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A review of vertebrate faunas from the Gyeongsang Supergroup (Cretaceous) in South Korea

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Abstract

The Early Cretaceous is rapidly being recognized as a crucial time in the origin and dispersal of living vertebrate groups. Cretaceous trackways in Korea are among the most abundant in the world and include the smallest sauropod tracks known, plus four avian ichnotaxa, one of which is the earliest record of a bird with webbed feet. Body fossils and egg shells are less well known, however, and have been reported mainly in Korean journals. An increase in the rate of discovery of vertebrate fossils in recent years has resulted in documentation of 38 localities from the entirely fluvio-lacustrine Gyeongsang Supergroup (Hauterivian to Cenomanian) in Korea. Specimens include fish, turtle, crocodilian, pterosaur, and dinosaur bones, and dinosaur eggs in nests, as well as dinosaur, bird, and pterosaur footprints. Scattered bones have been collected in road cuts, quarries, stream beds, and coastal exposures, but localities have yet to be systematically explored and excavated. Nevertheless, very recent finds of articulated fish skeletons and dinosaur egg nests indicate that further exploration may be expected to yield better preserved, more fully associated specimens of these and additional taxa. This would provide further important data for our understanding of this pivotal period in vertebrate evolution.

Keywords: Cretaceous; dinosaur eggs; dinosaur footprints; Gyeongsang Supergroup; Korea; vertebrate fossils

1. Introduction

The Mesozoic beds in South Korea consist of an entirely non-marine, sedimentary succession associated with volcanic activity that increased through time. The Mesozoic section is divided into the Daedong Supergroup (Late Triassic to Middle Jurassic), the Myogog Formation (Late Jurassic or Early Cretaceous), and the Gyeongsang Supergroup (Cretaceous) in ascending order. A depositional hiatus (at least in most areas) between Daedong and Myogog or Gyeongsang strata resulted from the Daebo Orogeny of the Late Jurassic time. The Daedong Supergroup occurs today as small patches mainly in the central part of South Korea, including the Mungyeong and Chungnam basins best known (since 1931) for coal deposits. Although extensive paleontological studies have been conducted (mainly on invertebrates and plants), fossil vertebrates are unknown so far from the Myogog Formation and the Daedong Supergroup, except for unstudied fish from the Amisan Formation, Boryeong, South Chungcheong Province (Lee, 1987).

On the other hand, abundant vertebrate faunas

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Table 1
Systematic list of vertebrate taxa from the Gyeongsang Supergroup

Vertebrate taxa	Occurrence	Material
Class Osteichthyes		
Order indet.	Hasandong Fm.	scattered scales
	Yusuri, Jinju	
Order Elopiformes	Jinju Fm.	17 complete skeletons
Suborder Albuloidei	Nahori, Guwi	
an unnamed new family		
Order Osteoglossiformes	Jinju Fm.	skeletons
Suborder Wakinoichthiidae	Doggogri, Dalseong	
Wakinoichthys		
Order Ichthyodectiformes		
chuingichthiid		
Order Semionotiformes	Jinju Fm.	skeletons and scales
Suborder Lepidotidae	Hotan-dong, Jinju	
Lepidotus		
Class Reptilia		
Order Chelonia	Geoncheonri Fm.	parts of carapace
Suborder Cryptodira		
macrobaenid	Gyeongsan	
Family indet.	Hasandong Fm.	isolated parts of carapace
	Yusuri, Jinju	
Order Crocodylia	Hasandong Fm.	a tooth
Suborder indet.	Yusuri, Jinju	
Superorder Dinosauria		
Order Saurischia		
Suborder Theropoda		
Infraorder indet.	Hasandong Fm.	two teeth and a claw
	Yusuri, Jinju	
	Hasandong Fm.	a tooth
	Dapyeongri, Sacheon	
	Hasandong Fm.	a tooth
	Sumunri, Hadong	
Suborder Sauropodomorpha		
Infraorder Sauropoda		
Family Euhelopodidae	Hasandong Fm.	a tooth
Chiayusaurus asianensis	Yusuri, Jinju	
Family Titanosauridae(?)	Hasandong Fm.	a tooth
Gen. et sp. indet.	Yusuri, Jinju	
Family Camarasauridae(?)	Hasandong Fm.	a tooth
Gen. et sp. indet.	Yusuri, Jinju	
Infraorder indet.	Hasandong Fm.	a scapular and coracoid(?)
	Doweonri, Euiseong	
	Gugyedong Fm.	a proximal end of humerus
	Tabri, Euiseong	

Vertebrate ichnotaxa	Occurrence	Material
Class Reptilia		
Order Pterosauria		
Suborder Pterodactyloidea		
an unnamed Ichnofamily	Uhangri Fm.	
	Uhangri, Haenam	400 manus and pes tracks
Superorder Dinosauria		
Order Saurischia		
Suborder Theropoda		
Ichnofamily indet.	Hasandong Fm.	
	Yusuri, Jinju	6 tracks (a trackway)
	Gawhari, Sacheon	
	Jinju Fm.	
	Geomjeongri, Sacheon	5 tracks
	Jindong Fm.	
	Dukmyeongri, Goseong	16 trackways
	Donghae-myeon, Goseong	3 trackways
	Haman Fm.	
	Gainri, Namhae	
	Gajinri, Jinju	3 tracks
	Geoncheonri Fm.	
	Cheonchonri, Gyeongju	4 trackways
	Geomunri, Changryeong	
	Sagog Fm.	
	Jaeori, Euiseong	
	Mancheonri, Euiseong	1 trackway
	Jeomgog Fm.	
	Guamri, Jeomgog	34 tracks (13 trackways)
	Uhangri Fm.	
	Uhangri, Haenam	
Suborder Sauropodomorpha		
Infraorder Sauropoda		
Ichnofamily indet.	Hasandong Fm.	
	Gawhari, Sacheon	1 trackway
	Jindong Fm.	
	Dukmyeongri, Goseong	120 trackways
	Donghae-myeon, Goseong	38 trackways
	Haman Fm.	
	Gainri, Namhae	
	Yongsanri, Haman	1 trackway
	Sagog Fm.	
	Jaeori, Euiseong	
	Mancheonri, Euiseong	1 trackway
	Uhangri Fm.	
	Uhangri, Haenam	105 manus-only tracks

	Nagdong Fm.	part of a femur
	Noyangri, Habcheon	
Order Ornithischia		
Suborder Ornithopoda	Hasandong Fm.	six eggs
Infraorder indet.	Sumunri, Hadong	
Order indet.	Hasandong Fm.	an elongate planar bone
	Hwajeonri, Euiseong	
	Hasandong Fm.	part of a scapular blade
	Yusuri, Jinju	a proximal end of limb bone
		skull elements(?)
		a complete humerus
	Hasandong Fm.	a rib
	Dapyeongri, Sacheon	part of a limb bone
	Hasandong Fm.	part of a vertebra
	Sumunri, Hadong	
	Nagdong Fm.	a rib
	Noyangri, Habcheon	
	Jinju Fm.	part of a limb bone
	Nahori, Guwi	
	Gugyedong Fm.	a complete femur
	Tabri, Euiseong	part of a vertebra
	Gyeongsang Supergroup	300 eggs and 30 nests
	Siwha Bay, Whasung	
	Gyeongsang Supergroup	120 eggs and 10 nests
	Beokryang Bay, Boseong	

Order Ornithischia			
Suborder Ornithopoda			
Ichnofamily indet.	Hasandong Fm.		
	Yusuri, Jinju	30 undertracks	
	Gawhari, Sacheon	over 100 tracks	
	Jinju Fm.		
	Geomjeongri, Sacheon	6 trackways	
	Gupori, Sacheon	11 tracks	
	Jindong Fm.		
	Dukmyeongri, Goseong	252 trackways	
	Donghae-myeon, Goseong	91 trackways	
	Gohyunri, Masan		
	Haman Fm.		
	Gainri, Namhae		
	Yongsanri, Haman	11 trackways	
	Geoncheonri Fm.		
	Cheonchonri, Gyeongju	2 trackways	
	Geomunri, Changryeong		
	Sagog Fm.		
	Jaeori, Euiseong		
	Mancheonri, Euiseong	4 trackways	
	Uhangri Fm.		
	Uhangri, Haenam		
Class Aves			
Ichnofamily unknown			
Koreanaornis hamanensis	Haman Fm.		
	Chilweon-myeon, Haman		
	Gajinri, Jinju	over 1000 tracks	
	Jindong Fm.		
	Dukmyeongri, Goseong		
	Gohyunri, Masan		
	Naesanri, Goseong		
	Galgotri, Geojae		
Jindongornipes kimi	Haman Fm.		
	Gajinri, Jinju		
	Jindong Fm.		
	Dukmyeongri, Goseong	32 horizons	
	Gohyunri, Masan		
	Naesanri, Goseong		
	Galgotri, Geojae		
Uhangrichnus chuni	Haman Fm.		
	Gajinri, Jinju		
	Uhangri Fm.		
	Uhangri, Haenam	over 1000 tracks	
Hwangsanipes choughi	Uhangri Fm.		
	Uhangri, Haenam	over 50 tracks	

have been reported piecemeal from the Cretaceous Gyeongsang Supergroup (major specimens and localities are listed in Table 1). The first discovery of vertebrate fossils was dinosaur eggshell fragments from the Hasandong Formation in Hadong, South Gyeongsang Province, in 1972 (S.Y. Yang, personal communication). Since then, scattered dinosaur bones and other vertebrate remains including fish, turtles, crocodilians, and pterosaurs have been found in quarries, road cuts, stream beds, and coastal outcrops mostly as a result of individual surveys. Abundant tracks (dinosaur, bird, pterosaur) have also been located from western and southern coastal areas. They clearly indicate that a diversity of vertebrate communities existed during the time of Gyeongsang deposition in Korea. Except for some of the trackways, however, the vertebrate faunas remain inadequately published. Therefore, the purpose of this paper is to review the vertebrate fossils from the Gyeongsang Supergroup and to report their occurrence to the wider paleontological community. The potential significance of Gyeongsang vertebrates may be seen especially in the context of roughly contemporaneous localities from the Shandong Peninsula in China (Chen, 1992; Cheng et al., 1995), Liaoning in northeastern China (recently redated by Swisher et al., 1999), and North America (Cifelli, 1999; Cifelli et al., 1997; see also Jacobs, 1997 and Currie, 1997).

2. Geological setting

The Gyeongsang Supergroup occurs within the Gyeongsang Basin and several small basins (Haenam, Neungju, Jinan, Kyokpo, Yongdong, Kongju, Eumsung). The Gyeongsang Basin, the

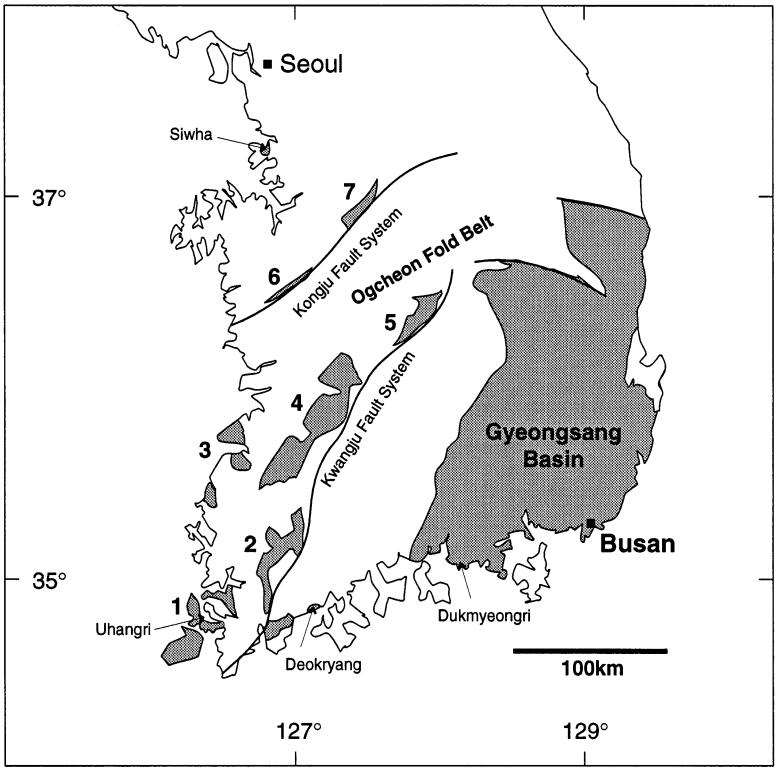

Fig. 1. Distribution of Cretaceous basins (shaded) and the main Jurassic exposures, as related to Cretaceous fault patterns in the Korean Peninsula. Numbers indicate smaller Cretaceous non-marine basins subordinate to the Gyeongsang Basin as follows: 1, Haenam; 2, Neungju; 3, Kyokpo; 4, Jinan; 5, Youngdong; 6, Kongju; 7, Eumsung.

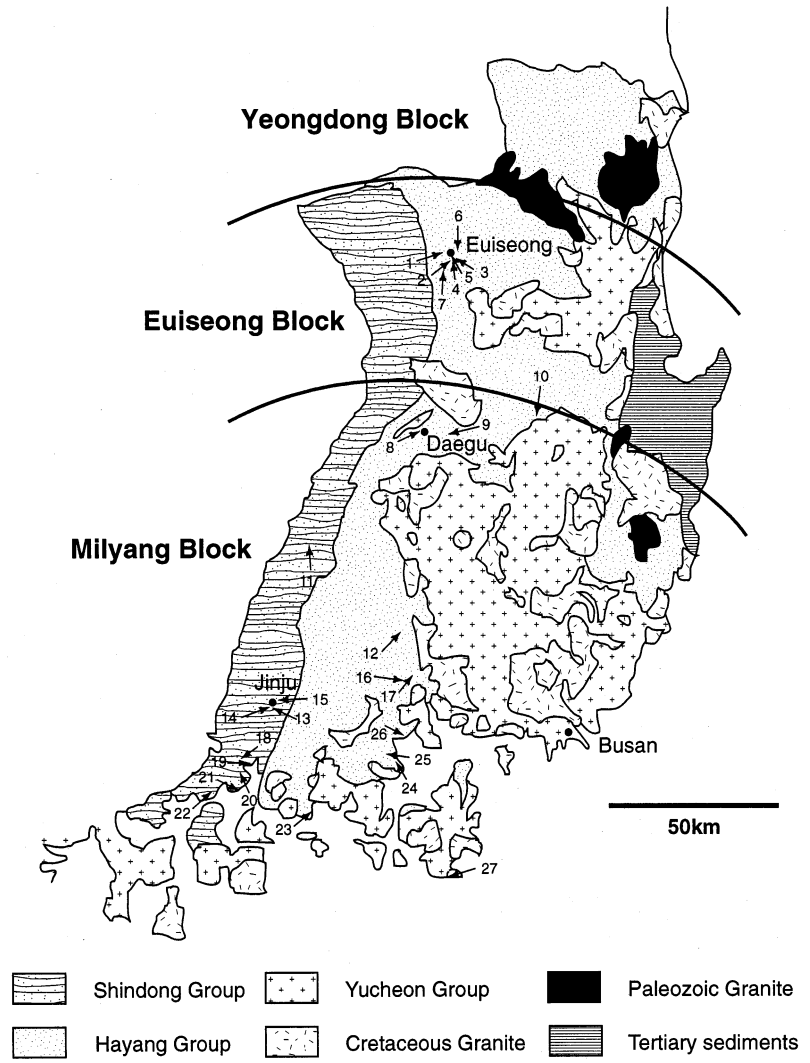

Fig. 2. Geologic map of the Gyeongsang Basin. Numbers indicate localities of vertebrate fossils as discussed in text: 1, Doweonri, Euiseong; 2, Tabri, Euiseong; 3, Hwajeonri, Euiseong; 4, Jaeori, Euiseong; 5, Mancheonri, Euiseong; 6, Guamri, Jeomgog-myeon; 7, Nahori, Guwi-gun; 8, Doggogri, Dalseong-gun; 9, Gyeongsan; 10, Cheonchonri, Gyeongju; 11, Noyangri, Habcheon; 12, Geomunri, Changryeong-gun; 13, Sumunri, Hadong; 14, Yusuri, Jinju; 15, Gajinri, Jinju; 16, Chiweon-myeon, Haman-gun; 17, Yongsanri, Haman-gun; 18, Gawhari, Sacheon; 19, Geomjeongri, Sacheon; 20, Gupori, Sacheon; 21, Dapyeongri, Sacheon; 22, Gainri, Namhae; 23, Dukmyeongri, Goseong-gun; 24, Donghae-myeon, Goseong-gun; 25, Naesanri, Goseong-gun; 26, Gohyunri, Masan; 27, Galgotri, Geojae-gun.

largest sedimentary basin of Korea, is widely distributed in the south-eastern part of the Korean Peninsula (Fig. 1). The outlying smaller basins occur along the Ogcheon Fold Belt in the south-western to central areas in a NE–SW trend. The smaller outliers are known as extensional basins formed in the overriding continental plate and frontal arc caused by oblique convergence, giving rise to strike–slip movement (Chun and Chough, 1992). This movement was forced along the Ogcheon Fold Belt by the amalgamation of Chinese–Korean Plates since Jurassic time (Lee et al., 1999).

The Gyeongsang Supergroup is divided into the Shindong and Hayang Groups, mainly comprised

of thick siliciclastic sequences of alluvial, fluvial and lacustrine sediments, and the Yuchon Group characterized by the dominance of volcanic rocks (Chang, 1975; Fig. 2). The Shindong Group is confined to the western margin of the Gyeongsang Basin with general trends to the NNE (Nagdong Trough, 2000 to 3000 m thick). The Shindong consists of the Nagdong, Hasandong, and Jinju Formations, generally showing a fining-upward trend and three facies associations characterized as alluvial fan fringe, fluvial system, and shallow lake (Choi, 1986a–c). Shindong sediment source areas have been indicated to the WNW by paleocurrent analysis (Chang and Kim, 1968; Kim, 1994; Cheong and Kim, 1996). The occurrence of calcisol and vertisol indicates that climates during Shindong deposition were arid to semi-arid (Paik and Lee, 1994; Paik and Kim, 1995; Paik and Lee, 1998). Abundant plant fossils collected from the Nagdong Formation were correlated with the floras of the Tetori Group in Japan (Tateiwa, 1925, 1929). The Sindong molluscan faunas have been studied extensively and all are assigned to non-marine taxa (Yang, 1974, 1975, 1976, 1978a,b, 1979, 1982a). In addition, charophytes and non-marine ostracodes were also recovered from the Nagdong and Jinju Formations, respectively (Choi, 1989b, 1990). The age of the Sindong Group has been determined as Aptian to Albian by molluscan faunas (Yang, 1982a) and as Hauterivian to Barremian by palynomorphs (Choi, 1985, 1989a; Yi et al., 1994) and ostracods (Matsukawa et al., 1998).

The Hayang Group overlies the Shindong Group in the western part of the Gyeongsang Basin and directly overlies pre-Cretaceous rocks in the northern part of the Gyeongsang Basin (Fig. 1). The Hayang Group (1000 to 5000 m thick) was deposited through subsiding and eastward expansion of the basin. It is composed of shale, sandstone interbedded with marl and conglomerate, and partly volcanic rocks extruded within the sedimentary basin. The paleocurrent directions indicate that dominant source areas were in the northwest and the east, somewhere in the vicinity of the present East Sea (Sea of Japan) (Chang, 1988; Chang et al., 1990). During the sedimentation of the Hayang Group, the basin was strongly controlled by WNW-trending growth faults, which divided the basement into smaller crustal segments such as the Milyang, Euiseong, and Yeongyang Blocks (Figs. 2 and 3). Therefore, under the influence of these syndepositional movements, the Hayang Group has different stratigraphic sequences from block to block (Chang, 1975, 1977).

The Hayang Group was deposited mainly in fluvio-lacustrine environments rather than alluvial plains, an inference supported by abundant channel beds in association with floodplain sediments (Choi, 1986a). However, poorly sorted coarse grains of clastic rocks and prevalent red rock color suggest more purely fluvial environments sometimes. The Hayang climate was generally arid to semi-arid judging from the occurrence of calcrete, rhizolith (Paik and Chun, 1993), and abundant pollen from *Corollina* and *Ephedripites* combined with scarcity of fern spores (Choi, 1985; Yi et al., 1993).

Since 40 specimens of plant fossils were reported from the Geoncheonri Formation and correlated with the Monobegawa Group and the Gyliak Series (Late Jurassic to Early Cretaceous) in Japan (Tateiwa, 1925, 1929), Hayang plant fossils have been intermittently studied by Japanese scholars (Oishi, 1940; Kimura, 1984). More recently charophytes have been recovered from the Geoncheonri, Daegu, and Iljig Formations (Choi, 1987, 1990). Angiosperm pollens such as *Retimonocolpites*, *Clavatipollenites*, and *Tricolpites* from the Geoncheonri and Iljik Formations suggest that the Hayang Group is Aptian to early Albian in age (Choi, 1985, 1989a; Yi et al., 1993).

The Yucheon Group (2000 to 3000 m thick), unconformably overlying the Hayang Group, consists of volcanic and associated sedimentary rocks. No fossils are known so far from the Yucheon Group and its isotopic age is 83 Ma by $^{40}K/^{40}Ar$ (Doh and Kim, 1994).

3. Vertebrate fauna

3.1. Shindong Group of the Gyeongsang Basin

3.1.1. Fish

Abundant fish fossils have recently been found in the Shindong Group. To date four localities

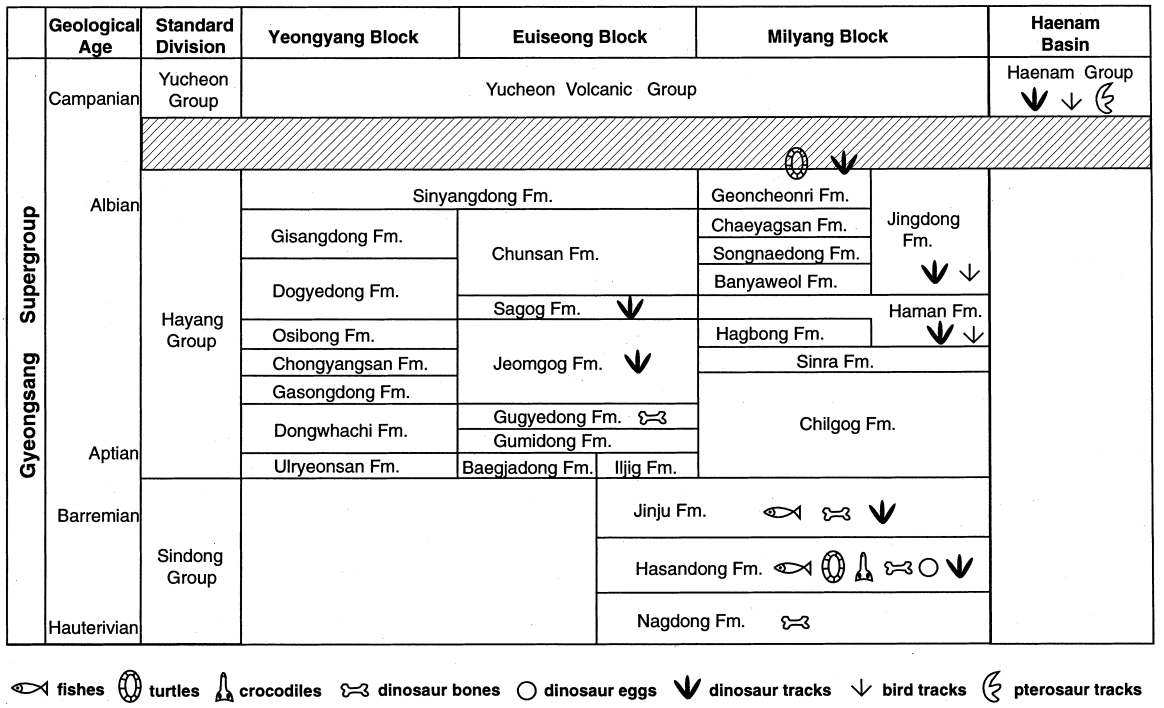

Fig. 3. Stratigraphic correlation of the Gyeonsang Supergroup and the vertebrate faunal horizons. Geological ages are based on palynomorphs (Choi, 1985, 1989a; Yi and Chun, 1993; Yi et al., 1994) and paleomagnetism (Doh and Kim, 1994).

have yielded articulated skeletons and/or isolated scales. Except at Yusuri (Naedong-myeon, Jinju, South Gyeongsang Province), which contains scattered ganoid scales from Hasandong Formation mudstones, these fish remains come from the black shale facies of the Jinju Formation. The most important among these localities is a small creek-bed outcrop (12 m^2) in Nahori (Ubo-myeon, Guwi-gun, North Gyeongsang Province). A total of 17 complete specimens (less than 6 cm in length) were recovered from the black shale horizons. The specimens appear to represent a new family belonging to Suborder Albuloidei (Lee, 1999). Apomorphies include villiform teeth on the surface of the anterior dentary (but not the maxilla) and an anal fin situated nearer to the pelvic fin than to the caudal peduncle. The total of 35 to 37 vertebrae including 15 to 16 caudals is far fewer than in any other families of Albuloidei.

Another locality is in the Jinju Formation exposed in Donggogri (Habin-myeon, Dalseong-gun, North Gyeongsang Province). It yielded *Wakinoichthys* (Wakinoichthiidae, Subdivision Osteoglossomorpha) and a chuingichthiid (Order Ichthyodectiformes). They are correlated with the *Paraleptolepis–Wakinoichthys* Zone (W3) and *Diplomystus–Wakinoichthys* Zone (W4) of the Wakino Subgroup (Early Cretaceous) in Japan, indicating faunal interchange between the Gyeongsang Basin and the Tetori Basin in Early Cretaceous time (Lee et al., 1998).

Lepidotus remains were found with abundant insect impressions from the black shale of the Jinju Formation exposed next to Sangpyeong Bridge near Hotan-dong, Jinju (South Gyeongsang Province) in 1997. These specimens are under investigation (S.Y. Yang, personal communication).

3.1.2. Dinosaurs

A total of seven localities have yielded dinosaur bones from the Shindong Group. Although they are isolated teeth and incomplete or fragmentary bones, the Hasandong Formation has produced

the most abundant dinosaur material from the Gyeongsang Supergroup. To date five localities are known from the Hasandong Formation in Euiseong and Jinju-Sacheon areas. Near Euiseong the localities are at Doweonri and Hawjeonri (Bongyang-myeon, Euiseong-gun, North Gyeongsang Province). A damaged scapula(?) with the coracoid, discovered in a road cut at Euiseong toll booth (Doweonri) in 1995, has remained unexcavated in a light gray, gravelly sandstone bed of the upper Hasandong Formation. Half of the scapula had already been lost by road construction when found. Although the Haversian canals are completely filled with calcite, the bone retains an unaltered white or light gray color. Most bones elsewhere in Gyeongsang are dark gray or black. The Hwajeonri site yielded an unidentifiable, elongate planar bone (15 cm long) in coarse-grained sandstone (Paik et al., 1998a).

The Jinju-Sacheon area (Yusuri, Naedong-myeon, South Gyeongsang Province) is one of the most important vertebrate fossil localities in the Gyeongsang Supergroup to date. Except during the rainy season (late June through mid-August) the bottom of the Gawha River channel (150 m wide) is well exposed from Yusuri southwest to Sacheon Bay (about 2 km). The stream bed at the Yusuri site consists of mainly upper Hasandong Formation and contains three dinosaur-bearing horizons (Paik et al., 1998b). The lower horizon (40–50 cm thick) is dominantly reddish, sandy mudstone with calcrete. Recovered bone fragments (5–40 cm long) are coated by calcite a few millimeters thick and filled with micrite and sparite. An incomplete scapular blade and proximal end of a limb bone were recovered among other, more poorly preserved pieces. The middle horizon (120 cm thick, located 8 m above the lower horizon) consists of reddish mudstone associated with some well-rounded crystalline rock pebbles and calcrete. A total of 200 bone fragments (mostly less than 5 cm long) were scattered within 200 m^2. The bone is coated by micrite or preserved as calcrete nodules, probably formed in floodplain mudstone. Most of the bone fragments are unidentifiable, but some pieces belong to skull elements such as the post-orbital or the jugal. The upper horizon (60 cm thick, 20 m above the middle horizon) is a dark gray shale layer which is different from the lower two horizons in having abundant plant material with no calcrete (Paik and Lee, 1994). Recent prospecting of the exposed channel bed yielded ganoid scales, turtle shell fragments, three sauropod teeth, two teeth (5 cm long) and an ungual (4 cm) from a theropod, and a complete humerus. Excepting the sauropod teeth, these specimens have not been described in print. The sauropod teeth may represent three different morphotypes which would indicate that three sauropod taxa inhabited Korea at the time of deposition (Lee et al., 1997).

Two dinosaur-bearing horizons were recognized from the upper Hasandong Formation where it is distributed along the west coastal outcrops in Dapyeongri, Seopo-myeon, Sacheon, South Gyeongsang Province (Paik et al., 1998a). The lower horizon (2 m thick) is greenish gray, sandy mudstone and produced a rib (1.8 m long) and an incomplete theropod tooth (1.5 cm long). Bones have partial micrite rims and are black in color. This bed is associated with calcic and vertic paleosol and some well-rounded pebbles. The upper horizon occurs 150 m above the lower horizon and consists of gray calcrete, intraclast-bearing, coarse sandstone. This horizon (50 cm thick) yielded an incomplete limb bone (20 cm in diameter) and a few additional, fragmentary bones.

In Sumunri (Geumseong-myeon, Hadong, South Gyeongsang Province) the upper Hasandong Formation is exposed intermittently along sea cliffs. The site is notable for the discovery of dinosaur eggshell fragments in 1972, the first find of dinosaur fossils of any kind in Korea. In 1996 a second find of eggshell pieces was made in greenish gray, sandy mudstone 50 m east of the first site. Six to seven elongate eggs (long axis 8.9 cm, short axis 6.9 cm) were reconstructed from the fragments (Yun and Yang, 1997). A thin horizon (50 cm thick) 20 m above the eggshell horizon produced unidentifiable bone fragments and an incomplete theropod tooth. These fossils occur in a gray calcrete, intraclast conglomerates with fine-grained interlayers. A third dinosaur-bearing layer occurs 25 m above the latter horizon. It is a reddish brown, sandy mudstone bed associated with calcic paleosol. It has yielded

isolated flat bone fragments and part of a vertebra within calcrete nodules (Paik et al., 1998a).

In addition to the five localities from the Hasandong Formation listed above, two dinosaur localities are known from the Nagdong and Jinju Formations. A middle part of a rib (45 cm long) and several unidentifiable fragmentary bones were collected from the Nagdong Formation in Noyangri and Wari (Yulgog-myeon, South Gyeongsang Province). Isolated bone pieces plus an unidentifiable limb bone (20 cm long) were recovered from the Jinju Formation in Nahori (Ubo-myeon, Gunwi-gun, North Gyeongsang Province) within a greenish gray, gravelly sandstone bed (Son, 1989). This locality is about 1 km west of the Nahori fish site.

3.1.3. Other vertebrates

In 1993 a bird fossil was found in the Sinuiju Series (Early Cretaceous) of the Amnok River Basin in North Korea. The specimen preserves part of the skull, neck, and wing associated with feathers. It was named *Proornis coreae*, but without a full description (Paek and Kim, 1996). Its exact phylogenetic position and the validity of taxonomy are therefore uncertain. Nevertheless, unlike *Archaeopteryx* the digits of *Proornis* are proportionately shorter than the metacarpals (Chiappe, 1997).

3.2. Hayang Group of the Gyeongsang Basin

3.2.1. Turtles

A turtle specimen was collected from the Geoncheonri Formation in Gyeongsan area near Daegu during the 1970s. It consists of parts of the carapace including much of the lateral peripheral series, a few costals including the first, and one neural. In preliminary investigation it compares best with the Early Cretaceous (Aptian–Albian) Macrobaenidae of China and Kazahkstan in general morphology, size, and stage of evolution, but detailed differences may suggest a different genus from those presently known (J.H. Hutchison, personal communication).

3.2.2. Dinosaurs

The Tabri area (Geumseong-myeon, Euiseong, North Gyeongsang Province) is an historical locality for dinosaur bones in Korea. In 1973 an incomplete dinosaur limb bone (42 cm maximum length at proximal end) was discovered in variegated calcrete intraformational conglomerate of the Gugyedong Formation near Tabri Station. It was excavated and identified as part of a sauropod femur or tibia (Chang et al., 1982). Kim (1983) identified the specimen as part of the proximal end of a right ulna belonging to the family Brachiosauridae and named it *Ultrasaurus tabriensis*, new genus and species, based on its supposed huge size compared with the ulna of *Supersaurus*. Lee et al. (1997) re-identified the specimen as the proximal portion of a left humerus; in this case *U. tabriensis* is a *nomen dubium* because of the lack of apomorphy for establishing a new taxon. From the same site, Kim (1983) recovered an almost complete femur (40 cm long) and an incomplete planar bone which he referred to *Deinonychus*, as well as a caudal neural spine which he referred to *U. tabriensis*. In fact, however, the femur is different from that of *Deinonychus* in having the fourth trochanter. Unfortunately, further systematic description of these fossils has yet to be published.

Very recently (1999), dinosaur eggs and nests have been found at Siwha Bay (Whasung-gun, Gyeonggi Province) and also at Deokryang Bay (Bosung-gun, South Chulla Province) (Fig. 1). In the preliminary investigation at the Whasung site, at least 30 nests and over 300 eggs have been observed in red sandstone and conglomerate beds. The eggs are arranged in a circular pattern at several different stratigraphic levels, suggesting multiple laying events. It is possible that this locality represents a large, repeatedly-used, colonial nesting ground. To date two morphotypes of eggs have been identified by the shell thickness and surface ornamentation. The eggs are spherical in shape (11–15 cm in diameter) and the eggshell is of basic dinosauroid–spherulitic type (Hirsch, 1994). At least 10 nests and 120 eggs were found along 3 km of coastline at the Bosung site (M. Huh, personal communication), which is approximately 290 km from the Whasung site. The Bosung

eggs are subspherical and are about 9–16 cm in diameter. The shells are thin (1.5–2.5 mm) and have dendrospherulitic, prolatospherulitic, and multispherulitic structures. The stratigraphic positions of both nesting sites are not yet certain.

4. Vertebrate ichnofauna

4.1. Shindong Group of the Gyeongsang Basin

4.1.1. Dinosaurs

The Shindong Group produces dinosaur tracks from the Hasandong and Jinju Formations in the vicinity of Jinju and Sacheon, South Gyeongsang Province. Tracks have been found in the exposed bottom of the Gawha River channel extending from Yusuri to Gawhari and Geomjeongri (about 2 km). In the Jinju area, eight track-bearing horizons were located in the upper Hasandong Formation at Yusuri, Naedong-myeon (Lim et al., 1997). A total of 30 undertracks belonging to three ornithopods have been mapped with one theropod trackway comprising six consecutive footprints. The fifth track horizon is the same horizon as the fossiliferous layer of the Yusuri site which produced three sauropod teeth. Another track site from the Hasandong Formation is Gawhari (Gonyang-myeon, Sacheon, South Gyeongsang Province); it includes 37 theropod, sauropod, and ornithopod footprints within six horizons. Around 100 ornithopod footprints were also observed 500 m south of this site.

Two track sites are known in the coastal outcrops of the Jinju Formation exposed at the estuary of Gawha River (Geomjeongri, Gonyang-myeon) and at Gupori (Seopo-myeon, Sacheon), and a total of 32 footprints from six horizons within 180 m^2 on the dark gray shale at the Geomjeongri site. They consist of six isolated theropod footprints and six ornithopod trackways. 11 ornithopod footprints are poorly preserved on the sandy shale at the Gupori site.

4.2. Hayang Group of the Gyeongsang Basin

4.2.1. Dinosaurs

Abundant dinosaur trackways have been discovered from the southern coastal areas and the inland areas of Gyeongsang Province. At least 30 track sites have been located in the Hayang Group by sporadic prospecting but have not yet been extensively published except for those of the Dukmyeongri area and the Donghae-myeon area of the Milyang Block. The best known track site internationally is at Dukmyeongri (Hai-myeon, Goseong-gun, South Gyeongsang Province) where more than 500 ornithopod and sauropod trackways occur in as many as 300 distinct horizons in a continuously measured (110 m thick) section of the Jindong Formation (Yang, 1982b; Lim et al., 1994). In addition, the Dukmyeongri site includes the smallest sauropod trackway currently known in the world (Lim et al., 1989) plus ornithopod tracks cast in intrusive igneous rock (Lockley et al., 1993). A new track site has recently been discovered in Donghae-myeon (Goseong-gun), 30 km east of Dukmyeongri. Tracks are present in coastal outcrops of the Jindong Formation in the Bongamri, Jangjaori, Yongjeongri, and Naesanri areas. A total of 1300 sauropod, theropod, and ornithopod footprints in 132 trackways have been measured and mapped in these areas (Baek and Seo, 1998). Another track site from the Jindong Formation is at Gohyunri (Jindong-myeon, Euichang-gun, Masan, South Gyeongsang Province) which yielded poorly preserved ornithopod and sauropod tracks within 12 dark gray mudstone horizons (Lee, 1993).

There are three track sites from the Haman Formation distributed in the vicinity of Namhae, Jinju, and Haman (Milyang Block). The Namhae locality (lower Haman Formation at Gainri, Changsun-myeon) has yielded around 50 theropod, sauropod, and ornithopod footprints in several horizons within a 10 m section, over an area of 80 m^2 (Seo, 1998). Three isolated theropod footprints were also found with abundant bird footprints from the lower Haman Formation at a construction site near the Gyeongnam Science High School, Gajinri, Jinseong-myeon, Jinju (Baek and Yang, 1998a). Two ornithopod and one sauropod trackways were measured on fine sandstone of the Haman Formation at Yongsanri (Chilweon-myeon, Haman-gun, Masan). Two ornithopod trackways consisting of four and seven consecutive footprints, respectively, have been deposited as

replicas in Kyungpook National University, Daegu. These appear to have morphologies similar to those of the Jindong Formation (Lim et al., 1995).

Another bed to produce dinosaur tracks in the Milyang Block occurs in the Geoncheonri Formation in the Gyeongju and Bugog area. At least eight track-bearing horizons were reported from the Middle Geonchonri Formation exposed in the stream bed in Cheonchonri (Seo-myeon, Gyeongju, North Gyeongsang Province) (Lim and Park, 1998). Tracks are poorly preserved (due to water erosion) on dark gray mudstone, but at least two ornithopod and four theropod trackways are traceable. Geomunri (Bugog-myeon, Changryeong-gun, South Gyeongsang Province) also has a Geoncheonri Formation site which has yielded ornithopod and theropod trackways.

Three track sites in the Euiseong Block are known in the vicinity of Euiseong-gun, North Gyeongsang Province. About 200 footprints belonging to theropods, sauropods, and ornithopods occur on two sandstone horizons in the Sagog Formation of Jaeori, Geumseong-myeon. The footprints are poorly preserved and not yet studied. Mancheonri, Geumseong-myeon, has a second track site from the Sagog Formation. One theropod, one sauropod, and four ornithopod trackways occur in two horizons. The lower horizon contains a theropod track (14.2 cm long) and the smallest ornithopod track (9.5 cm) in the Gyeongsang Supergroup (Lim and Yang, 1997). A third track site was located at Guamri, Jeomgog-myeon, in which 42 footprints occur in three horizons of the upper Jeomgog Formation. 34 theropod footprints (13–22.3 cm long, 10.7–16 cm wide) were mapped from 13 trackways in the upper horizon. This site has more abundant theropod footprints and trackways than any other sites reported in the Gyeongsang Basin (Son et al., 1998). No dinosaur tracks are known so far from the Yeongyang Block.

4.2.2. Birds

Abundant bird footprints occur in the Haman and Jindong Formations, South Gyeongsang Province. The first discovery of bird footprints in Korea (assigned to *Koreanaornis hamanensis*) was made in the upper Haman Formation located in Chilweon-myeon, Haman-gun, Masan (Kim, 1969). About 1000 bird footprints included in approximately 40 trackways have recently been found in the lower Haman Formation at the construction site near Gyeongnam Science High School (Gajinri, Jinseong-myeon, Jinju). They were assigned to three ichnotaxa, *Uhangrichnus chuni*, *Jindongornipes kimi*, and *Koreanaornis hamanensis*, of which the last is the most abundant (Baek and Yang, 1998b).

The Dukmyeongri site is well known not only for abundant dinosaur tracks, but also for the type locality of *Jindongornipes kimi* (Lockley et al., 1992). This ichnospecies was found sometimes on the same surface with *Koreanaornis hamanensis* at more than 30 localities in the Dukmyeongri area (Yang et al., 1995). The same two ichnotaxa were also reported from the Jindong Formation of Gohyunri, Jindong-myeon, Masan (Lee, 1993), Naesanri, Donghae-myeon, Goseong-gun (Baek and Seo, 1998), and Galgotri, Nambu-myeon, Geojae-gun (Kim et al., 1998).

4.3. Uhangri Formation of the Haenam Basin

The Haenam Basin (Haenam-gun, South Chulla Province) is one of a series of Cretaceous, NE–SW trending, isolated non-marine basins distributed to the NW of Gyeongsang Basin (Fig. 1). Haenam Basin contains four formations, in ascending order: an andesitic tuff with andesite intrusions and flows, the Uhangri Formation, the Hwangsan Tuff, and the Jindo Ryolite (Lee and Lee, 1976). The Uhangri Formation comprises a volcanic clastic and epiclastic sedimentary sequence made by approximately 400 m of interbedded conglomerate, gravelly sandstone and sandstone, laminated black shale, and cherty mudstone. It generally shows a fining-upward trend with four facies associations: alluvial fan fringe, subaqueous delta lobe, delta front, and shallow lake (Chun and Chough, 1995). The upper part of the Uhangri Formation is well exposed in sea cliffs and intertidal, wave-cut benches along the northern coast of Uhangri, Uhangpo, Sinsungri, and Naesanri including the Byongonri area (Fig. 4). The Uhangri section comprises laminated black

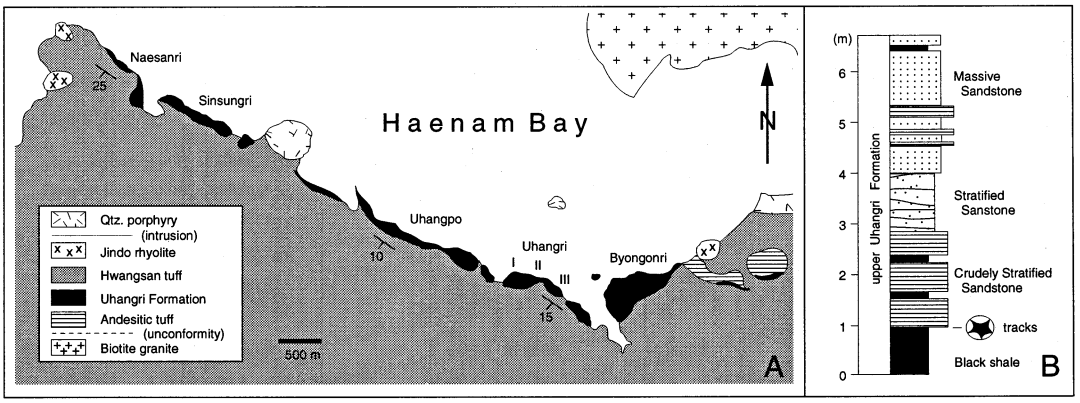

Fig. 4. (A) Simplified geological map of the Uhangri area (South Chulla Province). (B) Stratigraphic section of the Uhangri Formation indicating the track-bearing horizon.

shale and cherty mudstone alternating with crudely stratified sandstone. Symmetrical current ripples, syneresis cracks, and fossil plants, and various vertebrate tracks (dinosaurs, birds, pterosaurs), indicate that the water level remained rather low in the Uhangri area, which suggests a marginal lacustrine depositional environment. An incomplete shaft of a pterosaur limb bone (17 cm long) was recovered in the sandstone beds 1.5 m above the pterosaur track horizon. Invertebrate trace fossils such as *Planolites*, *Skolithos*, and indeterminate arthropod tracks are also occasionally observed on the sandstone surface. The Uhangri Formation has been dated by $^{40}K/^{40}Ar$ between 82.8 ± 1.7 Ma and 94.1 ± 2 Ma (Moon et al., 1990).

4.3.1. Dinosaurs

A total of 514 footprints have been excavated from three localities in the Uhangri area. They include ornithopod, sauropod, and theropod trackways. Notably, 105 deeply impressed, apparently manus-only sauropod trackways were excavated from one locality in an area of 270 m^2. If those trackways prove true sauropod manus prints, they support R.T. Bird's hypothesis of sauropod swimming ability (Bird, 1944), indicating also that manus-dominant trackways are not always undertracks (Lee and Huh, 2000).

4.3.2. Birds

Thousands of bird footprints in the Uhangri Formation were named *Uhangrichnus chuni* and *Hwangsanipes choughi*; they are unique in having traces of webbing (Yang et al., 1995). *H. choughi* presently exhibits the oldest webbed-foot bird footprints in the world, clearly indicating that shore birds had evolved before the Campanian, tens of millions of years earlier than the skeletal record may indicate.

4.3.3. Pterosaurs

Uhangri pterosaur tracks discovered in 1996 are the first ever reported from Asia (Huh et al., 1996). To date over 400 pterosaur footprints including a trackway (7.3 m long) with 14 consecutive footprints have been recorded on the black shale of the upper Uhangri Formation. Manus and pes footprints ranging from 20 to 35 cm are the largest on record. Pes morphology is different from those of other pterosaurs in having the impression of a prominent metatarsal V (Lockley et al., 1997).

5. Discussion

Although not yet widely reported to the international community, a diversity of vertebrate specimens and taxa have been reported from the thick sequences of the non-marine Gyeongsang Supergroup. These include a new family of fish, a macrobaenid turtle and other turtle fragments, crocodilian teeth, a pterosaur limb bone, and dinosaur teeth and bones. On the basis of tooth morphology at least three kinds of sauropod

appear to have lived in Korea during Early Cretaceous time. Theropods are also confirmed by teeth and an ungual. It is remarkable, however, that not a single ornithopod bone has been identified so far, considering that ornithopods account for over 80% of dinosaur tracks recorded from the Gyeongsang strata. This bias may be from lack of extensive (or at least systematic) prospecting in the Gyeongsang rather than from depositional or preservational events.

Most bones occur as scattered, broken, and isolated pieces. Sometimes the disarticulated bone fragments are enclosed in micrite, which appears as calcareous nodules. Although spongy bone textures were preserved, the compact bone is often damaged, probably due to weathering before burial, so that a large proportion of specimens are difficult or impossible to identify. This type of preservation occurs mainly in the lower horizons of Hasandong Formation in Yusuri and Dapyeongri, frequently associated with reddish brown calcic paleosols developed in floodplains. It indicates that these bones had probably undergone long aerial exposure, transportation, and scattering into lower land in the floodplain before burial. The Hasandong Formation also contains calcrete intraclast channel deposits and marginal floodplain lake deposits which have yielded reworked bones fragments and isolated teeth. The Hasandong Formation is nevertheless the most productive so far for vertebrate specimens, which is probably related to its abundant calcic paleosols (Paik et al., 1998b). Meanwhile, skeletal elements from channel deposits of the Nagdong and Gugyedong formations have better preservation than those from the Hasandong Formation. Although isolated and broken, they retain their compact bone and original shapes so that most of them are identifiable.

Most bones, teeth, and eggshells from the Gyeongsang Supergroup are dark gray to black in color, possibly indicating some degree of thermal maturity. Black color (CAI = 5, Color Alteration Index) indicates that the bed containing bones had undergone thermal alteration over 300°C (Epstein et al., 1977). Alteration would probably be caused by extensive volcanic activity during deposition of the Yuchon Group.

6. Conclusions

The Gyeongsang Supergroup has one of the richest Mesozoic ichnological records in the world, mainly distributed in the southeastern part of the Korean Peninsula. To date 23 dinosaur track sites have been reported with thousands of dinosaur footprints, and with bird and pterosaur tracks as well. The Dukmyeongri site is well known internationally for abundant sauropod and ornithopod trackways (Lim et al., 1994; Lockley, 1994, 1999). The Uhangri site is the only place in the world where dinosaur, pterosaur, and bird tracks all occur together at the same horizons. The Uhangri pterosaur tracks represent the first record in Asia. In addition, the Gyeongsang Supergroup has the best record of Cretaceous bird footprints anywhere in the world. Of seven Mesozoic bird ichnotaxa worldwide, four have been described in the Gyeongsang.

By comparison, the international paleontological community is less well aware of Cretaceous bones and teeth from Korea because, although several localities for dinosaur and other taxa have been located, they have not been published except in Korean journals nor has most of the material been identified. Bones have been found in quarries, road cuts, stream beds, and coastal outcrops by sporadic individual prospecting (including that of quite knowledgeable amateurs) but the Gyeongsang formations have yet to be explored systematically by professional teams. Sedimentary facies known to contain bones indicate that better skeletal material may be found with persistent searching. Further encouragement may be taken from recent discoveries of abundant, articulated fish skeletons (Nahori) and the two large egg nest sites at Whasung and at Bosung. The time period represented by the Gyeongsang Supergroup is especially critical for understanding the evolution of extant vertebrate groups (Cifelli et al., 1997; Cifelli, 1999; Swisher et al., 1999). Korea is and was situated geographically upon possible coastal migration routes between Asia and North America.

The now famous fossil localities of the Yixian Formation, Liaoning Province, northeastern China are volcano/tectonically enclosed lake-basin depos-

its of Early Cretaceous age (middle Barremian; Swisher et al., 1999) and are therefore contemporaneous with large parts of the Gyeongsang Supergroup. Liaoning localities are relatively near the northern boundary of the Korean Peninsula and have yielded well-preserved fossils of the 'feathered' dinosaurs *Sinosauropteryx* (Chen et al., 1998), *Protarchaeopteryx*, *Caudipteryx* (Ji et al., 1998), and *Sinornithosaurus* (Xu et al., 1999); some of the most primitive known birds such as *Confuciusornis* and *Liaoningornis* (Hou et al., 1995), and the mammal *Zhangheotherium* (Hu et al., 1997) and *Jeholodens jenkinsi* (Ji et al., 1999). We can hope therefore that it is only a matter of time until the Gyeongsang Supergroup adds significantly to our expanding knowledge of Early Cretaceous vertebrate from Asia and the rest of the world.

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