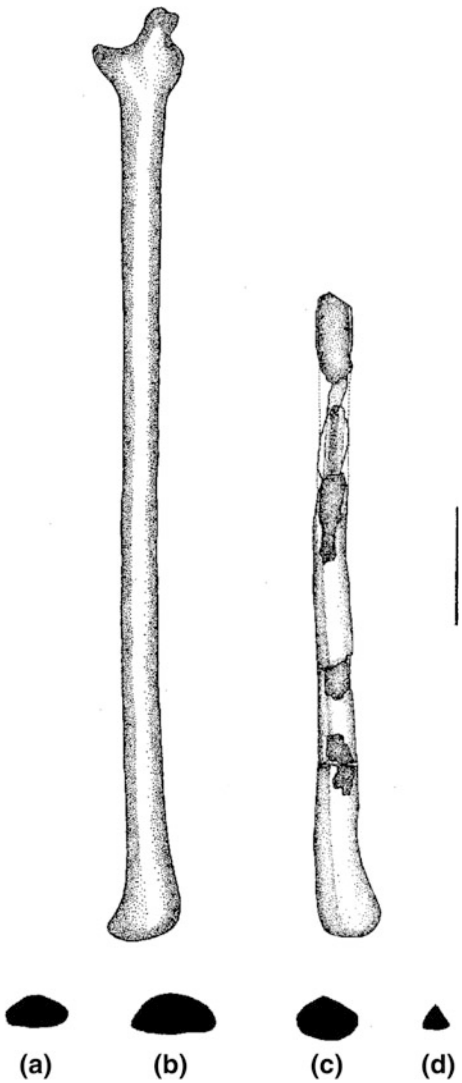



**Fig. 4.13** Pterosaur bone from the Gyeongsang Basin. *Notes* (Top right) SNU 1001; (top left) first wing-phalanx of *Dsungaripterus weii* (IVPP V. 2777, modified from Young 1964). Scale bar equals 5 cm; (bottom) cross-sections of wing-phalanges and limb bones of pterosaurs; **a** SNU 1001; **b** wing-phalanges of *D. weii* (IVPP V. 2777); **c** ulna of dsungaripteroidea from Inner Mongolia (IVPP V. 2778); **d** tibia of dsungaripteroidea (IVPP V. 2779). *Source* Lim et al. (2002)

Pterosaur bone was reported for the first time at the Lower Cretaceous in the Gyeongsang Basin (Lim et al. 2002). Unfortunately, geological information including formation and fossil location of the pterosaur bone-bearing deposits was not provided (Lim et al. 2002). The pterosaur bone (SNU 1001) is an incomplete wing-phalanx (247 mm in length, Fig. 4.13). The thickness of the cortical bone of the shaft is approximately 0.9–1.5 mm. The shaft of SNU 1001 is dorso-ventrally compressed, which is a characteristic of the wing-phalanges of a pterosaur. The overall configuration of SNU 1001 more closely resembles the first wing phalanx of *Dsungaripterus weii* from the Early Cretaceous in China (Lim et al. 2002).

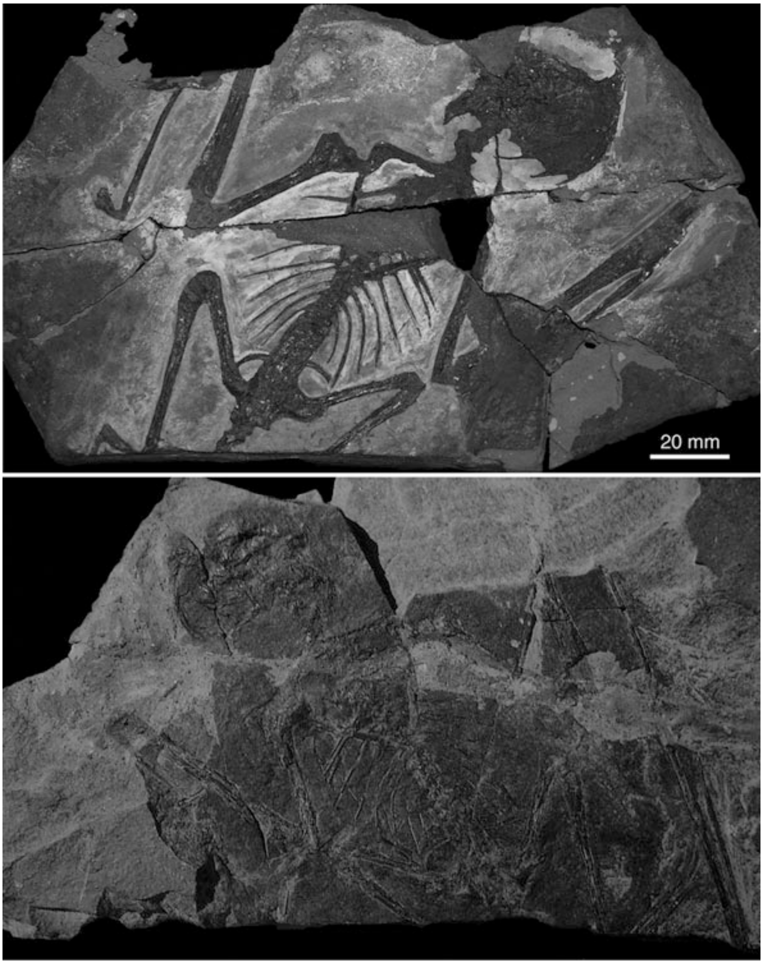



**Fig. 4.14** Part and counterpart skeleton of an anurognathidae pterosaur from the Sinuiju Series, North Korea. *Source* Gao et al. (2009)

A well-preserved pterosaur skeletal fossil was recently found at the Lower Cretaceous Sinuiju Series of the Jasong System at a road-cut approximately 6 km south of Sinuiju City, northwest of North Korea, where "*Archaeopteryx* of Korea" was also discovered (Gao et al. 2009). The specimen is approximately 25 cm long from the tip of its snout to the end of its tail, and it probably had a wingspan of more than 80 cm. The skull is bilaterally compressed, but the postcranial skeleton is dorso-ventrally compressed. The skull is short and deep, and the neck is evidently shorter than the trunk. The pectoral girdle has a fused scapula and coracoid, and the rod-like coracoids meet posteromedially at an angle to form a V-shaped structure (Gao et al. 2009, Fig. 4.14). Gao et al. (2009) reported that the Sinuiju pterosaur could be confidently recognized as a member of the family Anurognathidae, which has been known from the Jurassic Solnhofen lithographic limestones, Kazakhstan, and Inner Mongolia. The Sinuiju pterosaur provided the evidence for a geologically younger range extension of the family into the Lower Cretaceous and the geographical extension of the Jehol Biota from northeast China into the Korean Peninsula (Gao et al. 2009).

## 4.3 Pterosaur Teeth

Pterosaur teeth were first discovered at the Lower Cretaceous Jinju Formation of Gisanri, Seongsan District, Goryeong County (Yun and Yang 2001). The pterosaur tooth (KPE40001) is elongated and slender like a drill, and gently curved. The cross-section is oval or elliptical, having a long diameter of 6.3 mm and a short diameter of 3.4 mm at its basal part, and a long diameter of 9.8 mm at a point 14 mm from the base. The specimen KPE40001 is 68.5 mm in length (Fig. 4.15).

Another two specimens (KPE40002 and 40003) at the Lower Cretaceous Hasandong Formation of Hapgari, Seongsan District, Goryeong area, is similar in shape to KPE40001. The specimens are 35 mm in length and 7.6 mm in maximum diameter (Fig. 4.16). The Seongsan pterosaur teeth are covered with enamel and show longitudinal grooves and ridges (Yun and Yang 2001). According to Yun and Yang (2001), the Seongsan pterosaur teeth could be compared with *Rhamphorhynchus* described from the Solnhofen limestone (Wellnhofer 1975, 1988; Bennett 1995).

Yun et al. (2007) reported an additional pterosaur tooth; this is an incomplete specimen (YCS 2005), 15.1 mm in length and 5.7 mm in long diameter, and 3.9 mm in short diameter at its basal part.

## 4.4 Other Reptiles

### *4.4.1 Turtle Carapace*

The partial carapace of a macrobaenid turtle was first described at the lower Cretaceous Geoncheonri Formation in Gyeongsan City near Daegu Metropolian City (Lee et al. 2009). Carapace fragments are composed of a neural, right and left costals, and right and left peripherals (Lee et al. 2009, Fig. 4.17). The width of the carapace is approximately 278 mm. The Gyeongsan turtle carapace was referred to as *Kirgizemys* and represents the first turtle fossils described from the Mesozoic deposits in the Korean Peninsula.

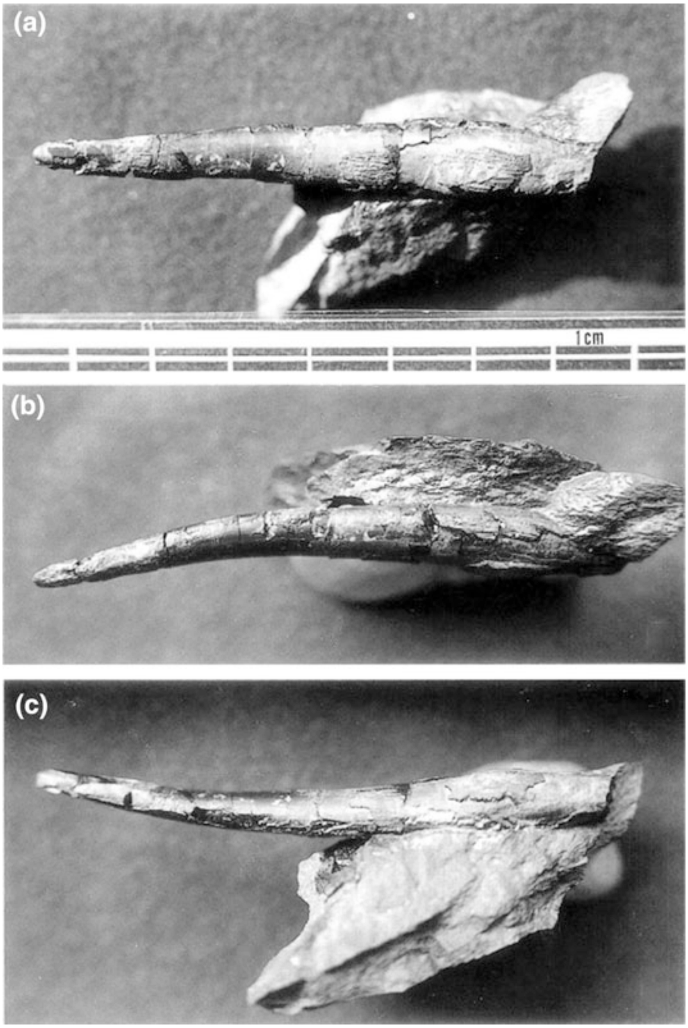



**Fig. 4.15** Pterosaur tooth KPE40001 at the Jinju Formation, Gisanri, Goryeong area. *Notes* This pterosaur tooth was collected by Cheol-Soo Yun. **a** Lingual view, **b** posterior view, **c** anterior carina view. *Source* Yun and Yang (2001)

### *4.4.2 Turtle Tracks*

Recently, a partial trackway of a turtle was described from the Jinju Formation, Bito Island, Sacheon City (Kim and Lockley 2016). A series of at least six more or less regularly spaced tridactyl and tetradactyl tracks (numbered 1–6) were interpreted as part of a trackway, or possibly two trackways, of a turtle (Fig. 4.18). The tracks are oriented toward the southwest, which is also the current direction inferred from the

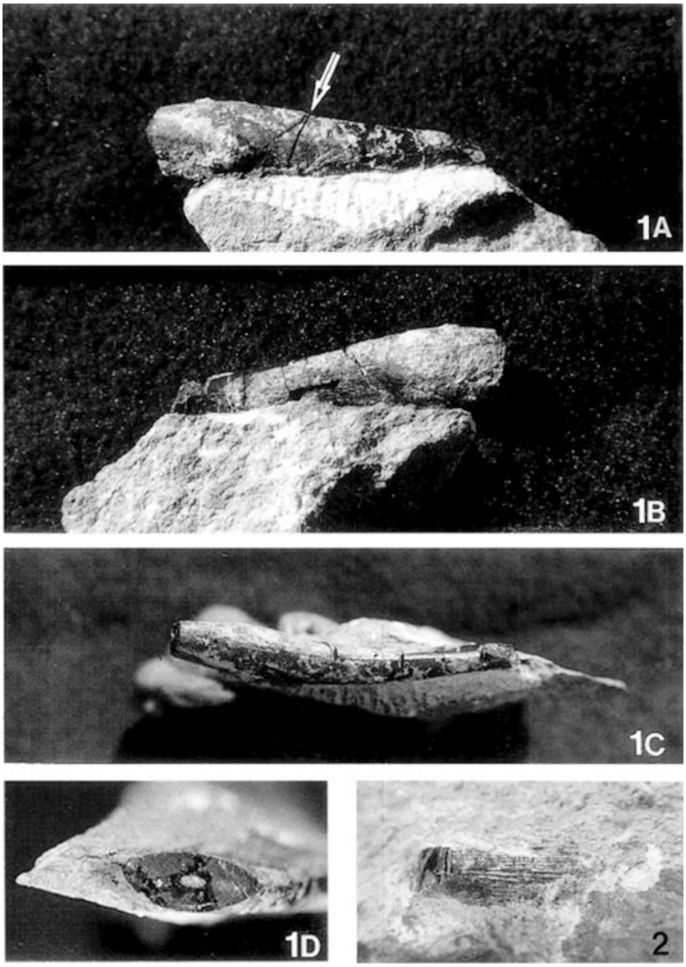



**Fig. 4.16** Pterosaur teeth from Hasandong Formation of Hapgari, Goryeong area. *Notes* 1: KPE40002 (collected by Jun-Ho Kwon), 1A: labial view, ×1.8; 1B: lingual view, ×1.8; 1C: posterior view, ×1.8; 1D: oblique section at position indicated by arrow given in 1A, ×2.4; 2: KPE40003 (collected by Jin-Ho Kim), partial fragment showing the fine longitudinal striations or bands on the surface, ×2.5. *Source* Yun and Yang (2001)

ripple marks. The tracks are short and wide, consisting primarily of the traces of an animal with short triangular toes. The best-preserved tracks appear to be the first two, or the two proximal tracks in the sequence, seen to the northeast or lower left portion of the map in Fig. 4.19. Both tracks are preserved together as a separate replica.

Both tracks (1 and 2) are similar in size and shape, consisting of three equi-dimensional triangular toe traces. The first, more proximal, track (1) is less deeply impressed. It is 7 cm wide with each toe trace between 1.5 and 1.8 cm long

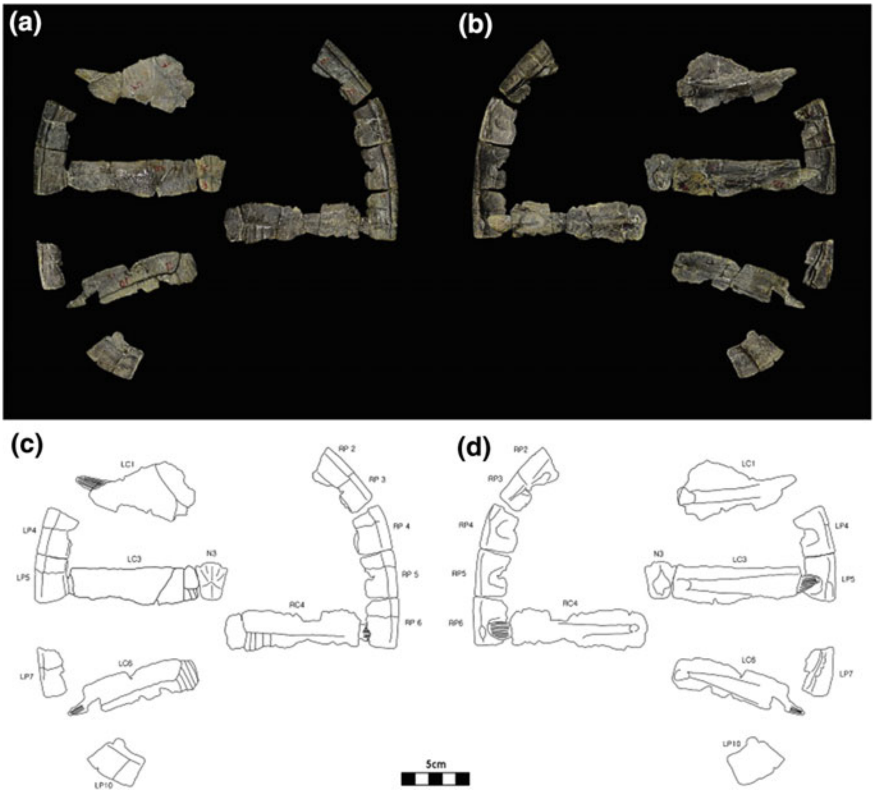



**Fig. 4.17** A reconstruction of *Kirgizemys* cf. *K. exaratus* (Nessov and Khosatzky 1973) at the Geoncheonri Formation, Gyeongsan area. *Notes* **a** External view (photo); **b** visceral view (photo); **c** external view (line drawing); **d** visceral view (line drawing). *Source* Lee et al. (2009)

and wide. The space between the toe traces is about 1.0 cm. The second track (2), a more distal track, is about 8.5 cm wide and 4.5 cm long at the point of maximum length, where the left of the three toes has registered. The track consists of three triangular toe impressions, each with a short sharp claw trace. The toe traces are connected by hypicies that are about half as deep (2.0–2.5 cm) as the maximum track length. The posterior margin of the track is concave. The space between the two tracks, measured from the point of the central toe trace, is 20.0 cm. Tracks 2–6 are interpreted as part of a trackway (Kim and Lockley 2016).

These turtle tracks from the Jinju Formation, Bito Island, were assignable to the ichnogenus *Chelonipus*, and represent the first record of Mesozoic turtle tracks in Korea. Turtle tracks have also recently been reported from the Cretaceous in Shandong, Nei Mongol, and Xinjiang, China.

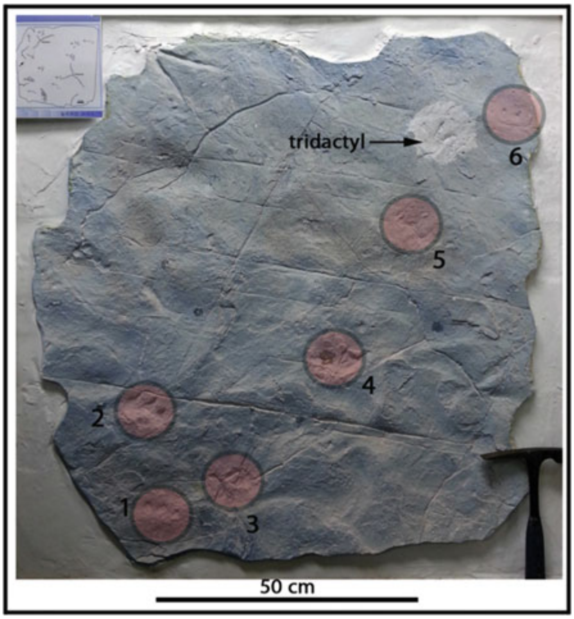



**Fig. 4.18** Photograph of a replica of specimen (KNUE 0601) of turtle tracks at the Jinju Formation, Bito Island, Sacheon area. *Notes* Compare with Fig. 4.19. *Source* Kim and Lockley (2016)

### *4.4.3 Crocodile Bones and Teeth*

A crocodilian mandible with a tooth (KPE40005) was first reported at the Lower Cretaceous Jinju Formation, Goryeong County (Yun et al. 2004, 2007; Fig. 4.20). The mandible is approximately 15 cm long and shows groove-like lines irregularly distributed at the side. A tooth in KPE40005 is 13.5 mm in length, and 6.5 mm and 4.7 mm in major axis and minor axis, respectively. The tooth is characterized by longitudinal lines and serrations that have developed on the surface. This fossil, assigned to crocodyliformes, represents the first record of a crocodile from the Cretaceous in Korea (Yun et al. 2004, 2007).

Nearly complete teeth (JYH7001 and JYH7002) from a crocodile were also reported at the Lower Cretaceous Hasandong Formation at the Yusuri site, Jinju County (Yun et al. 2007, Fig. 4.21). The JYH7001 tooth is 14.1 mm in length, and major axis and minor axis are 6.4 and 4.3 mm, respectively. The JYH7002 tooth is 17.0 mm in length, and 6.5 mm in major axis, 5.4 mm in minor axis. Like the Goryeong specimen (KPE40005), the Jinju teeth show characteristic features including well-developed serrations and longitudinal lines. The Jinju teeth were referred to as Mesosuchia (Yun et al. 2007).

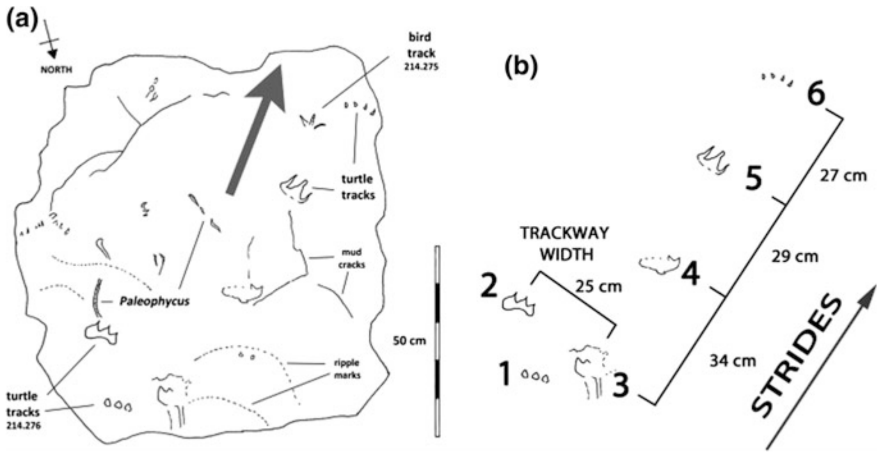



**Fig. 4.19** Turtle tracks and trackway at the Jinju Formation, Bito Island, Sacheon area. *Notes* **a** Map of slab (KNUE 0601) based on a tracing of the turtle tracks from the Jinju Formation, Bito Island, Sacheon area. (Compare with Fig. 4.18). The slab is oriented to show the progression of the turtle tracks to the top of map; i.e., towards the southwest. This is also the inferred direction of current flow and the anterior orientation of the single bird tracks, which were replicated separately as UCM 214.265 (top right of map). Two turtle tracks (lower left of map) were replicated separately as UCM 214.276. **b** Shows turtle tracks (1–6) trending southwest and isolated from the map to show the probable trackway configuration with inferred stride and trackway width measurements. *Source* Kim and Lockley (2016)

In 2004, a nearly complete skull of a crocodyliforme was reported from the lower Cretaceous Hasandong Formation, Hadong County (Lee et al. 2004, Fig. 4.22). The skull is 52 mm in length and 20 mm in width, and is composed of maxilla, nasal, lacrimal, prefrontal, squamosal, quadrate, dentary, angular, subangular, and palatal bones which are almost completely preserved (Lee et al. 2004).

The Hadong skull was regarded to be closely related with *Zosuchus*, discovered at the Cretaceous of the Gobi Desert, Mongolia (Lee et al. 2004).

### 4.4.4 Lizard Bones

Recently, Park et al. (2015) were the first to describe lizard skeletal fossils at the Upper Cretaceous Jangdong Tuff of the Bibongri dinosaur egg site of Boseong. These skeletal remains were originally interpreted as a turtle (Huh et al. 2006). The specimen (KDRC-BB4) is composed of skull, mandible, pterygoid, scapulocoracoid, humerus, metacarpal, and other bone fragments (Fig. 4.23).

The Boseong specimen was assigned to a new lizard, *Asprosaurus bibongriensis*, and represents the first lizard fossil recorded in the Cretaceous in Korea, and the largest Mesozoic terrestrial lizard known to date (Park et al. 2015).

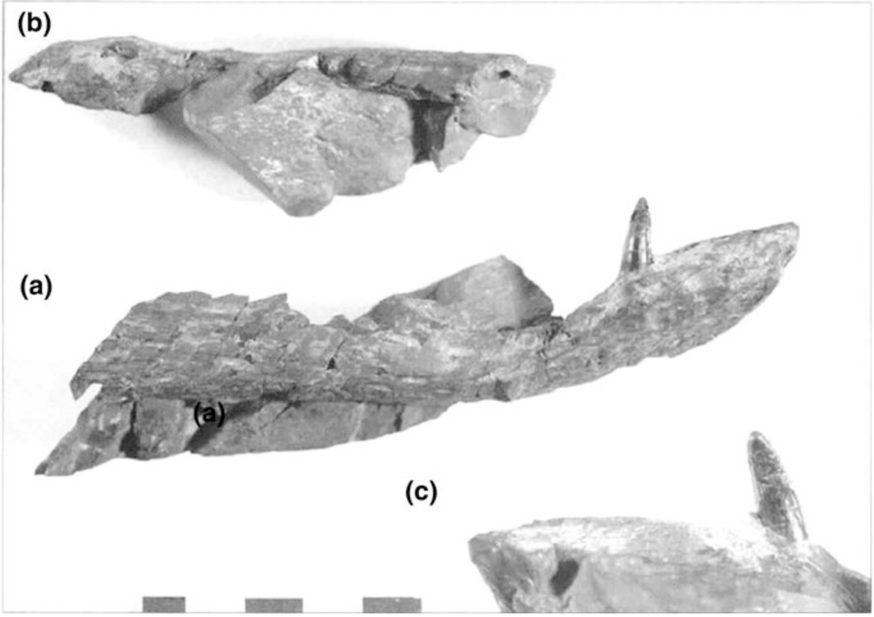


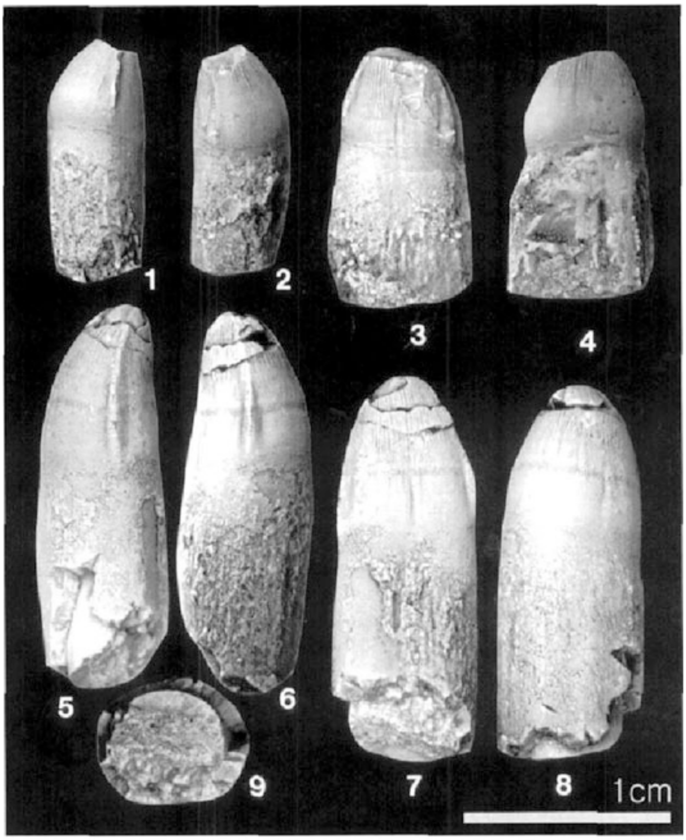

**Fig. 4.20** Mesozoic crocodilian mandible with a tooth, KPE40005 at the Jinju Formation, Goryeong area. *Notes* **a** External lateral view; **b** occlusal view; **c** internal lateral view of teeth part. *Source* Yun et al. (2007)

### *4.4.5 Amphibian Trackways*

Amphibian tracks have been known from the Late Paleozoic and Cenozoic strata (e.g., Gilmore 1926; Haubold et al. 2005; Petti et al. 2014). However, to date, Mesozoic amphibian tracks have proved rare. One important record of well-preserved amphibian trackways was reported at the Lower Cretaceous Hasandong Formation, Hadong area (Lee et al. 2004).

As shown in Fig. 4.24, the amphibian track-bearing block of black shale is nearly rectangular with an area of 70 × 30 cm. Four trackways composed of 21 tracks and two isolated tracks are preserved in concave epirelief on the bedding surface. Trackway A is composed of ten consecutive tracks with six manus tracks and four pes tracks. The manus tracks are longer than they are wide, 20.1 mm in length and 13.7 mm in width, and outwardly rotated at an angle of 10° (Table 4.4). The manus track is composed of digits II–V impressions, which are 7.7, 12.5, 17.0 and 9.6 mm, respectively. The digit traces are laterally curved. The digit V impression is characteristically offset from digits II–IV and anterolaterally diversed. The average stride length of the manus track is 160.2 mm.

The pes track is also much longer than it is wide, being 22.0 mm in length and 13.0 mm in width. The pes track is pentadactyl. The order of digital length is IV (17.7 mm), III (15.3 mm), II (9.8 mm), V (8.0 mm), and I (6.7 mm). Like the


1
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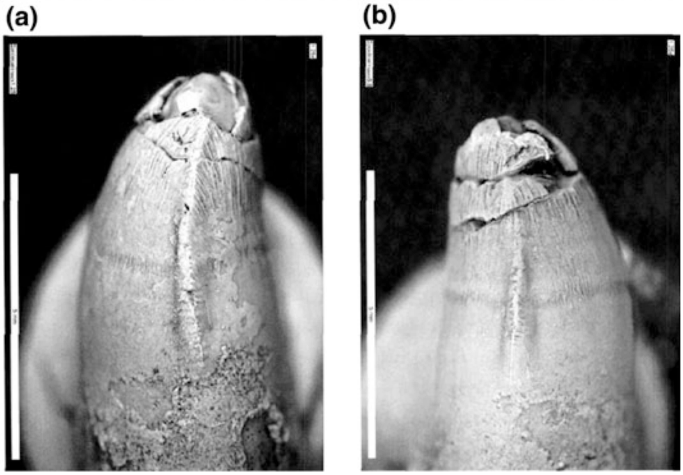
(a)
(b)

◀**Fig. 4.21** Crocodilian teeth at the Hasandong Formation, Yusuri site, Jinju area. *Notes* 1–4: JYH7001; 5–9: JYH7002. 1, 5: anterior view; 2, 6: posterior view; 3, 7: labial view; 4, 8: lingual view; 9: cross section at base. Close-up photograph of JYH7002, showing serrations and longitudinal lines (bottom): **a** anterior view, crown partly broken; **b** posterior view. *Source* Yun et al. (2007)

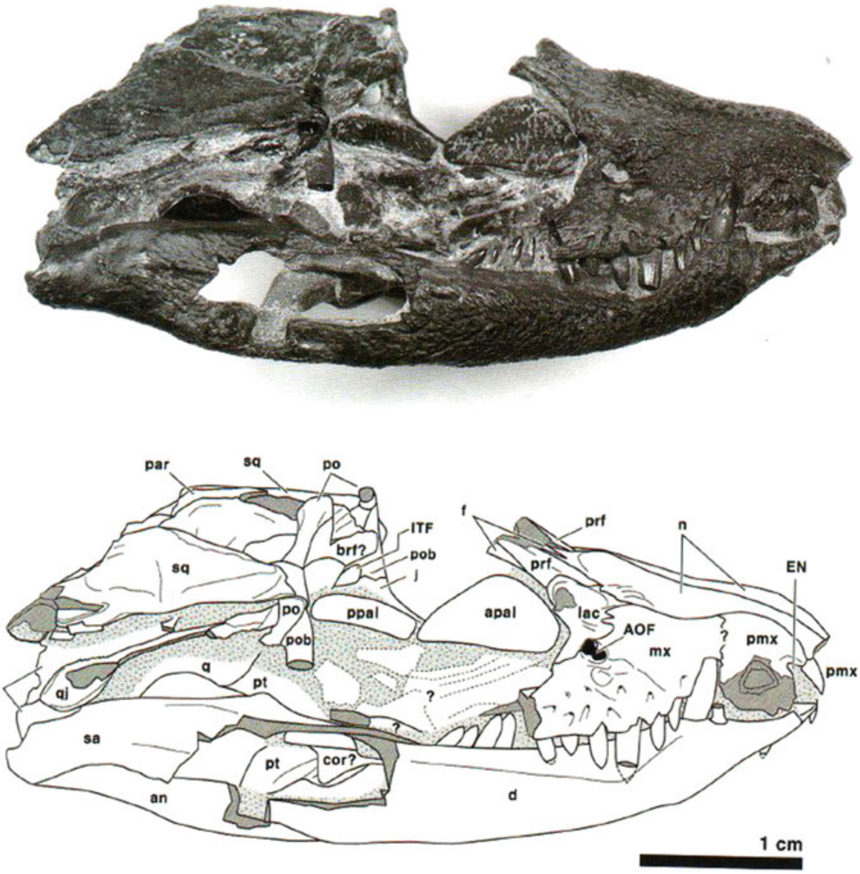


**Fig. 4.22** Righthand-side view of crocodilian skull at the Hasandong Formation, Hadong County. *Source* Lee et al. (2004)

manus tracks, the digit V impression is offset from the other impressions of digits I–V. All digit traces are outwardly curved. The stride length of the pes track is 162.1 mm, nearly the same as that of the manus track.

Trackway B, composed of four manus and two pes tracks, is nearly parallel but opposite to trackway A. The manus tracks are 23.2 mm in length and 12.1 mm in width. The order of digital length is digit IV (18.1 mm), III (15.0 mm), II (7.1 mm), and V (4.0 mm). The digit I impression observed in a manus (BR4) track is very

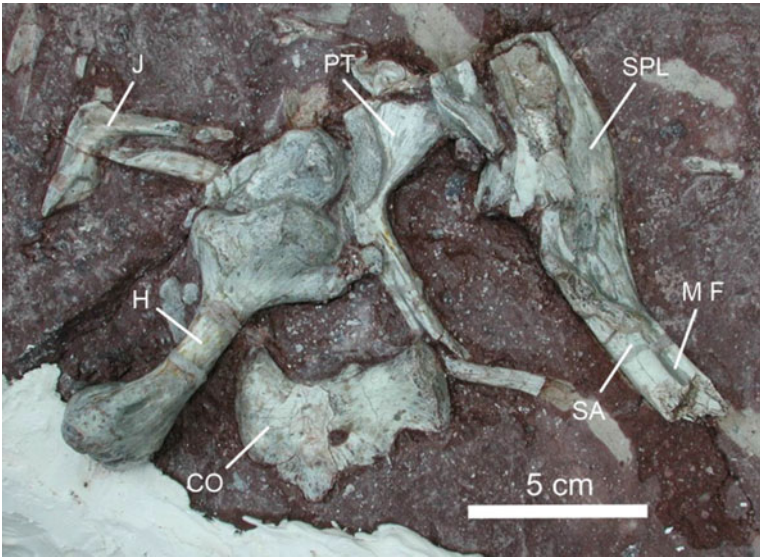


**Fig. 4.23** Photograph of associated specimen *Asprosaurus bibongriensis* (holotype; KDRC-BB4) from the Seonso Conglomerate, Boseong area, in original single block. *Notes* CO: scapulocoracoid; H: humerus; J: Jugal; MF: mandibular fossa; PT: pterygoid; SA: subangular; SPL: splenial. *Source* Park et al. (2015)

short, 2.1 mm in length. The pes tracks are 21.6 mm in length and 17.3 mm in width. Digits I–V are 4.4, 7.8, 14.3, 18.2, and 9.3 mm in length, respectively.

The Hadong tracks represent the first recorded amphibian tracks from the Cretaceous anywhere in the world (Lee et al. 2004), though the ichnotaxonomy of the tracks remains to be studied. Lee et al. (2004) considered that *Celtedes ibericus* (McGowan and Evans 1995) was the possible track maker for the Hadong amphibian trackways.

### *4.4.6 Mammaliform Trackway*

Recently, a trackway of a small hopping mammaliform track maker at the Jinju Formation (Lower Cretaceous) in the Jinju City area, Korea, was the first of this type reported from the Mesozoic in Asia, and globally (Kim et al. 2017). The animal left a narrow trackway (approximately 20 mm wide) with small tetradactyl footprints averaging less than 10 mm in diameter (Fig. 4.25). Only two footprints registered with each hop (a mean length of 41 mm) thus indicating a bipedal gait. All trackway evidence suggests a small “mouse-like” track maker. The Korean

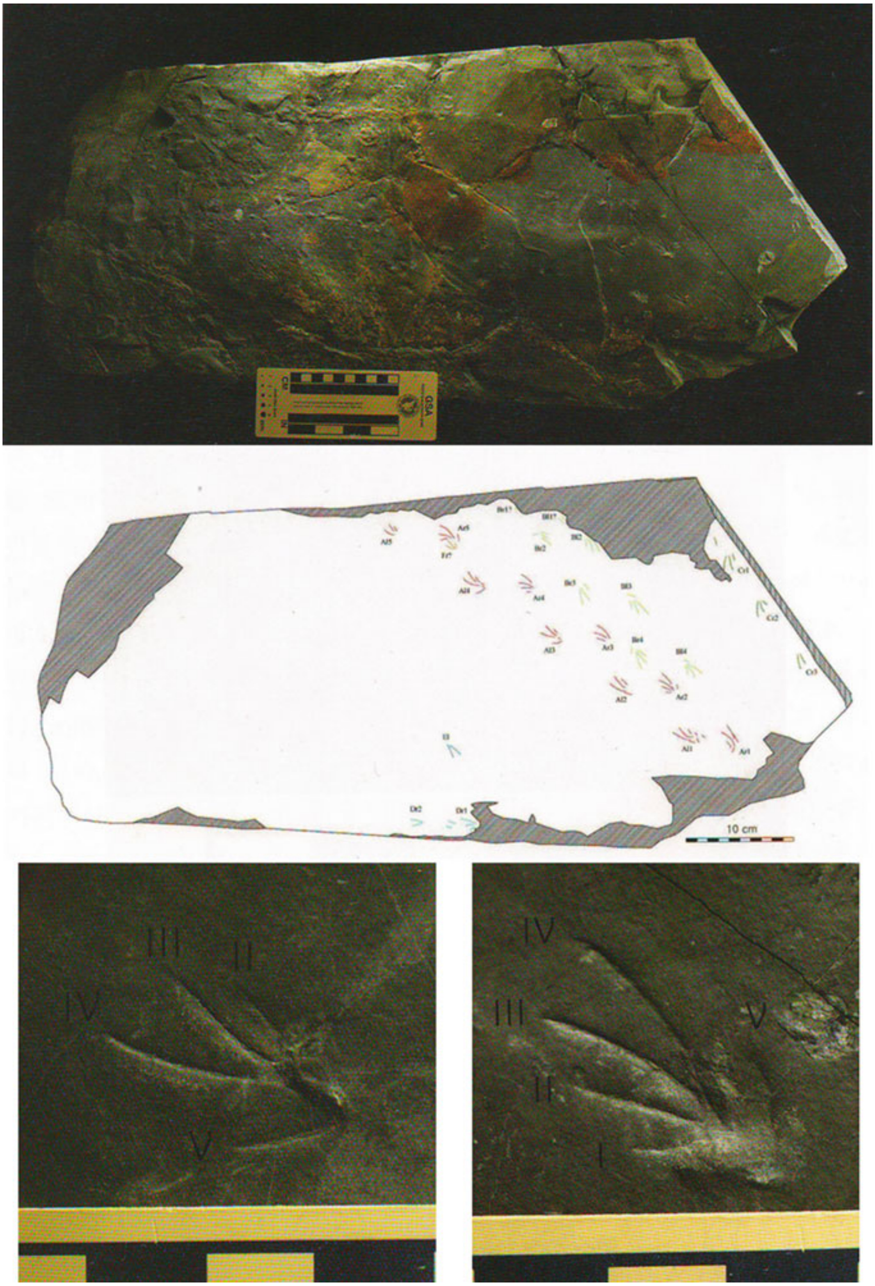


**Fig. 4.24** Photographs and sketch of amphibian trackways preserved on a block of black shale at the Hasandong Formation, Hadong area. *Notes* Details of manus (AL3) (bottom left) and pes (AR2) (bottom right). *Source* Lee et al. (2004)

**Table 4.4** Measurement of amphibian trackways and isolated tracks at the Hasandong Formation, Hadong area

| Number | M/P | L/R | L | W | I | II | III | IV | V | P | S |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Amphibian trackways (A)* | | | | | | | | | | | |
| AR1 | M | R | 19.6 | 14.4 | | 8.1 | 15.1 | 18.1 | | | |
| AL2 | M | L | 20.1 | 12.4 | | 7.6 | 14.7 | 19.2 | | 41.1 | |
| AR2 | P | R | 24.9 | 12.8 | 7.3 | 11.1 | 16.4 | 19.1 | 7.0 | | |
| AL2 | P | L | 23.7 | 11.6 | | 9.5 | 18.7 | 17.1 | 8.0 | 42.1 | |
| AR3 | M | R | 18.9 | 12.5 | | 11.0 | 17.2 | 17.4 | | 119.2 | 150.4 |
| AL3 | M | L | 22.2 | 13.7 | | 7.1 | 12.2 | 21.0 | 9.0 | 50.6 | 153.5 |
| AR4 | P | R | 18.3 | 11.8 | 6.4 | 9.5 | 13.4 | 16.9 | | 123.1 | 158.7 |
| AL4 | P | L | 20.9 | 15.7 | | 9.1 | 12.6 | 17.7 | 9.1 | 47.0 | 165.5 |
| AR5 | M | R | 19.6 | 17.1 | | 7.2 | 7.8 | 14.4 | 10.1 | 126.6 | 168.6 |
| AL5 | M | L | | 12.0 | | 5.3 | 8.0 | 11.6 | | 46.1 | 168.1 |
| Average | Manus | | 20.1 | 13.7 | | 7.7 | 12.5 | 17.0 | 9.6 | | 160.2 |
| Average | Pes | | 22.0 | 13.0 | 6.9 | 9.8 | 15.3 | 17.7 | 8.0 | | 162.1 |
| *Amphibian trackways (B)* | | | | | | | | | | | |
| BR2 | M | R | 19.7 | 13.7 | | 7.9 | 13.1 | 15.8 | 6.7 | | |
| BL2 | M | L | 22.8 | | | 5.3 | 18.4 | 21.4 | | | |
| BR3 | P | R | 18.0 | 17.7 | 4.4 | 9.9 | 14.4 | 15.6 | | | |
| BL3 | P | L | 25.1 | 16.9 | | 5.6 | 14.2 | 20.7 | 9.3 | 106.9 | |
| BR4 | M | R | 24.6 | 12.7 | 2.1 | 9.7 | 15.1 | 17.8 | 8.9 | 111.4 | 139.5 |
| BL4 | M | L | 25.7 | 9.9 | | 5.3 | 13.4 | 17.5 | 7.1 | 53.1 | 146.9 |
| Average | Manus | | 23.2 | 12.1 | 2.1 | 7.1 | 15.0 | 18.1 | 4.0 | | 143.2 |
| Average | Pes | | 21.6 | 17.3 | 4.4 | 7.8 | 14.3 | 18.2 | 9.3 | | |
| *Amphibian trackways (C)* | | | | | | | | | | | |
| CR1 | P? | R | 15.4 | 14.0 | | 7.3 | 14.2 | 13.6 | | | |
| CR2 | M? | R | 16.8 | 13.9 | | 6.6 | 11.3 | 16.6 | | | |
| CR3 | P? | R | 15.0 | | | | 11.4 | 9.9 | | | 111.8 |
| Average | | | 15.7 | 14.0 | | 7.0 | 12.3 | 13.4 | | | 111.8 |
| *Amphibian trackways (D)* | | | | | | | | | | | |
| DR1 | | R | 15.6 | 12.7 | | 5.7 | 8.7 | 14.9 | | | |
| DR2 | | R | 12.7 | | | | 12.2 | 12.4 | | | |
| Average | | | 14.2 | 12.7 | | 5.7 | 10.5 | 13.7 | | | |
| *Amphibian trackways (E)* | | | | | | | | | | | |
| EL | | L | 17.7 | | | | 14.1 | 17.0 | | | |
| *Amphibian trackways (F)* | | | | | | | | | | | |
| FR | | R | | | | 8.6 | 12.2 | 4.0 | | | |

*Notes* L: length; W: width; I–V: digits I–V; P: pace; S: stride; units in mm. Track numbers are the same as shown in Fig. 4.24

*Source* Lee et al. (2004)

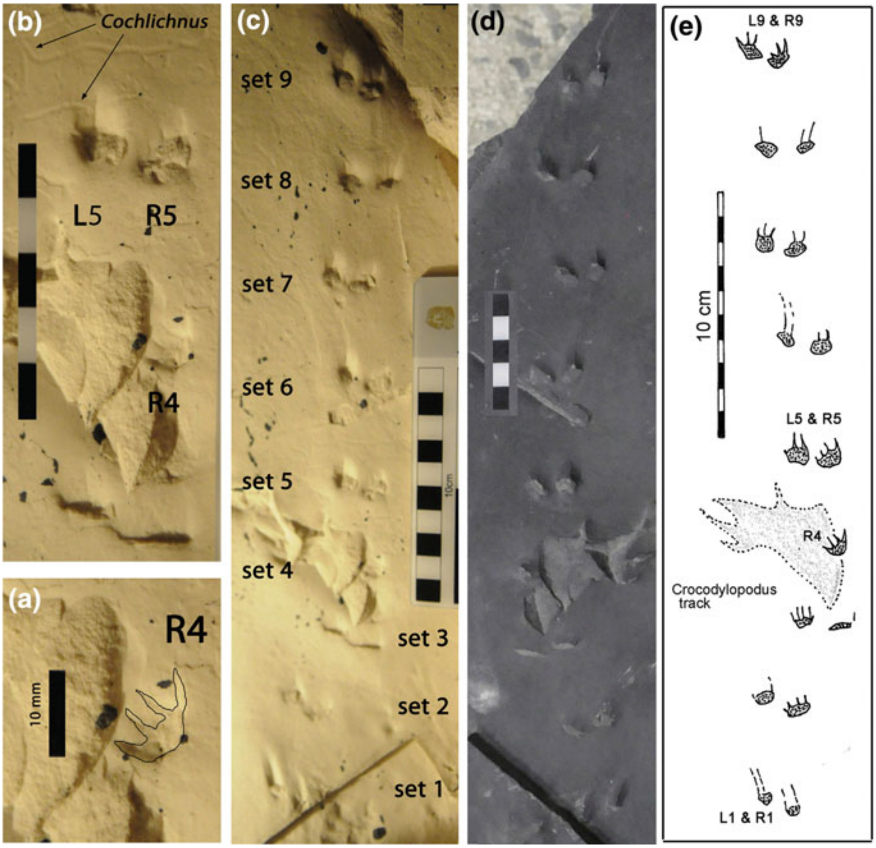


**Fig. 4.25** Holotype (CUE E4M001) of *Koreasaltipes jinjuensis*. **a** Latex mold showing the convex epichnia (impression) aspect of the best preserved track (R4) (with outline) with a wider view **b** and arrows showing nematode trails (*Cochlichnus* isp.). **c–e** whole 9-set trackway: **c** showing mold, **d** showing original natural cast aspect, and **e** showing line drawing tracing in a positive impression view (Kim et al. 2017)

specimen, named *Koreasaltipes jinjuensis*, is different from previously known ichnogenera representing hopping tracks in digit count, digit proportion and trackway configuration, as well as a lack of tail trace. *Koreasaltipes jinjuensis* was formed in a lake shore paleoenvironment associated with nematode tracks (*Cochlichnus* isp.), other small tetrapod tracks attributed to avian theropods (birds), pterosaurs, and crocodylomorphs, as well as larger saurischian dinosaurs.

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# Chapter 5
# Other Fossils from the Cretaceous Period of Korea

## 5.1 Molluscs

The mollusc is one of a large group of invertebrate animals living in marine, freshwater, and even terrestrial habitats. Temporal records of molluscs have been known from the Cambrian to Holocene Periods. In Korea, Mesozoic mollusc fossils have been discovered in Jurassic to Cretaceous strata, and are composed of many freshwater taxa of two groups: bivalves and gastropods.

Earliest records of Mesozoic molluscs from the Korean Peninsula have been described from the outcrops of the Amisan Formation near Boryeong City, South Chungcheong Province, South Korea, formed in the Jurassic and possibly also the Triassic Periods. The first reported discovery of molluscs at the Amisan Formation was described as *Margaritifera* sp. (Fig. 5.1) by Hwang and Hwang (1986). Lee (2001) found additional mollusc fauna at this AmisanFormation. However, he did not publish the result after his master's degree. Kim et al. (2015) recently described *Margaritifera* cf. *isfarensis*, and concluded that the morphological similarity is close to the Jurassic species *Margaritifera isfarensis* at deposits in Russia and China. The genus *Margaritifera* has been only reported at the Amisan Formation in Korea.

Pioneering research into Cretaceous molluscs found on the Korean Peninsula was conducted by Kobayashi and Suzuki (1936). After Japanese scientists, Cretaceous mollusc studies in Korea were mainly conducted by Prof. Seung-Young Yang and his colleagues. Earliest Cretaceous molluscs were described at the Myogok Formation distributed at Sangri, Jaesan District, Bonghwa County, North Gyeongsang Province. The Myogok Formation has been regarded as the oldest Cretaceous deposit in the Korean Peninsula; however, this formation has been classified as the Pre-Gyeongsang Supergroup. Yang (1976, 1984) described certain molluscs: *Trigonioides cheongi*, *Nagdongia leei*, *Cuneopsis kihongi*, and *Viviparus keishoensis* (Figs. 5.2 and 5.3). Based on the taxonomy of these molluscs, Yang (1984) concluded that the Myogok Formation was formed in the Upper Jurassic



J. Y. Kim and M. Huh, *Dinosaurs, Birds, and Pterosaurs of Korea*,
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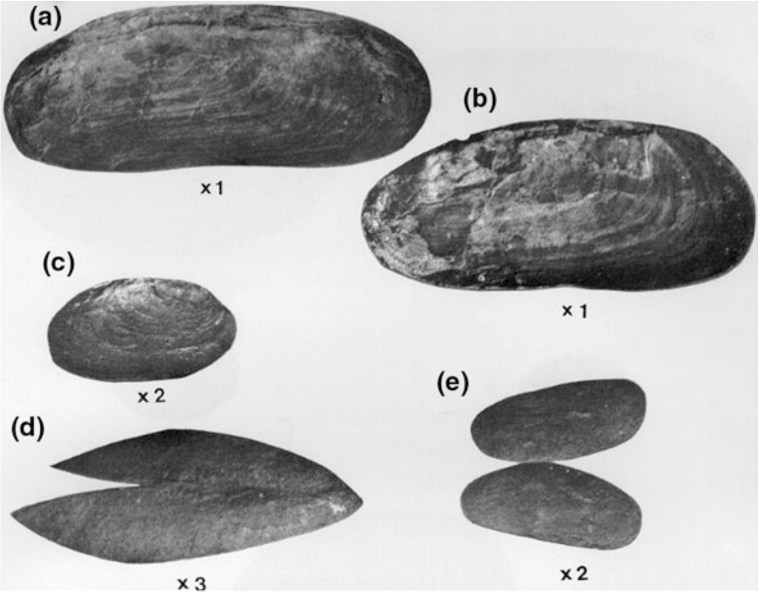


**Fig. 5.1** Bivalve species *Margaritifera* sp. at the Amisan Formation. *Source* From Hwang and Hwang (1986)

Period. Recently, Kang and Paik (2013) synthesized many results of biostratigraphic data and made comparison with other deposits. From this, they assumed the age of the Myogok Formation to range between the Valanginian to Hauterivian Period, and we followed their results.

Many of the studies undertaken into Mesozoic molluscs fossil were concentrated in the Lower Cretaceous deposits of the Gyeongsang Basin, working at the formations of the Sindong Group (Nakdong, Hasandong, and Jinju Formations, in ascending order). In this chapter, we largely follow Cretaceous molluscs synthesized in the Korean Peninsula by Park et al. (2003) and Kozai et al. (2005).

The Nakdong Formation (Barremian) is the oldest member of the Gyeongsang Basin, and this formation contains many freshwater mollusc fossils. These are known as "the Nakdong fauna" and comprise *Nippononaia ryosekiana*, *Nagdongia soni*, *Pseudohyria matsumotoi*, *Trigonioides* (*Wakinoa*) *wakinoensis*, *Spaerium coreanicum*, and *V. keishoensis*. Based on co-occurrences of *N. soni*, *P. matsumotoi*, and *N. ryosekiana* with the Tetori Group in Japan, Park et al. (2003) presumed that both deposits belonged to the same epoch.

Molluscs from the Hasandong Formation (Aptian) have been described by Yun and Yang (2001a, b; Figs. 5.4 and 5.5), Yun et al. (2005) and Yang (1982), and Lee et al. (1990). According to Park et al. (2003), eight (sub-)species of three genera of bivalvia and five species of two genera of gastropoda were reported at the Hasandong Formation. The bivalves comprise *Plicatounio naktongensis multiplicatus*, *P. naktongensis naktongensis*, *P. okjuni*, *P. yooni*, *Trigonioides jaehoi*,

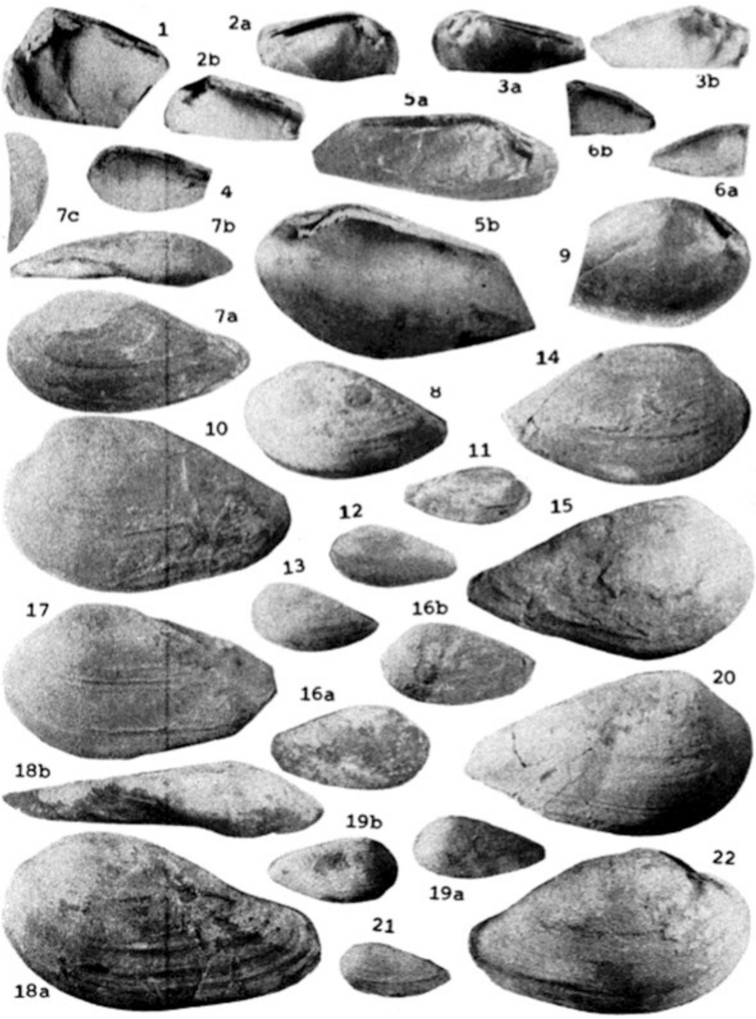


**Fig. 5.2** Bivalve *Cuneopsis kihongi* at the Myogok Formation. *Source* From Yang (1984)

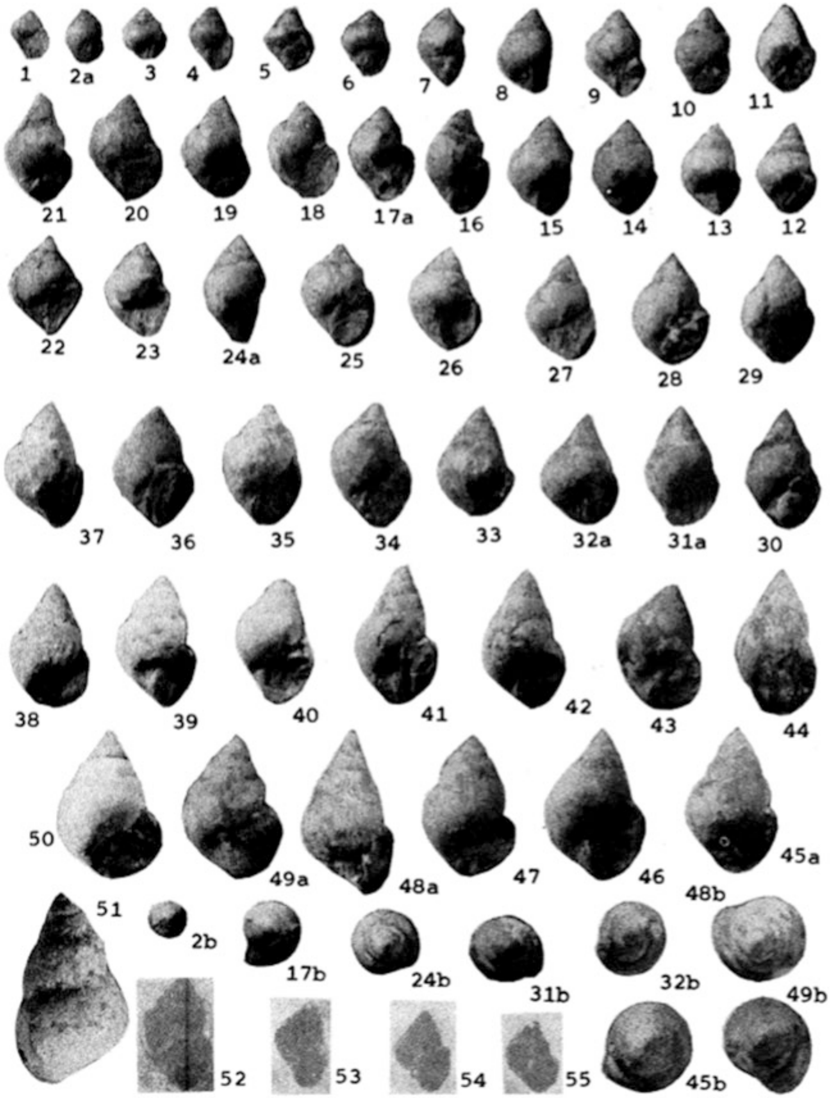


**Fig. 5.3** Gastropod *Viviparus* (?) sp. cf. *V. ongoensis* at the Myogok Formation. *Source* From Yang (1984)

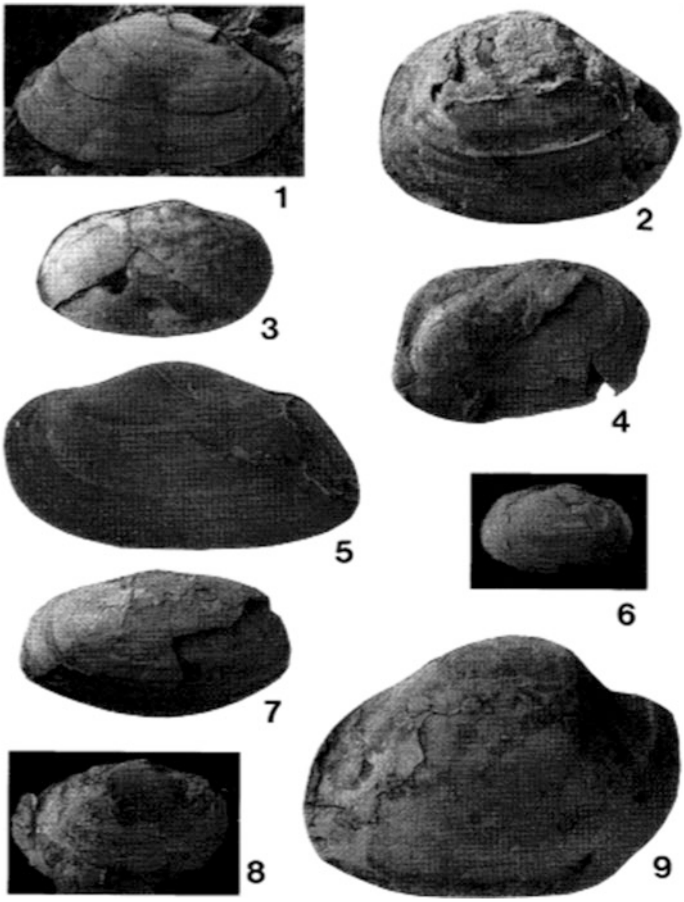


**Fig. 5.4** Bivalve *Nagdongia soni* (Yang 1975) at the Hasandong Formation. *Source* From Yun and Yang (2001b)

*T. kodairai*, *T. tamurai*, and *N. soni*. The gastropods comprise *Brotiopsis kobayashii*, *B. naktongensis*, *B. ryohoriensis*, *B. wakinoensis*, and *Micromelania kotoensis*. Yun and Yang (2001a) considered that the genus *Plicatounio* is stratigraphically restricted to the Hasandong Formation, Korea. Moreover, based on the similarities between molluscan fauna in Korea and in Japan, they considered that certain deposits in Japan (Kanmon and Tetori groups) could have been formed at the same

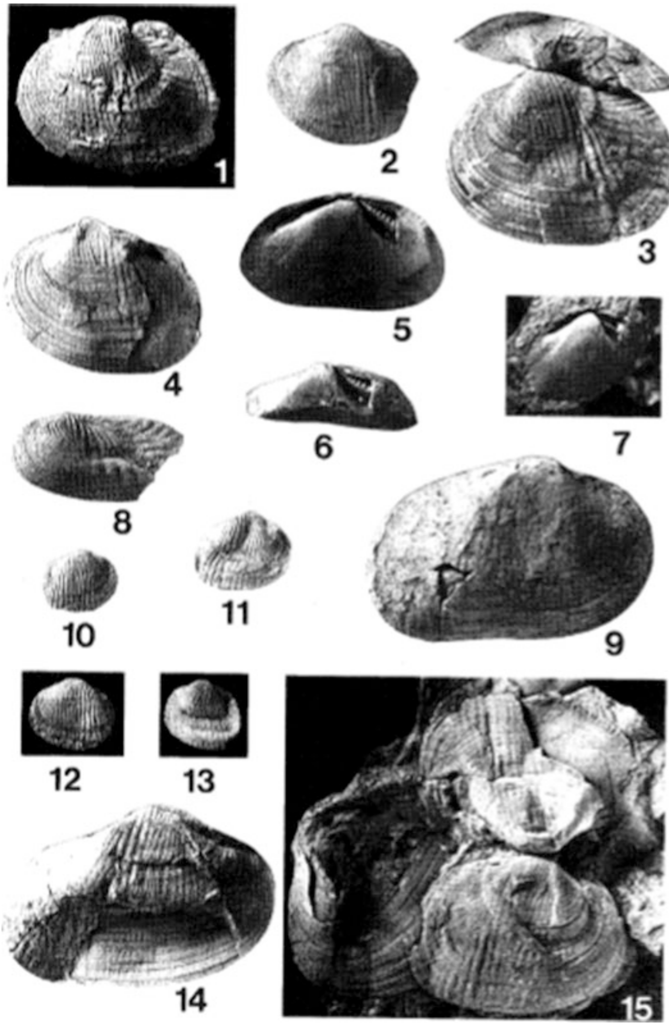


**Fig. 5.5** Bivalve *Trigonioides kodairai* at the Hasandong Formation. *Source* From Yun and Yang (2001a)

time as the Hasandong Formation. Thus, the molluscs at the Hasandong Formation are useful tools for biostratigraphy.

The molluscs at the Jinju Formation (Albian) are relatively less diverse than those of the Nakdong and Hasandong Formations. In the case of bivalves, three species of three genera were reported (*N. soni* and *T. jaehoi* shown in Fig. 5.6, and *S. coreanicum*) at the Jinju Formation by Yun and Yang (2004).

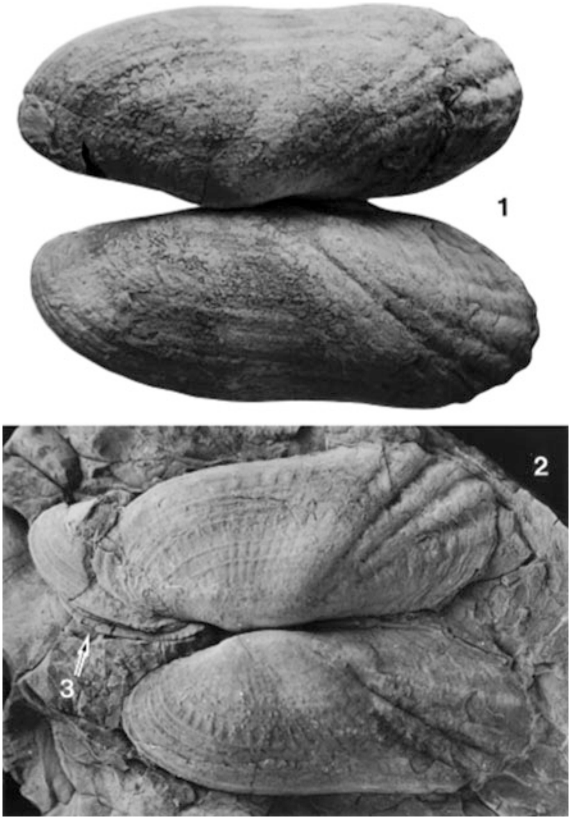


**Fig. 5.6** Two bivalve fossils: (1) *Plicatounio naktongensis*; (2, 3) *Trigonioides jaehoi* at the Jinju Formation. *Source* From Yun and Yang (2004)

## 5.2 Fish

Freshwater fish fossils have been discovered in the Mesozoic strata in the Korean Peninsula. Hwang and Hwang (1986) conducted pioneering research into Korean Mesozoic fish fossils, reporting fish fossils at the Amisan Formation (Upper Triassic (?)–Middle Jurassic) in Boryeong City, South Chungcheong Province, South Korea. However, they only presumed that fossils were affiliated to Family Cyprinidae, and could not provide more detailed descriptions or systematics. So far, after Hwang and Hwang (1986)'s work, neither geologists nor paleontologists have described the Triassic-Jurassic fish in Korea.

Since 2000, Mesozoic paleo-ichthyological studies have been focused on the Early Cretaceous fish. Cretaceous freshwater fish have been discovered at the Hasandong and Jinju Formations in the Gyeongsang Basin in the southeastern area of the Korean Peninsula. The earliest recorded Korean Cretaceous fish fossil is *Sinamia* sp. at the Hasandong Formation (Aptian). According to Yabumoto et al. (2006), *Sinamia* sp. has continued to be discovered at the Jinju Formation.

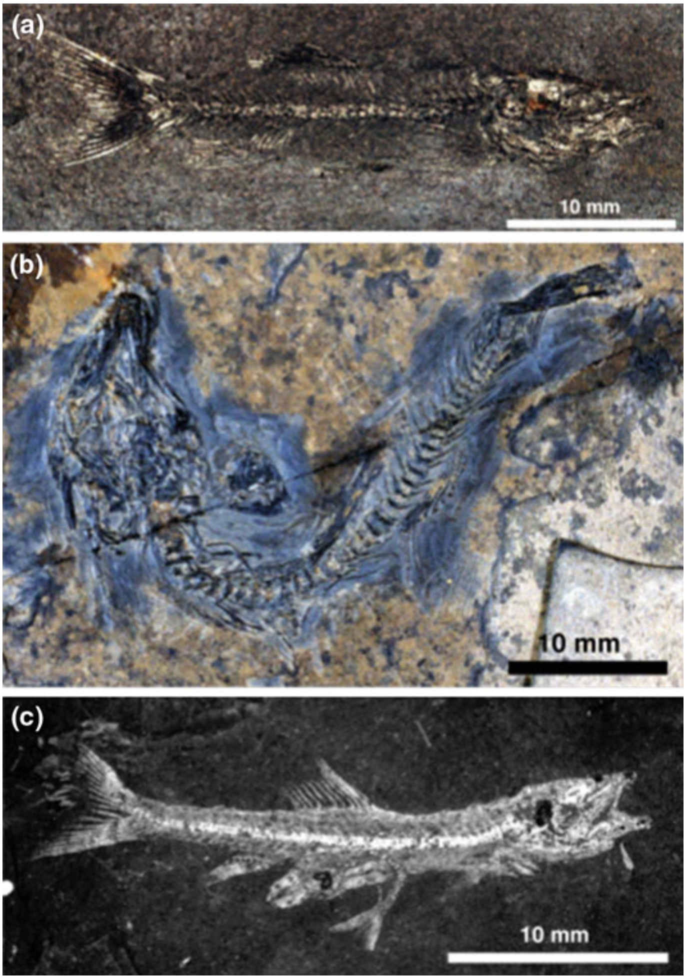


**Fig. 5.7** Early Cretaceous freshwater fish at the Jinju Formation. *Notes* **a** Elopiform fish; **b** albuliform fish; **c**: a film-like preserved specimen (presumed juvenile) of elopiform or albuliform fish. *Source* From Yabumoto et al. (2006)

The most diverse Cretaceous fish fossils of Korea were collected from the Jinju Formation. Yabumoto and Yang (2000) and Yabumoto et al. (2006) reported certain taxa, such as *Lepidotes* sp., *Sinamia* sp., *Wakinoichthys aokii* and some species of albuliformes and elopiformes (Figs. 5.7 and 5.8) at this formation. Based on the discovery of *W. aokii*, Yabumoto and his colleagues assumed that the Jinju Formation is probably the same age as the Wakino Subgroup in Japan (Yabumoto et al. 2006). However, Lee et al. (2010) reported that the Jinju Formation dates from about 106 Ma, which makes the Jinju Formation much younger than the formations of the Wakino Subgroup.

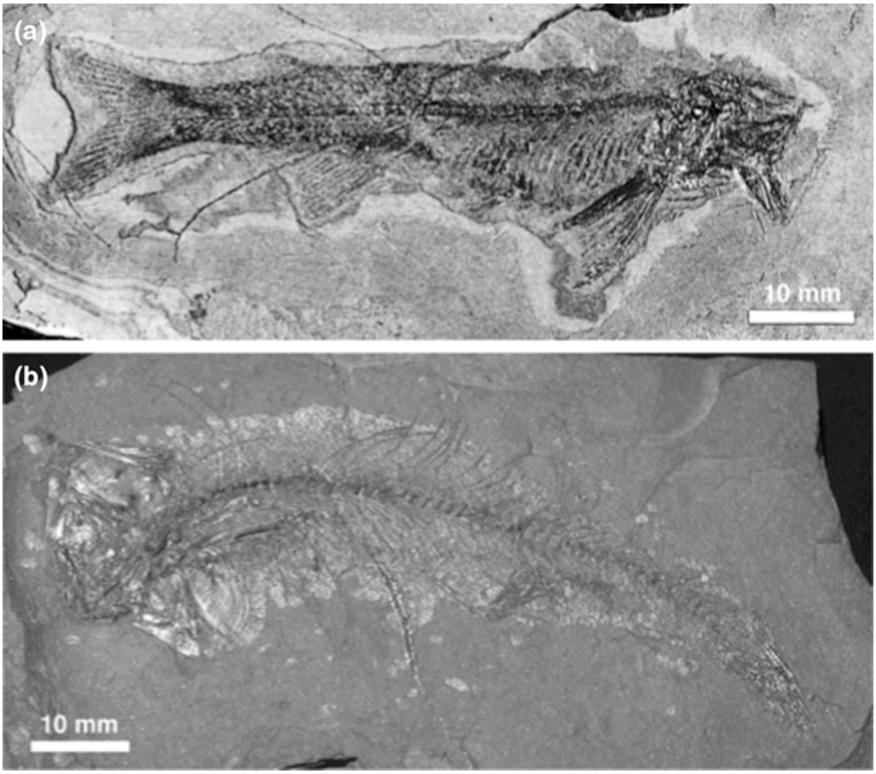


**Fig. 5.8** *Wakinoichthys aokii* at the Jinju Formation. *Sources* From Yabumoto and Yang (2000), Yabumoto et al. (2006)

Recently, Kim et al. (2014) described a new fish taxon, *Jinjuichthys cheongi* gen. et sp. nov. (Fig. 5.9); this is the first recorded instance of an extinct group of ichthyodectiform fish in Korea. Genus *Jinjuichthys* is similar to the genera *Chuhsiungichthys* and *Mesoclupea* found in the Lower Cretaceous of China and Japan, including the Wakino Subgroup. Thus, *Jinjuichthys* seems to be a good indicator for biostratigraphic correlation. However, as noted, further study regarding more detailed correlation is needed.

In summary, Mesozoic freshwater fish studies have concentrated on the Early Cretaceous taxa in Korea, and those results show very similar fauna compared with East Asian (China and Japan) Cretaceous fish. Therefore, fish fossils could provide a potentially useful biostratigraphic indicator. On the other hand, the study of Triassic-Jurassic fish is fragmentary, and further descriptions are needed. Although many fish fossils have been discovered, most of their information remains to be published. Unfortunately, there is no record of Korean fish fossils of the Late Cretaceous Period. This may be attributable either to the paleoenvironment being unsuitable for fish, or the conditions at that time not supporting fossilization.

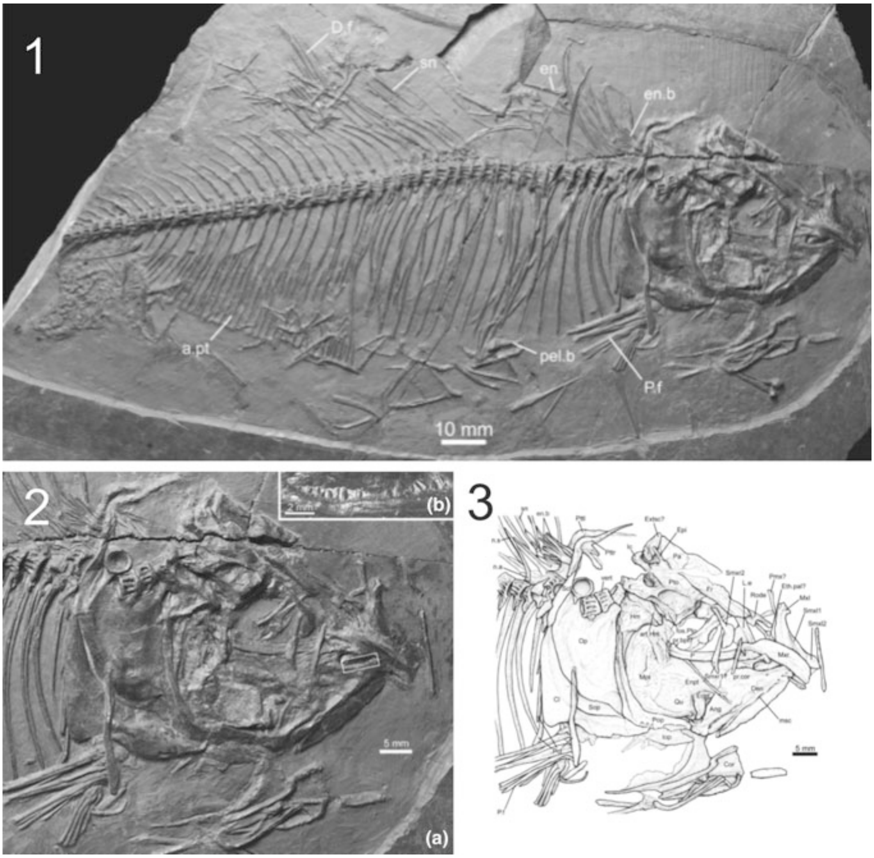


**Fig. 5.9** *Jinjuichthys cheongi* gen. et sp. nov. *Notes* (1) Photograph of holotype PSU V 1011, in right lateral view; (2) head of the holotype, in right lateral view, (B) box area in (A); (3) drawing of the head of the holotype. *Source* From Kim et al. (2014)

## 5.3 Arthropods

Arthropods comprise the most successful animal group in the world (accounting for over 80% of all living animal species). Their evolutionary success has been witnessed in the numerous fossils that have been discovered (e.g., trilobites). The Mesozoic arthropod fossils of Korea can be classified into four groups: insects, isopod (Crustacea), clam shrimp (Crustacea) and arachnid (Chelicerata; spider). While for convenience ostracod (Crustacea) is classified as one of the arthropod groups, this microcrustacean has generally been regarded as a “microfossil”.

### 5.3.1 Insects

Insects provide the most commonly found arthropod fossils in the Mesozoic strata in Korea. These were first described by Hwang and Hwang (1986), who found four taxa at the Amisan Formation: Perlidae, *Gibosia* sp., Pteronarcydae and Siphlonuridae. Despite the significance of these finds, many pioneering works include only sparse data and photos.

The Amisan Formation is an important insect fossil-bearing deposit because this formation contains the earliest recorded insect fossils in South Korea. Nam and Kim (2014), in their work on *Mesopsyche dobrokhotovae* (order Mecoptera), provided the first detailed study of insect fossils at the Amisan Formation. One year later, Nam (2015) reported comprehensive descriptions of insect fossils from the same formation in his PhD thesis. His results can be briefly summarized as follows: (1) the fossil insect fauna at the Amisan Formation consist of 8 orders which include 22 species, and these fauna afford the earliest record of insects in Korea; (2) the orders of insects are classified into ephemeroptera, odonata, plecoptera, blattodea, homoptera, orthoptera, mecoptera and coleoptera; (3) based on the occurrence of the species *Samarura gigantea*, *Mesobaetis sibirica*, and *Platyperla platypoda*, the age of the Amisan Formation is presumed to be Middle Jurassic; (4) co-occurrences of both lotic and lentic insects suggest that the paleoenvironment was that of either lake margin or a stream connected with a lake.

Cretaceous insect fossil studies have been carried out in the southern Korean Peninsula at the Jinju Formation (Albian) of the Gyeongsang Basin and the Hampyeong Basin (Aptian–Albian). The Jinju Formation has yielded many well-preserved insect fossils. Thus, many paleontologists have studied insect fossils from this Lower Cretaceous deposit.

- Baek and Yang (2004) described five genera belonging to mesoblattinidae (blattodea, cockroaches), and identified 12 other orders (Fig. 5.10).
- Park et al. (2013) reported larvae and images of the aquatic coleopteran genus *Coptoclava* at the Jeongchon, Jinju City, and Gwanghyeon, Gunwi County, sections. The predominance of *Coptoclava* indicates that the fauna of the Jinju Formation seems very close to those of Jehol Biota in China. However, the Jinju Formation is much younger than the Jehol Biota, therefore, the fauna of the

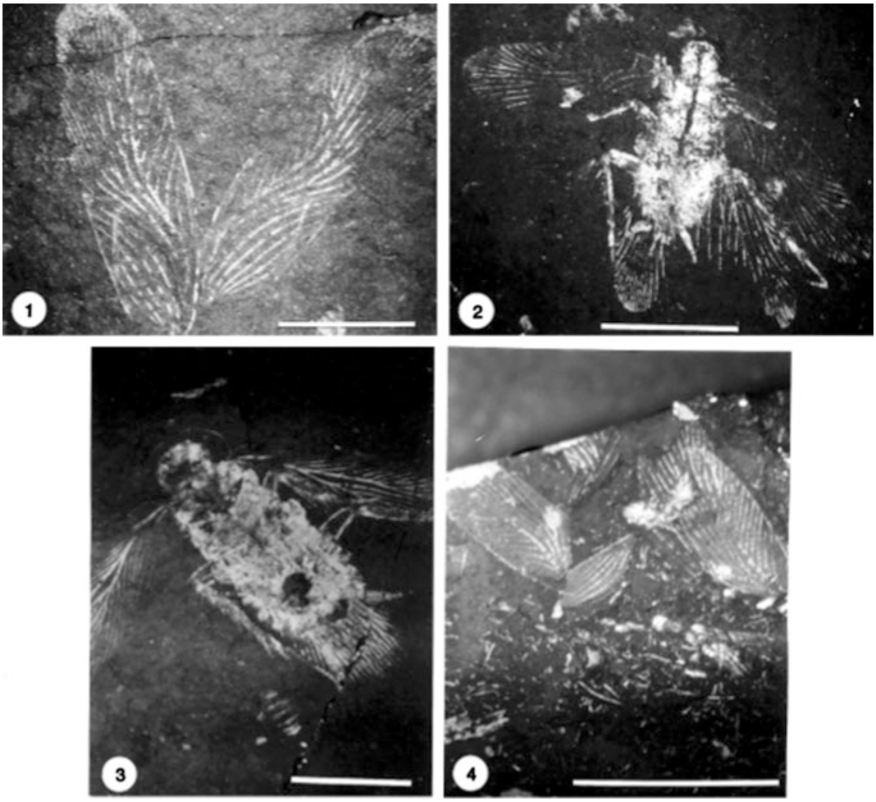

**Fig. 5.10** Cockroach fossils at the Jinju Formation. *Notes* (1) Gen. et sp. indet. D; (2) *Mesoblattina* sp. C; (3) *Mesoblattina* sp. B; (4) Gen. et sp. indet. E. *Source* From Baek and Yang (2004)

Jinju Formation would provide an important role in understanding East Asian insect fauna following the Jehol Biota discoveries (Park et al. 2013; Figs. 5.11 and 5.12).

- Recently, Nam and Kim (2016) described larvae and adults of *Hemeroscopus baissicus* (hemeroscopidae, extinct dragonfly group), concluding that this insect was a top-level predator in an aquatic ecosystem with the genus *Coptoclava*.
- Huh and Chung (2009) briefly reported fossil beetles from a small deposit in the Hampyeong Basin (Lower Cretaceous; Aptian-Albian) in the southwestern region of the Korean Peninsula. However, the state of preservation of the beetle fossils was poor and did not allow their identification. The taxonomy of the beetles was therefore limited to their family level (cupedidae, eucinetidae, chrysomelidae, carabidae, and gyrinidae; Fig. 5.13).

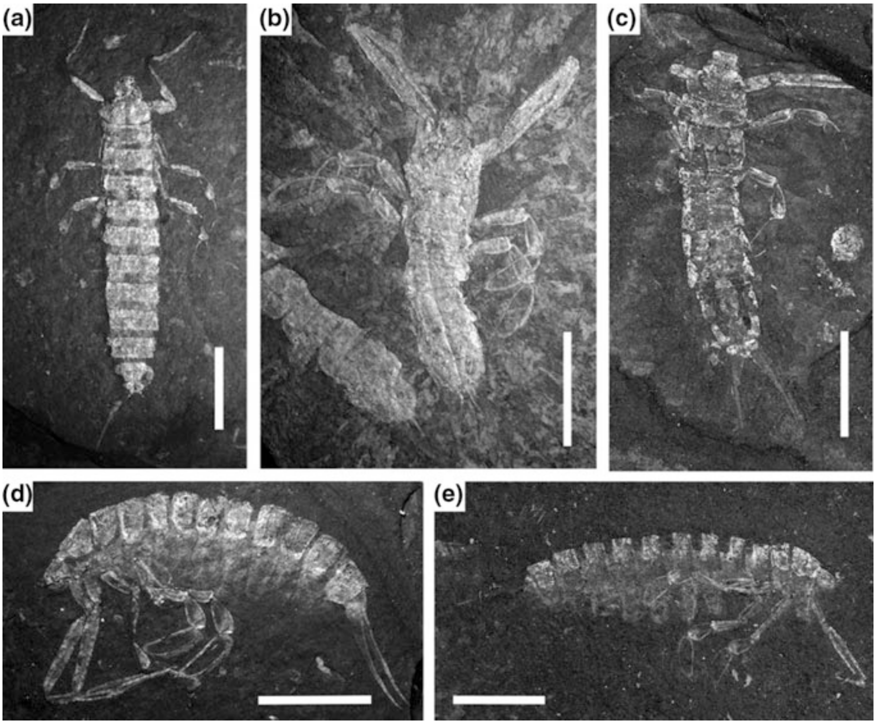


**Fig. 5.11** Larvae of *Coptoclava* sp. at the Jinju Formation. *Note* Scale bars are 1 cm. *Source* From Park et al. (2013)

### 5.3.2 Isopods, Arachnids and Clam Shrimp

Although many publications regarding the Korean Mesozoic fossil arthropoda dealt mainly with insects, other groups also existed at that time. Except for clam shrimp, the research history of other taxa of arthropod in Korea is limited. Thus, isopod and arachnid fossils have rarely been reported. Moreover, their stratigraphic age and deposits are limited to the Lower Cretaceous Jinju Formation at the Gyeongsang Basin.

- Isopod: Park et al. (2012) reported a new species, *Archaeoniscus coreaensis* (Figs. 5.14 and 5.15), and this is the only isopod species fossil in Korea. The genus *Archaeoniscus* has been identified in Western Europe, Mexico, and Egypt; therefore, its occurrence in East Asia implies that *Archaeoniscus* may

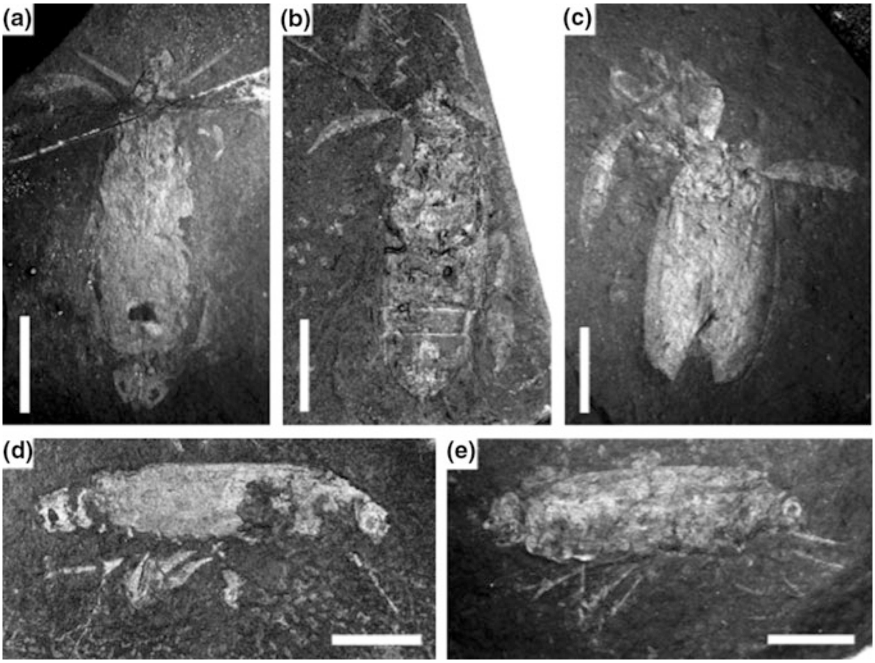


**Fig. 5.12** Images of *Coptoclava* sp. at the Jinju Formation. *Note* Scale bars are 1 cm. *Source* From Park et al. (2013)

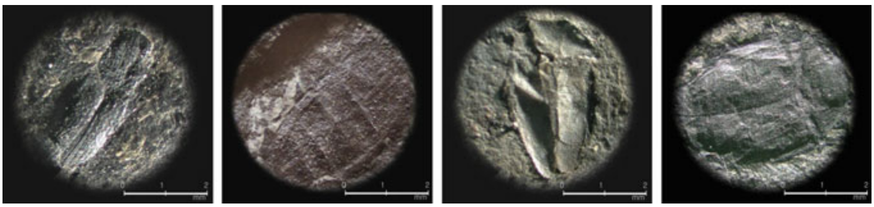

**Fig. 5.13** Beetle fossils at the Hampyeong Basin. *Source* Modified from Huh and Chung (2009)

have had a worldwide distribution (Park et al. 2012). According to Park et al. (2012), the lifestyle of *A. coreaensis* was probably benthonic, due to the form of the limbs and the flattened body.

- Arachnid (spider): The first reported spider fossil at the Jinju Formation was described by Kim and Nam (2008). However, due to the low resolution of the photograph and the absence of a description for the specimen, Selden et al. (2012) redescribed the fossil and designated it as a new genus and species, *Korearachne jinju* (Fig. 5.16). Generally, it is rare to discover spider fossils in rocks. Thus, a spider fossil in the Jinju Formation is unique and provides important material regarding the evolution of the Early Cretaceous spiders.

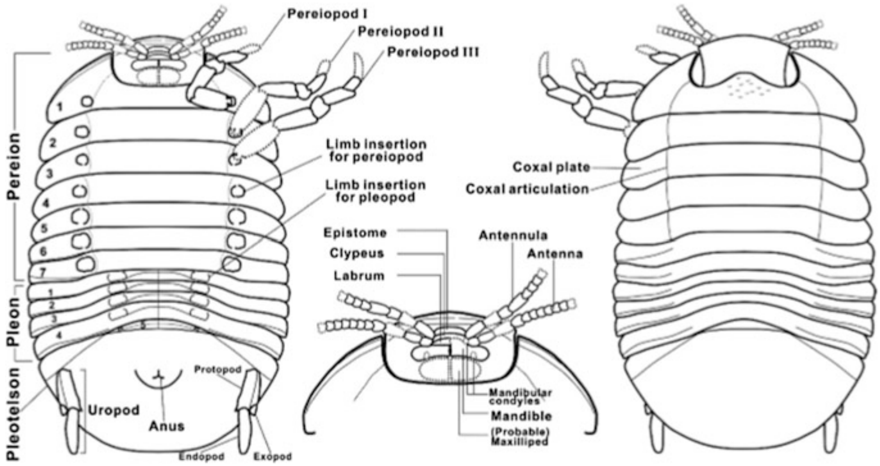


**Fig. 5.14** Reconstruction of *Archaeoniscus coreaensis* from the Jinju Formation. *Notes* Left to right: ventral view, close-up of cephalic region in ventral view, dorsal view. *Source* From Park et al. (2012)

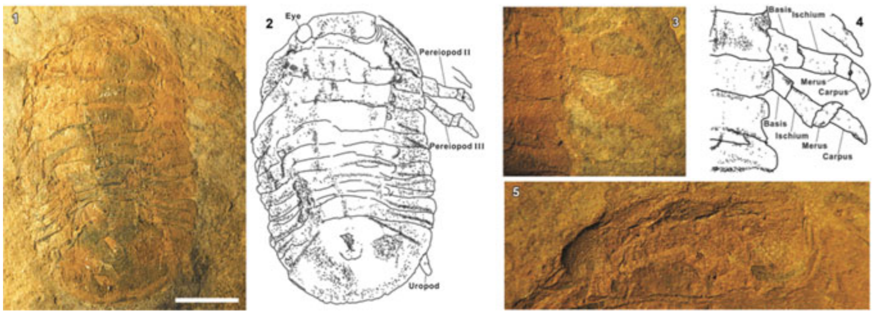


**Fig. 5.15** *Archaeoniscus coreaensis* in dorsal view. *Notes* (1) Photograph of the whole body; (2) drawing of the whole body; (3) close-up photograph; (4) drawing of the pereipods; (5) close-up photograph of the cephalon. Scale bar is 5 mm. *Source* From Park et al. (2012)

- Clam shrimp: This taxon resembles bivalved molluscs. However, this animal is one of the bivalved crustacean members included in the class branchiopoda. Many clam shrimp fossils (and living species) have been reported worldwide, from the Devonian to Holocene Periods. In Korea, Kim and Lee (2015) discovered the earliest clam shrimp fossils at the Amisan Formation. They described four species of three genera (*Euestheria kawasakii*, *E. shimamurai*, *Sphaerestheria koreanica*, and *Cyclestheroides rampoensis*) and, based on these results, the geological age of the Amisan Formation was assumed to be the Upper Triassic (Kim and Lee 2015). However, this cannot be stated with certainty as insect fossils and other geological studies support that the Amisan

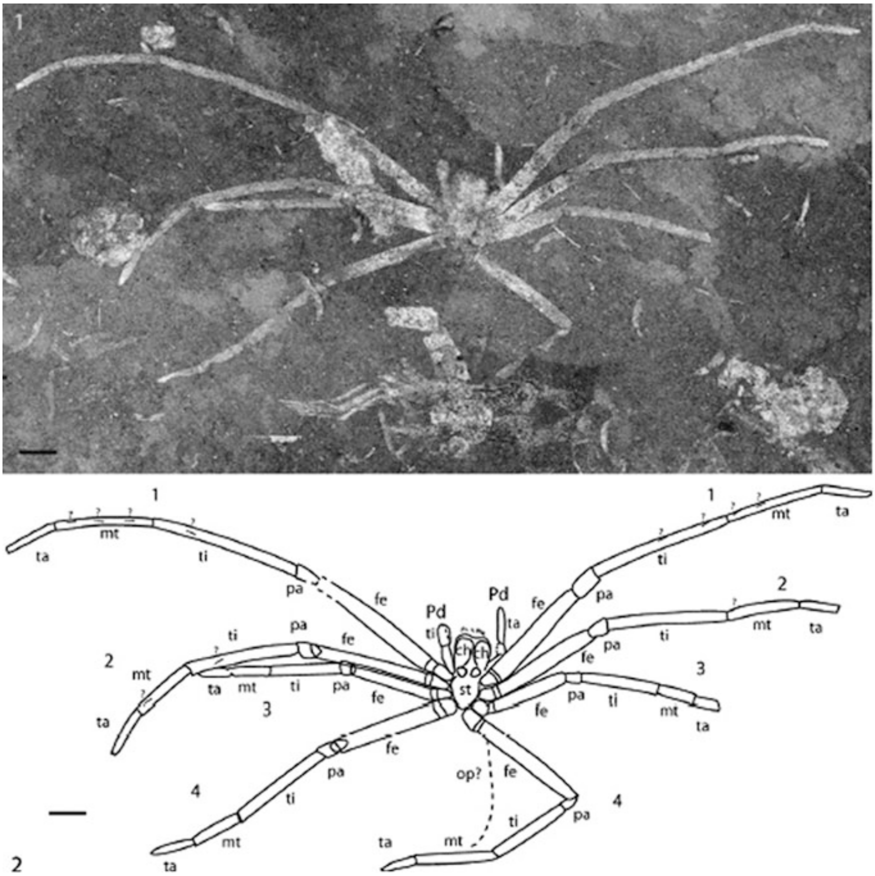


**Fig. 5.16** *Korearachne jinju*, holotype TSH-0808, at the Jinju Formation. *Notes* (1) Photograph of the specimen; (2) explanatory drawing to accompany. Scale bars are 1 mm. *Source* From Selden et al. (2012)

Formation is Jurassic. The first study of clam shrimps at the Gyeongsang Basin was conducted by the Japanese paleontologists Kobayashi and Kido (1947), who described four taxa (including variants) of clam shrimp. Decades later, Chang et al. (1976) emended the taxonomy of clam shrimps at the Gyeongsang Basin. For example, Kobayashi and Kido reclassified *Estherites kyongsangensis* as *Yanjiestheria kyongsangensis*. This species was also reported at the Upper Cretaceous Iljik Formation by Choi (1990; Fig. 5.17). Lee et al. (1993; Fig. 5.18) described four species of the genus *Yanjiestheria* from the Lower to Upper Cretaceous deposits (Jinju and Geoncheonri Formations); *Y. kyongsangensis* (Jinju and Geoncheonri Formations), *Yanjiestheria paucilineata* (Geoncheonri Formation.), *Yanjiestheria endoi* (?) (Geoncheonri Formation), and *Yanjiestheria proamurensis* (?) (Jinju Formation). More diverse clam

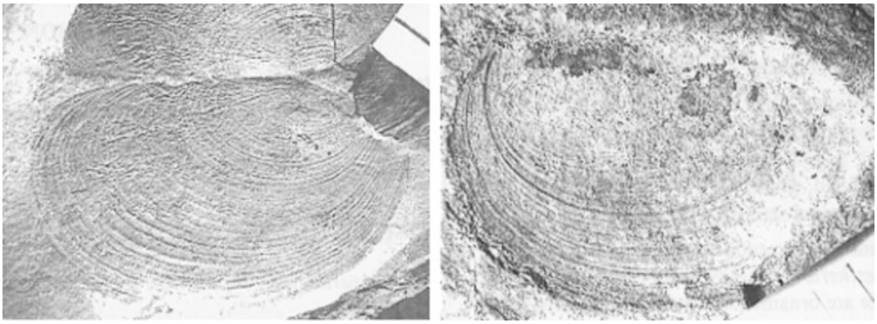

**Fig. 5.17** Clam shrimp *Yanjiestheria kyongsangensis* (Kobayashi and Kido 1947) from the Iljik Formation. *Notes* Left to right: left view of carapace; right view of carapace. *Source* From Choi (1990)

shrimp fauna were described by Park and Chang (1998), who classified thirteen species of three genera (*Yanjiestheria*, *Neodiestheria*, and *Eosestheria*) at the Jinju, Haman, and Jindong Formations in the Gyeongsang Basin (Fig. 5.19).

## 5.4 Plants

Early studies of Mesozoic plant fossils found on the Korean Peninsula were mainly investigated by German and Japanese scientists in the late nineteenth century to the early twentieth century, and those reports were briefly noted by Kim et al. (2004) and Kim (2015). Here, first, we describe the introduction by Kim and colleagues (Kim et al. 2004; Kim 2015) of plant fossil research history in relation to the Korean Peninsula. Additionally, we introduce some recent studies of Korean Mesozoic plant fossils.

### *5.4.1 Early Mesozoic Plants*

The first report of plant fossils was described by Gottsche (1886), who studied wood fossils from the Yugyeong Formation (Triassic) of Pyongyang, North Korea. Following his study, these woods were classified into three species of two genera (*Xenoxylon latiporosum*, *X. phyllocladoides*, and *Phyllocladoxylon heizyoense*) by Shimakura (1936). Nakamura et al. (1957) also noted *X. latiporosum*, *X. phyllocladoides*, and *Cedroxylon* cf. *regulare* discovered near Pyeongyang. In South Korea, Paek (2003) described two species (*Xenoxylon* sp. and *Dadoxylon* sp.) at the Jogyeri Formation (Upper Triassic) of the Nampo Group in South Chungcheong Province; however, these were reclassified as *X. phyllocladoides* and *Agathoxylon* sp.

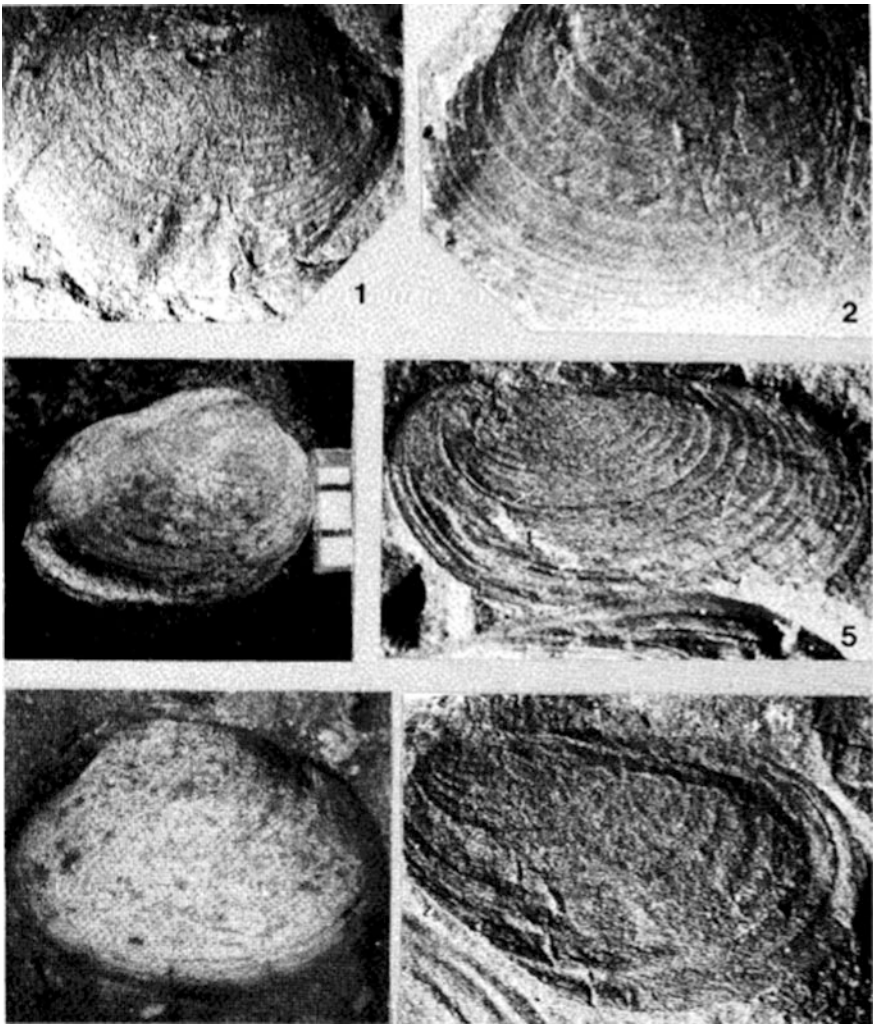


**Fig. 5.18** Clam shrimp fossils at the Gyeongsang Basin. *Notes* (1, 2) *Yanjiestheria endoi* (?) from the Geoncheonri Formation; (3, 4) *Yanjiestheria proamurensis* (?) from the Jinju Formation; (5, 6) *Yanjiestheria paucilineata* from the Geoncheonri Formation. *Source* From Lee et al. (1993)

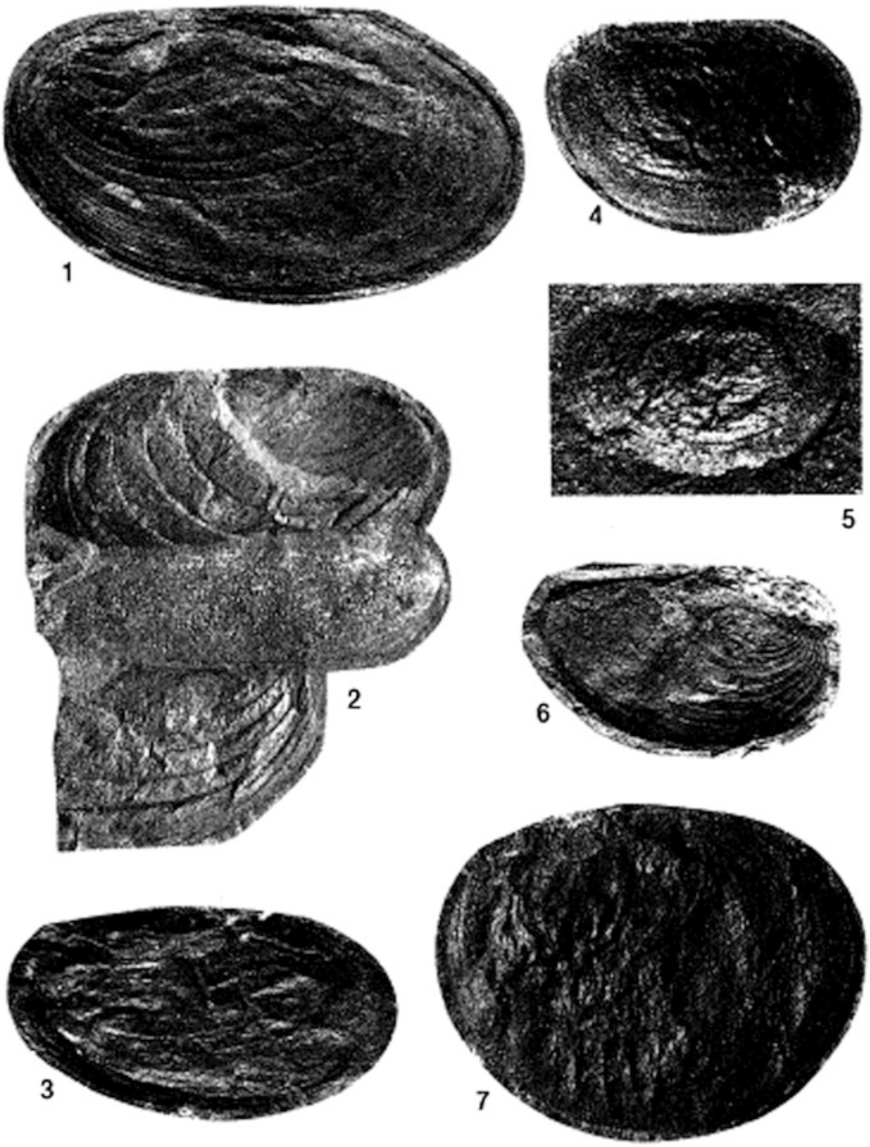


**Fig. 5.19** Clam shrimps at the Upper Cretaceous Haman Formation. *Notes* (1–3) *Eosestheria* cf. *qingtanensis* (Chen 1976); (4, 5) *Eosestheria* sp. A; (6) *Eosestheria* sp. B; (7) *Eosestheria hamanensis*. *Source* From Park and Chang (1998)

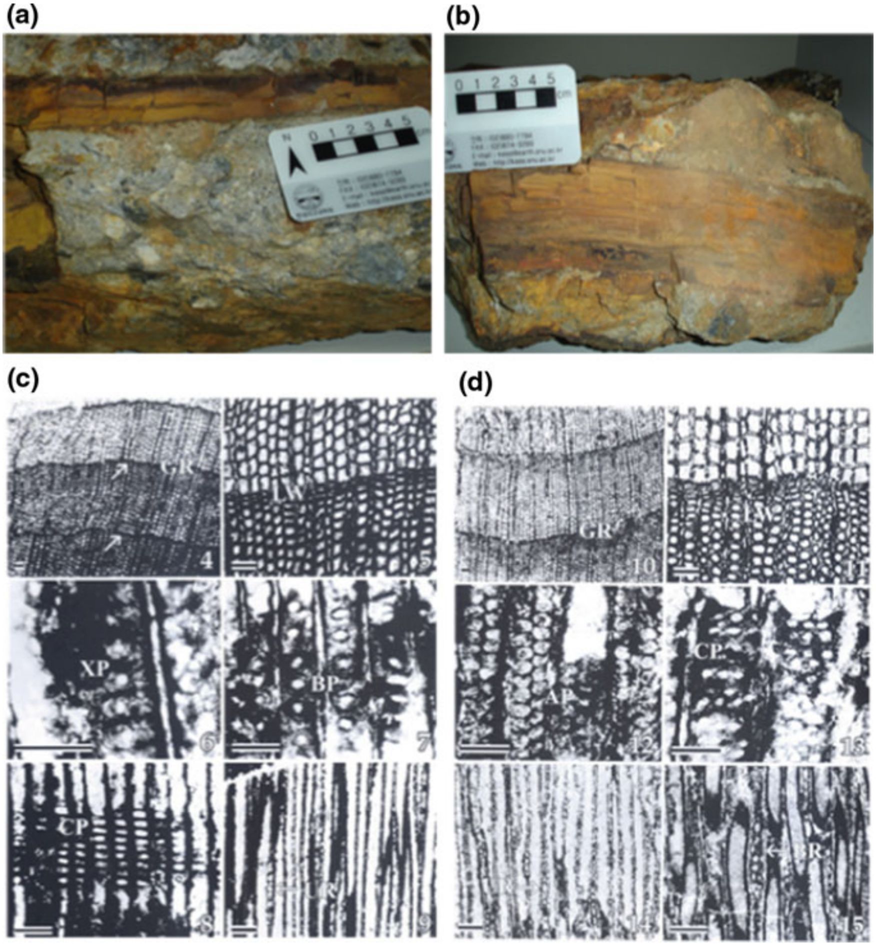


**Fig. 5.20** Fossil woods at the Jogyeri Formation of the Nampo Group. *Notes* **a**, **b** Conglomerate bearing silicified wood fossils; **c** *Xenoxylon phyllocladoides* Gothan; **d** *Agathoxylon* sp. *Sources* From Kim et al. (2005a, b) Kim (2015).

(Fig. 5.20) by Kim et al. (2005a, b). Therefore, all taxa of Early Mesozoic fossil woods in Korea comprised six species of four genera (Kim 2015). In contrast, Chun (2004) noted that the floral arrays of the Lower Mesozoic formations of Daedong Supergroup in Korea could be classified into the *Dictyophyllum-Clathropteris* floral province. Chun also indicated them as belonging to the Late Triassic to Early Jurassic Periods and having grown in a tropical or subtropical environment (Fig. 5.21).

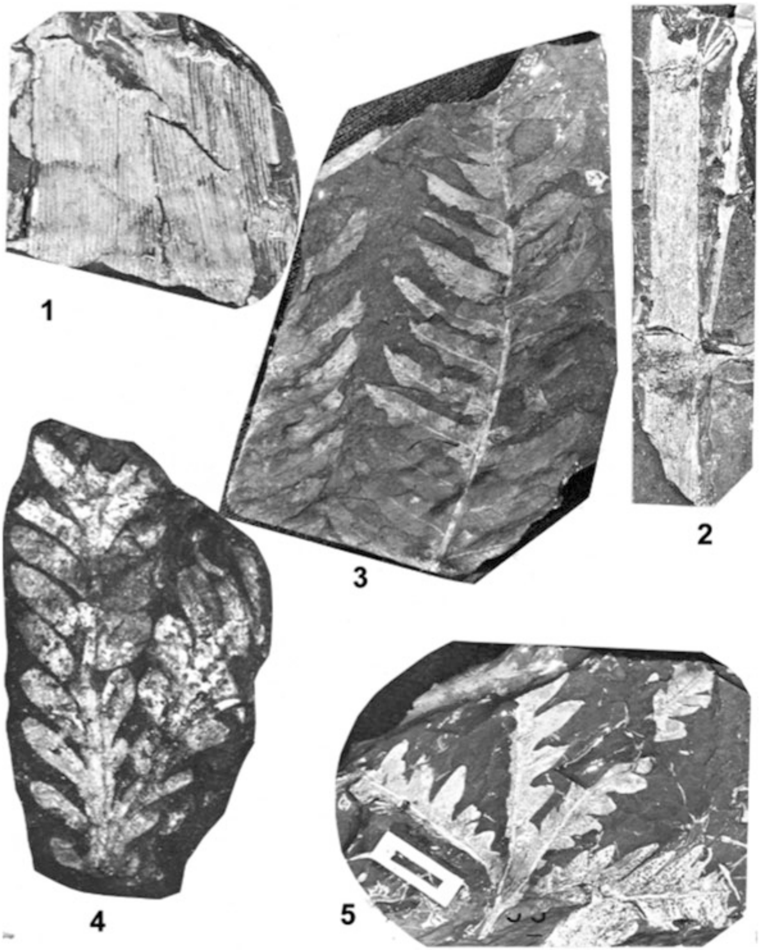


**Fig. 5.21** Early Mesozoic plant fossils in the Mungyeong area. *Notes* (1) *Neocalamites carrerei* (Zeiller) Halle; (2) *Equisetites ferganensis* Seward; (3) *Cladophlebis argutula* (Heer) Fontaine; (4) Corystospermales (?); (5) *Dictyophyllum* sp. cf. *D. nathorstii* Zeiller. *Source* From Chun (2004)

## 5.4.2 Late Mesozoic Plants and Tree Ferns

The late Mesozoic plants found in Korea are much more diverse and well-studied than Early Mesozoic plants. Tateiwa discovered two tree ferns (in 1925) at the Lower Cretaceous Nakdong Formation (Barremian-Aptian) of the Gyeongsang Basin in the Mt. Geummubong area (Fig. 5.22), Chilgok County, North Gyeongsang Province, and Ogura (1927, 1941) designated these species, which were new to science, as *Cyathocaulis nakdongensis* and *Cyathocaulis tateiwai*. In addition, Ogura (1944) described fossil wood species *X. latiporosum* at the same


**Fig. 5.22** Map showing plant fossil site and geological map of Mt. Geummubong, Waegwan, Korea. *Source* From Jeong et al. (2014)

location, but this was re-identified as *Xenoxylon meisteri* Palib. et Jarm. (Fig. 5.23) by Jeong et al. (2014). It is proposed that the co-occurrence of the genus *Xenoxylon* and tree ferns suggests a cool/temperate Early Cretaceous climate in southern Korea (Jeong et al. 2014). In addition, some partially preserved Early Cretaceous wood fossils were described by Lee and Yang (2006). They collected fossils from Chilgok County (*Cyathocaulis* sp.), Gumi City (*X. latiporosum*, Fig. 5.24) and Andong City (*Cupressioxylon* sp. and *Araucarioxylon* sp.), North Gyeongsang Province. One specimen, *Cyathocaulis* sp. from Chilgok, was discovered as a boulder; therefore, the age of the woods is uncertain. However, the authors presumed that fossil to be from the upper part of the Hasandong Formation or the Jinju Formation. The presence of *Cyathocaulis* sp. suggests that the paleoclimate was tropical or subtropical. Two studies focused on Korea's southwestern Lower Cretaceous deposits. You et al. (2000) reported platanoid leaves at the Hampyeong Basin in Hampyeong County, South Jeolla Province (southwestern Korean Peninsula), which deposit includes Oishi's angiosperm series. It indicates that the age of the Hampyeong Basin is Aptian/Albian, or younger. Also, Kenrick et al. (2000)

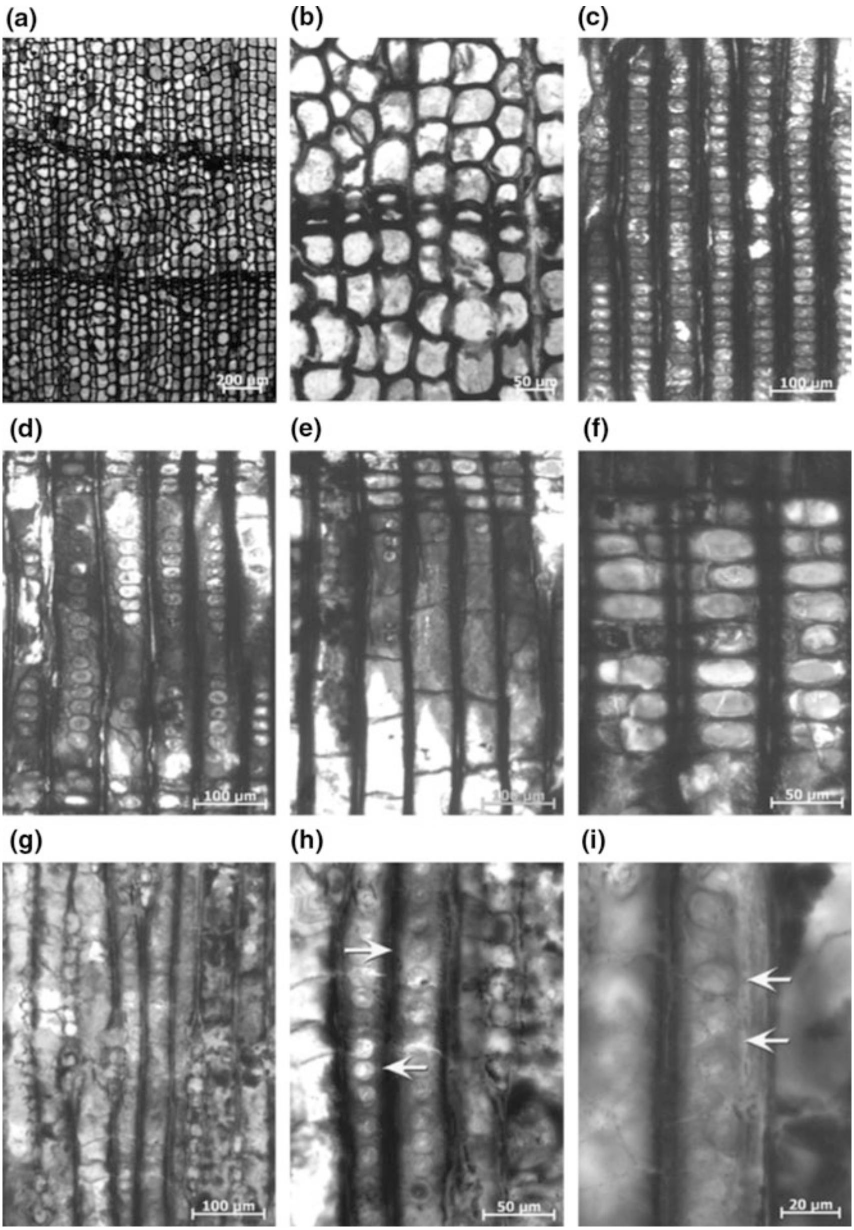


**Fig. 5.23** Microphotographs of *Xenoxylon meisteri*, sample number Xe1, from the Nagdong Formation in the Mt. Gummubong area. *Notes* **a**, **b** Cross-section showing the distinct growth rings and squarish, rounded, or polygonal tracheids; **c** radial section showing contiguous and horizontally flattened bordered pits on radial walls of tracheids; **d**, **e** radial section showing locally round, distant, and clustered bordered pits on radial walls of tracheids; **f** radial section showing window-like cross-field pits; **g**, **h** tangential section showing rays and bordered pits (arrows) on tangential walls of tracheids; **i** tangential section showing partly alternate two-row bordered pits (arrows) on tangential walls of tracheids. *Source* From Jeong et al. (2014)

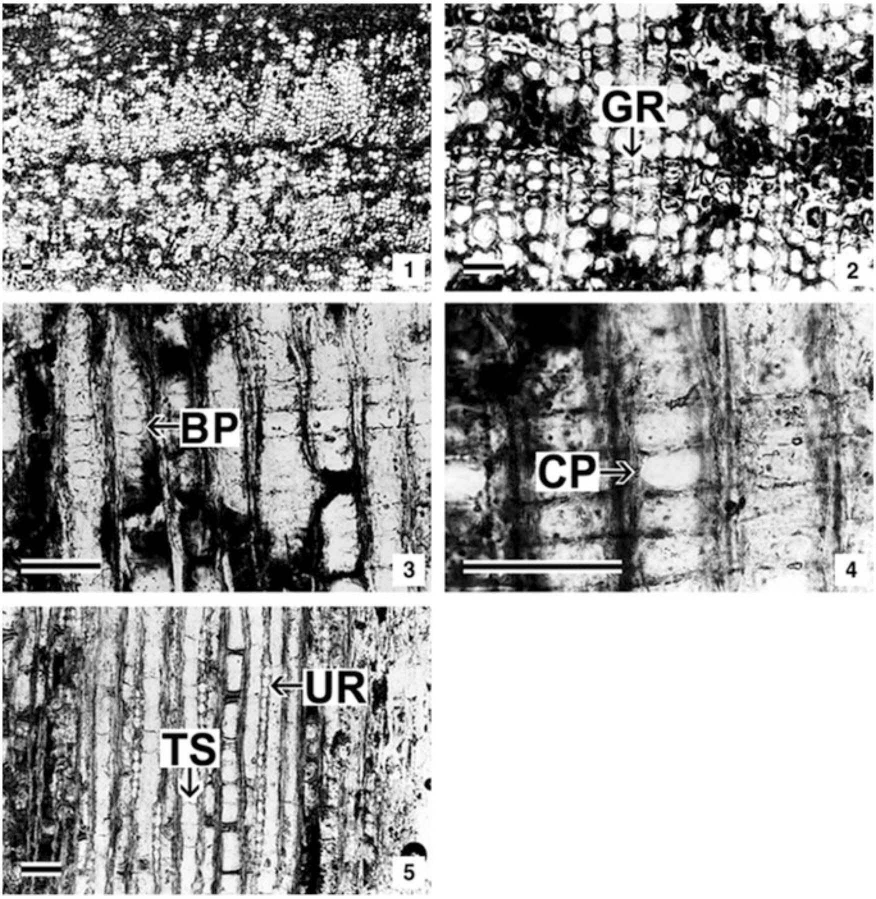


**Fig. 5.24** Anatomical features of *Xenoxylon latiporosum* (KPE P102) in the Gumi area. *Notes* (1, 2) cross-section showing the growth rings (GR); (3) radial section showing flattened bordered pits (BP) on radial walls of tracheids; (4) radial section showing the large simple pits of cross-fields (CP); (5) tangential section showing the uniseriate rays (UR) and tracheid septa (TS). Scale bars = 100 μm. *Source* From Lee and Yang (2006)

presented the flora of the Lower Cretaceous deposits of Goheung County, South Jeolla Province. This flora mainly comprises bennettitales, conifers and ferns, and Kendrick et al. suggested that the age of flora is no younger than Barremian.

Oh et al. (2013) reported *Agathoxylon* sp. and *Taxodioxylon* sp. at the Hwawon Formation (Mid-Cretaceous) of Haenam County, South Jeolla Province (Fig. 5.25). The presence of traumatic resin canals in the *Taxodioxylon* (Fig. 5.26) specimens indicates that flooding occurred repeatedly due to the alternation between dry and rainy seasons. The low diversity observed for the Cretaceous fossil wood arrays in Korea could be explained by the paleoclimatologically stressful environment, as a

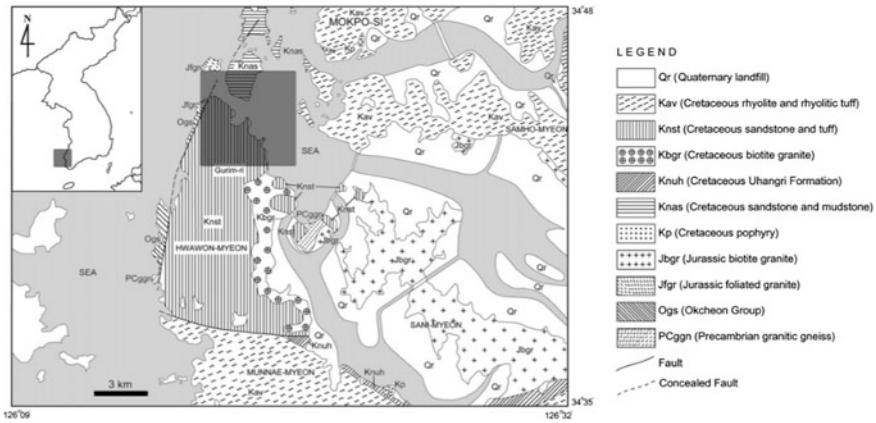


**Fig. 5.25** Location and geological map showing plant fossil site (gray square) of the Hwawon Formation in Hwawon District, South Jeolla Province, Korea. *Source* From Oh et al. (2013)

dry tropical/subtropical climate prevailed over the region at that time (Oh et al. 2013).

Kim et al. (2002a, b) described five species of four genera at several Upper Cretaceous deposits (Fig. 5.27) in Korea: the Uhangri Formation, at the Haenam Basin, the Dadaepo Formation, at the Gyeongsang Basin, and several small Cretaceous deposits in the southwestern islands. These species were *Dadoxylon byeongpungense* sp. nov. (at Byeongpung Island, Sinan County, South Jeolla Province), *Cupressinoxylon uhangriense* sp. nov. (at the Uhangri Formation, Haenam Basin, Haenam County, South Jeolla Province), *Taxodioxylon* cf. *nihongii* (at the Uhangri Formation, Haenam Basin, Haenam County, South Jeolla Province), *Taxodioxylon albertense* (on Gwanmae Island, Jindo County, South Jeolla Province), and *Mesembrioxylon* sp. (at the Dadaepo Formation, Busan). Four of these five were first discovered in Korea, *Mesembrioxylon* being the exception.

Oh et al. (2011) reviewed the paleobiological implications of the Cretaceous conifer in Korea, and described new species. According to Oh et al. (2011), the fossil wood taxa indicating the paleovegetation in the southern Korean Peninsula shows a transition from a mixed-type flora largely dominated by tetori-type taxa in the early Early Cretaceous to a mixed-type flora dominated by ryoseki-type taxa in the late Early Cretaceous. Also, the Late Cretaceous flora was similar to the ryoseki-type flora of the Early Cretaceous Period (Oh et al. 2011). They also described a new species, *Agathoxylon togeumense* sp. nov. (Fig. 5.28), at the Togeum Formation (Albian) of the Gurye Basin.

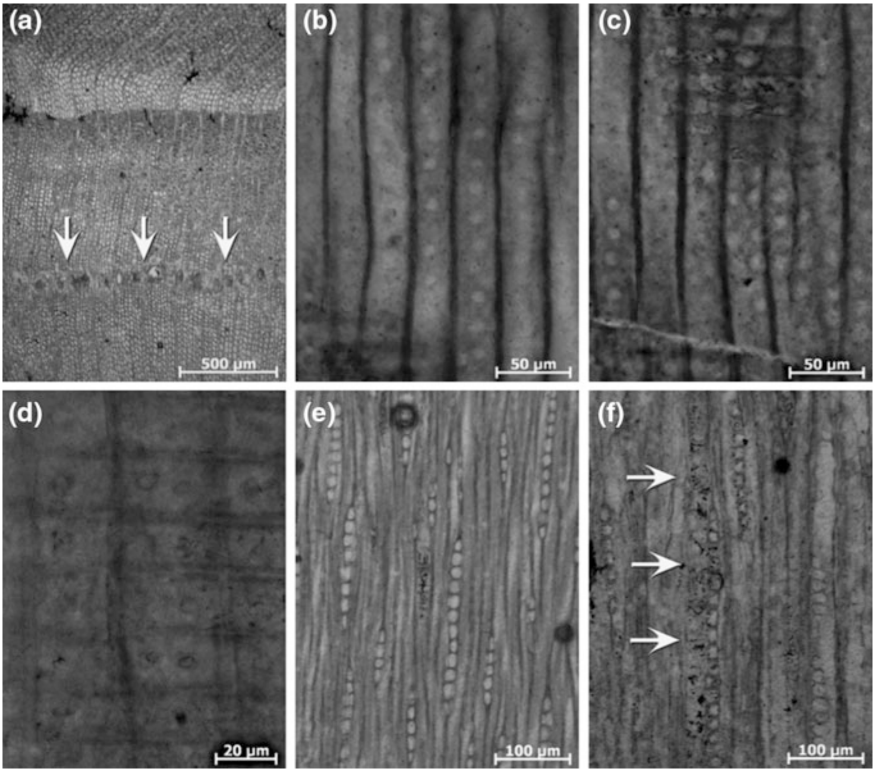


**Fig. 5.26** Photomicrographs of *Taxodioxylon* sp. *Notes* **a** Transverse section showing a distinct growth ring and traumatic resin ducts (arrows); **b** radial section showing one row and distant radial tracheid bordered pits; **c** radial section showing two rows and opposite radial tracheid bordered pits; **d** radial section showing taxodioid or cupressoid cross-field pits; **e**, **f** tangential section showing uniseriate rays and black resinous materials within axial parenchyma (arrows). *Source* From Oh et al. (2013)

## 5.5 Stromatolites

Stromatolites are biochemical sedimentary structures and rocks which are formed in shallow water through the trapping, binding, and cementation of sedimentary grains by a surficial microbial mat (algal mat) composed mainly of cyanobacteria (formerly called "blue-green algae") and other microbes. Stromatolites are very common in Precambrian carbonates but they also occur in many Phanerozoic limestones, particularly those of peritidal origin (Tucher 2003). They have provided useful information on the paleoenvironmental conditions of the deposits of which they are composed (Walter et al. 1992; Grotzinger 1994).

In Korea, stromatolites have also been found not only in the Precambrian deposits, but also in the Mesozoic continental deposits. Mesozoic stromatolites

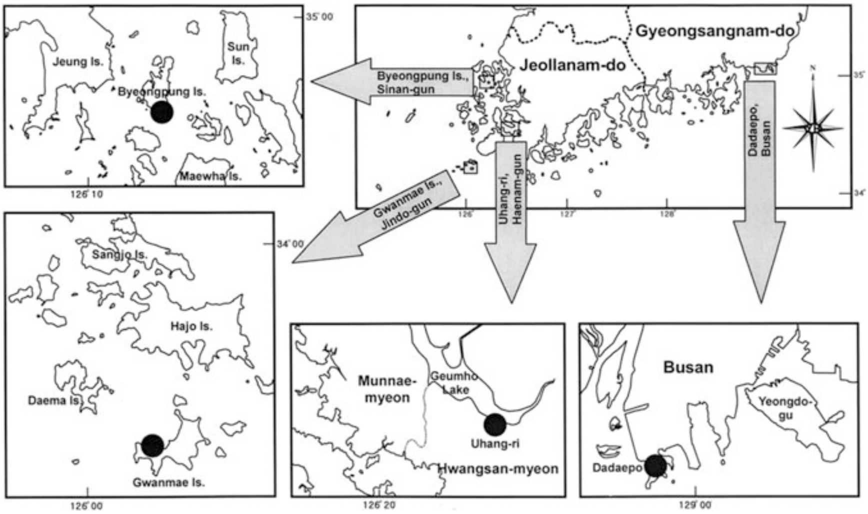


**Fig. 5.27** Sampling sites of coniferous woods. *Source* From Kim et al. (2002a, b).

have been mainly reported in the Gyeongsang Basin, which is the largest of the several Cretaceous depositional basins in South Korea. Korea's Cretaceous stromatolites occurred in the lacustrine deposits of the Hasandong and Jinju Formations (Sindong Group) and Banyawol, Sinyangdong, and Hwasan Formations (Hayang Group) of the Gyeongsang Supergroup (Lee and Paik 1988; Lee et al. 1991; Paik and Lee 1994; Lee and Kong 2004; Nehza and Woo 2006; Choi 2007). They have morphological diversity and good preservation of microalgae fossils. These fossils have been classified into several types: domal stromatolites, oncolite, algal mat fragments, irregular algal bioherms and rod-shaped stromatolites, based on their occurrences and morphology.

Stromatolites from the floodplain lake deposits of the Hasandong Formations in Hadong County and Jinju City, South Gyeongsang Province, are irregular algal bioherms surrounding carbonized woods and oncolites (also oncoids) which are spherical to subspherical stromatolites and unattached microbial structures, commonly with a crude concentric lamination (Lee and Paik 1988; Paik and Lee 1994).

Abundant and diverse stromatolites occur in the Jinju Formation, which is representative of lacustrine deposits in the Gyeongsang Supergroup. Of the various types of stromatolites, rod-shaped stromatolites have rarely been reported worldwide (Monty 1972; Freytet and Plaziat 1982; Herman and Hubbard 1990; Neuweiler et al. 1997). Massive distributions of rod-shaped stromatolites were found at the Jinju Formation in Namhae County and Sacheon City (Lee and Kong 2004; Choi 2007). Rod-shaped stromatolites are characterized by concentric lamination with curd-shaped, stratiform, and small columnar stromatolites (Figs. 5.29 and 5.30). Isolated and scattered rod-shaped stromatolites occur in coarse-grained to pebbly sandstone, and aggregated rod-shaped stromatolites in as a tomb-like array

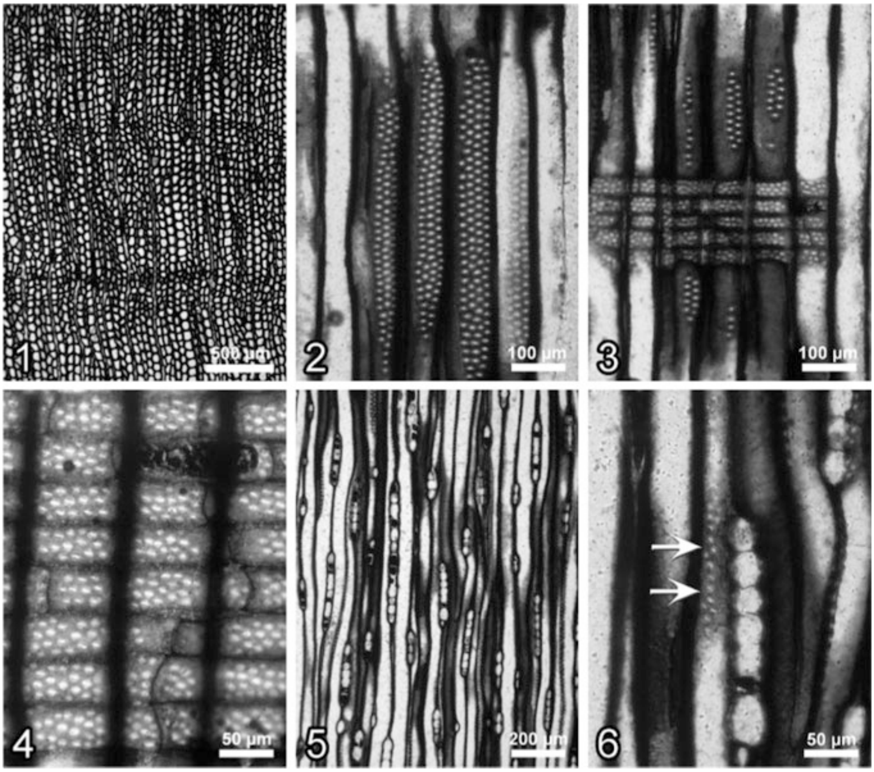


**Fig. 5.28** Photomicrographs of *Agathoxylon togeumense* sp. nov. *Notes* (1) Cross-section showing indistinct growth rings and elliptical, rectangular or polygonal tracheids; (2–4) radial sections showing contiguous, alternate, or partly opposite bordered pits on radial walls of early wood tracheids and araucarioid cross-field pits; (5, 6) tangential sections showing uniseriate rays and bordered pits on tangential walls of tracheids (arrows). *Source* From Oh et al. (2011)

occur in dark gray shale. Filaments of stromatolitic algae are preserved in these stromatolites (Fig. 5.31). These rod-shaped stromatolites have been interpreted as being formed by stromatolitic algal and microbial encrustations over dead or living plant twigs.

A large number of stromatolites from the Banyawol, Hwasan, and Shinyangdong Formations, which are Cretaceous lacustrine deposits in North Gyeongsang Province, have been reported, and their paleoenvironmental and paleoclimatological implications interpreted (Lee and Paik 1988; Lee et al. 1991; Woo et al. 2005; Nezha and Woo 2006). Stromatolites from the Banyawol Formation have a

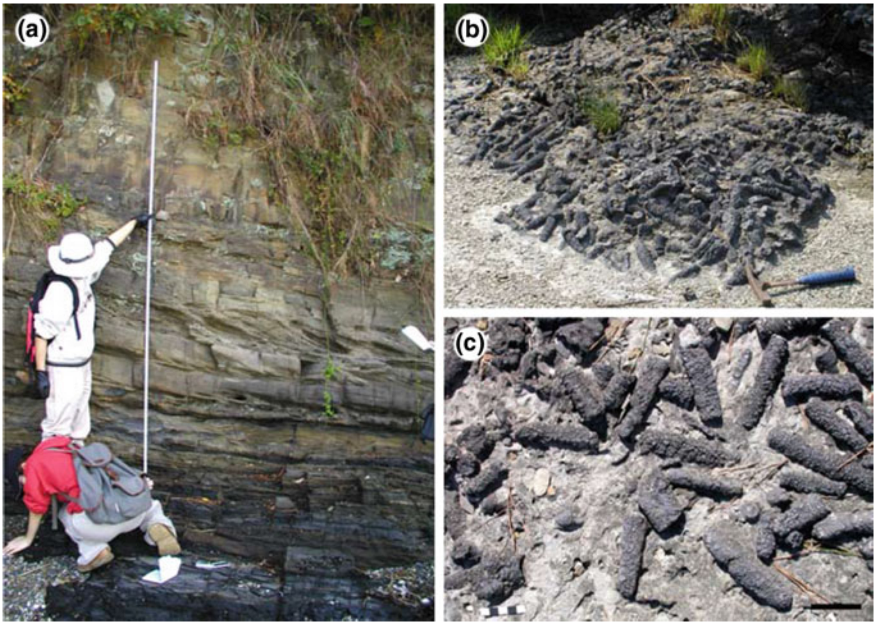


**Fig. 5.29** Cretaceous rod-shaped stromatolites at the Jinju Formation, Namhae County. *Notes* **a** Stratigraphic section containing rod-shaped stromatolites within coarse-grained and/or pebbly sandstones; **b** aggregated, tomb-like array of rod-shaped stromatolites; **c** bedding plane view of rod-shaped stromatolites. Note that the long axes of the rod-shaped stromatolites are randomly distributed. *Source* From Lee and Kong (2004)

relatively large algal head and are usually developed in laterally-linked hemispheroid (LLH) types (Lee and Paik 1988). Massive domed stromatolites at the Banyawol Formation were found at the Daegu Catholic University, Gyeongsan City, and they were designated as Natural Monument No. 512 (Fig. 5.32). The massive stromatolites are in a good state of preservation and have a unique morphology, so these have important value to the study of the Cretaceous lacustrine environments in Korea. Woo et al. (2005) and Nehza and Woo (2006) interpreted a cyclic variation of the paleoclimate based on studies of the microstructure, morphology, and stable isotope of stromatolites at the Sinyangdong Formation (Fig. 5.33).

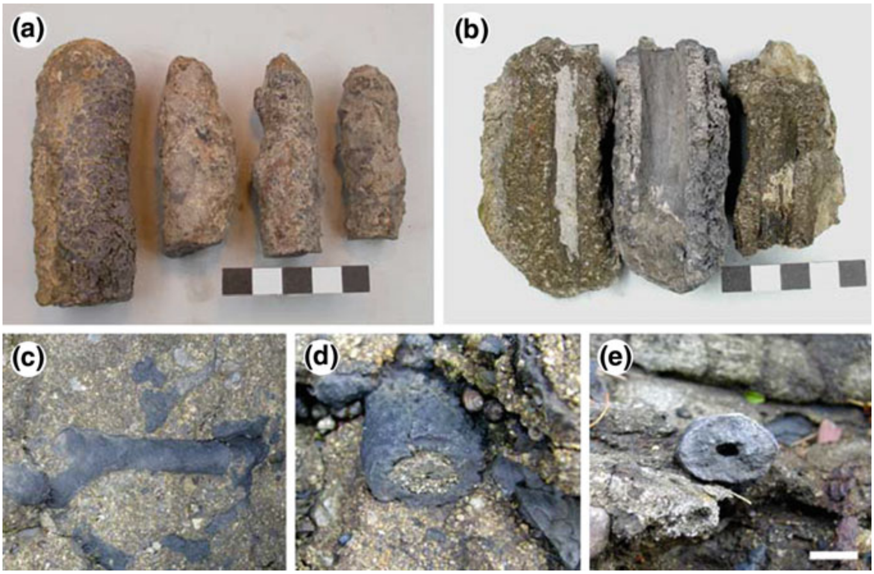

**Fig. 5.30** Various rod-shaped stromatolites. *Notes* **a** Rod-shaped stromatolites showing different lengths and widths; **b** rod-shaped stromatolites broken parallel to the long axis. Remnants of original plant materials are visible in the center of the specimen on the left; **c** branched twig still remains; **d** the central part of the rod-shaped stromatolites is filled with siliciclastic sediments identical to those surrounding them; **e** clastic sediments are missing. Scale bars represent 1 cm in (**e**) and (**d**), and 3 cm in (**c**). *Source* From Lee and Kong (2004)

## 5.6 Invertebrate Trace Fossils

Trace fossils (except for vertebrate tracks) are very commonly discovered at the outcrops of Korea, as is the case for many deposits around the world. In the case of the deposits of the Cretaceous Gyeongsang Basin, many studies of trace fossils were conducted by Prof. Jeong Yul Kim, who investigated traces from several formations through the Lower to Upper Cretaceous of the Gyeongsang Basin. Here, we introduce a short description of trace fossils in a bio-chronological order. Although numerous trace fossils were discovered, many of them are remain undescribed.

Invertebrate trace fossils from the Cretaceous Gyeongsang Basin were described for the first time at the Hasandong Formation, Jinju area (Kim and Paik 1997a). Trace fossils including *Planolites*, *Skolithos*, *Taenidium*, as well as *Diplocraterion*, freshwater bivalves including *Trigonioides* and *Plicatounio*, fossil tree stumps, carbonized woods, and stromatolites were found at the Hasandong Formation. These fossils had been deposited in a floodplain lake environment (Fig. 5.34). Especially, several tens of thousands of U-shaped burrows, described as *Diplocraterion luniforme*, were discovered on the bedding surface of laminated gray shale (Figs. 5.34 and 5.35). The burrows are nearly straight and vertical, and

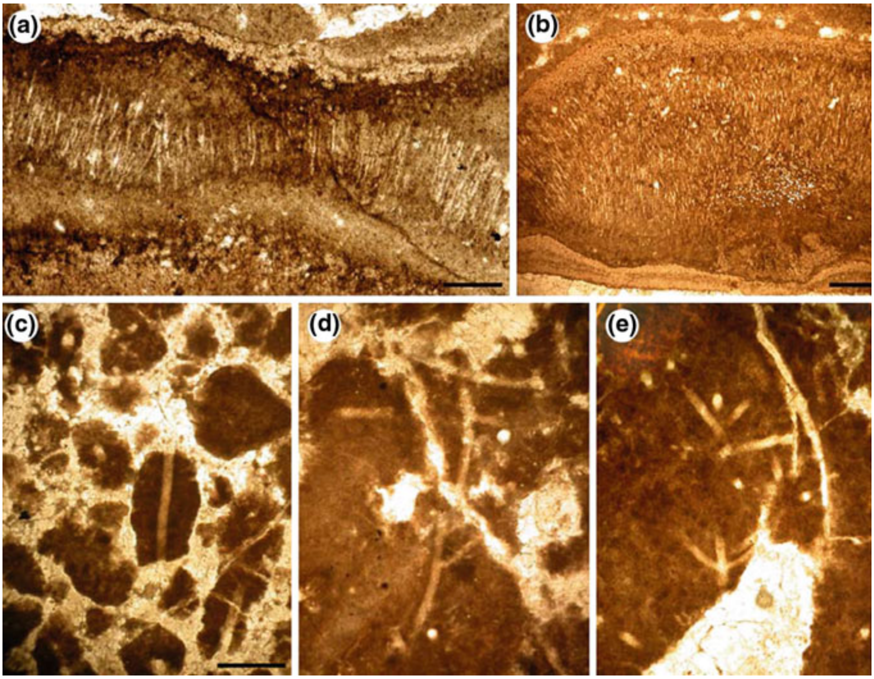


**Fig. 5.31** Calcified filamentous microfossils. *Notes* **a**, **b** Cyanobacterial filaments oriented perpendicular to lamination forming organic-rich layers; **c**–**e** green algal filaments showing unbranched (**c**), dichotomously (**d**), and trichotomously (**e**) branched fossils. Scale bar in (**a**), (**b**), and (**c**) represents 150 μm, and scale bar in (**c**) applies to (**d**) and (**e**). *Source* From Lee and Kong (2004)

can be observed as straight bars or dumbbells on the bedding plane. U-shaped morphology is only rarely observed in the field, but is clearly seen in a vertical section of blocks. The width of U-burrows varies from 5 to 18 mm (mode 10–12 mm), the depth varies from 4 to 20 mm (usually <15 mm), and the marginal tube diameter is 1–2 mm. The width of the burrows is generally consistent along the burrow's depth. The spreiten are generally well-developed, predominantly protrusive, and regular or irregular. The passive fill of coarse sediment, generally variably sized, up to 2 mm long, is occasionally oriented nearly parallel to the spreite in the upper part of the U-burrows (Fig. 5.34e, f). The occurrence of *D. luniforme* described from the non-marine deposits of the Hasandong Formation represents a very unusual record, because *Diplocraterion* has been generally regarded as a diagnostic marine trace fossil (Kim and Paik 1997a).

Additionally, Kim (1997) presented the spatial distribution of *D. luniforme* (genus *Diplocraterion* has vertical U-shaped burrows, Fig. 5.36) at floodplain lake deposits of the Hasandong Formation (Aptian) of Jinju City, South Gyeongsang Province. According to Kim (1997), the ratio between the expected square of T-square nearest-neighbor distance and index of the spatial pattern indicates that

**Fig. 5.32** Massive stromatolites at the Banyawol Formation, Gyeongsan City. *Note* These stromatolites are designated as Natural Monument No. 512. *Source* Photo provided by Dr. Hyun Joo Kim

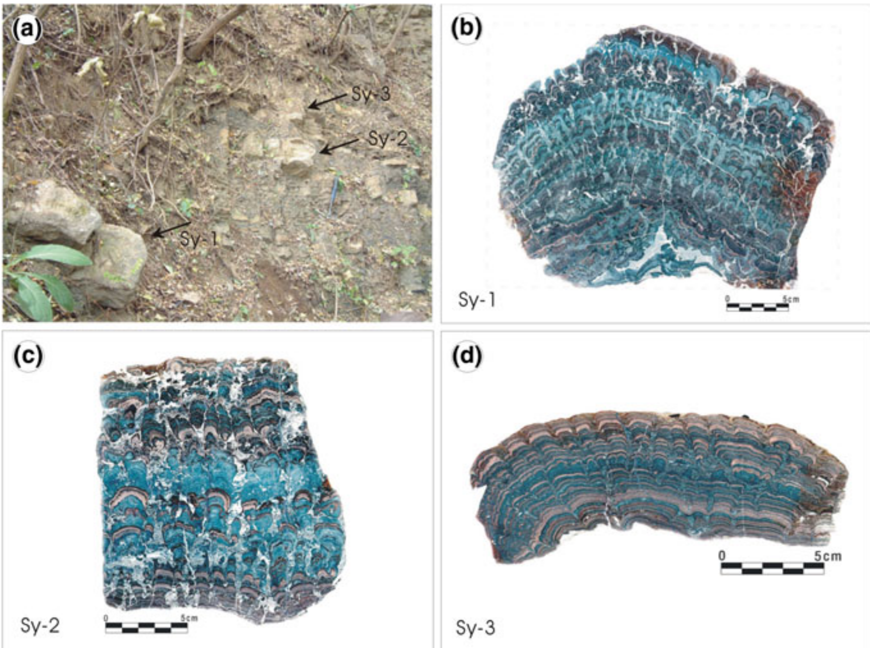


**Fig. 5.33** **a** Outcrop view of three layers of stromatolites; **b** acetate peel of the Sy-1 stromatolite; **c** acetate peel of the Sy-2 stromatolite; **d** acetate peel of the Sy-3 stromatolite. *Source* From Woo et al. (2005)

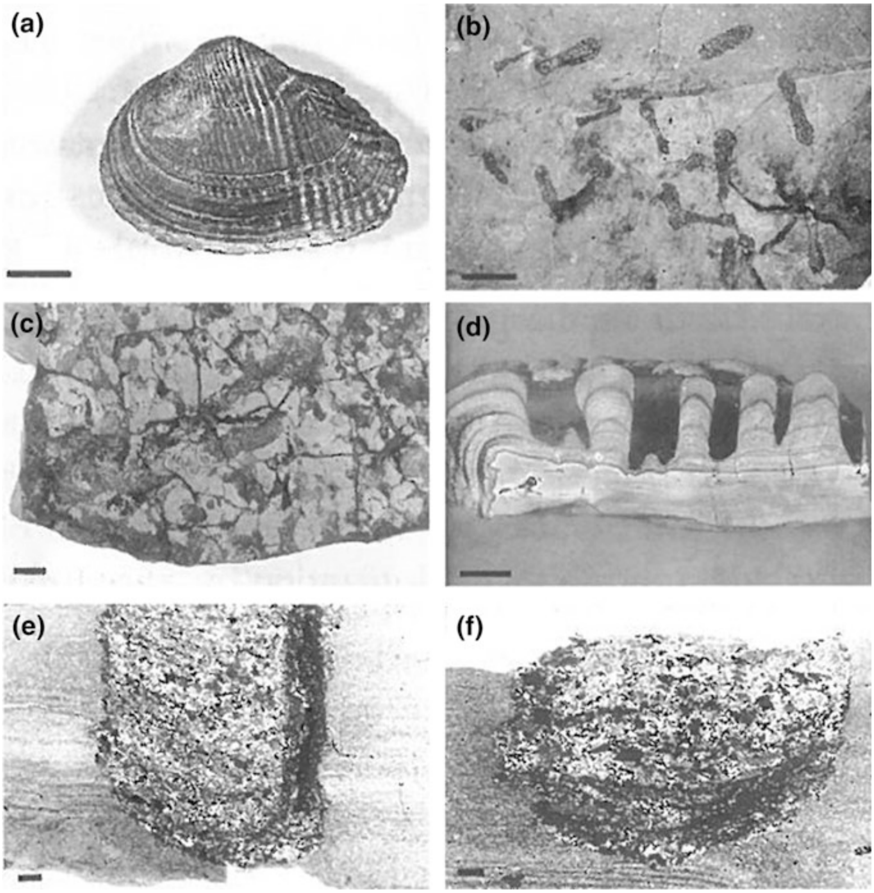


**Fig. 5.34** Body and trace fossils from the floodplain lake deposits of the Hasandong Formation, Jinju area. **a** Non-marine bivalve fossil, *Trigonioides* sp., from gray siltstone; **b** *Diplocraterion luniforme* on a bedding surface of gray shale; **c** *Skolithos* ichnosp. and *Taenidium* ichnosp. on a bedding surface of gray shale; **d** vertical polished-section view of stromatolite; **e**, **f** vertical thin section view of *Diplocraterion luniforme* from gray shale (KNUE 95101, 95102). Scale bars in **a**–**d** = 1 cm, in **e**, **f** = 0.1 cm. *Source* From Kim and Paik (1997a)

populations of *D. luniforme* exhibit clumped patterns in five quadrats and a random pattern in one quadrat (Fig. 5.37). The substrate condition of the floodplain lake environment seems to be one of controlling factors for the spatial distribution patterns of suspension-feeding producers of *D. luniforme*; the heterogeneously firm substrate condition, formed by subaerial exposure of the generally uneven substrate of a shallow lake, probably caused a mostly clumped distribution pattern of trace fossils (Kim 1997).

Kim et al. (2002a, b) introduced abundant ichonofauna (including domichnia, fodinichnia, pascichnia and repichnia) from three sections of the Hasandong

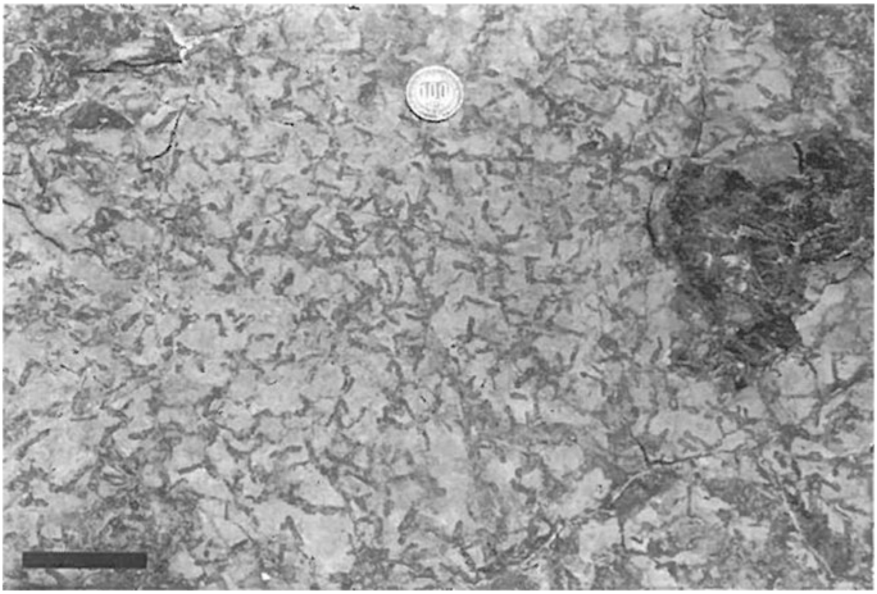

**Fig. 5.35** Occurrence of *Diplocraterion luniforme* on the bedding surface of a gray shale deposit at the Hasandong Formation, Jinju area. *Note* Observe the mud crack cross-cut by *Diplocraterion luniforme* (upper center) and dark carbonized wood (right center). Scale bar = 5 cm. *Source* From Kim and Paik (1997a)

(Aptian) and Jinju (Albian) formations (Fig. 5.38). The authors classified these ichnofauna as *Skolithos*, *Palaeophycus*, and *Chondrites* ichnocoenoses. They described twenty-two ichnotaxa (Table 5.1; Fig. 5.39) with some dinosaur tracks and rhizoliths. According to Kim et al. (2002a, b), the paleoenvironment of *Skolithos* ichnocoenose was characterized by a high-energy channel levée environment, which is not similar to previous reports of non-marine ichnofacies. The *Palaeophycus* ichnocoenose has low diversity, and is interpreted as low-energy floodplain settings. The *Chondrites* ichnocoenose shows moderately low diversity and reflects low-energy marginal lacustrine environments (Kim et al. 2002a, b).

Kim et al. (2005a, b) described thirty trace fossil assemblages including fourteen ichnotaxa (*Beaconites antarcticus*, *B. coronus*, *Cochlichnus anguineus*, *Diplichnites* (*Octopodichnus*) cf. *didactylus*, *D.* type A, *D.* isp., *Helminthopsis hieroglyphica*, *Palaeophycus tubularis*, *Planolites annularis*, *P. beverleyensis*, *Protovirgularia dichotoma*, *Skolithos magnus* and *Taenidium barretti*) with sauropod dinosaur tracks from the gray beds of the Jinju Formation. Among these taxa,

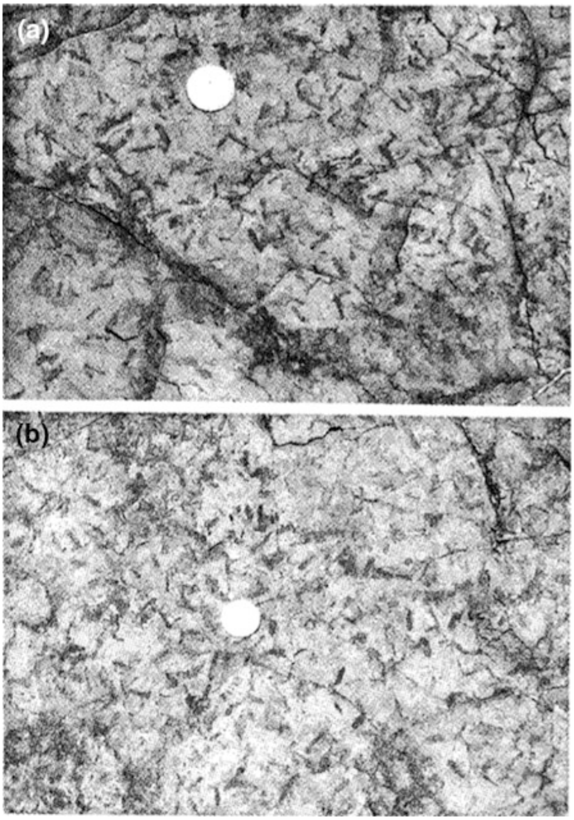


**Fig. 5.36** View of *Diplocraterion luniforme* population analysed for spatial distribution pattern. *Notes* **a** Random pattern (quadrat 1); **b** clumped pattern (quadrat 2). Diameter of coin = 2.4 cm. *Source* From Kim (1997)

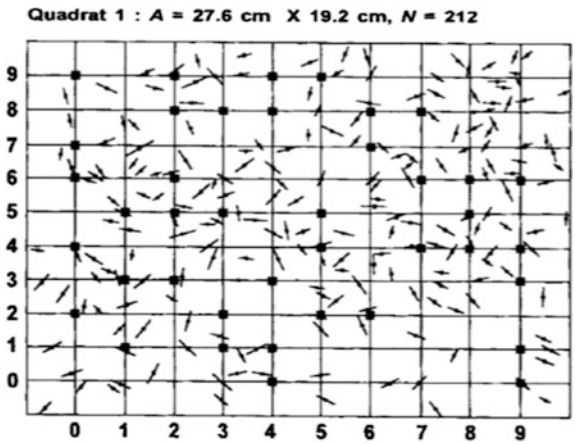


**Fig. 5.37** Quadrat map for T-square distance sampling of *Diplocraterion luniforme* population at the Hasandong Formation, Jinju area (quadrat 1). *Notes* Individuals (bars), mid-points between burrow limbs (solid circles), and 50 random points from the table of random digits (solid squares, partly overlapped) are plotted. *Source* From Kim (1997)

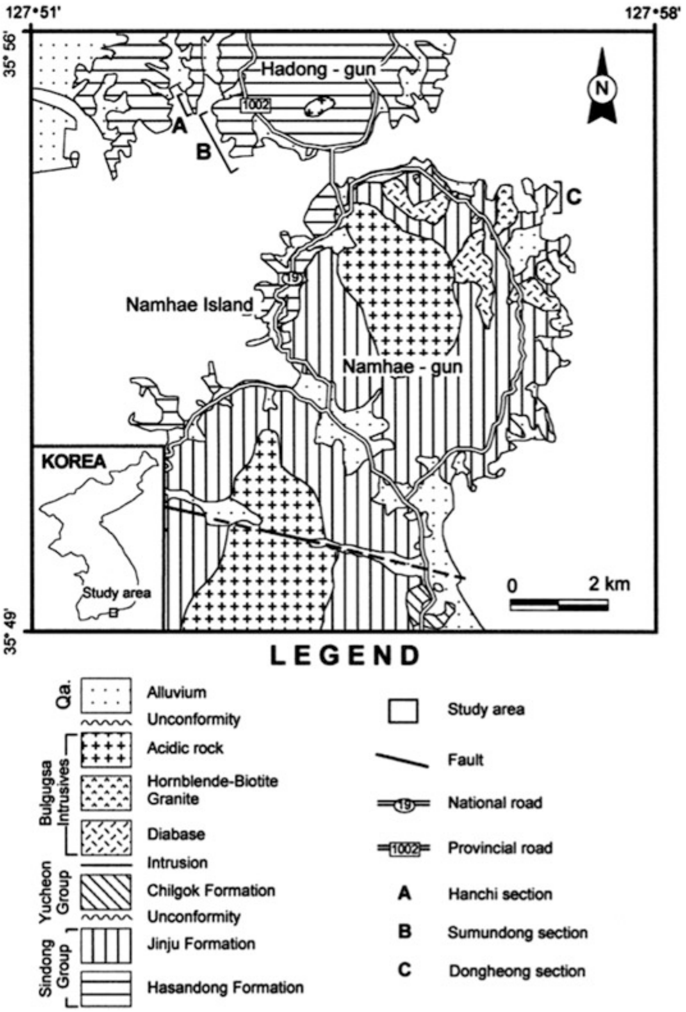


**Fig. 5.38** Geologic map of the Namhae area, southeast Korea, with locations of measured sections. *Source* After Choi (1986); from Kim et al. (2002a, b)

**Table 5.1** Summary of trace fossils at the Cretaceous Hasandoing and Jinju Formations in the Namhae area, southeast Korea

| Ichnotaxa | Feeding | Ethology | Toponomy | *N* |
|---|---|---|---|---|
| *Beaconites antarcticus* | Deposit | Pascichnion | COH/CXH | R |
| *B. coronus* | Deposit | Pascichnion | EN | C |
| Branched trace fossil | ? | Domichnion | COH | R |
| *Chondrites* isp. type A | Deposit | Fodinichnion | CXH | R |
| *Chondrites* isp. type B | Deposit | Fodinichnion | COH/EN | A |
| *Circulichnus montanus* | Deposit | Pascichnion | CXH | R |
| *Cochlichnus anguineus* | Deposit | Pascichnion | CXH | R |
| *Helminthopsis abeli* | Deposit | Pascichnion | CXH | R |
| *H. hieroglyphica* | Deposit | Pascichnion | CXH | R |
| *Laevicyclus* isp. | Suspension (?) | Domichnion | EN | R |
| Ornithopod tracks | – | Repichnion | COH | R |
| *Palaeophycus tubularis* | Suspension | Pascichnion | CXH | C |
| *Planolites annularius* | Deposit | Fodinichnion | CXH | R |
| *P. beverleyensis* | Deposit | Fodinichnion | COH | R |
| *P montanus* | Deposit | Fodinichnion | COH | A |
| Rhizoliths | – | – | CXH | R |
| Sauropod tracks | – | Repichnion | COH | C |
| *Skolithos magnus* | Suspension | Domichnion | EN | A |
| *S. verticalis* | Suspension | Domichnion | EN | R |
| *Skolithos* isp. | Suspension | Domichnion | EN | R |
| *Spirodesmos* isp. | Deposit | Pascichnion | CXH | R |
| *Taenidium barretti* | Deposit | Fod./Pas. | CXH | C |
| *Thalassinoides paradoxicus* | Suspension (?) | Domichnion | EN | R |
| *T. suevicus* | Suspension (?) | Domichnion | EN | A |
| *Torrawangea rosei* | Deposit (?) | Fod./Pas. | CXH | R |

*Source* From Kim et al. (2002a, b)
*Notes* COH = Concave hyporelief, CXH = convex hyporelief, EN = endorelief, N = number of trace fossils, A = abundant (>10), C = common (3–10), *R* = rare (<3)

*Diplichnites* is the first record from the Cretaceous; six measured sections were examined, and these were grouped into four lithofacies associations (1. thickly bedded, coarse-grained sandstone; 2. interbedded medium- to fine-grained sandstone; 3. mudstone-shale; 4. interbedded sandstone-shale; see Figs. 5.40,

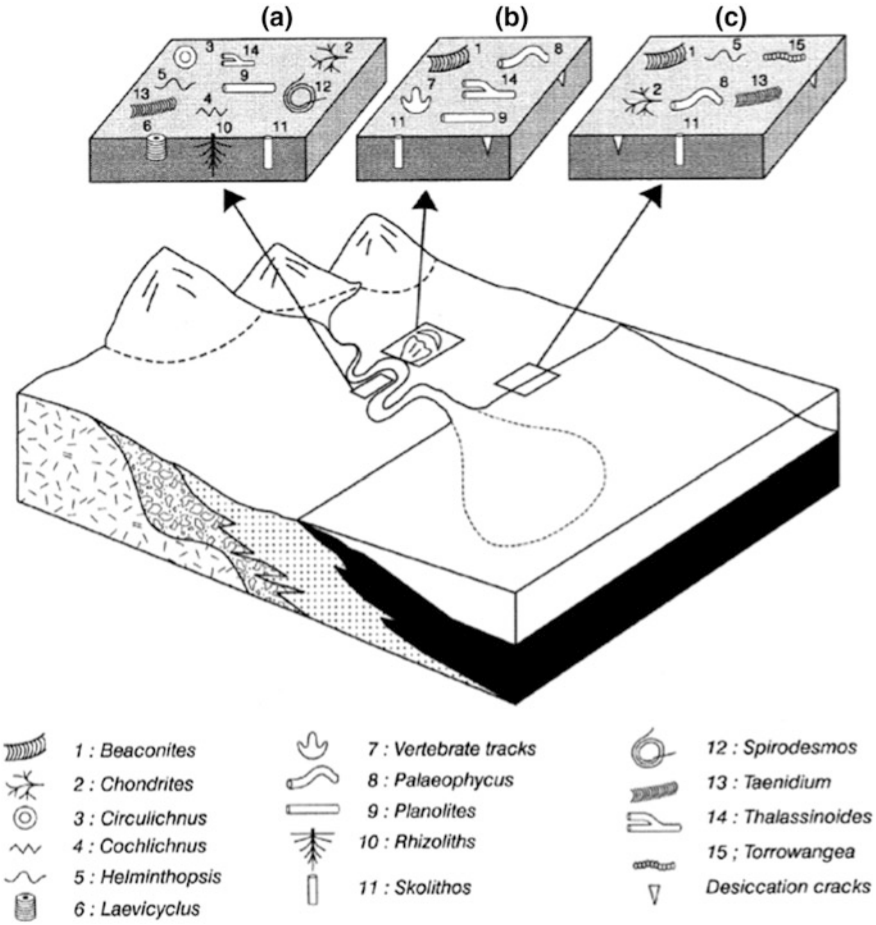


**Fig. 5.39** Schematic diagram showing three suites of trace fossils within fluvial-marginal lacustrine environments of the Cretaceous Hasandong and Jinju Formations, southeast Korea. *Notes* **a** *Skolithos* ichnocoenose in a channel levée environment; **b** *Palaeophycus* ichnocoenose in a floodplain environment; **c** *Chondrites* ichnocoenose in a marginal lacustrine environment. *Source* From Kim et al. (2002a, b)

5.41 and 5.42); however, the trace fossils were identified from 2, 3 and 4 lithofacies associations. Most of the ichnotaxa seem to have been produced by environmentally tolerant, vagile animals which are considered to be responsible for arthropod trackways (Fig. 5.43). Also, Kim et al. (2005a, b) divided four ichnocoenoses into two ichnofacies (*Mermia* and *Scoyenia*) from their study.

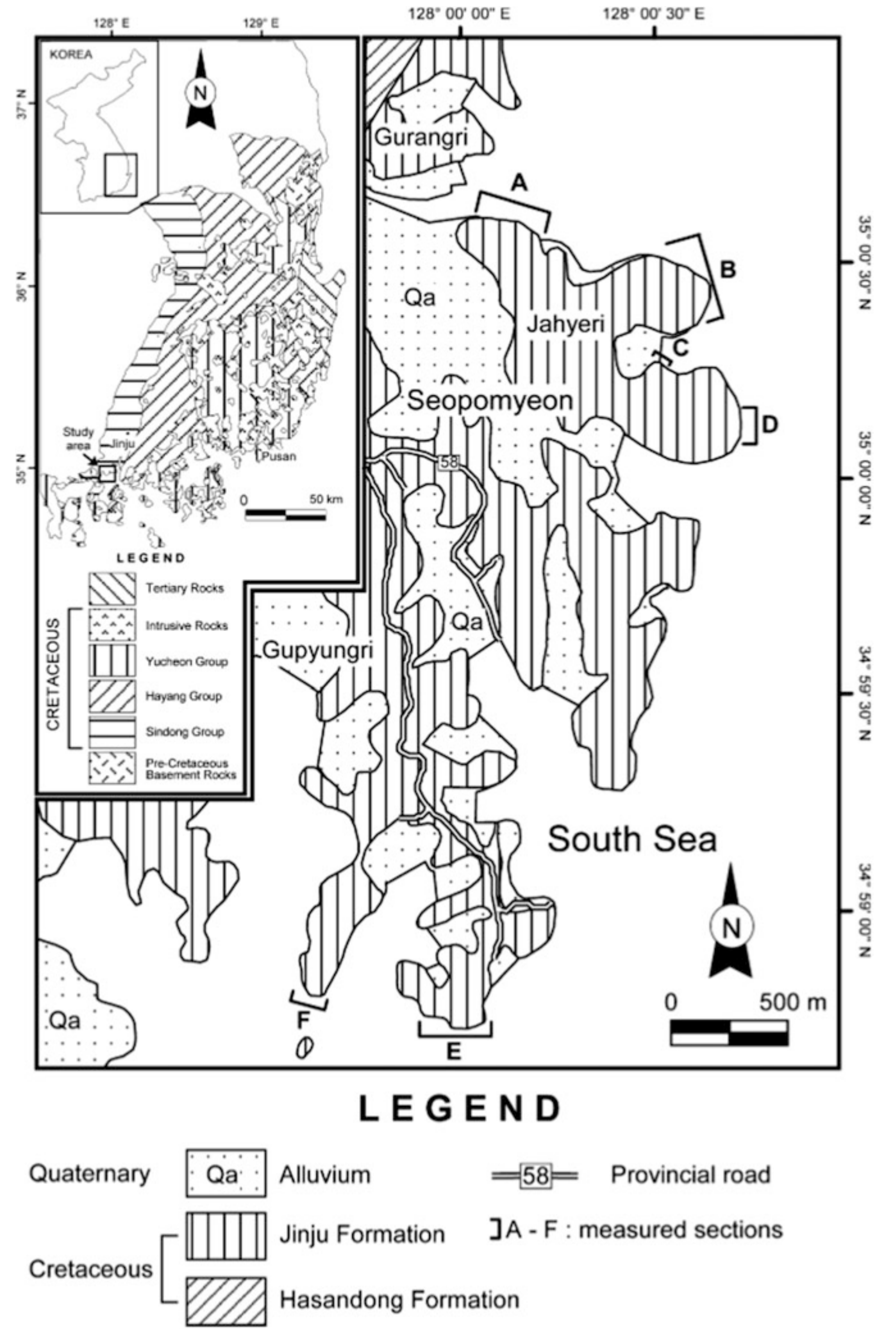


**Fig. 5.40** Geologic map of the Jahyeri and Gupyungri areas. *Source* Kim et al. (2005a, b)

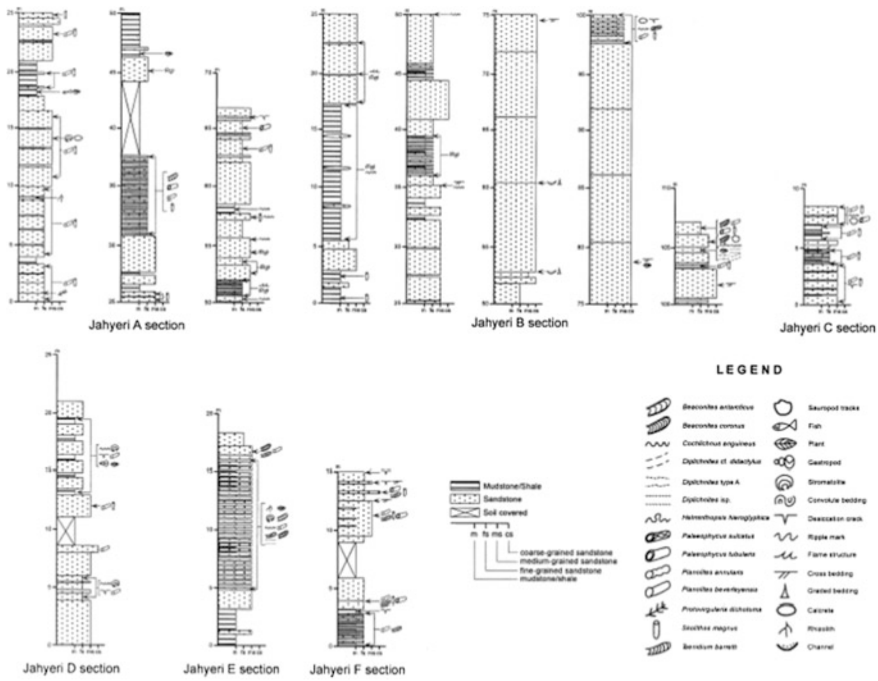


**Fig. 5.41** Simplified lithologic logs of the measured sections at the Jinju Formation. *Source* Kim et al. (2005a, b)

The first report of a trace fossil (*P. dichotoma*) at the Jinju Formation was conducted by Kim et al. (2000). It is the first non-marine record of *Protovirgularia*.

Recently, Lee (2017) described a new ichnogenus *Radialimbricatus* with type species *Radialimbricatus bitoensis* isp. nov. (Fig. 5.44) at the river mouth bar sandstone beds of the Jinju Formation in Bito island, Sacheon City, South Gyeongsang Province. The features of this ichnotaxon are that it is horseshoe-shaped or elliptical, and has a convex hyporelief structure characterized by imbrication of traces with radial ridges and a median furrow (Lee 2017). Additionally, Lee (2017) described *Radialimbricatus* being formed as an open epigenic burrow at the water/mud interface, or an endogenic burrow along the sand/mud interface at the same time (Fig. 5.45). The tracemakers were possibly arthropods, cnidarians, or annelids.

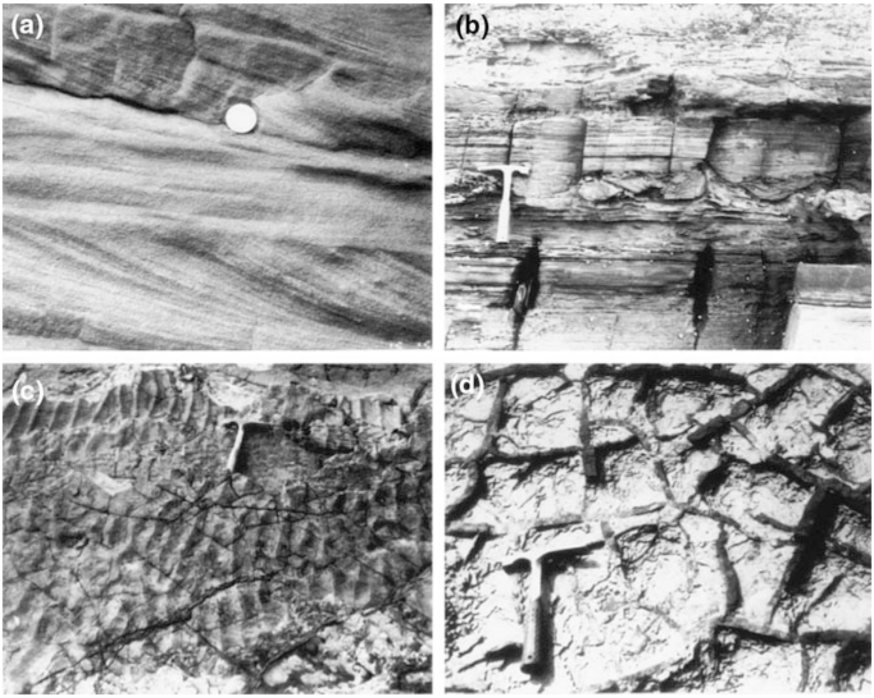


**Fig. 5.42** Sedimentary structures of the Jinju Formation. *Notes* **a** Cross-bedding (coarse-grained sandstone, 80 m above the base of section B); **b** parallel laminations and flame structures (medium-grained sandstone, 20 m above the base of section B); **c** long-crested symmetrical (wave) ripples (medium-grained sandstone, 13 m above the base of section B); **d** polygonal (desiccation) cracks (medium-grained sandstone, 14 m above the base of section F). For scale, the coin has a diameter of 23 mm and the hammer is 0.28 m long. *Source* From Kim et al. (2005a, b)

Also, the fossil microbial-caddisfly bioherms identified at the Jinju Formation. Paik (2005) were described as microbial-caddisfly bioherms in shallow to marginal lake deposits of the Jahyeri sections (Figs. 5.46 and 5.47), Sacheon City, South Gyeongsang Province. This discovery is not only the first report of microbial-caddisfly bioherms in Asia but is also representative of the oldest record.

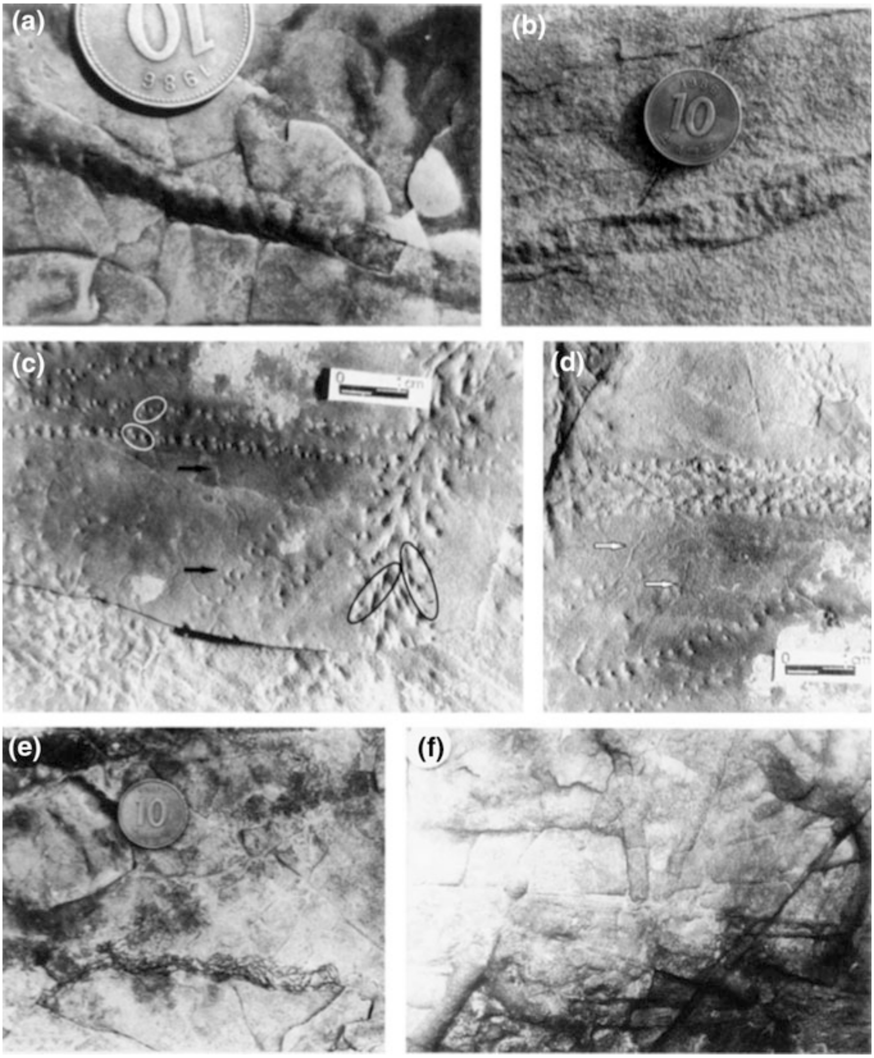


**Fig. 5.43** Trace fossils at the Jinju Formation. *Notes* **a** *Beaconites antarcticus*; **b** *Beaconites coronus*; **c** *Cochlichnus anguineus* (between black arrows); *Diplichnites* (*Octopodichnus*) cf. *didactylus* (example rows in white ellipses), *Diplichnites* type A (example rows in black ellipses), and various overprinting *Diplichnites* isp. (bottom left); **d** *Helminthopsis hieroglyhica* (white arrows), *Diplichnites* type A (less well-preserved specimen), and *Diplichnites* (*Octopodichnus*) cf. *didactylus*; **e** *Palaeophycus sulcatus* (medium-grained sandstone, 17 m above the base of section B); **f** *Palaeophycus tubularis*. Coin, for scale, is 23 mm in diameter. *Source* From Kim et al. (2005a, b)

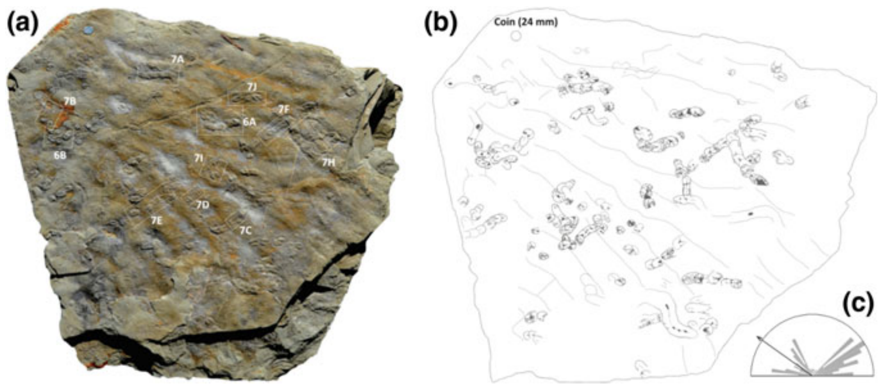


**Fig. 5.44** Occurrences of *Radialimbricatus* on a sandstone float block on which approximately 160 traces and trails are present. **a** Photograph of the surface of the block; **b** line drawing of *Radialimbricatus* specimens and ripple crests expressed as topographic lows (indicated by dotted lines); **c** rose diagram showing the orientations of *Radialimbricatus* traces ($n$ = 103) relative to the ripple orientation; the arrow indicates the mean orientation of ripples. *Source* From Lee (2017)

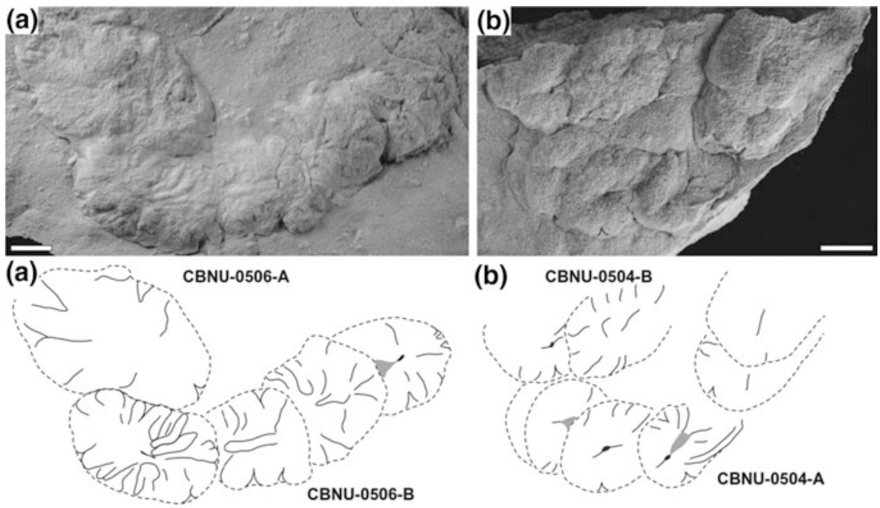


**Fig. 5.45** Photographs of *Radialimbricatus bitoensis* isp. nov. *Notes* Scale bar = 10 mm. Line drawings are provided for each photograph. **a** CBNU-0506B (lower trail), holotype; a trail of four imbricating traces with a discrete elliptical trace at the left end; CBNU-0506-A (upper-left trace); the trace is not considered to be a part of the lower trail; **b** CBNU-0504-A (lower trail); six traces are considered to imbricate to form a single trail; CBNU-0504-B (upper trail); two traces imbricate to form a trail. *Source* From Lee (2017)

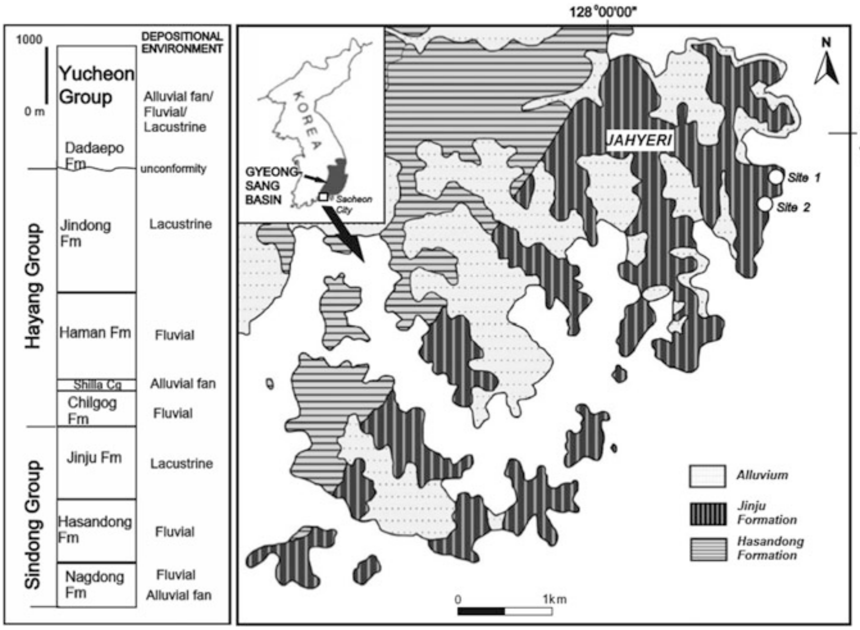


**Fig. 5.46** Stratigraphy of the Gyeongsang Supergroup, microbial-caddisfly bioherms locations and a geological map of study area. *Source* Paik (2005)

These bioherms (Figs. 5.48 and 5.49) occurred in oolitic sandstone, which means that the bioherms formed in shallow and turbulent water. The depositional condition of the Jahyeri caddisfly bioherms is thus correspondent with the wave-washed and well-oxygenated biotope of modern lentic Trichoptera (Leptoceridae), and the occurrence of the Jahyeri bioherms may reflect the development of a drought stage which resulted in a limited supply of clastic sediments in the lake (Paik 2005).

Late Cretaceous trace fossils were described from the Gyeongsang and Haenam basins; Kim and Paik (1997b) described *Skolithos* ichnosp. at the Yucheon Group deposit (upper part of the Gyeongsang Basin) of Mt. Hwangryeong, Busan.

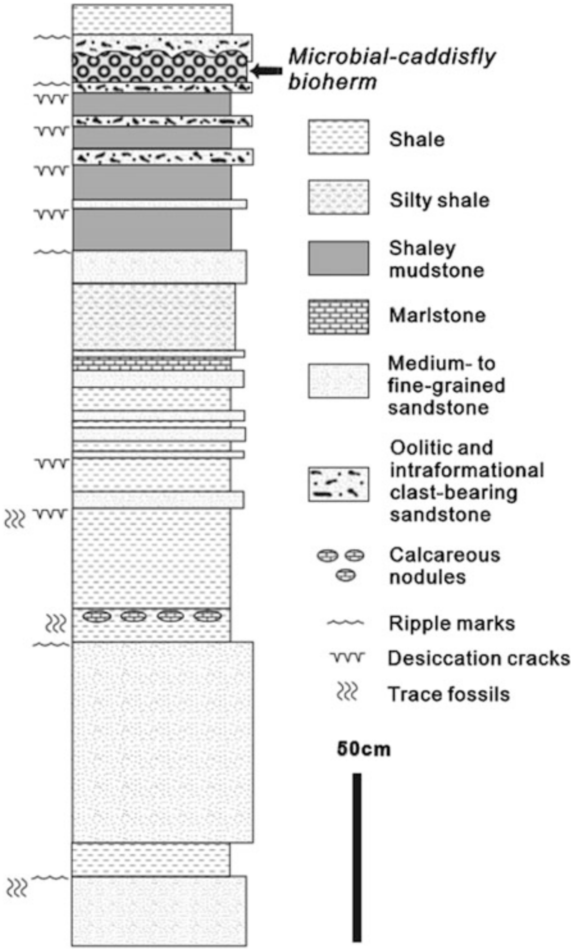


**Fig. 5.47** Stratigraphic section of the Jahyeri microbial-caddisfly bioherm-bearing deposits at site 1, Jahyeri. *Source* From Paik (2005)

The deposit including trace fossils is a graded cherty bed, and this bed is composed of basal graded sandstone, parallel-laminated cherty sandstone, cherty sandstone with hummocky cross stratification, and flat-laminated cherty siltstone, in ascending order. The trace fossils of this deposit are the only known biogenic evidence of the Yucheon Group, and they are characterized by low diversity and high density. Therefore, trace fossils are interpreted to have been produced by opportunistic animals in storm events (Kim and Paik 1997b).

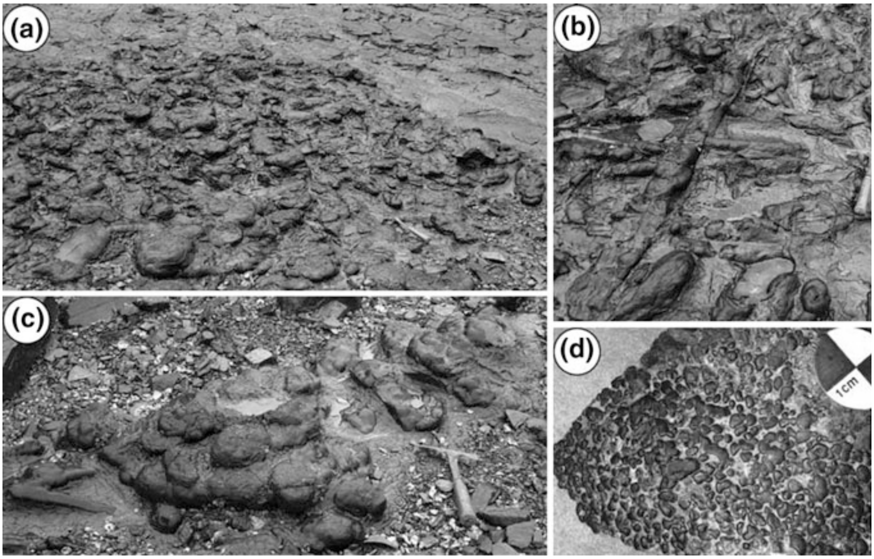


**Fig. 5.48** Occurrence of microbial-caddisfly bioherm at site 1, Jahyeri. *Notes* **a** Overall view of the larger bioherm with bulbous surface; **b** rod-shaped stromatolite (arrow) in the larger bioherm; **c** overall view of the smaller bioherm; **d** botryoidal surface of stromatolite of the larger bioherm. *Source* From Paik (2005)

Minter et al. (2012) described an enigmatic arthropod trackway from the Uhangri Formation, Haenam Basin, at the dinosaur, pterosaur and bird tracksite, Uhangri, Haenam County, South Jeolla Province. The authors discovered eighty trackways ranging from 0.1 to 1 m in length. This trackway was classified as *Lithographus hieroglyphicus* (Fig. 5.50), and this genus is the first record of a trackway *Lithographus* in Cretaceous Korea. The trackways are preserved in cherty mudstones that formed in the margins of an alkaline lake in the vicinity of active volcanoes (Minter et al. 2012). A possible trackway maker was pterygote insects (e.g., cockroaches or beetles). However, another arthropod (isopod) could also be responsible.

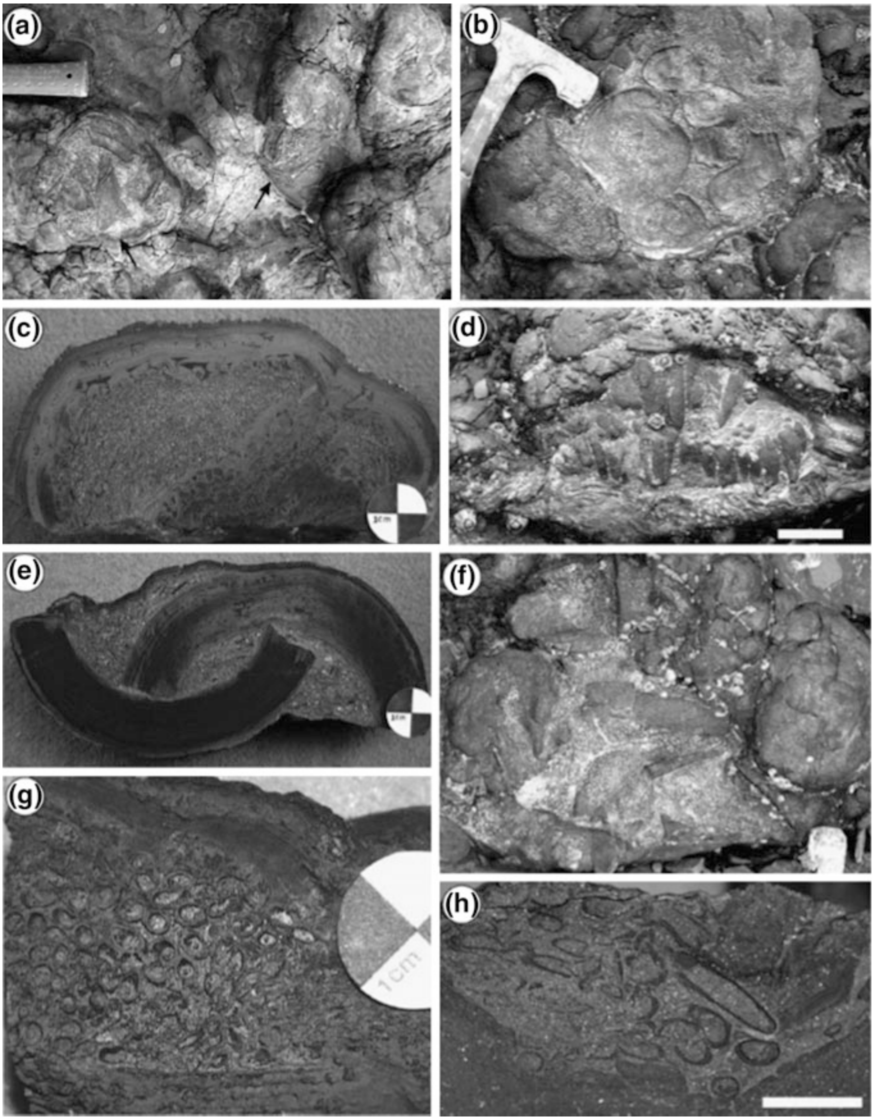


**Fig. 5.49** Occurrence of caddisfly cases in microbial-caddisfly bioherm at site 1, Jahyeri. *Notes* **a** Planar sections of stromatolite columns (arrow) with cores of colonial caddisfly cases; **b** planar section of larger stromatolite column bounding several small stromatolite columns with cores of colonial caddis cases; **c** cross-section of stromatolite column showing cores of colonial caddis cases on stromatolite fragment, etched slab; **d** three successive layers of colonial caddis cases forming terraces within one larger stromatolite column; **e** fragmented and rebounded stromatolite columns, etched slab; **f** planar sections of regular arrays of parallel, subvertically aligned caddis cases. Scale bars are 2 cm; **g** cross-section of parallel, subhorizontally aligned cases. Scale bars are 2 cm; **h** randomly distributed discrete cases. Scale bars are 1 cm. *Source* From Paik (2005)

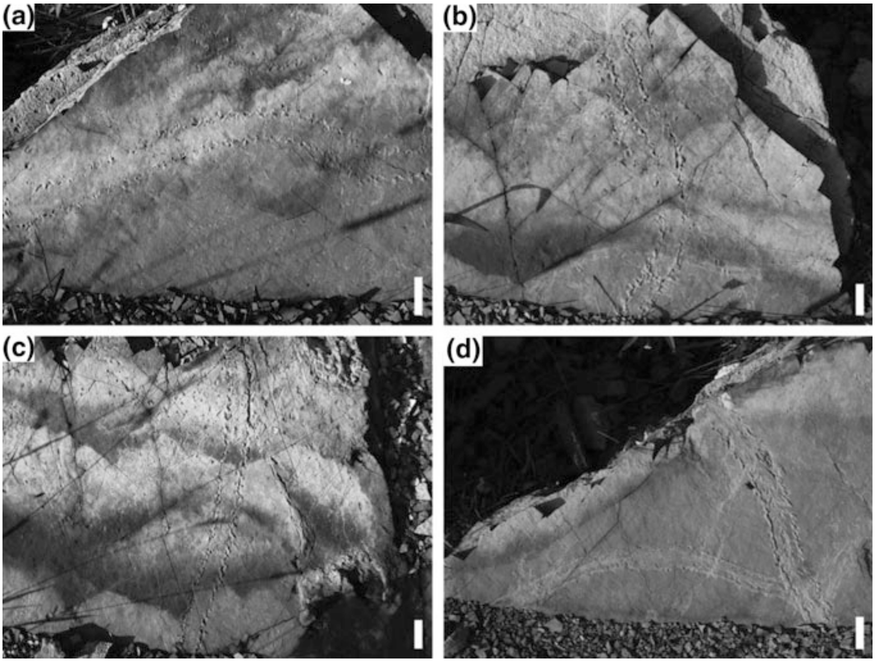


**Fig. 5.50** Field photographs of *Lithographus* trackways at the Uhangri Formation. *Notes* **a** Trackways showing a well-spaced series of tracks (replica, CU214.209); **b** trackway showing closely spaced series of tracks (replica, CU 214.212); **c** trackway showing closely spaced series of tracks (replica, CU 214.208); **d** one trackway with a chevroned medial region and another where the track series have merged into two parallel track rows (replica, CU 214.211). Scale bars are 40 mm. *Source* From Minter et al. (2012)

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# Chapter 6
# Major Cretaceous Fossil Sites in Korea

## 6.1 Vertebrate Track Sites

### *6.1.1 Haenam Dinosaur Track Site*

#### 6.1.1.1 Location and General Geology

The Haenam dinosaur track site is located in the north coastal area of Uhangri, about 20 km from Hwangsan District, Haenam County, South Jeolla Province (Fig. 6.1). The track site is on the shore of large lake formed by the Geumho seawall at present. Outstanding features of the Haenam track site include the first-reported Mesozoic bird tracks indicating webbed-feet (*Hwangsanipes choughi* and *Uhangrichnus chuni*), and a rich assemblage of well-preserved arthropod trails (*Lithographus*). The Uhangri Dinosaur Museum was constructed to protect and exhibit the track site.

The lithology of the Haenam track site is composed of andesitic tuff, the Uhangri Formation, Hwangsan Tuff, and Jindo Rhyollite in ascending order (Fig. 6.1c; Kim et al. 2003), which are correlated with the Yucheon Group in the Gyeongsang Basin (Kang et al. 1995). The tracks are included in the Uhangri Formation, the middle unit of the Haenam Group in the Haenam Basin. The Uhangri Formation consists mainly of sandstone, shale, and conglomerate with minor chert and black shale including volcanic clast matrix. The depositional environment of the Uhangri Formation is interpreted to be a fluvio-lacustrine environment (Chun 1990; Chun and Chough 1992). The well-developed stratification includes various sedimentary structures such as ripples, synsedimentary deformation structures, and sedimentary dykes (Paik et al. 2012). The track-bearing strata distributed in the Uhangri track site are from the Late Cretaceous Period (96–78 Ma; Cenomanian to Campanian) (Kim et al. 2003).



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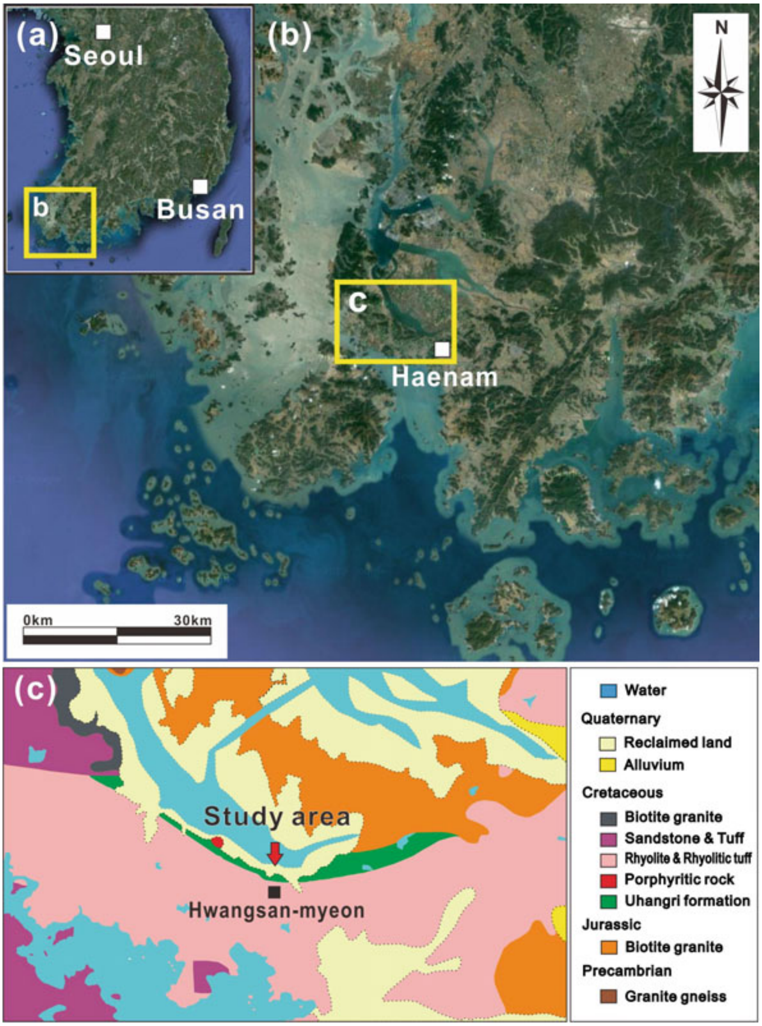


**Fig. 6.1** Satellite images of: **a** the southern Korean Peninsula; **b** South Jeolla Province; **c** geological map of the Haenam track site. *Sources* Modified from Choi et al. (2002), Kim et al. (2003). *Photo* by Min Huh

#### 6.1.1.2 Dinosaur, Pterosaur and Bird Track-Bearing Deposits

The pterosaur, dinosaur, and bird tracks are found in the upper part of the Uhangri Formation in association with ripple marks (Hwang et al. 2002a). This part consists of tuffaceous sandstone with graded bedding, interbedded with interlaminated tuffaceous sandstone and mudstone, laminated cherty mudstone, and dark grey to black shale (Hwang et al. 2008). Also, many ostracod microfossils occurred in the

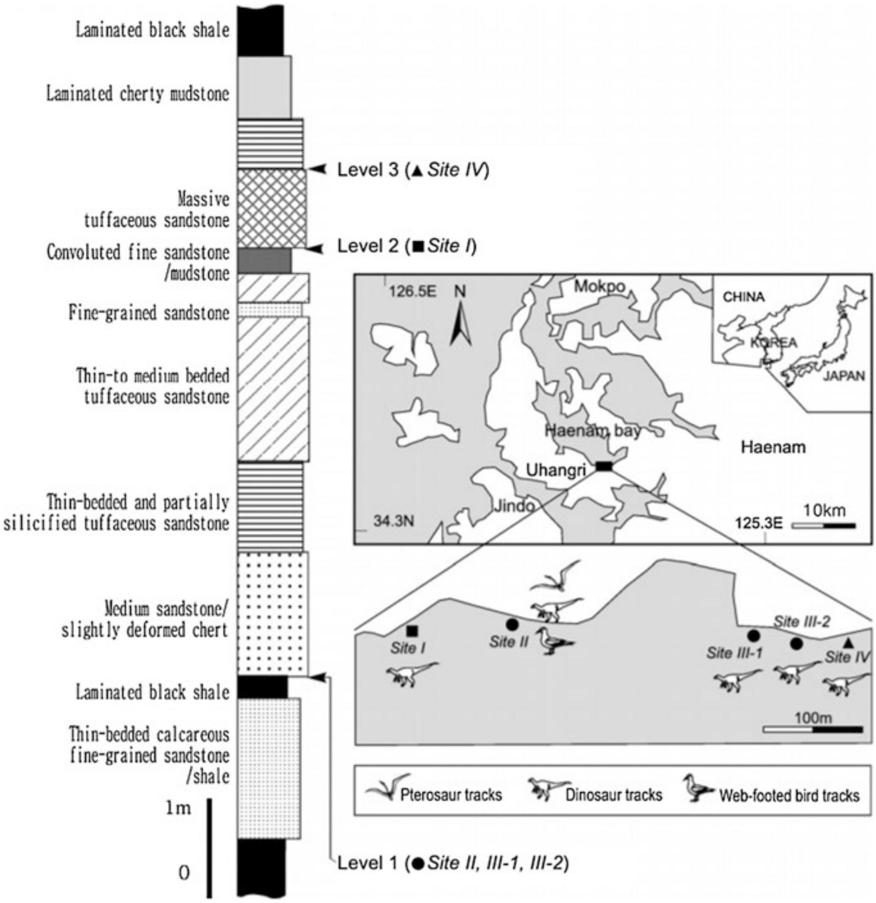


**Fig. 6.2** Location of the Uhangri track site and stratigraphic section of the Upper Cretaceous Uhangri Formation. *Notes* Dinosaur, pterosaur, and bird footprints have been found in three track layers. The dinosaur footprints with internal radial ridges were found in the lowest level, which contains pterosaur and bird footprints at sites II, III-1 and III-2. *Source* From Hwang et al. (2008). *Photo* by Min Huh

black shale. The lower part of the Haenam dinosaur track site is known as Level 1 (site 2, 3-1, 3-2), which comprises laminated black shale and medium-grained sandstone/slightly deformed chert (Fig. 6.2), and contains many footprints of dinosaurs and pterosaurs (*Haenamichnus*), arthropod tracks (*Lithographus*) and bird tracks (*H. choughi* and *U. chuni*). The upper part consists of fine-grained sandstone, mudstone (Level 2; site 1) and tuffaceous sandstone/laminated cherty stone (Level 3; site 4), and these layers include large dinosaur footprints and tracks. Unfortunately, this site has no vertebrate skeletal remains or large invertebrate body fossils.

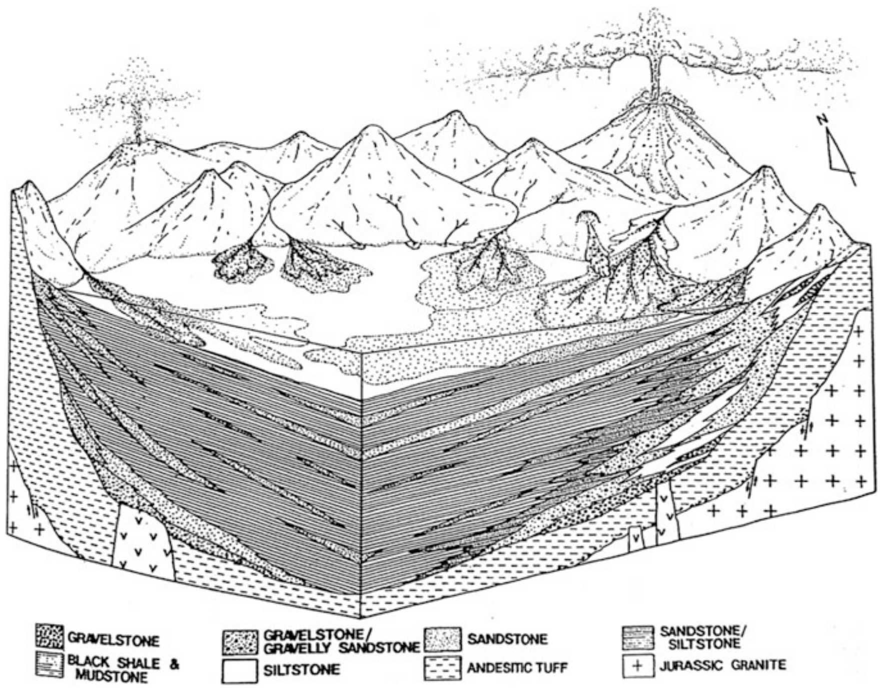


**Fig. 6.3** Inferred depositional model of the Uhangri Formation. *Notes* Lacustrine deltas were developed in the northern margin, radiating generally southward, and formed channelized subaqueous lobes. *Source* From Chun and Chough (1992). *Photo* by Min Huh

Chun and Chough (1992) provided a depositional model of the Uhangri Formation on the basis of sedimentological study. They showed that lacustrine deltas were developed in the northern margin, radiating generally southward, and formed channelized subaqueous lobes when the Uhangri Formation was formed in the Haenam Basin (Chun and Chough 1992, Fig. 6.3).

## *6.1.2 Hwasun Dinosaur Track Site*

### 6.1.2.1 Location and General Geology

The Hwasun dinosaur track site belongs to the Neungju Basin, southwestern Korean Peninsula, and is located at Seoyuri, Buk District, Hwasun County, South Jeolla Province (Fig. 6.4). The site is located on the southeastern slope of a mountain ridge that stretches out from Mudeung Mountain to the northeast. Various dinosaur footprints were found over a wide-ranging surface of a stratum that had been exposed through active excavation in a quarry inside the Hawsun Hot Spring Complex.

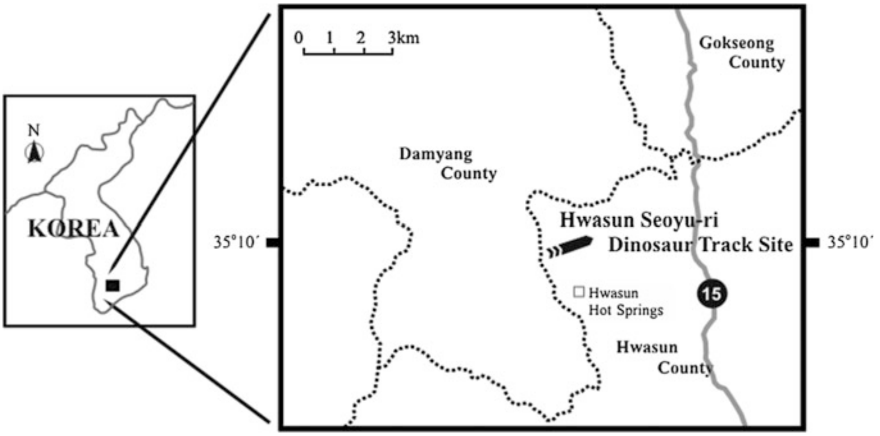


**Fig. 6.4** Location map of the Hwasun track site. *Sources* Modified after Kim (2002), Kim and Huh (2010). *Photo* by Min Huh

The basinfill of the Neungju Basin, the Neungju Group, mainly consists of tuffs, lava flows, tuffaceous conglomerates, and epiclastic deposits. Most of the volcanic rocks have a felsic composition and are interpreted to be extruded during the Late Cretaceous Period (Huh and Paik 2001; Huh et al. 2001). The Neungju Basin is thus chronostratigraphically correlated with the Yucheon Group of the Gyeongsang Basin. The track-bearing deposits belong to the Jangdong Tuff overlying the Manweolsan Tuff and underlying the Yeonhwari Formation and the Jeokbyeok Tuff (Fig. 6.5). Detailed sedimentology of these units has yet to be studied.

#### 6.1.2.2 Dinosaur Track-Bearing Deposits

The Jangdong Tuff consists of tuffs, tuffaceous sandstones, and epiclastic deposits approximately 800 m thick. The lithology of the track-bearing deposit is comprised of interbedded medium-grained sandstone-mudstone, interlaminated fine-grained sandstone-siltstone-mudstone, graded tuffaceous sandstone, planar- to cross-laminated fine-grained sandstone to siltstone, interlaminated silty mudstone-mudstone, chert, and lenticular-bedded conglomerate (Fig. 6.6). Interbedded medium-grained sandstone-mudstone and interlaminated fine-grained sandstone-siltstone-mudstone beds dominate these deposits, and the tracks mostly occur in the interlaminated fine-grained sandstone-siltstone-mudstone. Sedimentary structures include desiccation cracks, wave ripples, and bioturbation features (Paik and Kim 1998). Carbonized wood fragments are distributed in the tuffaceous sandstone. The sedimentary structures indicate that the depositional environment was a marginal to shallow lacustrine environment. The lack of carbonates and invertebrate bioturbation suggests a moderate sedimentation rate, while the presence of desiccation cracks and subaerial lenticular cracks implies the alternation of periods of deposition and drying,

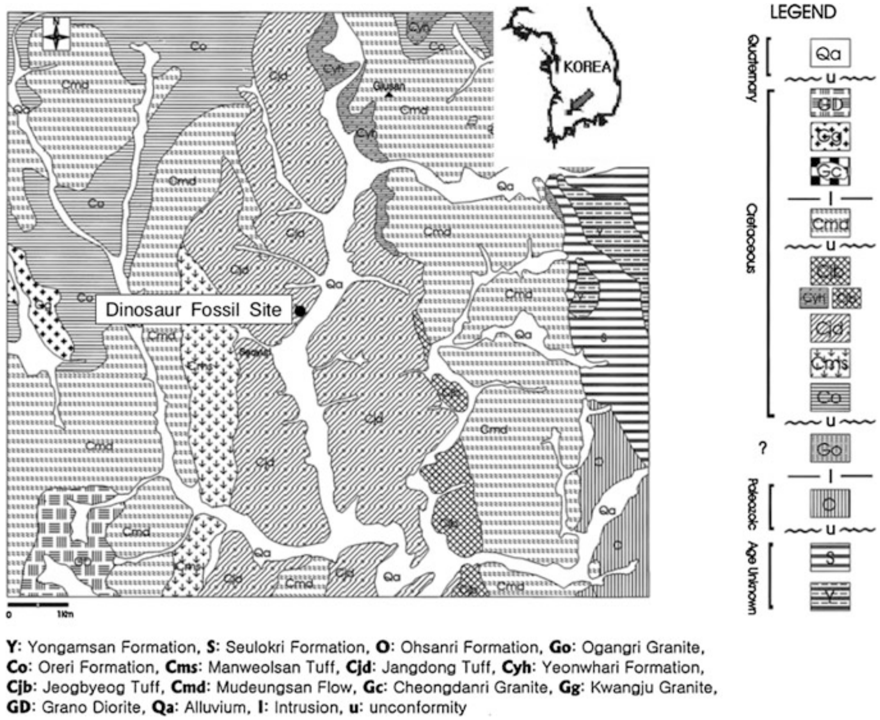


**Fig. 6.5** Geologic map of the Hwasun track site. *Source* Huh et al. (2003a). *Photo* by Min Huh

resulting in the preservation of the tracks. The frequent intercalation of the tuffaceous deposits suggests intermittent volcanic activity near the lake during deposition. Dinosaur footprint fossils were mainly found in the lacustrine deposits alternating sandstone, siltstone and mudstone formed by sheet floodings under semi-arid climatic conditions (Chough and Chun 1987; Lee 1999; Huh et al. 2006; Paik et al. 2007).

## *6.1.3 Yeosu Dinosaur Track Site*

### 6.1.3.1 Location and General Geology

The Yeosu dinosaur track site is one of the most beautiful of all the dinosaur track sites found on the islands along the southern coast of the Korean Peninsula. The Yeosu dinosaur track site comprises five islands, including Sado, Chudo, Nangdo, Mokdo, and Jeokdeumdo ("do" is the Korean word for island), designated as a part of Korean Natural Monument 434 (Fig. 6.7). Besides multiple track-bearing layers, first identified in 1999, the Yeosu track sites have interesting sedimentary cycles

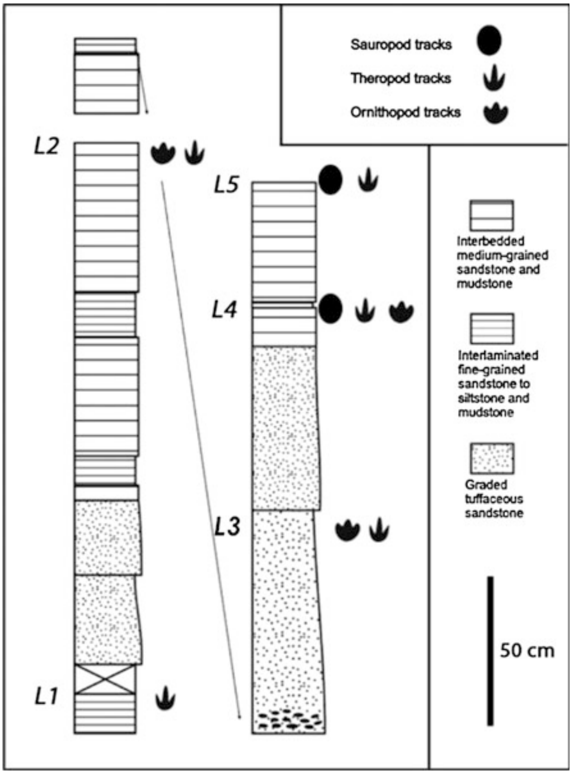


**Fig. 6.6** Stratigraphy of the Hwasun track site. *Sources* Modified after Huh et al. (2006), Lockley et al. (2012c). *Photo* by Min Huh

and thick volcaniclastic sequences that have yielded fossil woods. The depositional age of the track site is inferred as the late Cretaceous (81–65 Ma; Paik et al. 2006).

The depositional environments of the Yeosu track site are alluvial fan, fluvial plain, and lacustrine environment, in ascending order. The islands are composed of sedimentary rocks such as conglomerate, sandstone, and shale, as well as igneous rocks of a wide compositional range formed by Mesozoic igneous activity. The magmatism formed various types of sills, dykes, lava flows, and/or tuffs covering the sedimentary rocks and provided a considerable amount of volcanic material to the sedimentary successions. The basaltic trachyandesite dyke of Chudo intruded the dinosaur track-bearing deposits almost perpendicularly. A thick trachyandesitic flow overlies the Chudo sedimentary rocks almost conformably. The acidic to intermediate tuff overlies the dinosaur track-bearing deposits on Sado. Conglomerates contain volcanogenic materials up to boulder size. Volcanic pebbles in the Jeokgeumdo conglomerate include basaltic andesite, andesite, basaltic trachyandesite, trachyandesite, and trachyte, indicative of the first stage of volcanic activity (Paik et al. 2006).

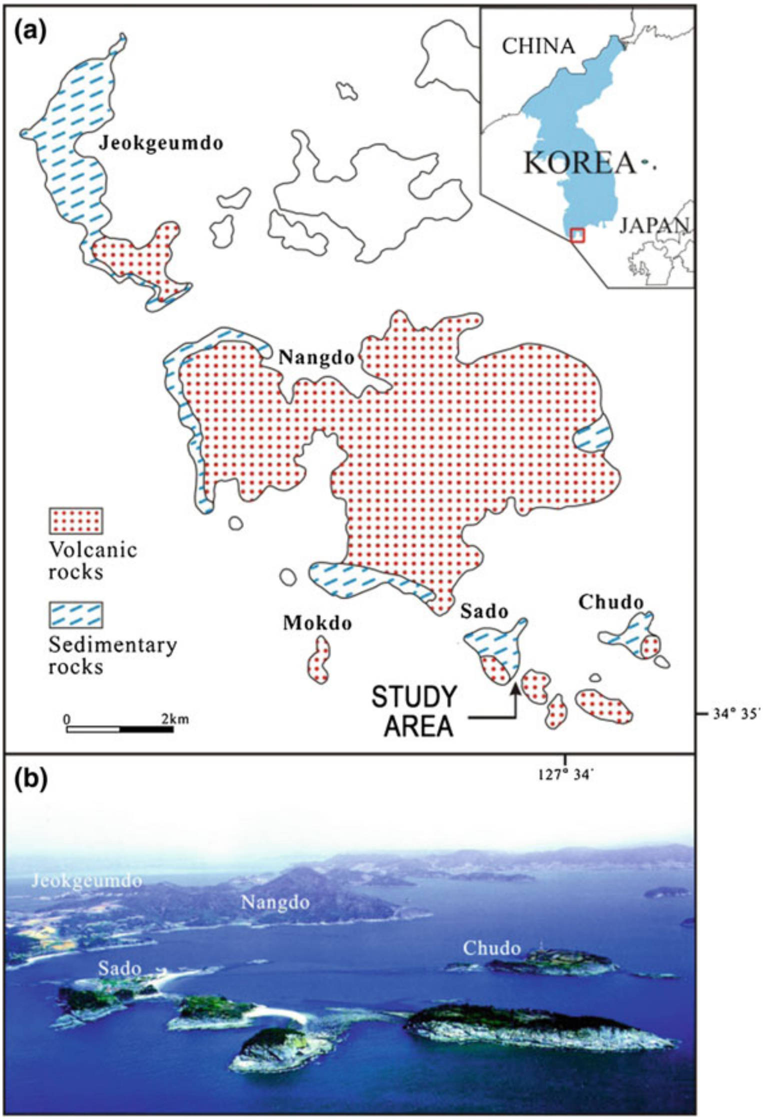


Fig. 6.7 Simplified geological map of the Yeosu dinosaur islands showing **a** the location of dinosaur track-bearing outcrops on Sado, **b** and an oblique aerial view of the islands with the tombolo connecting two parts of the Sado group. *Sources* Paik et al. (2006), Lockley et al. (2012b), Huh et al. (2012). *Photo* by Min Huh

### 6.1.3.2 Dinosaur Track-Bearing Deposits

Marginal to shallow lake deposits are extensively distributed in the Yeosu dinosaur track site. These lacustrine deposits consist of interlaminated to thinly interbedded fine-grained sandstone-siltstone-mudstone, planar- to cross-laminated sandstone-siltstone, tuffaceous sandstone, flaser- to lenticular-bedded fine-grained sandstone-siltstone-mudstone, chert, marlstone, shales, and intraformational conglomerate (Figs. 6.8 and 6.9; Paik et al. 2006). Most dinosaur tracks occur in the interlaminated to thinly interbedded, fine-grained sandstone-siltstone-mudstone in the marginal lake deposits. These deposits contain various sedimentary structures such as desiccation cracks, lenticular cracks, symmetrical and asymmetrical ripples, rain prints, invertebrate burrows and trails, *Skolithos*-type burrows, circular resting marks, and evaporite mineral casts (Paik and Kim 1998).

In general, these deposits are calcareous and thin laminar calcretes associated with clusters of calcispheres. The laminar calcretes usually occur as intraformational chips (Paik et al. 2006). Ripple bedding, climbing ripples (Fig. 6.10a), flaser- to lenticular-bedded fine-grained sandstone-siltstone-mudstone beds, which are typical in tidal deposits (Fig. 6.10b), exist in the marginal lake deposits. In places, marlstones containing ostracod carapaces are present. Chert, possibly originating from tuffaceous deposits, and convolute lamination are clearly observed (Fig. 6.10c). Pyroclastic deposits are associated with the lacustrine deposits and consist of a pyroclastic flow and surge deposits (Fig. 6.10d). Silicified or calcified wood fragments occur in the pyroclastic flow deposits and are usually subparallel to the bedding planes. In the surge deposits, large-scale cross-bedding is present (Paik et al. 2006).

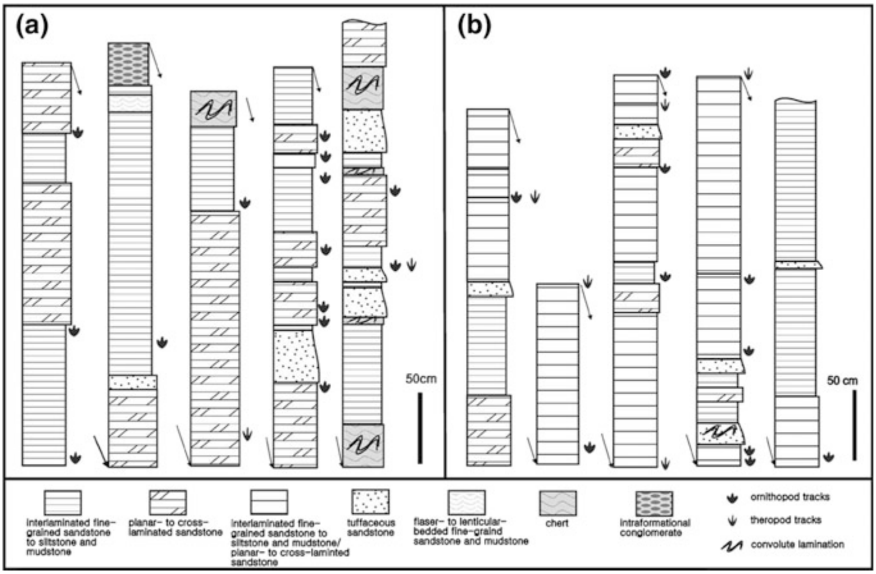


**Fig. 6.8** Stratigraphic sections of dinosaur track-bearing deposits at **a** Sado and **b** and Chudo. *Source* Paik et al. (2006). *Photo* by Min Huh

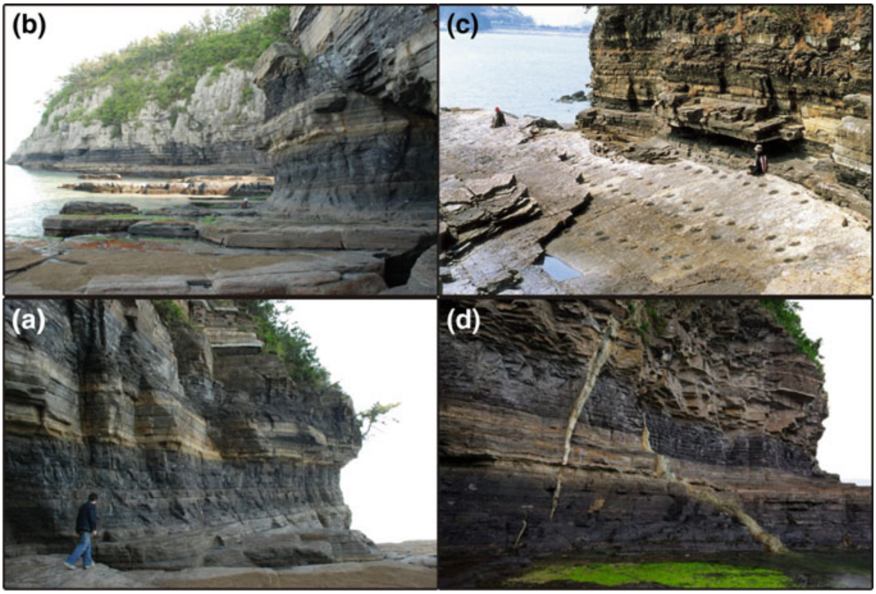


**Fig. 6.9** Track-bearing sections at Chudo and Sado (after Lockley et al. 2012b). *Notes* **a** lower part of sequence on Chudo shows alternating dark shale and light-colored sand units; **b** upper part of sequence on Chudo as wave-cut platform in foreground. Upper part of the sequence including massive volcanics is seen in background; **c** Chudo track site showing the longest ornithopod trackways, including an 84 m trackway; **d** alternating dark and light deposits on Sado with small igneous dykes. *Source* Lockley et al. (2012b). *Photo* by Min Huh

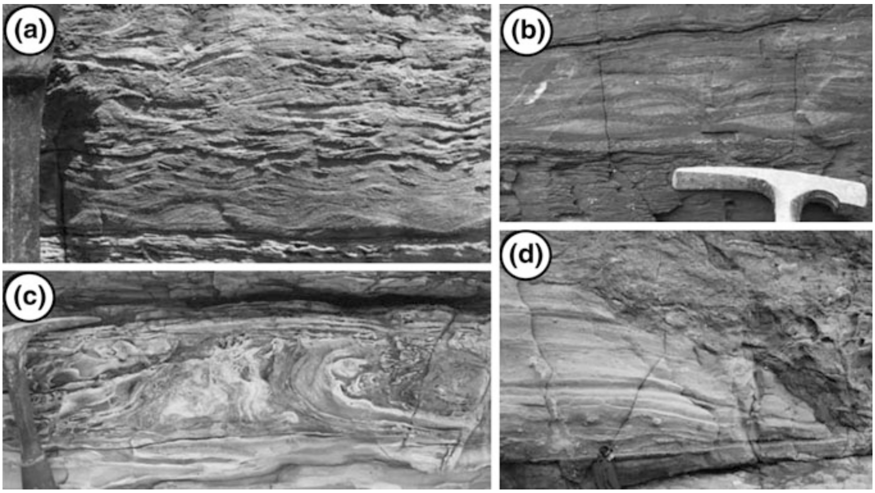


**Fig. 6.10** Features of shallow lake deposits (**a**, **b**) and pyroclastic deposits (**c**, **d**) in Yeosu track site. *Notes* **a** climbing ripple bedding with bicurrential cross-lamination; **b** flaser bedding to lenticular bedding; **c** convolute lamination in chert bed; **d** cross-bedded pyroclastic surge deposits. *Source* Paik et al. (2006). *Photo* by Min Huh

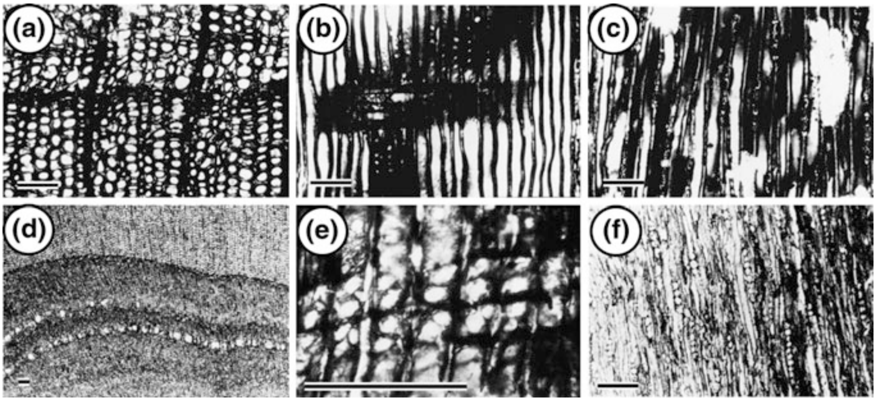


**Fig. 6.11** Thin section photomicrographs of *Cupressinoxylon vectense* (**a**–**c**) and *Taxodioxylon nihongii* (**d**–**f**). *Notes* **a** transverse section showing growth ring, **b** radial section showing bordered pits on radial wall of tracheids; **c** tangential section showing uniseriate rays; **d** transverse section showing growth rings; **e** radial section showing taxodioid cross field pits; **f** tangential section showing uniseriate rays. Scale bars are 100 mm. *Source* Paik et al. (2006). *Photo* by Min Huh

#### 6.1.3.3 Petrified Wood

Fossil woods are found as fragments in the pyroclastic and tuffaceous deposits at the Yeosu dinosaur site (Paik et al. 2006). No upright fossil trees were found, suggestive of their derivation from the hinterland. All petrified wood fragments are conifer trees, except for one, which is a discotyledon. However, the discotyledon is too poorly preserved to identify its specific taxon. The conifers are classified into five taxa including three species of cupressaceous conifer (Fig. 6.11a–c) and two species of taxodiaceous conifer (Fig. 6.11d–f).

### *6.1.4 Goseong Dinosaur Track Site*

#### 6.1.4.1 Location and General Geology

The Goseong dinosaur track site yields the greatest number of dinosaur tracks in the world. Dinosaur and bird tracks occur at all the sites in Goseong County, which is especially well-known for ornithopod trackways at many sites (Figs. 6.12 and 6.13; Lockley et al. 2006). The occurrence of tracks is mainly focused around Dukmyeongri and the Sangokri area, not far from Samcheonpo City.

The Goseong track site belongs to the Jindong Formation of the Hayang Group in the Gyeongsang Basin. The depositional age of the Jindong Formation has traditionally been regarded as Aptian-Albian, based on the non-marine molluscs and palynomorphs that have been discovered (Yang 1982; Choi 1985;

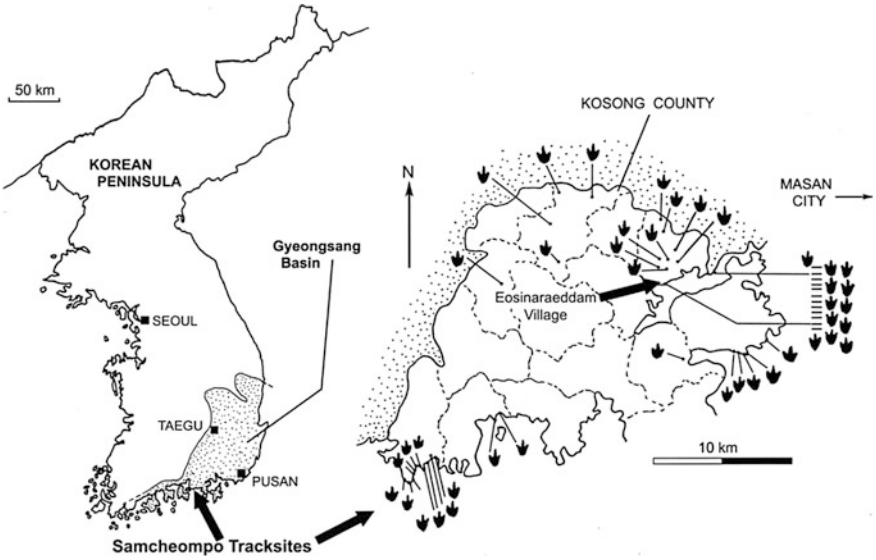


**Fig. 6.12** The Goseong track site in Goseong County showing the abundance of tracks found in the southwest of Samcheonpo and also in the northeast of the county. *Source* After Lockley et al. (2006). *Photo* by Min Huh

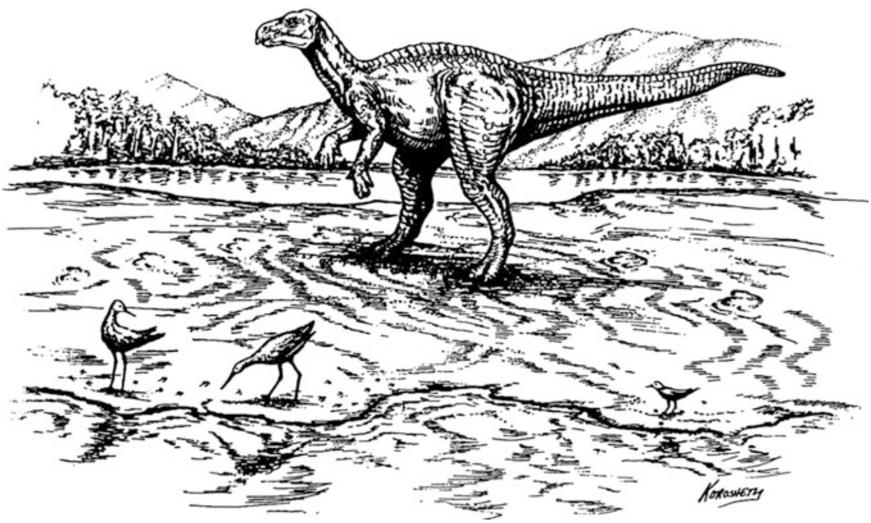

**Fig. 6.13** Reconstruction of bird and ornithopod track makers in a Cretaceous lakeshore paleoenvironment. *Note* Based on trackway evidence from the Jindong Formation, South Korea. *Source* From Lockley et al. (1992). *Photo* by Min Huh

Lee et al. 2000). However, recent research reveals that the Jindong Formation deposited in the Cenomanian to Campanian Periods (Jwa et al. 2004; Paik and Kim 2006; Lim et al. 2012). Intrusive rocks are common throughout the track site area, and a dacite-sill preserved a sauropod trackway on its top, where the lava molded the natural sauropod track casts on a bedding plane (Lockley et al. 1993). The Jindong Formation is composed of alternated laminated to thin-bedded fine-grained sandstone, siltstone-mudstone yielding desiccation cracks, and intercalated units of silicified and calcified tuffaceous sediments (Paik and Kim 2006; Lim et al. 2012).

#### 6.1.4.2 Track-Bearing Jindong Formation

Outcrops of the Jindong Formation occur mainly on wave-cut platforms along the rocky coast. They consist of well-indurated mudstone, minor sandstones, and reworked volcaniclastics with gently inclined bedding planes (Fig. 6.14). There are also a few horizons with prominent diagenetic carbonate nodules. Most bedding planes reveal wave ripples with short amplitude and mud cracks. Plant, invertebrate, and vertebrate body fossils are scarce or absent (Houck and Lockley 2006). Considering ubiquitous ripple marks, mud cracks, and other sedimentary structures such as an extraordinary abundance of well-preserved tracks, the depositional environment of the Goseong area was interpreted as a lacustrine setting in an intra-arc basin, subject to periodic volcanism and flooding (Houck and Lockley 2006). Also, the sections show intense calcrete and/or paleosol development, which means a more arid setting (Paik et al. 2001, 2003). The outcrops of the Goseong track site are cut by multiple small faults that can complicate local correlation (Houck and Lockley 2006; Lockley et al. 2006).

### *6.1.5 Jinju Gajinri Dinosaur and Bird Track Site*

#### 6.1.5.1 Location and General Geology

The Jinju Gajinri dinosaur and bird track site (Figs. 6.15, 6.16, and 6.17) is housed in the Fossil Heritage Hall at the Gyeongsangnamdo Institute of Science Education, Gajinri area, Jinju City. The site has been designated as Natural Monument No. 395. The institute was built over two track-bearing outcrops of the Cretaceous Haman Formation so as to create two fossil halls (Heritage Halls I and II). The Haman Formation belongs to the Hayang Group in the Gyeongsang Basin, southeastern Korea. The depositional environment of the Haman Formation was interpreted to be fluvial (Paik et al. 2012). Both halls reveal dinosaur (sauropod and theropod) footprints and numerous bird tracks. Hall I contains two new tetrapod

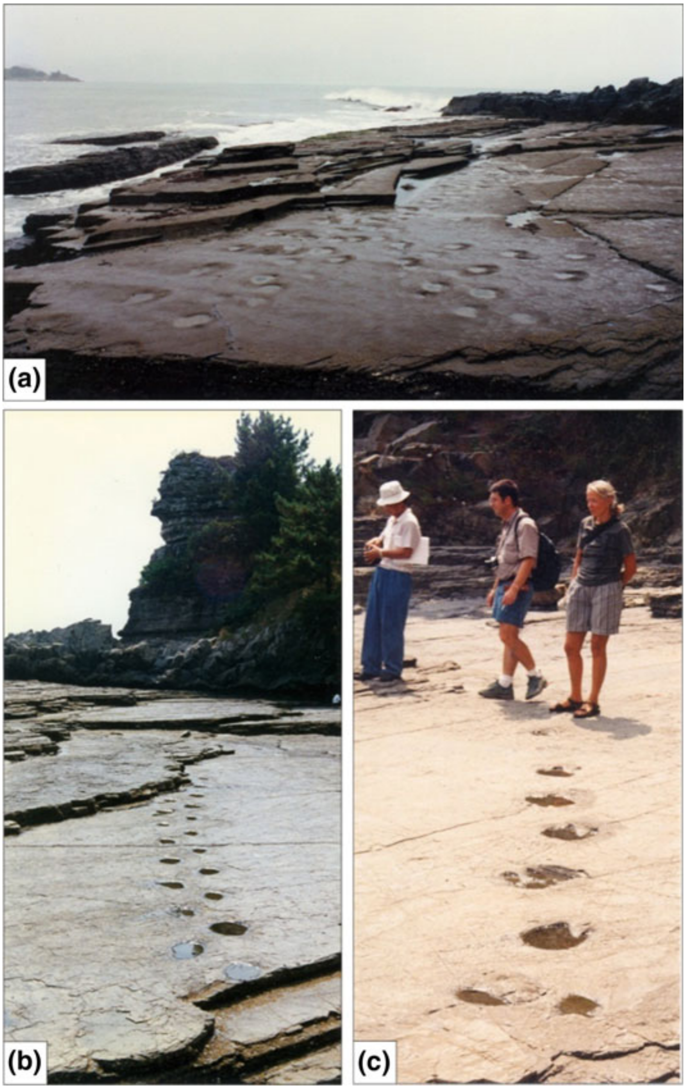


**Fig. 6.14** Typical outcrops of the Goseong track site at Sangjok, near the Goseong Dinosaur Museum. *Source* Lockley et al. (2006). *Photo* by Min Huh

ichnospecies of a sauropod and a bird (Kim and Lockley 2012; Lockley et al. 2012a). The bird track site is the world's densest assemblage of Cretaceous avian tracks, and preserves more than 2000 bird tracks in an area of approximately 27 $m^2$. The site has been dubbed as a "paradise" for Mesozoic birds (Kim et al. 2012; Lockley et al. 2012a), as a source of abundant and diverse bird tracks. On the track site are two interesting sauropod trackways oriented in different directions.

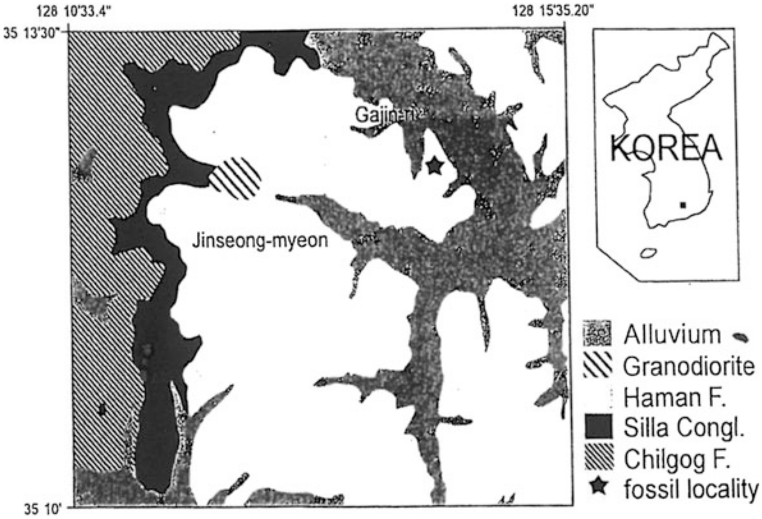


**Fig. 6.15** Geologic map of the Jinju Gajinri dinosaur and bird track site. *Source* From Kim et al. (2012). *Photo* by Min Huh

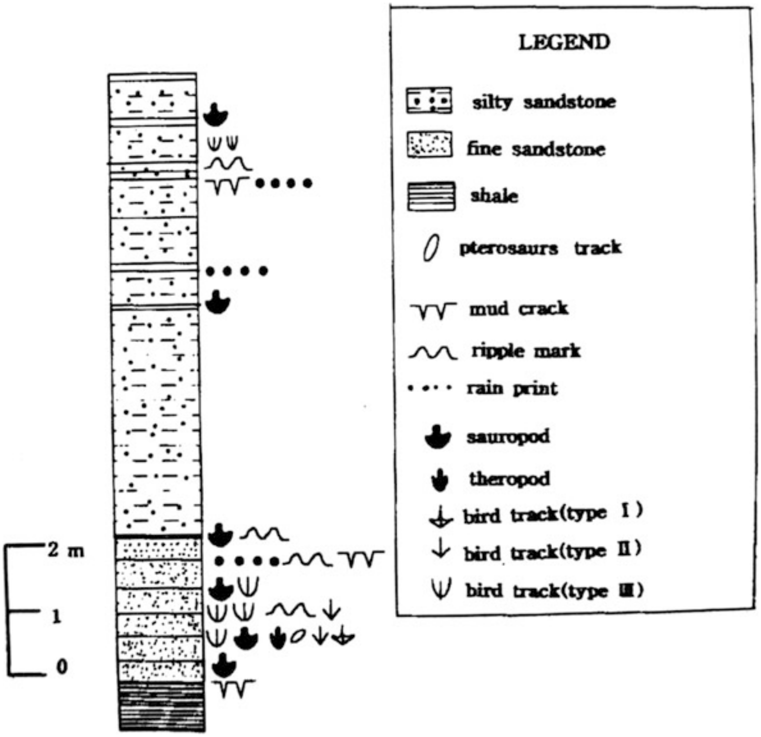


**Fig. 6.16** Columnar section showing fossil occurrences at the Jinju Gajinri dinosaur and bird track site. *Source* From Baek and Yang (1998). *Photo* by Min Huh

**Fig. 6.17** Sauropod tracks at the Gyeongsangnamdo Institute of Science Education, Gajinri, Jinju City. *Source* From Kim et al. (2012). *Photo* by Min Huh

## *6.1.6 Namhae Gainri Dinosaur Track Site*

### 6.1.6.1 Location and General Geology

The Namhae Gainri dinosaur track site is located in northeastern Changseon Island (Gainri, Changseon District, Namhae County) and on Adu Island (Sinsudong, Sacheon City), which is located approximately 2 km northeast of the Gain track site and occupies a smaller area than the Gain site (Fig. 6.18). The track site comprises various kinds of dinosaur, pterosaur, and bird tracks. The basinfill of the Haman Formation in the Namhae Gainri area generally dips less than 20°SE and was intruded by Late Cretaceous igneous rocks. It contains various dinosaur and bird tracks including *Koreanaornis hamanensis* and *Jindongornipes kimi* (Kim 1969; Lim et al. 2000; Lockley et al. 1992). These finds include the oldest web-footed bird tracks (*Ignotornis yangi*). Diminutive dinosaur tracks (*Minisauripus zhenshuonani*) and didactyl theropod tracks (*Dromaeosauripus hamanensis*) were also reported at the Haman Formation in the Gain area on Changseon Island, Sinsu Island, and Chu Island (Kim et al. 2006, 2008; Lockley et al. 2008). The depositional environment of the track site may have been that of a lakeshore, inferred from diverse invertebrate trace fossils, ripple marks, mud cracks, and raindrop imprints.

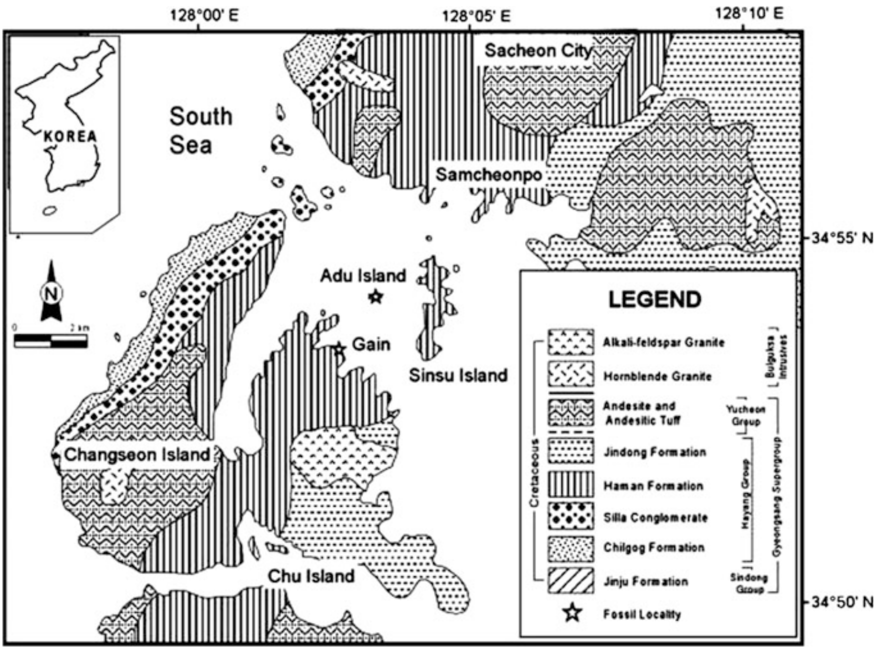


**Fig. 6.18** Geologic map of the Namhae Gainri dinosaur track site and fossil locations. *Source* After Kim et al. (2008a). *Photo* by Min Huh

### 6.1.6.2 Track-Bearing Deposits

Footprints of pterosaurs, sauropods, ornithopods, and theropods occur on a bedding plane of 20 cm thick light gray fine-grained sandstone at the Gain section (Fig. 6.19). The main outcrop is approximately 18 m long and 5.6 m wide, and the bed has a strike of N20°E and a dip of 28°SE. The track-bearing sandstone bed is distributed along the shoreline and part of the outcrop becomes submerged during high tide. The tidal range is about 2 m at the fossil location. The pterosaur and dinosaur track-bearing layer belongs to the middle part of the Haman Formation (Fig. 6.19), which consists of rhythmic alternations of fine-grained siliciclastic sediments. Fine- to medium-grained sandstones at the Gain section frequently show parallel lamination, cross-lamination, convolute bedding, flame structures, and ripple marks. Interbedded shales and mudstones yield fossil plants, raindrop imprints, and mud cracks. The ichnospecies *I. yangi* occurs approximately 5 m below the pterosaur and dinosaur track-bearing sandstone bed (Kim et al. 2006; Lockley et al. 2012a). Five consecutive pterosaur tracks occur in a single trackway on Adu Island, which is only approximately 80 m long and 30 m wide. Many dinosaur bones and *Grallator*-like dinosaur tracks also occur in the medium- to coarse-grained sandstone on Adu Island.

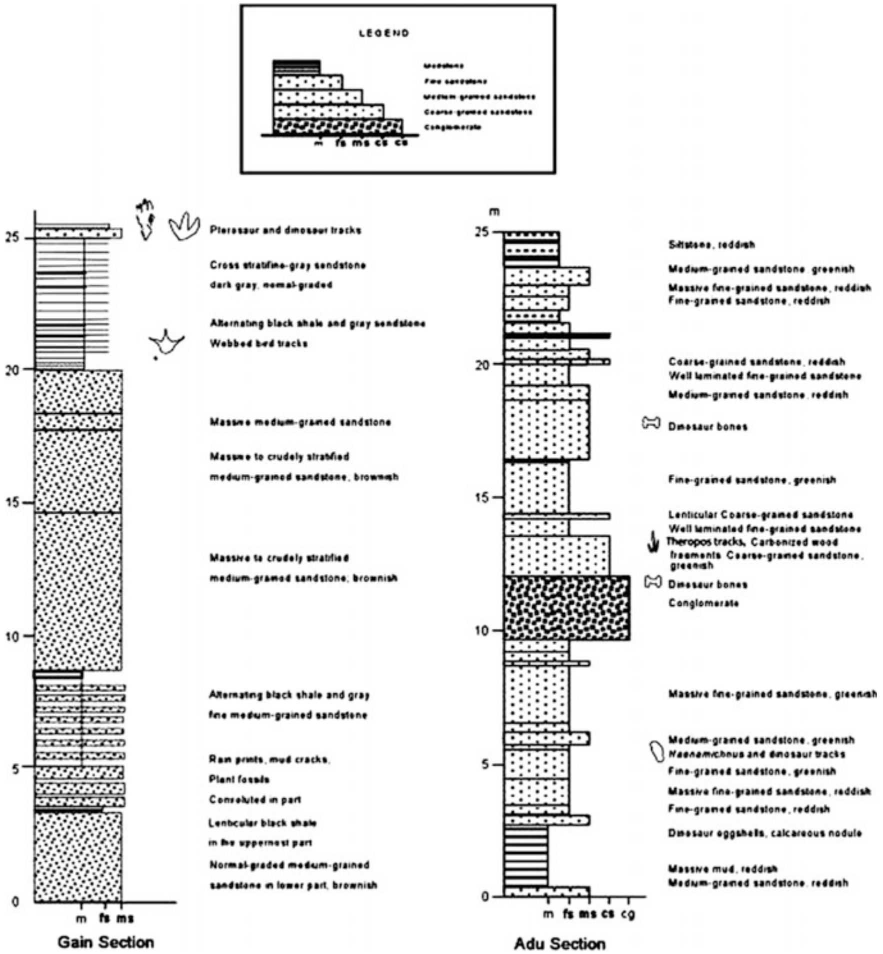


**Fig. 6.19** Measured sections showing the stratigraphy of the pterosaur and dinosaur tracks-bearing beds in Gain and on Adu Island. *Source* Kim et al. (2006). *Photo* by Min Huh

## *6.1.7 Other Track Sites*

### 6.1.7.1 Geoje Galgotri Track Site

The Geoje Galgotri track site (Figs. 6.20 and 6.21) is located at Galgotri, southeast of Geoje Island in South Gyeongsang Province on a rocky coast, about 500 m west of the Sinseondae (meaning "a hermit rock"). The lithology is mainly composed of sandstone of the Seongpori Formation. Several layers of purple laminated shale intercalated with sandstone have yielded numerous tracks of pterosaurs, sauropods, and birds, and also many invertebrate trace fossils. Well-developed ripple marks

**Fig. 6.20** Outcrop view of the Geojae Galgotri track site. *Source* Huh et al. (2010b). *Photo* by Min Huh

**Fig. 6.21** Bird tracks at the Geojae Galgotri track site. *Photo* by Min Huh

and diverse mud cracks occur on the bedding surface. Bird tracks of *K. hamanensis* are predominant at the site though there are some large bird tracks resembling *Jindongornipes*. *Pteraichnus*-like pterosaur tracks are less commonly observed on the bedding planes (Yang et al. 2008).

#### 6.1.7.2 Masan Hogyeri and Gohyeonri Track Sites

The Masan Hogyeri (Figs. 6.22 and 6.23) and Gohyeonri track sites (Fig. 6.24) are located at Naeseo-eup and in the Jindong District of Masan City in South Gyeongsang Province, respectively. At the Hogyeri track site, dinosaur and bird tracks occur on the inclined bedding surfaces exposed at the roadside of the Expressway (Hwang et al. 2002b; Kim et al. 2008b). The track site belongs to the Jindong Formation and consists of black shales, siltstones, sandstones, and calcareous sediments alternating with each other. Sauropod and bird tracks and invertebrate trace fossils are commonly discovered at the site (Hwang et al. 2002b). The sauropod tracks number more than 100 and comprise seven trackways. The bird tracks are composed of *K. hamanensis*, *J. kimi*, and unidentified web-footed birds. Petrified wood fragments are also observed, which are very rare in the Jindong Formation. Various sedimentary structures such as mud cracks, ripple marks, and evaporite mineral casts are present on the bedding planes. Alternating

**Fig. 6.22** Outcrop view of the Masan Hogyeri track site. *Source* Huh et al. (2010b). *Photo* by Min Huh

**Fig. 6.23** Dinosaur tracks at the Masan Hogyeri track site. *Source* Huh et al. (2010b). *Photo* by Min Huh

laminated- to thin-bedded fine-grained sandstone and mudstone lithofacies with sedimentary structures indicate that the track-bearing strata were deposited in a mudflat of a lake margin environment with a semi-arid climate.

At the Gohyeonri track site, dinosaur tracks from twenty-four horizons, bird tracks from two horizons, and ornithopod tracks from one horizon were found in

**Fig. 6.24** Ornithopod tracks along the seashore outcrop of the Gohyeonri track site. *Source* Huh et al. (2010b). *Photo* by Min Huh

20 m thick fine-grained strata of the Jindong Formation (Huh et al. 2003b; Lee 1993). Of the over 400 dinosaur tracks observed at the Gohyeonri track site, medium-sized ornithopod tracks predominate and medium-sized sauropod tracks are also common. The ornithopod tracks are preserved in fifteen trackways on the submerged bedding surface. The bird tracks at the Gohyeonri track site are similar

to *K. hamanensis*. At a hill about 400 m west of the Jeonjin shipbuilding yard, two manus and two pes tracks of a small sauropod have been found.

#### 6.1.7.3 Euiseong Jeori Track Site and Cheongnori Fossil Site

The Geumseong District of Euiseong County in North Gyeongsang Province has two fossil and track sites: the Jeori dinosaur track site and the Choengnori fossil site. The Jeori track site (Fig. 6.25) is located at the roadside (local road No. 930) which is about 4 km NNW from Geumseong District. The track site belongs to the Sagok Formation of the Hayang Group, the middle sequence of the Gyeongsang Supergroup, and mainly consists of light gray sandstone and dark gray shale (Um et al. 1983). The Sagok Formation is correlated with the Early Cretaceous Haman Formation on the basis of stratigraphy, lithology, and the depositional environment. Dinosaur tracks are densely distributed on the widely exposed bedding surfaces. Over 300 dinosaur tracks are observed from four horizons of light gray sandstone deposited in the fluvial channel and dark gray shale deposited in the floodplain environment (Chang et al. 1982; Kim 1983). More than twelve sauropod trackways, more than ten ornithopod trackways, and one theropod trackway were recognized at the track site.

The Cheongnori fossil site (Fig. 6.26) is the first dinosaur bone fossil site discovered in Korea. The lithology of the site consists of the Hupyeongdong Formation of the Hayang Group. The Hupyeongdong Formation is about 500 m in thickness and is composed of conglomerates, purple sandstone, mudstone, and

**Fig. 6.25** Jeori dinosaur track site on roadside. *Photo* by Min Huh

**Fig. 6.26** Outcrop view of the Cheongnori fossil site. *Photo* by Min Huh

siltstone which were deposited in an alluvial plain environment. The conglomerate is mainly composed of limestone gravels together with some mudstone and granite gravels, and has a maximum thickness of about 1 m. The dinosaur bone-bearing conglomerate is thought to have been deposited in a fluvial channel environment. Radiorarian chert fragments are included in conglomerates. Mud cracks, invertebrate trace fossils, and calcareous nodules are commonly observed in the purple mudstone.

#### 6.1.7.4 Haman Yongsanri Bird Track Site

The Haman Yongsanri bird track site (Fig. 6.27) is located at the middle part of a mountain in Yongsanri, about 10 km northwest of Masan City, in South Gyeongsang Province. This track site is the first bird track site in Korea and the second in the world (Kong and Kim 2008). The bird tracks were described as *K. hamanensis*, which means “the Korean bird from the Haman area”. The bird track-bearing strata belong to the Haman Formation, which is mainly composed of gray mudstone, grayish green shale, sandy shale, purple shale, and siltstone. More than 1000 bird tracks, some sauropod tracks, and many invertebrate trails and burrows are observed on the bedding surface. Abundant raindrop impressions are also observed on the rippled surface (Kim 1969). On the basis of these features, the track-bearing strata are considered to have been deposited in a fluvial to lake margin environment.

**Fig. 6.27** Outcrop view of the Yongsanri bird track site. *Photo* by Min Huh

## 6.2 Dinosaur Egg Sites

### *6.2.1 Boseong Dinosaur Egg Site*

The Boseong dinosaur egg site is located in a small cauldron basin belonging to a series of Cretaceous transtensional basins in South Korea (Fig. 6.28). The sedimentary sequences in the egg site consist of the Seonso Conglomerate, the Seonso Formation, the Pilbong Rhyolite, the Mudeungsan Flow, the Obongsan Brecciated Tuff, and the Docheonri Rhyolite, in ascending order (Hwang and Cheong 1968). Abundant volcanic and pyroclastic rocks in the basin suggest that the sedimentary sequences can be chronostratigraphically correlated with the Yucheon Group (Upper Cretaceous) of the Gyeongsang Basin. The fossiliferous sediments are interpreted to have been deposited in the Santonian to Campanian Periods (Huh et al. 2006; Kim et al. 2008a). Dinosaur bones and eggs are included at the base of the Seonso Conglomerate. This formation consists of conglomerates, greenish grey to variegated sandstones, and purple mudstones. The dinosaur bones are included the in purple mudstones, interpreted as terminal fan deposits (Paik et al. 2004). The mudstones hosting the dinosaur eggs and bones show various pedogenic features such as calcite rims aureoles around detrital grains, pedotubular to nodular calcretes, and circumgranular to circumnodular cracks, suggestive of a calcareous pedogenesis.

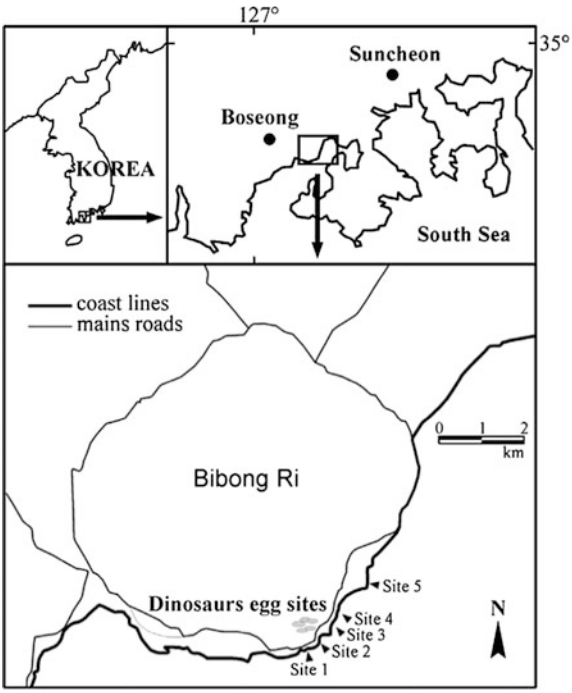


**Fig. 6.28** Location maps of the Boseong dinosaur egg site. *Sources* Paik et al. (2004), Huh et al. (2010a). *Photo* by Min Huh

As Paik et al. (2004) described, the Boseong egg site includes vertic features such as pedogenetic slickensides, pseudoanticlines, and calcite-filled deep desiccation cracks. The fossiliferous mudstones contain small burrows filled with sandstone and are perpendicular to subperpendicular in relation to the bedding planes. The paleoclimate was interpreted to have been semi-arid and seasonal with regard to water availability, evidenced by the preservation of the dinosaur fossils in calcic and vertic paleosols.

#### 6.2.1.1 Dinosaur Egg-Bearing Deposits

The prevailing lithology of the Seonso Conglomerate at the Boseong egg site shows vertical and lateral variation among pebble- to cobble-bearing coarse-grained sandstone (greenish gray to variegated) that grades upwards into sandy mudstone to purple mudstone (Paik et al. 2004). The dinosaur eggs are concentrated in the mudstone which dominates the middle part, while the gravel-bearing sandstones dominate the lower part. The thickness of the mudstones in the middle part increases eastwards. Tuffaceous deposits are common in the upper part. The grains comprising these rocks are mainly epiclastic with minor tuffaceous ones. The coarse-grained sandstone beds commonly overlie the mudstone beds with a relief ranging from a few cm to 2 m on the erosive contact. The erosive surfaces generally contain lag gravels which are poorly sorted and subangular to subrounded. Planar bedding and cross-bedding are common in the sandstone. Planar bedded couplets consisting of pebbly coarse-grained sandstone and sandstone are often observed. They are usually discontinuous and in places occur as U-shaped narrow channel fills or lenses (Paik et al. 2004).

The mudstones are host to the dinosaur eggs and bones at the site, and have a variety of pedogenic features. Their detrital grains show calcite aureoles and micrite rims indicative of pedogenesis (Freytet and Plaziat 1982). The micrite rims generally occur adjacent to crystalline limestone fragments. Pedogenic calcrete nodules are common and up to 20 cm in size. Some of them occur as rhizocretions with circumnodular cracks. In addition, pedogenic circumgranular cracks and peloids were observed under a microscope. The pedogenic development shows vertical and lateral variation in the egg-bearing deposits. Especially in the dinosaur egg deposit that includes most of the clutches at the site, the degree of calcrete development laterally changes from stage 1 to 3 (Machette 1985). The deposits also contain vertic features such as pedogenic slickensides, pseudoanticlines, and calcite-filled deep desiccation cracks (Paik and Lee 1998). Bioturbation in the mudstones lying beneath the sandstone beds is evidenced in the form of burrows. The burrows are perpendicular to sub-perpendicular to the bedding surface and filled with sandstone from the overlying sandstone (Paik et al. 2004).

As Paik et al. (2004) reported, the Boseong site seems to have been a dinosaur nesting site, taking into account the preservation of numerous dinosaur clutches on several horizons (Fig. 6.29). Such an occurrence indicates a species of animal showing habitual visitation (Martin 2001). This is evidenced by the occurrence of two clutches in the same site with a vertical interval of 30 cm. The preference of the Boseong dinosaurs for this site seems to have been related to the relatively arid climate, which made it less likely that eggs would be washed away by flooding. Hence, dinosaurs may have preferred the Boseong egg site as their nesting site as it was suitable for the preservation of their eggs.

### *6.2.2 Hwaseong Dinosaur Egg Site*

The Hwaseong Gojeongri dinosaur egg site is located in a reclaimed area approximately 16 $km^2$ at the Sihwa Lake in Hwaseong City, southwest of Gyeonggi Province. Sedimentary rocks at the site were named the Sihwa Formation (or Tando Formation), the basinfill of the Sihwa Basin. The Sihwa Basin was supposed to be opened by transtension due to dextral strike-slips on the eastern border fault, based on the fault geometry (Hwasung City 2005). The Sihwa Formation consists of rhyolitic tuff and andesitic breccia, and was interpreted to have been deposited in an alluvial fan, braided stream, and alluvial plain environment (Kim 2003; Kim et al. 2009). The formation mainly composed of deposits of conglomerate, gravelly sandstone, planar sandstone, and fine- to medium-grained purple sandstone approximately 3 km thick. The clasts consist mainly of granitic

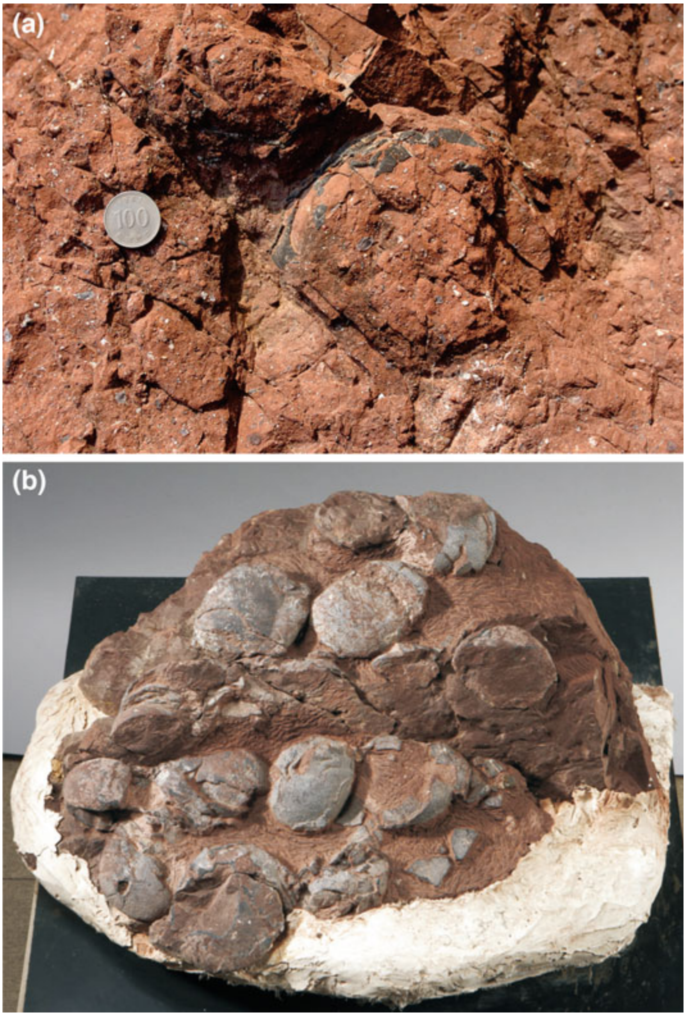


**Fig. 6.29** Dinosaur egg fossils at the Boseong egg site. *Notes* **a** An egg fossil preserved in the outcrop; **b** a nest fossil including several eggs. *Photo* by Min Huh

gneiss, banded gneiss, green or blue schist, and quartzite, with minor amounts of limestone, granite, and volcanic rocks. The depositional age is presumed to be Early Cretaceous (later than 119 Ma), based on K-Ar dating of the volcanic clasts (Park 2000). Thirty dinosaur egg nests, including more than 300 eggs, were found in purple conglomeratic sandstone beds on six small inlands, small mountains on the flat reclaimed tideland. Dinosaur bone fossils including rib bones were also discovered around the egg fossil site. The dinosaur egg nests mainly occur in gravelly sandstone or gravelly mudstone deposited in braided stream and alluvial plain environments.

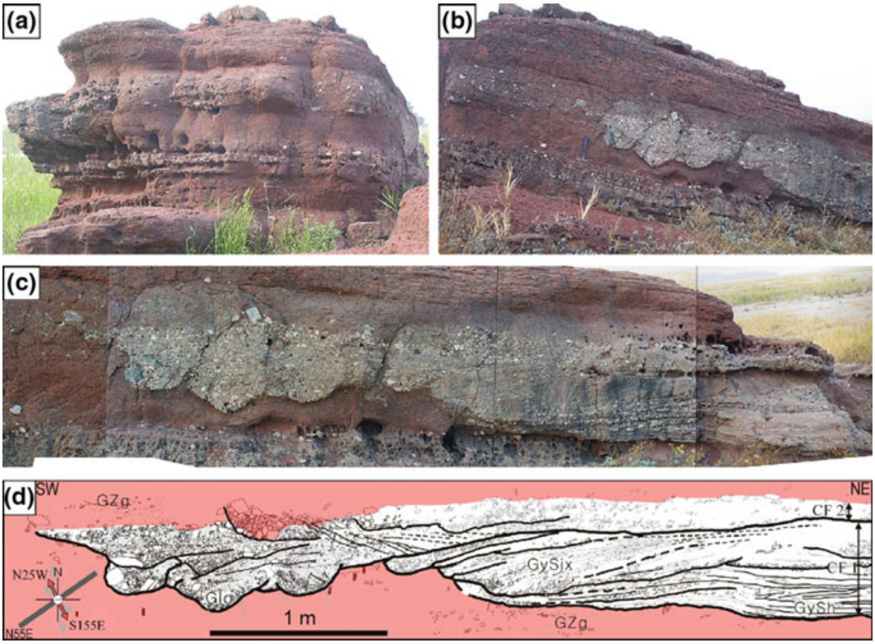


**Fig. 6.30** Representative photographs and sketch of the floodplain and channel fill of the Sihwa Basin. *Source* Kim et al. (2009). *Photo* by Min Huh

The depositional environment of the Sihwa Basin was categorized into three elements: alluvial fan, ephemeral braided stream, and channel-margin to floodplain, based on architectural analysis of the sedimentary facies (Fig. 6.30; Kim et al. 2009). The alluvial fan deposits mainly occur along the eastern basin margin forming discrete sedimentary bodies, while the braided-stream channel fills occur in the northwestern part of the basin intertonguing with the channel margin and floodplain deposits. The sedimentary fill of the Sihwa Basin was divided into the lower terminal-fan succession, widely distributed in the western and central parts of the basin, and the alluvial-fan succession, sharply overlying the terminal-fan succession along the eastern margin. The predominance of the ephemeral braided streams and the reddish floodplain deposits with associated calcareous nodules indicates an arid to semi-arid climate during the deposition of the Sihwa Basin (Kim et al. 2009).

### 6.2.3 Hadong Dinosaur Egg Site

The Hadong dinosaur egg site (Fig. 6.31), the first dinosaur egg site in Korea (Yang 1976), is located on the coast of Sumunri, Hadong County in South Gyeongsang

**Fig. 6.31** Outcrop view of the Hadong dinosaur egg site. *Source* Huh et al. (2010b). *Photo* by Min Huh

Province, and belongs to the Hasandong Formation. The Hasandong Formation mainly consists of gray or purple shales and mudstone, coarse-grained sandstones, gravelly sandstone, and conglomerates. Sediments in the site were deposited in fluvio-lacustrine environments such as channels, crevasse splays, floodplain, and lake (Paik et al. 1998). Ripple marks and mud cracks are common, and the floodplain deposit contains calcareous paleosol and vertisol. Dinosaur egg fragments were found in calcareous paleosol consisting of a greenish gray sandy mudstone layer. The dinosaur egg-bearing strata are composed of light gray sandy mudstone, and coarse-grained or gravelly sandstone.

### 6.2.4 *Tongyeong Dinosaur Egg Site*

The Tongyeong dinosaur egg site is located in the coastal area and islands of Tongyeong City, South Gyeongsang Province. The site is divided into five small areas (on Yeondo Island, Ddabakseom Island, and in the Pyeongri area; Fig. 6.32), and these belong to the Goseong Formation (Upper Cretaceous, Campanian). The paleoenvironment of the sites was floodplain. Dinosaur eggs in these sites were described as two oospecies by Kim et al. (2011), and one of them was designated as a new ootaxon; *Macroelongatoolithus goseongensis* oosp. nov. and *Dictyoolithus neixiangensis* (Figs. 6.33 and 6.34).

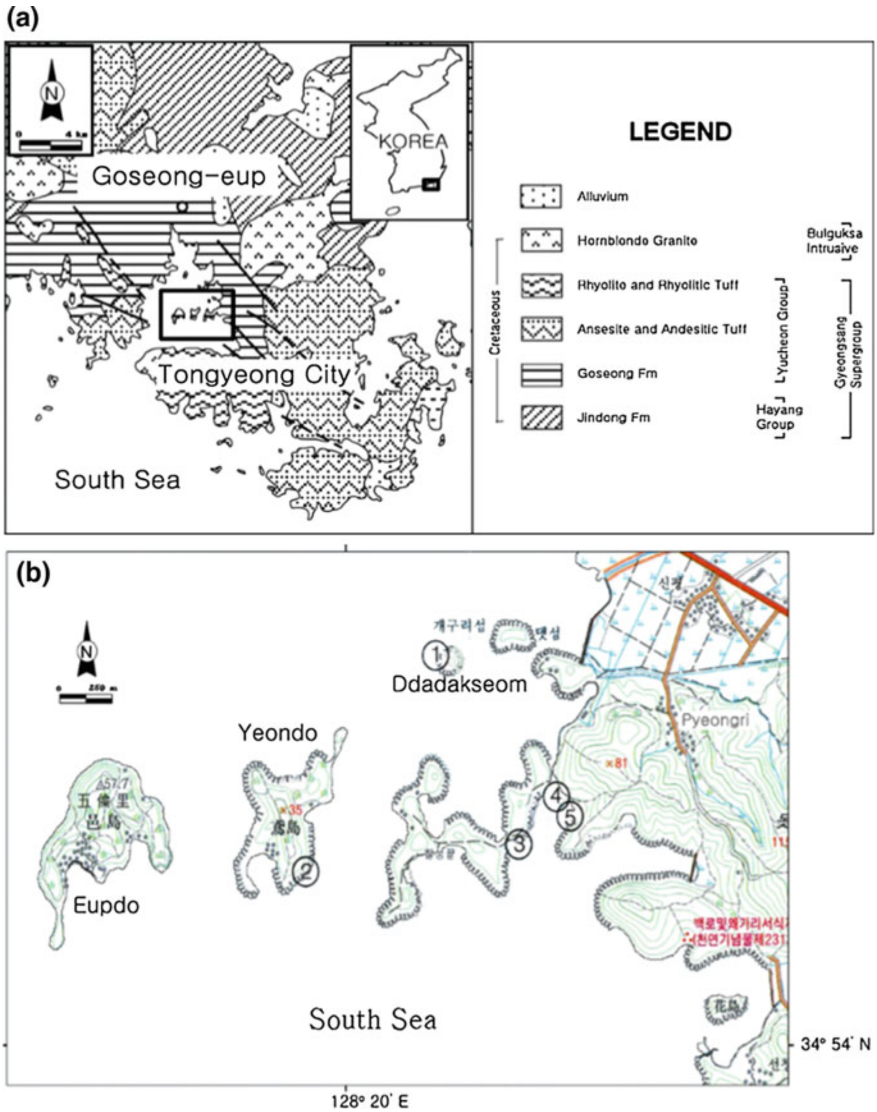


**Fig. 6.32** Geological map and fossil sites of Tongyeong dinosaur egg site. *Source* From Kim et al. (2011). *Photo* by Min Huh

Here, we describe the Tongyeong dinosaur egg site as five separate sites. (1) The Yeondo egg site consists of fine-grained tuffaceous sandstone and siltstone intercalated with thin black mudstone (Kim et al. 2011). The egg fossils of Yeondo are preserved as two nests in green siltstone beds. (2) The Ddabakseom egg site has the biggest dinosaur eggs in the Tongyeong area; there is a dinosaur egg nest composed of six giant eggs (*M. goseongensis*), the largest of which is 390 mm in length and

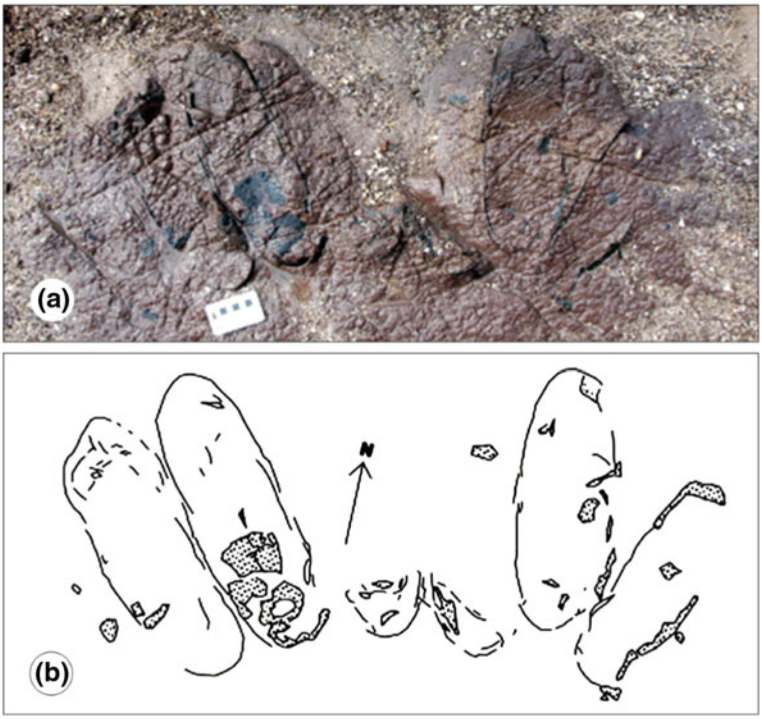


**Fig. 6.33** Photograph and sketch of six giant theropod dinosaur eggs at the Ddabakseom, Tongyeong, dinosaur egg site. *Source* Kim et al. (2011). *Photo* by Min Huh

115 mm in width, with a shell 2.3–3.1 mm thick. This nest is preserved in floodplain purple mudstone (Kim et al. 2011). (3–5) The Pyeongri egg site consists of green siltstone to mudstone and fine-grained sandstone, and twenty-eight dinosaur eggs forming at least three nests were observed (Kim et al. 2011).

According to Kim et al. (2011), the genus *Macroelongatoolithus*, which is probably the egg of oviraptosaurs, has been reported in China and America. This means that the giant oviraptosaurs, or a similar taxon, inhabited the Korean Peninsula at that time.

## 6.3 Other Fossil Sites

### *6.3.1 Boryeong Fossil Site*

The Boryeong fossil site is located in the Seongju District of Boryeong City in South Chungcheong Province, on the western coast of the middle part of the Korean Peninsula (Fig. 6.35). The sediment of the fossil site belongs to the Amisan

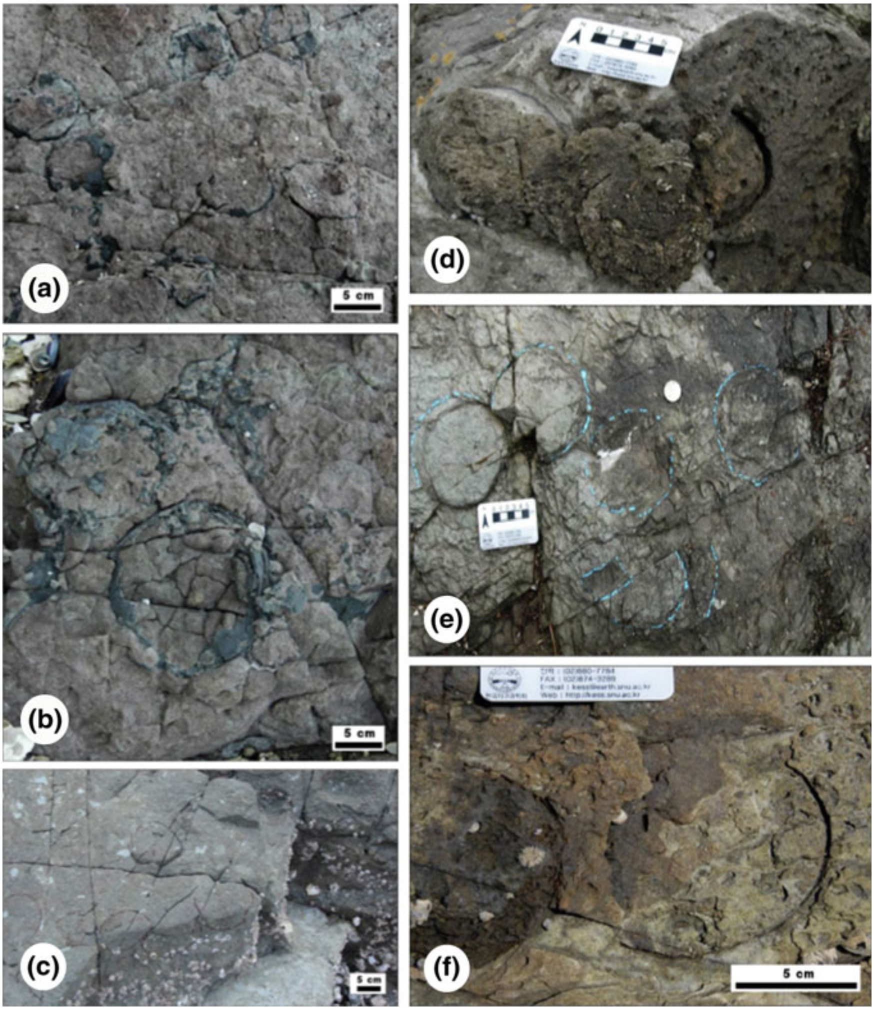

**Fig. 6.34** Occurrence of sauropod dinosaur eggs at the Tongyeong egg site. *Notes* **a**–**c** Yeondo site 2; **d** Pyeongri site 3; **e** Pyeongri site 4; **f** Pyeongri site 5. *Source* From Kim et al. (2011). *Photo* by Min Huh

Formation in the Nampo Group, which is known to have been deposited during the Triassic to Jurassic Period, based on plant fossils (Chun et al. 1990; Jeon et al. 2007; Kimura 1988; Min et al. 1992). The Nampo Group is composed of the Hajo, Amisan, Jogyeri, Baekwoonsa, and Seongjuri Formations in ascending order (Fig. 6.36; Suh et al. 1980; Egawa and Lee 2006) and is known to have been deposited in a fluvial-delta-lacustrine environment (Choi 1988). The Hajo, Jogyeri, and Seongjuri Formations mainly consist of conglomerate and sandstone, while the Amisan and Baekunsa Formations consist of sandstone and black shale. The earliest

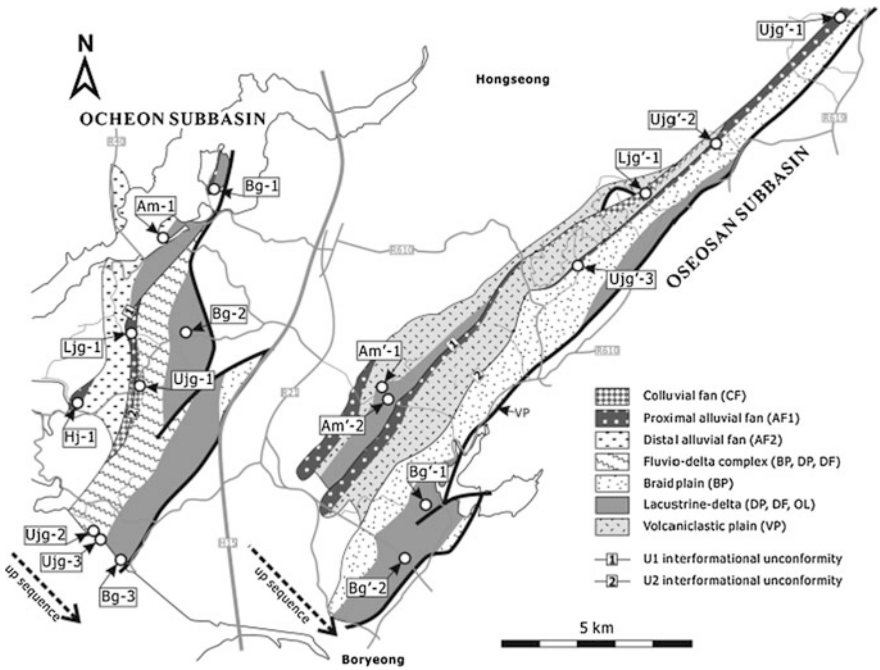


**Fig. 6.35** Geological map of the Nampo Group in South Chungcheong Province, South Korea. *Source* From Egawa and Lee (2009). *Photo* by Min Huh

Mesozoic biota in South Korea—such as fish, molluscs (bivalves), clam shrimps, insects, and plant fossils—occur at the Boryeong fossil site.

The Amisan Formation is mainly distributed in the Boryeong area, South Chungcheong Province, which is located in the middle of South Korea. This deposit was divided into lower sandstone, lower shale, middle sandstone, middle shale, and upper sandstone belts (Suh et al. 1980). The depositional environment of the Amisan Formation was interpreted to be fluvial to lacustrine. The depositional age of the Amisan Formation has been presumed to be the Late Triassic Period, inferred from clam shrimps and plants. However, recent research reported the depositional period of the Amisan Formation as Jurassic, based on fossil insect fauna found in the formation (Nam 2015). The maximum tectonic burial metamorphism of the Nampo Group was estimated as 157–140 Ma (Late Jurassic–Early Cretaceous) by illite K-Ar dating (Egawa and Lee 2011). The depositional environment of the Amisan Formation was interpreted to be a lake margin or fluvial environment connected to a lake (Nam 2015). The basinfill of the Amisan Formation at the Boreong fossil site consists mainly of shale, siltstone mudstone, siltstone, and sandstone. In the shale, insect fossils co-occur with fish, clam shrimps, and plants. The plant fossils were mainly discovered in siltstone.

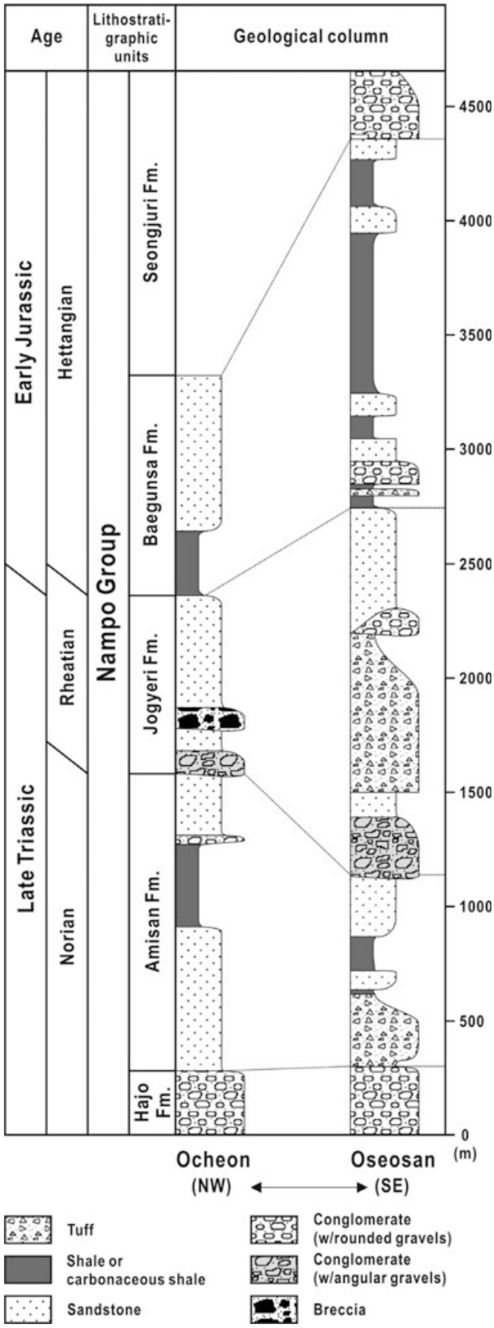


**Fig. 6.36** Schematic stratigraphic columns of the Nampo Group. *Source* From Egawa and Lee (2009) and references therein. *Photo* by Min Huh

**Fig. 6.37** Outcrop view of the Myogok Formation at the Bonghwa fossil site. *Photo* by Min Huh

### *6.3.2 Bonghwa Fossil Site*

The Bonghwa fossil site is located at Sangri, Jaesan District of Bonghwa County in North Gyeongsang Province, southeastern Korean Peninsula (Fig. 6.37). The basinfill of the Bonghwa Fossil site is the Myogok Formation, which was deposited earlier than the Gyeongsang Supergroup. The Myogok Formation is the oldest Cretaceous deposit in the Korean Peninsula. Mollusc, plant, spore, and pollen fossils occur in this formation (Chun et al. 1991). The formation is distributed in a very small area in Bonghwa County. Yang (1976, 1984) suggested that the Myogok Formation is Upper Jurassic, based on the similarity of Jurassic freshwater mollusc fauna. On the other hand, Yi and Chun (1993) discovered the palynomorph genus *Cicatricosiporites*, suggestive of Late Berriasian-Valanginian. Detrital zircon U-Pb geochronology on the Myogok Formation revealed its maximum depositional age as 138 Ma (Hauterivian; Lee et al. 2015). The Myogok Formation consists mainly of gray to black mudstone-shale and gray coarse sandstone, deposited in the point bar of a meandering river which ran from north to south (Chun et al. 1991).

### *6.3.3 Hampyeong Fossil Site*

The Hampyeong fossil site is in the Hakgyo District of Hampyeong County in South Jeolla Province. Despite the fact that the basinfill of the Hampyeong fossil

**Fig. 6.38** Outcrop view of the Hakgyo District section of the Hampyeong Basin. *Photo* by Min Huh

site has not been named, it belongs to the Hampyeong Basin, a small Cretaceous basin distributed along the Okcheon folded belt. The basinfill is approximately 500 m thick and consists of conglomerate, sandstone, mudstone, tuff, and intrusive volcanic rocks (Figs. 6.38 and 6.39; Hong et al. 2007; You et al. 2000). The Hampyeong Basin sediment was deposited in a fluvio-lacustrine environment during the Aptian-Albian Period (You et al. 2000). The main fossil sites of the Hampyeong Basin are distributed in Hakgyo District, in a small town in Hampyeong County, and has yielded ostracods, insects, gastropods and plants (Fig. 6.40; Huh and Chung 2009; Jugdernamjil 2009).

### *6.3.4 Jinju Jeongchon Fossil Site*

The Jeongchon fossil site (Figs. 6.41 and 6.42) is located in Jeongchon District, Jinju City, South Gyeongsang Province, and belongs to the upper part of the Lower Cretaceous Jinju Formation. It is a famous outcrop because various fossils were

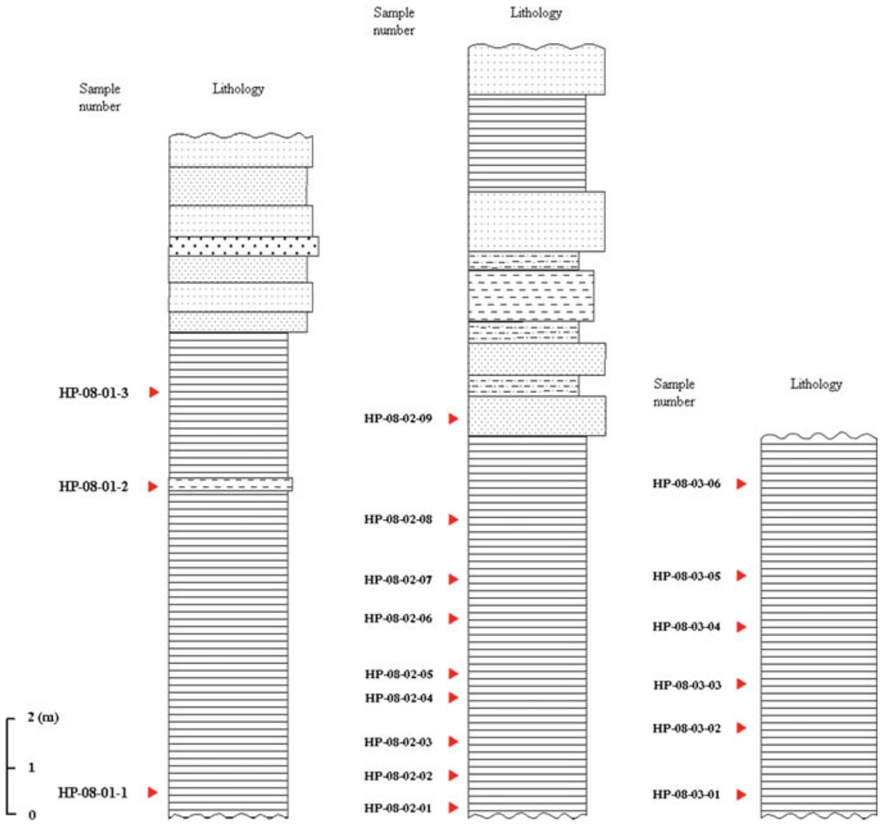


**Fig. 6.39** Measured stratigraphic columnar sections of the Hampyeong Basin. *Notes* Arrows indicate ostracod layers. *Source* Modified from Jugdernamjil (2009). *Photo* by Min Huh

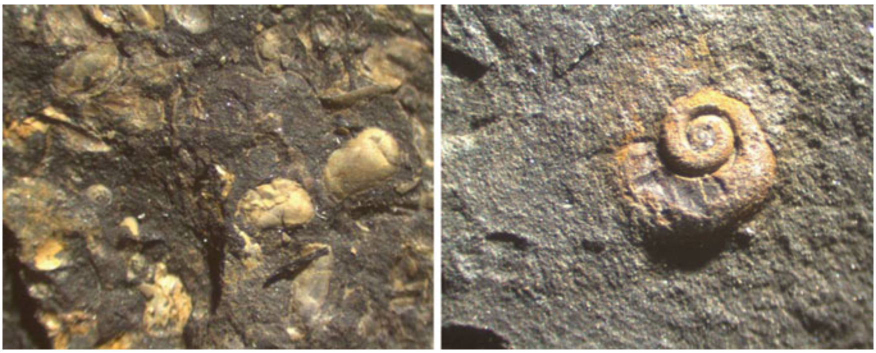

**Fig. 6.40** Ostracods and gastropod in mudstone of the Hampyeong Basin. *Photo* by Min Huh

**Fig. 6.41** Outcrop view of the Jinju Formation at the Jeongchon section of Jinju City. *Photo* by Min Huh

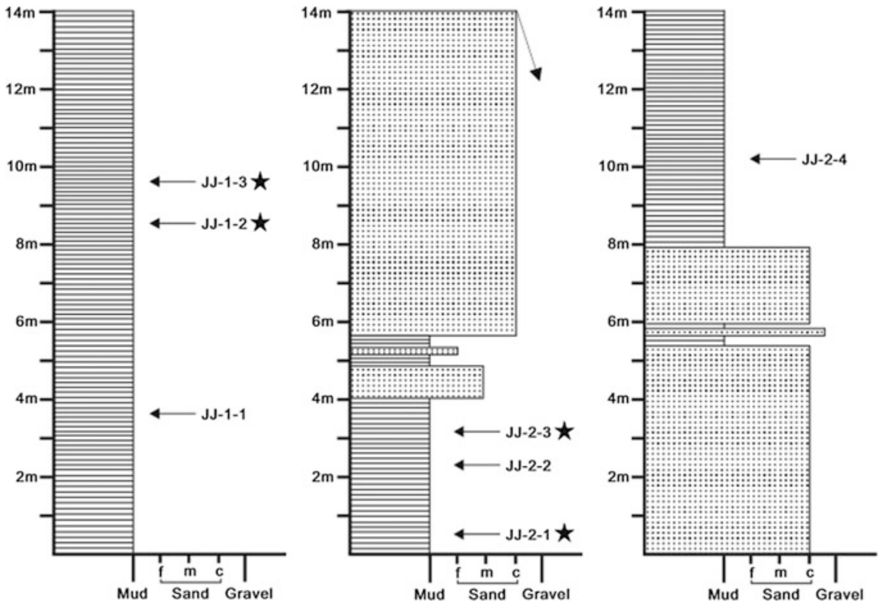


**Fig. 6.42** Columnar sections and ostracod-bearing horizons of the Jinju Formation at Jeongchon area (the Jinju Formation). *Source* From Choi and Huh (2016). *Photo* by Min Huh

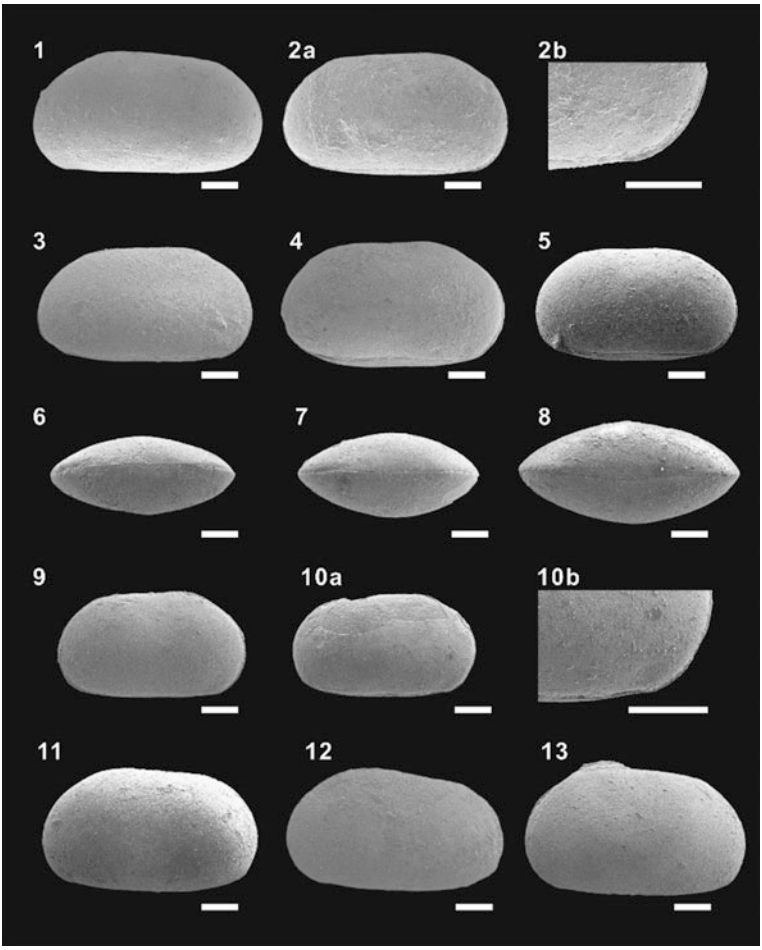


**Fig. 6.43** Ostracod *Mongolocypris kohi* sp. nov. at the Jinju Formation, Jeongchon area. *Note* Scale bars = 200 µm. *Source* From Choi and Huh (2016). *Photo* by Min Huh

discovered over a large area. This site was revealed by industrial complex construction, and most of the area has been destroyed. However, it still yields various fossils such as fish (ganoid fish and *Wakinoichthys aoii*), clam shrimp, ostracods, isopods, plants, and trace fossils. A beetle species, *Coptoclava* sp., was also found at the site, which was suggested as an important taxon for understanding the Jehol Biota in China (Park et al. 2013). Choi and Huh (2016) described a new ostracod species, *Mongolocypris kohi* sp. nov., which is supposed to be an ancient form of the genus *Mongolocypris* (Fig. 6.43).

The Jinju Formation is in the upper part of the Lower Cretaceous Sindong Group in the Gyeongsang Supergroup, which has been considered as pre-Aptian sediment deposited in a fluvio-lacustrine environment (Choi 1985; Choi and Park 1987;

Yi et al. 1994). Yi et al. (1993) proposed that the age of the formation was Aptian to early Albian. Lee et al. (2010) concluded the maximum depositional age of the Jinju Formation as 106 Ma (Albian), based on the youngest detrital zircon U-Pb age of the Jinju Formation.

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# Chapter 7
# Summary and Prospects

## 7.1 Summary of Researchers on the Cretaceous Vertebrates in Korea

Since the late 1960s, many studies have been carried out on Korea's stratigraphy, sedimentology, and paleontology, for the better understanding of the Cretaceous environment and paleoecology. Those studies related to stratigraphy include Chang (1975, 1977, 1978, 1988, 2002), Chang and Park (2008), Chang et al. (1990, 2003), and Chough and Sohn (2010). Choi (1985a, 1985b, 1986), Chun (1990), Chun and Chough (1995), and Paik et al. (2012) researched the sedimentology of Korea, and Yang (1975, 1976, 1978, 1979), and Choi (1985a, b, 1987) undertook research into Korea's paleontology. In 1969, the first named bird track, *Koreanaornis hamanensis*, was reported at the Haman Formation (Kim 1969). Dinosaur skeletons have been sporadically described from the Cretaceous of Korea (e.g., Chang et al. 1982; Kim 1983, 1993; Kim et al. 2005; Huh et al. 2010; Lee et al. 2011). The first record of dinosaur tracks was described at the Jindong Formation of the Goseong tracksite in 1982 (Yang 1982). In 1997, the First International Dinosaur Symposium for the Uhangri Dinosaur Center and Theme Park was held in Korea. The Gyeongnam Goseong Dinosaur International Symposium and the Gyeongnam Goseong Dinosaur World Expo were held in 2006, 2009, 2012, and 2016. Over 1.5 million tourists visited the 2016 Gyeongnam Goseong Dinosaur World Expo.

Two remarkable discoveries of new dinosaurs took place in 2010–2011: *Koreanosaurus boseongensis* and *Koreaceratops hwaseongensis*. *K. boseongensis* is a new basal ornithopod dinosaur described at the Upper Cretaceous of the Boseong dinosaur egg site (Huh et al. 2010); is the first ceratopsian dinosaur, *K. hwaseongensis*, described at the Lower Cretaceous of Hwaseong County (Lee et al. 2011). In 2012, the Eleventh Symposium on Mesozoic Terrestrial Ecosystems (MTE) was held in Gwangju, Korea. In addition, a special volume of the journal *Ichnos* entitled "Tracking on the Korea Cretaceous Dinosaur Coast: 40 years of Vertebrate Ichnology in Korea" (2012) was published.



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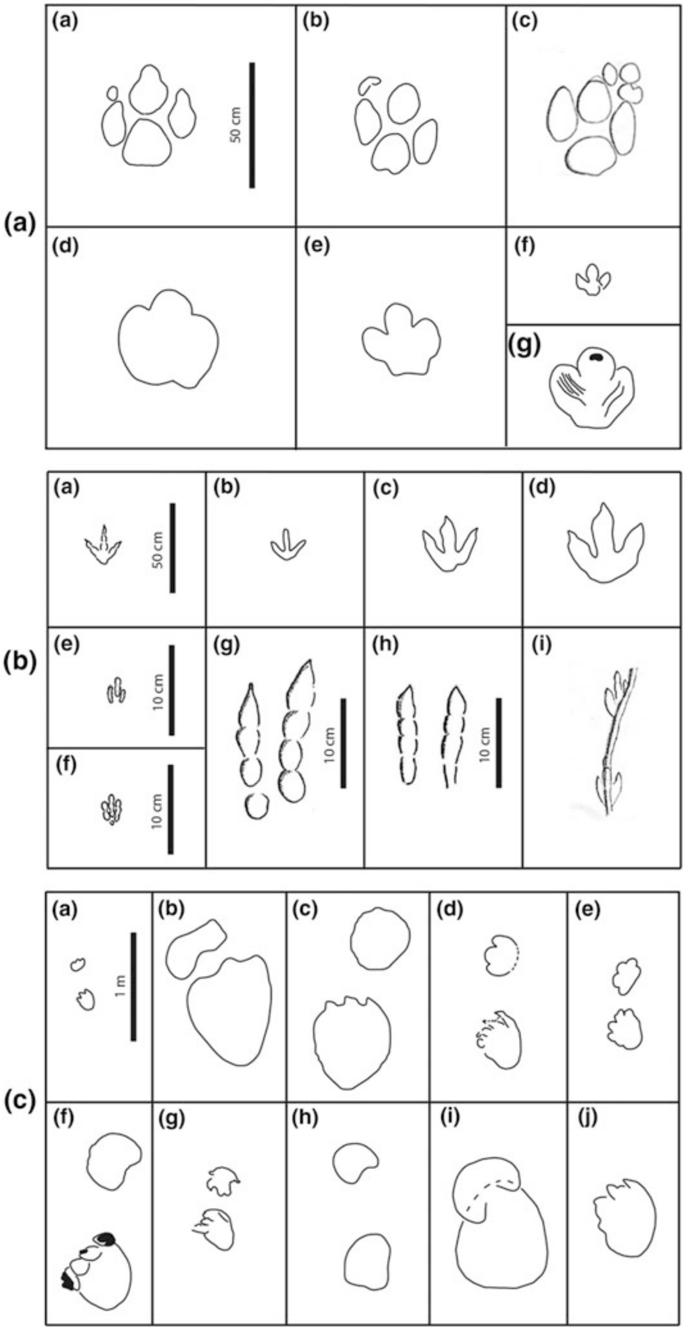
**Table 7.1** The number of vertebrate tracks and trackways in the Cretaceous basins of Korea

| Basin | Bird tracks/ trackways | Pterosaur tracks/ trackways | Sauropod tracks/ trackways | Ornithopod tracks/ trackways | Theropod tracks/ trackways | Dinosaur tracks/ trackways |
|---|---|---|---|---|---|---|
| Gyeongsang | 5017/124 | 2851/51 | 2619/295 | 3836/502 | 670/106 | 11,872/ 1058 |
| Haenam | 1000/1 | 443/6 | 138/9 | 300/7 | 6/1 | 528/200 |
| Neungju | – | – | 61/3 | 330/7 | 909/68 | 1500/78 |
| Yeongdong | 2/– | – | 47/7 | 11/2 | 7/1 | 65/10 |
| Gueokpo | – | – | 57/6 | – | – | 57/6 |
| Gunsan | – | 26/– | – | 184/11 | 72/9 | 256/20 |
| Total | 6019/125 | 3320/57 | 2922/320 | 4661/529 | 1664/185 | 14,278/ 1372 |

*Source* Kim and Kim (2016)

◂**Fig. 7.1** Examples of well-preserved dinosaur tracks from the Cretaceous Period in Korea. *Notes* (A) Ornithopod tracks: **a** left manus-pes set of ornithopod track, *Caririchnium* at the Uhangri Formation, Haenam (Huh et al. 1997); **b** left manus-pes set of ornithopod track, *Caririchnium kyoungsookimi* at the Jindong Formation, Goseong (Lim et al. 2012); **c** left manus-pes set of ornithopod track, *Caririchnium yeongdongensis* at the Saniri Formation, Yeongdong (Kim et al. 2016a, b); **d** left pes track, *Ornithopodichnus masanensis* at the Jindong Formation, Masan (Kim et al. 2009); **e** ornithopod track at the Jindong Formation, Goseong (Lim et al. 1989; Lockley et al. 2006); **f** left pes track, *Ornithopodichnus* at the Jangdong Tuff, Hwasun (Lockley et al. 2012b); **g** left pes track (cf. *Caririchnium*) with ungual impressions (black) at the Jindong Formation, Goseong (Lockley et al. 2006). (B) Theropod tracks: **a** theropod track at the Jindong Formation, Goseong (Lockley et al. 2006); **b–d** theropod tracks at the Jangdong Tuff, Hwasun (Huh et al. 2006); **e–f** theropod tracks, *Minisauropus* at the Haman Formation, Namhae (Lockley et al. 2008a; Kim et al. 2012e); **g** didactyl theropod track, *Dromaeosauripus hamanensis* at the Haman Formation, Namhae (Kim et al. 2008a, 2008b); **h** didactyl of theropod track, *Dromaeosauripus jinjuensis* at the Jinju Formation, Namhae (Kim et al. 2012d); **i** theropod trackway with tail trace at the Saniri Formation, Yeongdong (Kim et al. 2016a, b). Images a–d, and i are to the same scale. (C) Sauropod tracks: **a** left manus-pes set of small sauropod tracks at the Jindong Formation, Goseong (Lim et al. 1989, 1994); **b** left manus-pes set of sauropod tracks at the Uhangri Formation, Haenam (Huh et al. 1997); **c** left manus-pes set of sauropod tracks, *Brontopodus birdi* at the Haman Formation, Namhae (Kim et al. 2012b); **d–e** left manus-pes set of sauropod tracks, *Brontopodus pentadactylus* at the Haman Formation, Jinju (Kim and Lockley 2012); **f** right manus-pes set, which was rotated for comparison with left manus-pes set of other sauropod tracks, of sauropod tracks from the unnamed strata at Yeosu (Lockley et al. 2012c); **g** left manus-pes set of sauropod tracks at the Jindong Formation, Changnyeong (Hwang et al. 2004); **h** left manus-pes set of sauropod tracks, cf. *Brontopodus* at the Jindong Formation, Goseong (Lockley et al. 2006); **i** partly overprinted left manus-pes set of sauropod tracks at the Jindong Formation, Goseong (Lockley et al. 2006); **j** pes-only sauropod track, which was interpreted to have probably overprinted a manus track, at the Jangdong Tuff, Yeosu (Lockley et al. 2012c)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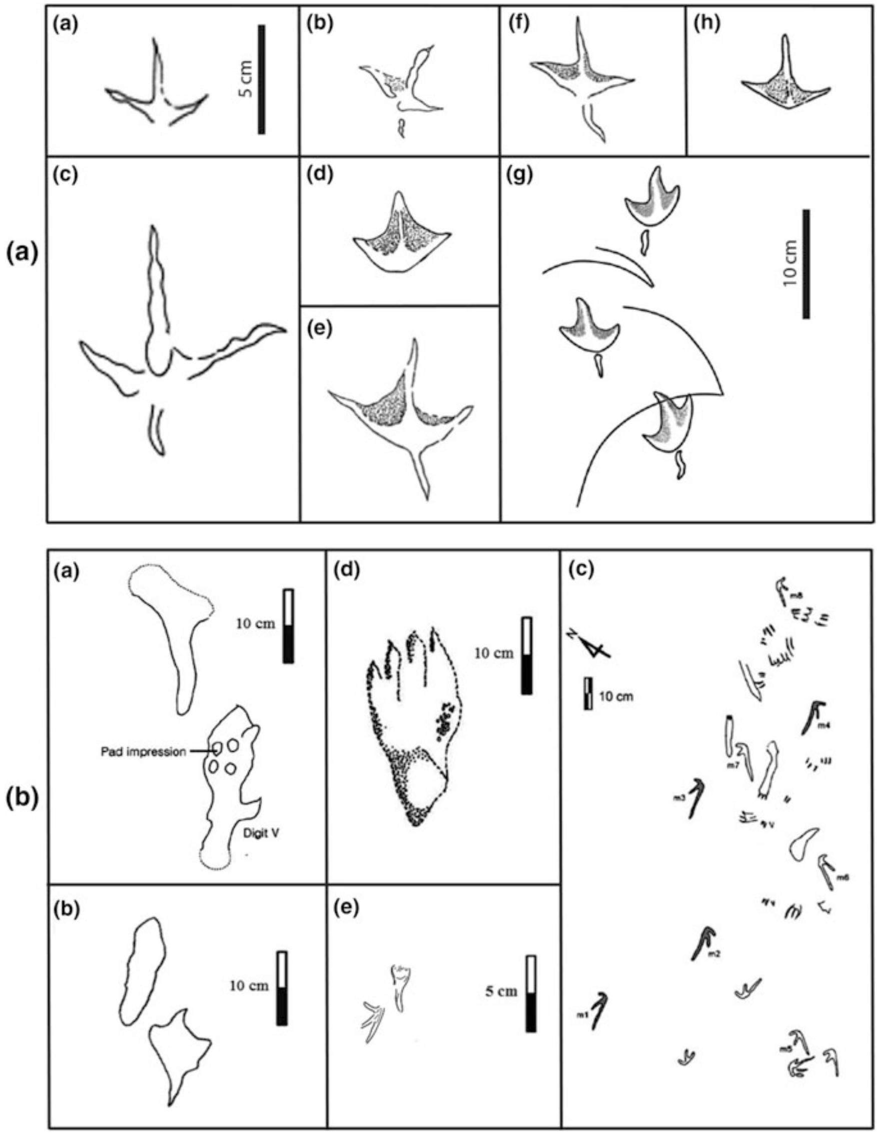
◀**Fig. 7.2** Bird and pterosaur tracks from the Cretaceous Period in Korea. *Notes* (A) Bird tracks: **a** left track of *Koreanaornis hamanensis* at the Haman Formation, Haman (Kim 1969); **b** left track of *Goseongornipes markjonesi* at the Jindong Formation, Goseong (Lockley et al. 2006); **c** left track of *Jindongornipes kimi* at the Jindong Formation, Goseong (Lockley et al. 1992); **d** *Uhangrichnus chuni* at the Uhangri Formation, Haenam (Yang et al. 1995); **e** left track of *Hwangsanipes choughi* at the Uhangri Formation, Haenam (Yang et al. 1995); **f** left track of *Ignotornis yangi* at the Haman Formation, Namhae (Kim et al. 2006); **g** *Ignotornis gajinensis* trackway with arcuate double grooves at the Haman Formation, Jinju (Kim et al. 2012c); **h** left track of *Gyeongsangornipes lockleyi* at the Jindong Formation, Goseong (Kim et al. 2013a, b). Images a–e are to the same scale. (B) Pterosaur tracks: **a**–**b** right manus-pes set of *Haenamichnus uhangriensis* at the Uhangri Formation, Haenam (Lockley et al. 1997; Hwang et al. 2002); **c** swimming traces of *Pteraichnus* ichnosp. at the Haman Formation, Namhae (Kim et al. 2006); **d** pes only track of *Haenamichnus gainensis* at the Haman Formation, Namhae (Kim et al. 2012b); **e** left manus-pes set of *Pteraichnus koreanensis* at the Hasandong Formation, Hadong (Lee et al. 2008a, b, c)

The history of research into the Cretaceous vertebrates in Korea may be divided into four developmental stages: Dawn (1969–1981), Growth (1982–1996), Take-off (1997–2011), and Settlement (2012–). Since the reporting of *K. hamanensis* in 1969, approximately 150 scientific papers concerning Cretaceous vertebrates have been published. In particular, research papers have rapidly increased in number since the Take-off stage (1997–2011).

Between 1969 and 2015, a total of 6019 tracks including 125 bird trackways, 3320 tracks including 57 pterosaur trackways, and 14,278 tracks including 1372 dinosaur trackways have been reported from the Cretaceous formation in Korea (Kim and Kim 2016; Table 7.1). Of the dinosaur tracks and trackways, ornithopod tracks and trackways predominate; theropod tracks and trackways are relatively uncommon. However, theropod tracks and trackways are unusually predominant at the Hwasun site in the Neungju Basin (Table 7.1).

In the Gyeongsang Basin, the largest Cretaceous basin in the Korean Peninsula, diverse vertebrate tracks have been those most abundantly reported at the Goseong, Namhae, Sacheon, Jinju, Haman, Hadong, and Yeosu track sites. The second most diverse and abundant vertebrate tracks have been reported at the Uhangri Formation at the Haenam track site (see Table 7.1).

Figures 7.1 and 7.2 shows diverse tracks of dinosaurs, birds, and pterosaurs described from the Cretaceous Period in Korea. As shown in Fig. 7.1, significant discoveries of sauropod tracks found in Korea include *Brontopodus birdi*, the first recorded in Asia (Kim et al. 2012b), and *Brontopodus pentadactylus*, a new *Brontopodus* track with a pentadactyl manus trace (Kim and Lockley 2012). Theropod tracks include *Minisauripus*, the smallest theropod track (only about 10 mm in length) (Lockley et al. 2008a; Kim et al. 2012e); new raptor tracks showing only two digits, *Dromaeosauripus hamanensis* (Kim et al. 2008a, b) and *Dromaeosauripus jinjuensis* (Kim et al. 2012d); and a theropod trackway with tail trace (Kim and Lockley 2013; Kim et al. 2016a, b). Significant ornithopod tracks discovered in Korea include new quadrupedal tracks, *Caririchnium kyoungsookimi*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(Lim et al. 2012) and *Caririchnium yeongdongensis* (Kim et al. 2016a, b), and a new *Iguanodon* track, *Ornithopodichnus masanensis* (Kim et al. 2009).

Significant Cretaceous bird tracks named in Korea include *K. hamanensis*, the second avian track in the world to be named (Kim 1969); *Jindongornipes kimi* (Lockley et al. 1992); web-footed bird tracks *Uhangrichnus chuni* and *Hwangsanipes choughi* (Yang et al. 1995); *Goseongornipes markjonesi* (Lockley et al. 2006); *Ignotornis yangi*, the oldest web-footed bird track (Kim et al. 2006); *Ignotornis gajinensis*, a web-footed bird track with arcuate double grooves (Kim et al. 2012c); and *Goseongornipes lockleyi* (Kim et al. 2013a, b) (Fig. 7.2). Bird tracks assigned to *Aquatilavipes* at the Gajin and Yeosu track sites (Kim et al. 2012c; Huh et al. 2012) are not shown in Fig. 7.2.

The discoveries of significant pterosaur tracks in Korea include *Haenamichnus uhangriensis*, the youngest pterosaur tracks in Asia (Hwang et al. 2002); *Pteraichnus* ichnosp., swimming traces of pterosaurs (Kim et al. 2006); *Pteraichnus koreanensis* (Lee et al. 2008a, b, c); and *Haenamichnus gainensis*, the largest and the first pes only pterosaur track (Kim et al. 2012b).

Figure 7.3 A shows number of dinosaur, bird, and pterosaur tracks recorded from the Cretaceous basins, and Fig. 7.3b shows a number of sauropod, ornithopod, and theropod tracks reported in the Cretaceous basins in Korea (cf. Table 7.1).

In addition to the abundance of vertebrate tracks, diverse morphotypes of dinosaur, bird, and pterosaur tracks as well as vertebrate eggs, skeletons, and teeth have been reported since 1969. As shown Table 1.3, thirty-four new vertebrate taxa and ichnotaxa have been described in the Cretaceous in Korea. Of these vertebrates, the avian ichnotaxa named in Korea represent one of the most diverse. The bird track site in the Gajin area was dubbed “the paradise of Mesozoic birds” (Kim et al. 2012c). At the Eleventh Symposium on Mesozoic Terrestrial Ecosystems held in 2012, Kim et al. (2012a) presented a paper entitled “A paradise for Mesozoic

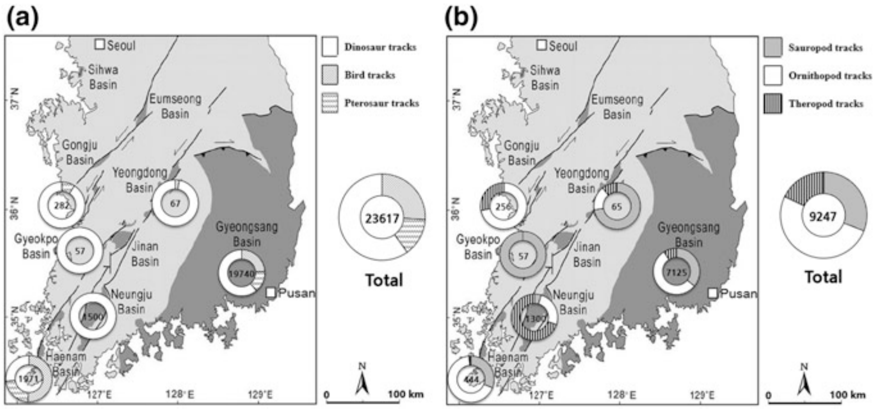


**Fig. 7.3** Census diagram of vertebrate tracks from the Cretaceous Period in Korea. *Notes* The circled numbers in this figure refer to vertebrate track numbers. Map **a** shows the dinosaur, bird, and pterosaur tracks in the Cretaceous basins; Map **b** shows the sauropod, ornithopod, and theropod tracks in the Cretaceous basins. *Source* Kim and Kim (2016)


**Fig. 7.4** Map showing the distribution of vertebrate taxa and ichnotaxa described from the Cretaceous Period in Korea. *Notes* Vertebrate taxa and ichnotaxa named in type locations are shown in bold. ○ = skeletons, eggshells, and teeth of dinosaurs; ● = tracks of dinosaurs; ▲ = tracks of birds; □ = skeletons of pterosaurs or lizards, or carapace of turtle; ■ = tracks of pterosaurs

vertebrates: Diverse, world-class, dinosaur, bird, and pterosaur tracksites from the Cretaceous of Korea."

Table 1.4 also shows that sixteen well-preserved vertebrate fossilsites have been designated as Korean Natural Monuments, the best of which has been nominated for UNESCO's World Heritage status. Korea is one of the richest and most exciting regions on Earth for the study of vertebrate ichnology (Lockley et al. 2012a). Thus, highly diverse and well-preserved vertebrate ichnofossils and body fossils from the Cretaceous in Korea have provided evidence for further understanding of the Mesozoic history of the terrestrial vertebrates that flourished on our planet.

Figure 7.4 shows the geographic distribution of vertebrate taxa and ichnotaxa described from the Cretaceous Period in Korea during 1969–2016. The locations of vertebrate fossils from the Cretaceous Period in Korea are mainly located along the southern coastal areas, except for a few fossil sites such as the Yeongdong, Hwasun, and Haman sites (Fig. 7.4). With regard to the diversity of vertebrate taxa and ichnotaxa previously described, the Namhae, Goseong, Jinju, Haenam, Boseong, and Yeosu fossil sites are of significance (see Fig. 7.4).

Figure 7.5 shows the distribution of the Cretaceous bird and pterosaur ichnotaxa named in eight countries. Eight avian ichnotaxa (*Koreanaornis hamanensis*, *Jindongornipes kimi*, *Hwangsanipes choughi*, *Uhangrichnus chuni*, *Ignotornis yangi*, *I. gajinensis*, *Goseongornipes markjonesi*, and *Gyeongsangornipes lockleyi*) and three pterosaur ichnotaxa (*Haenamichnus uhangriensis*, *H. gainensis*, and *Pteraichnus koreanensis*) have been named and described in Korea's Cretaceous deposits. In other countries, eight avian ichnotaxa have been named and described in China, three avian ichnotaxa in the Cretaceous strata of Canada and Argentina, and three pterosaur ichnotaxa of *Pteraichnus* in the Cretaceous in Spain, though

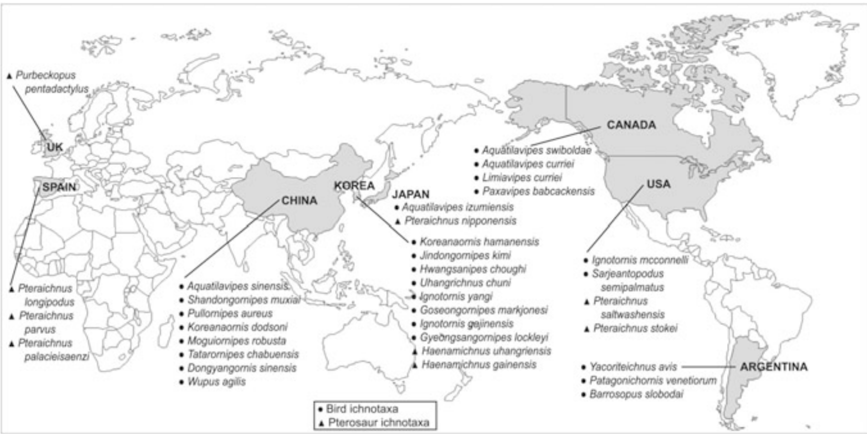


**Fig. 7.5** Map showing the distribution of the Cretaceous Period bird and pterosaur ichnotaxa named in eight coumtries. *Notes* ● = bird ichnotaxa; ▲ = pterosaur ichnotaxa. *Pteraichnus koreanensis* (Lee et al. 2008a, b, c) and several pterosaurian ichnotaxa of Spain are not included here due to their being regarded as invalid (Lockley et al. in press)

several purported ichnospecies of *Pteraichnus* remain to be reassessed for their validity (e.g., Sánchez-Hernández et al. 2009). With regard to the diversity of the Cretaceous avian and pterosaur ichnotaxa, the most diverse and the highest density of bird and pterosaur ichnospecies have been named and described in the Cretaceous in Korea (see Fig. 7.5).

In addition to diverse bird and pterosaur tracks, new dinosaur ichnotaxa have been named in Korea that are highly significant for understanding the locomotor behavior of dinosaurs. These ichnotaxa are *Minisauripus* (the smallest theropod tracks, about 1.0 cm in length, Lockley et al. 2008a; Kim et al. 2012e), *O. masanensis* (new tracks attributable to an *Iguanodon*-like ornithopod, Kim et al. 2009), *D. jinjuensis* and *D. hamanensis* (deinonychosaurid tracks with only two digit impressions, Kim et al. 2009, 2012d), *B. pentadactylus* (a medium-gauge trackway with wide pentadactyl manus tracks, Kim and Lockley 2012), *C. kyoungsookimi* (quadrupedal ornithopod tracks with a small crescentic manus track, Lim et al. 2012), and *C. yeongdongensis* (quadrupedal ornithopod tracks with a manus track composed of three small circular digit impressions placed in front of digits II and III of a quadripartite pes track, Kim et al. 2016a, b). Furthermore, new dinosaurs, *Koreanosaurus* (Huh et al. 2010) and *Koreaceratops* (Lee et al. 2011) recently described in the Cretaceous in Korea are important with regard to the evolution of basal ornithopod and ceratopsian dinosaurs.

## 7.2 Prospects of Researchers on the Cretaceous Vertebrates in Korea

Despite the rapid increase in the number of papers written based on the discovery of highly diverse and well-preserved tracks and body fossils of vertebrates in the Cretaceous in Korea, certain problems remain to be solved in relation to the development of scientific research into Korea's Cretaceous vertebrates.

The taxonomy is basically significant to paleontology as it furthers the understanding of prehistoric life, the relationship between their relatives, and their phylogeny. Like many ichnotaxa of sauropods and pterosaurs which have been regarded as *nomen dubia* (Lockley 1994; Lockley et al. 2008b), some taxa and ichnotaxa of vertebrates described in Korea's Cretaceous have been known to be *nomen dubia* (see Table 1.2). This is probably due to incomplete material, insufficient description, and (or) incorrect identification. Furthermore, over 35% of tracks and over 25% of trackways described in the Cretaceous of Korea have been only assigned to dinosaur tracks and trackways (see Table 7.1).

Thus, surprisingly, about 30% of the total number of dinosaur tracks and trackways have not even been classified into sauropod, ornithopod or theropod tracks and trackways. In addition, certain dinosaur tracks have been arbitrarily classified as the B type, Q type, B1 type, Q2 type, and so on. In fact, many dinosaur tracks have been only described on the basis of the measurement of their length, width, pace, the stride of tracks and trackways, without any systematic description of the detailed morphology and comparison with previously reported ichnotaxa. Therefore, for scientific communication and the development of scientific research, taxonomic or ichnotaxonomic study based on the systematic description of well-preserved trace fossils and body fossils of vertebrates in the Cretaceous in Korea is essential.

Lithostratigraphy, biostratigraphy, and chronostratigraphy provide evidence of change in the paleoenvironment and in paleobiology through geologic time. Since the late 1960s, lithostratigraphical and biostratigraphical research on the Cretaceous Gyeongsang Supergroup has been carried out mainly by Chang, Yang, and Choi. However, chronostratigraphical researches on the Gyeongsang Supergroup have been relatively rare, except for a few studies such as those by Kim et al. (2003, 2008a, b), Kim (2008), Lee et al. (2008a, b, c), and Paik et al. (2012). To date, various geological ages have been proposed for the Cretaceous deposits of the Gyeongsang Basin, the primary differences arising from the methods used. Furthermore, the stratigraphy of the vertebrate fossil-bearing strata in some small Cretaceous basins has not yet been precisely defined. Therefore, systematic study on chronostratigraphy as well as litho- and bio-stratigraphy is necessary to establish stratigraphical correlation for the Cretaceous deposits distributed in several of Korea's Cretaceous basins. The results of such studies would make it possible to correlate the stratigraphy of Korea's Cretaceous with those of other countries.

In addition—except for the southern part of the Gyeongsang Basin, the Haenam Basin, and the Neungju Basin, which reveal diverse trace fossils and body fossils of vertebrates—several small Cretaceous basins have yet to be examined for vertebrate fossils. Recent discoveries of diverse and abundant vertebrate tracks from the Gunsan, Yeongdong, and Kyeogpo areas outside the Gyeongsang Basin suggest there is the potential to discover of new fossil sites in the other small Cretaceous basins in Korea. The discovery of dinosaur tracks in the Cretaceous of Pyeongsan County, and the skeletons of birds (the Korean *Archaeopteryx*) and pterosaurs in the Lower Cretaceous of the Sinuiju area of North Korea also suggest many possibilities for the discovery of significant vertebrate fossils in north Korea in the future.

In some cases, diverse and abundant vertebrate tracks that have already been discovered remain to be studied systematically. For example, diverse and abundant dinosaur tracks have not been systematically studied at the Jeori track site, Uiseong, although the site was designated as Natural Monument No. 373 in 1993. The recently discovered track sites, including the Sanbukdong site of Gunsan area (Choi and Hwang 2013) and the Hotandong site at Jinju, where 545 pterosaur tracks, 642 bird tracks, and 67 theropod tracks were found (Kim et al. 2013a, b), were also designated Korean Natural Monuments. Even so, scientific papers based on the systematic study on these vertebrate tracks have not yet been published.

Compared with well-preserved and diverse dinosaur, bird, and pterosaur tracks, skeletal remains of vertebrates have rarely been reported in Korea's Cretaceous. However, exceptional examples are remarkably well-preserved, and new dinosaurs have been discovered: *K. boseongensis* at the Upper Cretaceous of Boseong area (Huh et al. 2010) and *K. hwaseongensis* at the Lower Cretaceous of Hwaseong area

(Lee et al. 2011). It is noteworthy that a new lizard was recently described as *Asprosaurs bibongriensis* in the Cretaceous of Boseong site (Park et al. 2015). These reports show the potential for discovery of new vertebrates in Korea's Cretaceous.

A new example of an interesting discovery is small scale scrapes with a *Minisauripus*-like track described in the Cretaceous Haman Formation, Jinju area (Kim et al. 2016a, b). The scrapes were interpreted as evidence of display behavior, and suggested that the track maker (possibly *Minisauripus*) was an adult engaged in avian-like courtship behavior. The scrapes are the first to be interpreted as evidence of display behavior in such a diminutive species (Kim et al. 2016a, b, Fig. 7.6). The large paired or bilobed scrapes in the Cretaceous were recently named *Ostendichnus bilobtus* and interpreted as display behavior (Lockley et al. 2016). Other interesting new discoveries are new quadrupedal ornithopod tracks named *C. yeongdongensis*, associated with a theropod trackway showing tail traces, described in Yeongdong, in the central part of Korea (Kim et al. 2016a, b); turtle tracks assigned to *Chelonipes* described in the Jinju Formation (Kim and Lockley 2016); and a hopping mammaliform trackway described as *Koreasaltipes jinjuensis* at the Jinju Formation (Kim et al. 2017).

Further development of study on the Cretaceous vertebrates in Korea can hopefully be anticipated. Young vertebrate paleontologists who wish to carry out active research in the field and laboratory may receive financial support for their endeavors from the Korea Research Foundation and the Korean Science and

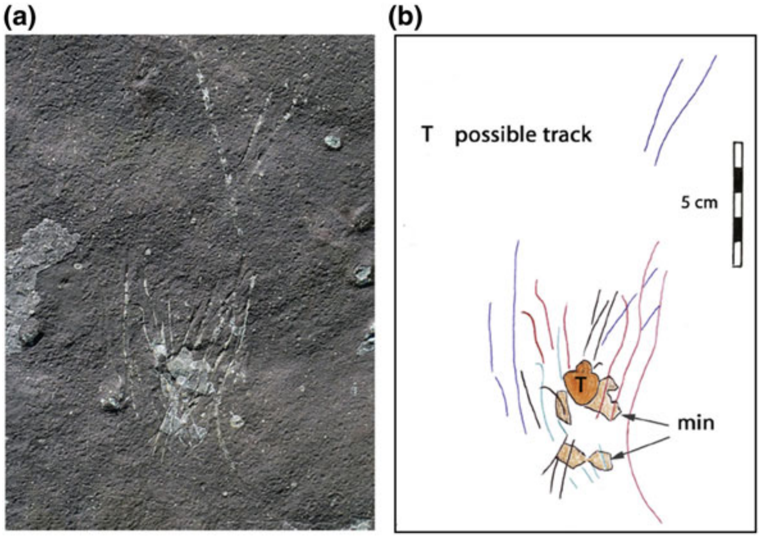


**Fig. 7.6** Photograph and drawing of scratch marks (possibly made by a *Minisauripus*). *Notes* **a** Photograph of scratch marks. Note mineralized veneer on part of surface and in some scratches. **b** Drawing of scratch marks showing bilobed pattern, and central area with possible track. *Source* Kim et al. (2016a, b)

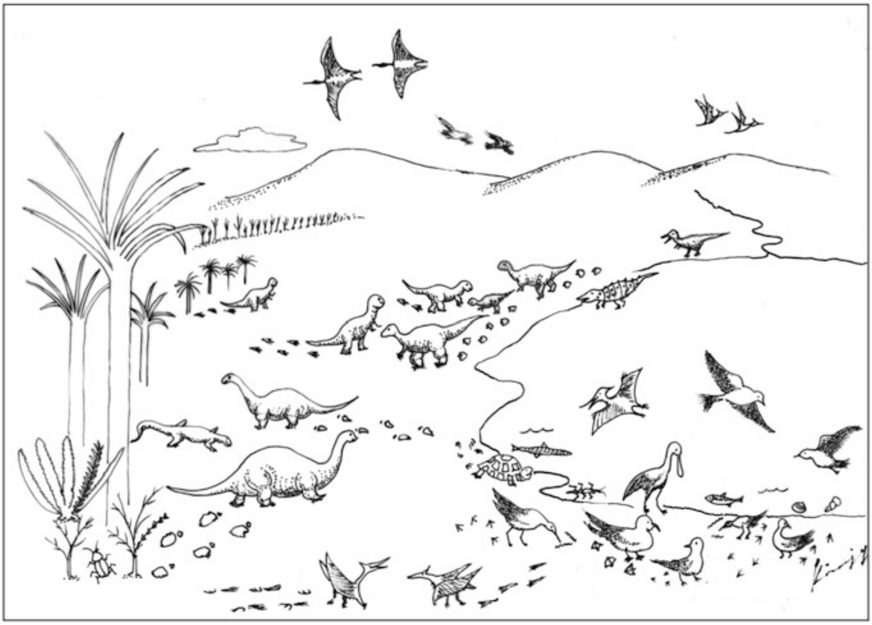

**Fig. 7.7** Reconstruction of the Cretaceous Paradise based on diverse fossils from the Cretaceous of Korea. Artwork by Jeong Yul Kim in 2016

Engineering Foundation. Also, opportunities to join a team engaged in international research may arise.

Finally, we anticipate that the many visitors from around the world that attend the Gyeongnam Goseong Dinosaur World Expo, held every three years at Korea's world famous Goseong dinosaur track site, and the 2024 International Geological Congress, which will be held in Korea, will have an unforgettable opportunity to experience Korea's Cretaceous Paradise and its remarkable vertebrate fossils (Fig. 7.7), and will attain a greater understanding of the history of Mesozoic life on Earth introduced in this book.

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# Appendix 1



J. Y. Kim and M. Huh, *Dinosaurs, Birds, and Pterosaurs of Korea*,
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**Administrative district map showing the locations of vertebrate fossils from the Cretaceous Period in Korea**.

*Notes* Districts: 1: Gyeonggi Province, 2: Gangwon Province, 3: North Chungcheong Province, 4: South Chungcheong Province, 5: North Gyeonsang Province, 6: South Gyeongsang Province, 7: North Jeolla Province, 8: South Jeolla Province, 9: Jeju Province.

Key: ○ = dinosaurs; △ = birds; □ = dinosaurs and pterosaurs; ◇ = dinosaurs and birds; ☆ = dinosaurs, birds, and pterosaurs; ● = dinosaurs and turtles; ▲ = dinosaurs and lizards; ■ = dinosaurs, pterosaurs, and crocodiles; ◆ = dinosaurs, birds, and crocodiles; ★ = dinosaurs, pterosaurs, crocodiles, and amphibians.

# Appendix 2

**Haenam Uhangri Dinosaur Museum**
(http://uhangridinopia.haenam.go.kr)
The Haeman Uhangri Dinosaur Museum, which was opened on April 27, 2007, is composed of the Uhangri Hall, Dinosaur Science Hall, Dinosaur Hall, Mesozoic Era Hall, Marine Reptile Hall, Pterosaur Hall, Hall of Bird Evolution, Gigantic Dinosaur Hall, and Earth Science Hall. The museum provides diverse science education opportunities for visitors.

- **Uhangri Hall |** Visitors can learn about the scientific significance and paleoenvironments of dinosaurs, pterosaurs, and birds discovered at the Uhangri fossil site.
- **Dinosaur Science Hall |** Visitors can learn about the definition, classification, and ecology of dinosaurs.

- **Dinosaur Hall |** Visitors can observe the diverse dinosaurs of the Triassic, Jurassic, and Cretaceous Periods of the Mesozoic Era. In this hall, diverse dinosaurs including *Allosaurus*, *Omeisaurus*, *Tyrannosaurus*, and *Triceratops* are exhibited.
- **Mesozoic Era Hall |** Visitors can observe a robotic model of *Tyrannosaurus* attacking *Edmontosaurus*, *Deinonychus*, and *Malawisaurus*.



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- **Marine Reptile Hall |** Visitors can observe marine reptiles that were rulers of the water in the dinosaur age, including *Tylosaurus*, *Elasmosaurus*, *Pliosaurus*, and *Nothosaurus*.
- **Pterosaur Hall |** Visitors can observe diverse pterosaurs that were the rulers of the sky in the dinosaur age, including *Quetzalcoatlus*, the largest known pterosaur, with a wingspan of 12 m.
- **Gigantic Dinosaur Hall |** Visitors can observe gigantic herbivorous dinosaurs, including *Jobaria*.

- **Hall of Bird Evolution |** Visitors can observe diverse birds including *Archaeopteryx*, the first bird fossil, feathered dinosaurs, and modern birds.
- **Earth Science Hall |** Visitors can learn about Earth science including the origin of the Earth, rock cycles, the geology of the Haenam area, plate tectonics, and the geology of Korea.

**Goseong Dinosaur Museum**
(http://museum.goseong.go.kr)
The Goseong Dinosaur Museum is the first of its kind in Korea to be constructed in the image of a dinosaur's body. It is located within the perimeter of the Sangjokam County Park. It has one underground floor and three floors above the ground in an aggregate area of 1324 $m^2$. It has a total of 93 items on exhibition, including dinosaur fossils. In the museum square, the tallest dinosaur tower in the world, 24 m high, stands with an observation platform on its top floor. The Goseong Dinosaur Museum has emerged as one of the most celebrated destinations sought by international tourists.

- **The Main Hall |** Two Asian dinosaurs, *Klamelisaurus* and *Monolophosaurus*, are shown fighting in the main hall. *Klamelisaurus* is a sauropod dinosaur and *Monolophosaurus* is a theropod dinosaur. Both lived during the Jurassic Period and were discovered in the Wucaiwan layer in inland China. Three pterosaurs

(*Dsungaripterus*, *Quetzalcoatlus*, and *Pteranodon*) are hanging from the ceiling in the main hall.

- **The First Exhibit (Capital of Dinosaurs) |** In this exhibit, we can see various Cretaceous dinosaurs, such as the *Tyrannosaurus*, *Bactrosaurus*, *Velociraptor*, *Tuojiangosaurus*, and *lguanodon*. The exhibit gives us the opportunity to see dinosaur skeletons and to expand our horizons. From looking at their characteristics, we can explore the world of dinosaurs.
- **The Second Exhibit (Dinosaur Tracks in Goseong) |** Goseong is well-known for dinosaur tracks; more than 5000 dinosaur tracks have been found there. The Second Exhibit introduces us to the dinosaur tracks in Goseong. While doing so, it shows visitors the differences between the tracks left by various dinosaurs. For example, compare the theropod and ornithopod tracks. By doing so, you examine the characteristics of these tracks. Through this exhibit, you will learn the major characteristics of each track based on the investigation of each dinosaur.

- **The Third Exhibit (Cretaceous Park) |** The dioramas in this exhibit show particular dinosaurs and their behaviors in the Cretaceous Period. Here, you will see *Dromaeosaurus* the Hunter, *Pachycephalosaurus* the Fighter, and more. Not only will you learn the anatomy of each dinosaur, you will also learn their distinctive characteristics. In addition, you will learn the ways in which the characteristics of each dinosaur's teeth differ, and about the differences in their behaviors and their activities. Now, enter the world of the dinosaur during the Cretaceous Period!

- **The Fourth Exhibit (Dinoland) |** In Dinoland, you will have the chance to meet dinosaurs in real life!
- **The Fifth Exhibit (Traces of the Past) |** Various fossils are displayed in this exhibit.

**Geological Museum**
(http://museum.kigam.re.kr)
The Korea Institute of Geoscience and Mineral Resources (KIGAM) has collected a large variety of geologic specimens since its birth as the Geological Survey in 1918. On the occasion of the Daejeon Expo '93, an international science exposition, parts of the collections were first made public in a small geological museum. Thereafter, due to the increasing interest of visitors, it became necessary to display the collections, information, and technology acquired by KIGAM more efficiently. For this, a newly built Geological Museum, with an area of 2500 $m^2$, was opened in November 2011. The Museum introduces geoscience to the public by means of films and lectures, and by both oudoor and indoor exhibits of specimens. In addition, attached to the museum is the Sample Repository, which keeps large collections of various specimens and drill cores that are managed by a systematic control system.

- **Main Hall |** The Main Hall is the first space for visitors to view prior to their tour of the exhibition halls. Here, they can see a large globe showing suboceanic topography, and also the skeletons of *Tyrannosaurus* and *Maiasaura*. In addition, fossil skeletons and eggs of other dinosaurs and a pterosaur are exhibited, which is why the hall is often called “Dinosaur Hall”.

**Cretaceous Tyrant *Tyrannosaurus***

The skeleton exhibited is a precise replica of a fossilized *Tyrannosaurus* excavated from the late Cretaceous Hell Creek Formation in South Dakota. This *Tyrannosaurus* has been nicknamed STAN, after the name of its discoverer.

*Maiasaura* was a herbivorous ornithopod dinosaur whose nests, containing eggs, were discovered in Montana, USA.

The other two dinosaurs on display are replicas of skeletons of *Dromaeosaurus*. These are small carnivorous dinosaurs akin to the *Velociraptor* of Mongolia and *Deinonychus* of North America.

***Maiasaura*, falling after an attack by two *Dromaeosaurus***

*Triceratops* is one of the most famous Ceratopsia—horned, plant-eating dinosaurs. It was a giant, being up to 9 m long and 8 tons in weight. It roamed North America together with *Tyrannosaurus* through late Cretaceous times. Characteristically, it had a unique beak and a broad frill.

*Psittacosaurus* was a small primitive ceratopsid dinosaur that lived in the interior of Asia, mainly in Mongolia and northern China, during the early Cretaceous, a few tens of millions years before the era of *Triceratops*. It was characterized by a comparatively small body and a skull lacking both horns and a frill, and also by bipedalism (walking on two hind legs).

***Triceratops***

Pterosaurs are divided into two groups—rhamphorhynchoids and pterodactyloids. The former were small primitive pterosaurs living in the Triassic and Jurassic Periods.

*Pteranodon longiceps* belongs to thepteroda-ctyloid group and had the largest skull among the flying reptiles. The largest skull of *Pteranodon* was 1.8 m long, which is longer than its body.

**The ruler of the Mesozoic sky, *Pteranodon***

- **1st Exhibition Hall |** In the 1st Exhibition Hall, the Earth, the home of all living creatures including mankind with living space, is introduced through models and videos explaining its internal structures and the process of continental drift.

The history of the evolution of life is also explained, using fossils both from Korea and from abroad as examples. In addition, the purposes and procedures of geological mapping, the exploration and development of mineral and fuel resources, and hydrogeological surveys are explained. The 1st Exhibition Hall is mainly composed of six themes as follows:

– Fossils and Evolution (including Ammonites)
– Fish and Amphibians
– Mesozoic Marine Reptiles (including Ichthyosaurs)
– Evolution of Birds (including *Archaeopteryx)*
– Triumph of the Mammals
– Evolution of Plants and Forests (including Mesozoic plants).

**The slab of Berlin *Archaeopteryx* specimen**

- **2nd Exhibition Hall |** The 2nd Exhibition Hall is dedicated to the display and classification of rocks comprising the Earth's crust, to building stones, rock textures, and geological structures, meteorites, brilliant and beautifully shaped minerals, gem stones, and fluorescent minerals.
- **Discovery Room |** The Discovery Room is fully equipped with virtual experience facilities using motion-sensing KINECT technology and haptic devices. Visitors can enjoy vivid virtual experiences in paleoecologic exploration, virtual excavation, the dinosaur skeletal puzzle, and the virtual reality of the Earth.
- **Science Room |** The Science Room is a laboratory in which visitors can observe major rocks and minerals with the naked eye and with microscopes. Visitors can obtain geological information about the area in which they are interested, using the virtual geological map of Korea, and also be miners through the virtual mining experience. In addition, thousands of science books are available for visitors in a library.

- **Outdoor Exhibition Garden |** Visitors can observe large specimens of rocks, minerals and fossils, including huge blocks of limestone, gneiss, conglomerate, calcite, petrified wood, concretion, and ammonites.

**Natural Heritage Center of the National Research Institute of Cultural Heritage**
(http://nhc.go.kr)

The Natural Heritage Center is a national research institute that was established with the purpose of informing the public of the value and importance of natural heritage through systematic investigations and research, as well as exhibitions and education regarding natural monuments and scenic landscapes.

Since the designation of the Cypress Forest of Dalseong as Natural Monument No.1 by the Cultural Heritage Administration in December 1962, a total of 455 natural monuments and 109 scenic landscapes have been designated by May 2015. The designations serve to protect these natural heritages to be passed onto our decendants.

The Natural Heritage Center has exhibitions of fossils, including dinosaur eggs and footprints, taxidermied animals, including the Asiatic black bear, otter and eagle, and plant specimens to facilitate researchers and students in their studies. Also, the Experiential Space, Browse Kiosk, Bird Sound Hearing Corner and Video Room provide an opportunity for creative experiential learning that is unique to the Natural Heritage Center.

In addition, it is emerging as a world-class heritage research institute through conducting academic exchange activities with UNESCO, as well as various natural heritage institutes and natural history museums worldwide.

- **Exhibition Hall |** The Main Hall of exhibition displays diverse specimens designated as natural heritages, including geological heritages of Korea. Representative examples of the geological heritages displayed include dinosaur tracks, dinosaur eggs, dinosaur skeletons, Mesozoic plant fossils, and rock samples.

- **Tree Fern Fossils at Geummubong, Waegwan**
  The *Cyathocaulis naktongensis* fossils on Geummubong Peak in Waegwan are located about 4 km to the southeast of Waegwan-eup. *Cyathocaulis naktongensis* was very abundant in this area about 130 million years ago. It is a type of fern brake that has a straight root and undivided branches.
- **Bird Footprints from the Mesozoic Era**
  Bird footprints from the Mesozoic Era are academically quite valuable, as very few have been found throughout the world.
  In Korea, six new types of bird footprints have been found in the strata formed during the Cretaceous Period.
- **Bird Footprint Fossils in Gajinri, Jinju**
  The bird footprint fossils in Gajinri, Jinju, were discovered at the Gyeongnam Science Training Center's new constructon site. The fossils were discovered in the strata from the Cretaceous Period. A total of 365 rocks, including 2500 bird footprints and 80 dinosaur footprints, and the footprints of the world's oldest web-footed bird were also found here.
- **Dinosaurs in Korea**
  In Korea, a piece of a dinosaur's egg was first discovered in 1972 in Hadong, Gyeongnam. This piece proved that dinosaurs had existed on the Korean Peninsula. In 1973, the excavation of skeletal fossils began as a part of the humerus of a sauropod dinosaur (a herbivore with a long neck and small body) was found in Uiseong, Gyeongbuk.
- **A Partial Humerus of a Sauropod Dinosaur**
  It was the first dinosaur bone fossil found in Korea. It was discovered in Tapri, Uiseong County, Gyeongbuk, in 1973. At that time, researchers believed that it was the lower arm bone of a sauropod dinosaur. It was initially named *Ultrasaurus tabriensis* because it was thought to be a part of one of the largest dinosaurs, but it was later found to be part of the the humerus from the left side.
- **Footprints of Ornithopoda Dinosaurs**
  These are the footprints of Ornithopoda dinosaurs found along the coast of Dukmyeongri, Goseong, Gyeongnam. Ornithopoda dinosaurs are herbivores and include *Iguanodon* and *Hadrosaurus*.

– **Dinosaur Eggsite at Gojeongri, Hwaseong** Dinosaur eggs at Gojeongri, Hwaseong, Gyeonggido, were found in small islands discovered during embankment construction at Sihwa Lake. Here, about 300 pieces of three different types of fossilized dinosaur egg and over 30 nests were discovered. The sedimentary strata are generally composed of reddish conglomerate and sandstone, telling us that this place was where dinosaurs used to lay eggs and was located by an upstream river at that time.

- **Open Style Repository |** The newly built repository was designed as a repository open to visitors for scientific research and education. The repository shows well-preserved original specimens (or replicas) mainly of dinosaur, bird, and pterosaur tracks, skeletal remains, eggshells, mollusca and plant fossils, and sedimentary structures.

- **Out Door Exhibition |** Visitors can observe original specimens with dinosaur trackways named *Ornithopodichnus masanensis*. The rock specimen bearing the trackways is about 7 m × 15 m in area, about 50 tons in weight and was rescued from the Jindong Formation, Masan area. The parallel trackways were attributable to the gregarious behavior of *Iguanodon*-likeornitho-pod dinosaurs (Kim et al. 2009).

**Mokpo Natural History Museum**
(http://museum.mokpo.go.kr)
The Mokpo Natural History Museum (MNHM) opened in the middle of an era when interest is prevalent about human beings and the environment, such as ecosystem disturbance, environmental disruption and so on due to global warming. The MNHM is an international museum displaying 4.6 billion-years' natural history of the earth. It houses artifacts of local history and culture. Specifically, it has the preserved species of a rare pregnant marine reptile. The museum is a 9166 $m^2$ two-storey structure. It displays literature in the History Hall depicting local history and culture. A large number, approximately 40,000 artifacts, are exhibited.

- **Main Hall |** Here, you will see an *Allosaurus* attacking a *Diplodocus*, a large herbivorous dinosaur, and the egg thief *Oviraptor* and three *Dromaeosaurus* menacing a *Triceratops*. You can also find *Coelophysis* and *Herrerasaurus*, related to the mysterious origin of the dinosaur kingdom. *Mosasaurus* and *Archelon*, ancient forms of sea turtles, are dynamically realized in life-size.

***Diplodocus carnegiei***
*Diplodocus* grew longer than a tennis court, and its weight was equivalent to that of two large elephants. Most of its length was composed of its slender neck and tail. Its weight was reduced its due to the deep hollows in the spinal bones. Its teeth were arranged at the front of its head, like a comb. The position of its nostril was somewhat strange. There were holes between the eyes, rather than at the end of the snout, like other animals. It dominated the shallow continental sea in the Cretaceous Period in the Mesozoic Era. It could grow more than 15 m long. It could devour *Plesiosaurus* and large fish and turtles with its big, conic teeth and powerful jaw. *Mosasaurus* developed its feet through its streamlined

fins. It could swim by shaking its long, flexible tail left and right, and set its direction by using its fins.

***Mosasaurus***

- **Earth History Hall |** Falling stones, believed to drop from outer space, ores, stones, fossils, and so on are exhibited here, showing the 4.6 billion-year history of the Earth at a glance. Exhibited are the fossils of Ediacara, the first multi-cell living creature, and the fossil of a mammoth, a kind of mammal during the Cenozoic Period. These help people understand the appearance and evolution of living creatures. Furthermore, a beautiful ore crystal consisting of a natural genuine cold crust, an Eonyang Amethystand similar items are also exhibited. There is also a special corner where you can actually touch an *Apatosaurus* thighbone and make a copy of it.

Also available on display is a *Prenoceratops* with a slanting horn, a dinosaur which inspires the scientific imagination of childeren about the history of the Earth.

Visitors will spend time recognizing the value of the Earth's 4.6 billion-year history. Times beyond recall and their meaning through the fossils are evidenced by multi-cell living creatures that were the first to develop on Earth. On display are trilobites and ammonites, depending on the year of extinction and the appearance of life, the great land adventure, the evolution of plants, and the era of mammals starting from the fossil of Ediacara.

The *Confuciusornis* is well-known as a peacock. It is a bird that inhabited the Earth in the early stage of the Cretaceous Period, approximately 120 million years ago. *Confuciusornis* showed the combination of advanced and conventional characteristics. The toes had nails, with a flat sternum, wrist, pelvis and legs which served as a reminder of the deeper *Archaeopteryx* chest. It had coracoid-shaped columns, and a horny beak with no teeth; the tail bone was reduced. These details were the basis of its classification as *Confuciusornis*.

As the marine reptiles during the Mid-Paleozoic period, the *Stenopterygius* is famous for resembling a shark or whale. Specifically, the *Stenopterygius* was found with the bones of a baby whale/shark in its belly. Originally, it was believed that the content of the belly was of the same species and had been eaten by the creature. However, it is now clear that it was pregnant at the time of death. For the baby, it had a tail, which means that it could swim upon delivery.

This dinosaur has pelvis. It has a short, deep beak like a parrot and has slanting horns. This is a rare species in the world. It was found together with three others, but two were perfectly restored and placed in the Indiana Children's Museum in the USA.

- **Land Animals, Hall 1 |** This section is filled with a vivid display of stuffed specimens and bone structures of mammals, birds, reptiles, and amphibians.
- **Land Life, Hall 2 |** This area provides 900,000 species of insects from planet Earth. In particular, there is the the opportunity to view the true beauty of exquisite insects.
- **Marine Life Hall |** This area provides you with the wonderful experience of aquatic life and the environment covering 70% of the Earth, including a marine ecology diorama, a stuffed specimen of a stingray, sharks, the skeletons of minke whales, and rough-toothed dolphins.

**Gwacheon National Science Museum**
(http://sciencecenter.go.kr)

Gwacheon National Science Museum is Korea's largest popular science museum with various science exhibitions, and educational and cultural contents.

- **Basic Science Hall |** The Basic Science Hall is where you can experience the principles of science in daily life. It holds a collection of exhibits of 70 themes spanning five different fields: Mathematics, Physics, Chemistry, Microbiology, and Earth Science. Main exhibits include the "Tesla Coil," which demonstrates the principles of lightning; the "4D Earthquake Experience Room," in which you can experience magnitude 7 earthquakes; the "Polar Experience Room," in which you are able to video chat with researchers at the King Sejong Station in the South Pole; and the "Typhoon Experience Room," in which you are able to learn about the principles of typhoons and their strengths while experiencing typhoons, tornados, wind, and rain.

- **Children's Hall |** Featuring five different themes—dream, nature, energy, "meets science and art"—the Children's Hall is a place dedicated to infants and young children up to 10 years-old. Hands-on exhibits which help you gain an understanding of scientific principles, including "let's create light," which lets you generate electricity by pedaling a bicycle; "performing musician," which lets you flash lights by stepping on the keys; and "splash pump," which let you learn about the role of dams.
- **Advanced Science and Technology Hall |** The Advanced Science and Technology Hall is where you can experience the cutting-edge science and technology driving the future growth engines of South Korea. It holds a collection of 719 exhibits spanning six fields: robotics, life science, information and communication, energy and environment (on Level 1), air and space, and nano technology (on Level 2). The main exhibits include "Brain Waves are a Magician," where you drive a car in a game using your brainwaves; "Robot Performance Hall," where you can watch robots dance brilliantly; "Space Camp," where you can experience what it feels like to undergo training as a space pilot; "ISS" (International Space Station), where you can attempt to dock a spaceship in zero-gravity conditions; and "Cyber Avatar," which leverages on motion capture technology used in filming James Cameron's *Avatar*.

- **Natural History Hall |** In the Natural History Hall, you can see 4.6 billion years of Earth's history at a glance. It holds a collection of 1362 exhibits spanning five fields: the birth of space and the Earth, the geology of the Korean Peninsula, the evolution of life, vibrant Earth, and the ecosystem of the Korean Peninsula. The main exhibits include a fossil of the world's largest palm tree leaf; the oldest fossil in South Korea—a cyanobacteria fossil kept in a one billion year-old stromatolite; Science on a Sphere (SOS), showing the view of the Earth from 20,000 km up in 3D; remains of a baby mammoth excavated in Siberia (nicknamed "TIMA"); and aquariums that reveal the ecosystem of waters of the Korean Peninsula.
- **Korean Traditional Science Hall |** The Korean Traditional Science Hall is where you can experience a variety of traditional scientific techniques that demonstrate Korean ancestors' wisdom and knowledge. It holds a collection of 777 exhibits spanning five themes: sky, earth, people, life, and applied sciences. The Main exhibits include "Jageongru," which is depicted on a ten thousand won bill, "Honchuneui," "Cheonsang Yeolcha Bunyajido," and "Girigocha," which tells the distance by striking the drum of a gong, and "Digital Oriental Medical Experience Equipment" (a pulse wave analyzer, voice-based constitution diagnosis, and tongue health checker). The list also includes Korean-style houses, and a platform for crocks of sauces and condiments, which are some of the fruits of the everyday science of Korean ancestors.
- **Insect Ecology Hall/Ecological Park |** The Insect Ecology Hall is where visitors can experience the living ecosystem of insects. It holds various exhibits spanning 46 themes. It includes terrestrial insects, aquatic insects, spiders, larvae, an insect specimen collection room, and a larva breeding room. A small ecosystem for living insects was created so that visitors can experience the importance of the diversity of biological resources and their preservation.
- **Outside Exhibition Hall/Playground |** The Outside Exhibition Hall is a science theme park featuring six themes: space and aviation, energy, transportation, a history plaza, a knoll of geological features, and a knoll of dinosaurs. The main exhibits include the Delta II rocket, which shot the Mugunghwa artificial satellite into space; the Naro spaceship, which was the first spaceship developed by South Korea; the actual diesel locomotives used in the past; sedimentary layers—a work of art made by magma; and various astronomical observation instruments, such as a sundial from the Silla dynasty. Meanwhile, the knoll of dinosaurs has on display huge life-size dinosaur models, and is immensely popular with visitors bringing their entire family.

**Seodaemun Museum of Natural History**
(http://namu.sdm.go.kr)
The Seodaemun Museum of Natural History is the first museum in Korea to be established not by a school or an individual, but by local government.

The role of the Seodaemun Museum of Natural History is to preserve and research geological and biological facts from the local environment, and to share information with the public. The museum also has a mission to show that humans are a part of nature, and we can live in harmony with nature.

The Seodaemun Museum of Natural History, located in the heart of Seoul, is a place of learning for students, a place of culture for residents, and a place of leisure for families. It aims to provide an opportunity for city dwellers to experience animals and plants, and to help people learn to appreciate and love nature.

- **Earth Environment Hall |** The Earth Environment Hall is composed of eight sections. They are as follows:
  - Birth of the Earth
  - Structure of Earth
  - Plants in the Solar System
  - Dynamic Earth
  - Geological Phenomena
  - Joint and Unconformity Panels
  - Rocks and Minerals
  - Natural History Tour of the Korean Peninsula.


- **Section of Natural History Tour of the Korean Peninsula**
  When was Korea created? Is the Korea of old the same as the new Korea? The Natural History Tour of the Korean Peninsula corner answers these questions. The evolution of Korea is shown through changes in the sea levels through the ages, and the Natural History Tour introduces the top ten geological places to visit in Korea, including Jeju Island. This corner has a exhibit where the local representative rocks can be touched, and videos introduce details of minerals. This corner shows the natural history of Korea, including resource minerals, and fossils.
- **Evolution Hall |** The Evolution Hall is composed of eleven sections. They are as follows:

  – Origin and Birth of Life
  – Paleozoic Era—Start and Evolution of Life


  – World of Mesozoic Dinosaurs
  – Mammal Prospering in Cenozoic Era
  – Marine Mammals
  – Emergence of Mankind
  – Diversity of Terrestrial Animals
  – Varieties of Marine Species
  – Sharks in Korea
  – Living Marine Species
  – Asian elephant.


- **Section of World of Mesozoic Dinosaurs**
  The Mesozoic Era marks the period from 245 million years to 65 million years ago, and ran for approximately 180 million years. The ancient reptiles that appeared in the late Paleozoic Era rapidly developed and experienced explosive growth during the Jurassic Period (213–144 million years ago), when large dinosaurs thrived on land, plesiosaurs in the sea, and avian dinosaurs in the sky. At that time, ammonites, the invertebrate marine lifeforms, thrived; therefore, this period is also called the Reptilian Age of the Dinosaur Age.

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