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Dinosaur egg-bearing deposits (Upper Cretaceous) of Boseong, Korea: occurrence, palaeoenvironments, taphonomy, and preservation

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Abstract

Dinosaur (sauropod and ornithopod) egg-bearing deposits of the Upper Cretaceous Seonso Conglomerate, Boseong, Korea were examined sedimentologically for palaeoenvironmental and preservational interpretation. Dinosaur eggs are commonly preserved as clutches, although isolated eggs also occur. The clutches are found in at least six horizons consisting of sandy mudstones to mudstones. These strata are interpreted as terminal fan deposits. Calcite rims and calcite aureols around detrital grains, pedotubular to nodular calcretes, and circumgranular to circumnodular cracks are present in the dinosaur egg deposits. These features indicate calcareous pedogenesis which appears to have assisted in the preservation of the eggs. In one egg deposit, in which clutches are mostly found, vertic features including pedogenic slickensides, pseudoanticlines, and calcite-filled deep desiccation cracks occur. The preservation of these dinosaur eggs in calcic and vertic palaeosols suggests that the palaeoclimate of the nested area was semiarid. The lack of displacement of eggs and egg shells, the presence of some egg clutches 5–10 cm below flood deposits, and the porous nature of the eggshells suggest that the eggs were laid in excavated nests that were buried during incubation. The preservation of numerous dinosaur clutches in several horizons at Boseong is consistent with site fidelity.

Keywords: Dinosaur eggs; Boseong; Korea; Cretaceous; Palaeoenvironment

1. Introduction

Although more than 200 sites of dinosaur eggs and eggshells have been documented worldwide (Carpenter and Alf, 1996), studies that focus on dinosaur eggs tend to address morphologic, taxonomic, palaeobiologic, and biostratigraphic issues (Dong, 1992; Carpenter et al., 1996; Mikhailov, 1997; Hirsch, 2001; Zelenitsky et al., 2002). There have been many palaeoenvironmental or taphonomic studies with respect to dinosaur eggs or egg-bearing deposits (Mohabey et al., 1993; Tandon et al., 1995; Cousin et al., 1996; Mikhailov et al., 1996; Sahni, 1997; Hayward et al., 2000; Martin, 2001; Cojan et al., 2003). However, our understanding of dinosaur nesting sites is still limited. More studies on taphonomy and sedimentology of

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egg-bearing deposits are thus needed in order to further understand the palaeoenvironmental and palaeoecological aspects of dinosaur nesting sites.

In Korea, Cretaceous nonmarine deposits are distributed in several sedimentary basins, from which numerous sites of dinosaur footprints (Lim et al., 1994; Huh et al., 1998, 2001; Paik et al., 2001a) and a few of dinosaur bones (Paik, 2000; Paik et al., 1998, 2001b) have been documented. Recently, dinosaur eggs and clutches were discovered in the Cretaceous deposits in Boseong (Huh et al., 1999), Sihwa (Lee et al., 2000), and Goseong (Yang, 2000). The Boseong sites (Fig. 1) are distinguished by the preservation of intact clutches, which have been identified as belonging to ornithopod and sauropod dinosaurs, based on their eggshell structure (Huh and Zelenitsky, 2002). In addition, the egg-bearing deposits are well exposed along the coast at the Boseong sites. Dinosaur bones, turtle bones, and turtle eggs were also found at Boseong. The Boseong sites provide an ideal opportunity to study the palaeoenviroment of nesting site of Cretaceous dinosaurs. The occurrences of dinosaur eggs and egg-bearing deposits at Boseong are described, and the palaeoenvironments and taphonomic preservation of the nesting sites are interpreted.

2. Geological setting

During the Cretaceous, a number of transtensional basins formed in South Korea (Lee, 1999; Chough et al., 2000), in which sedimentation was controlled by

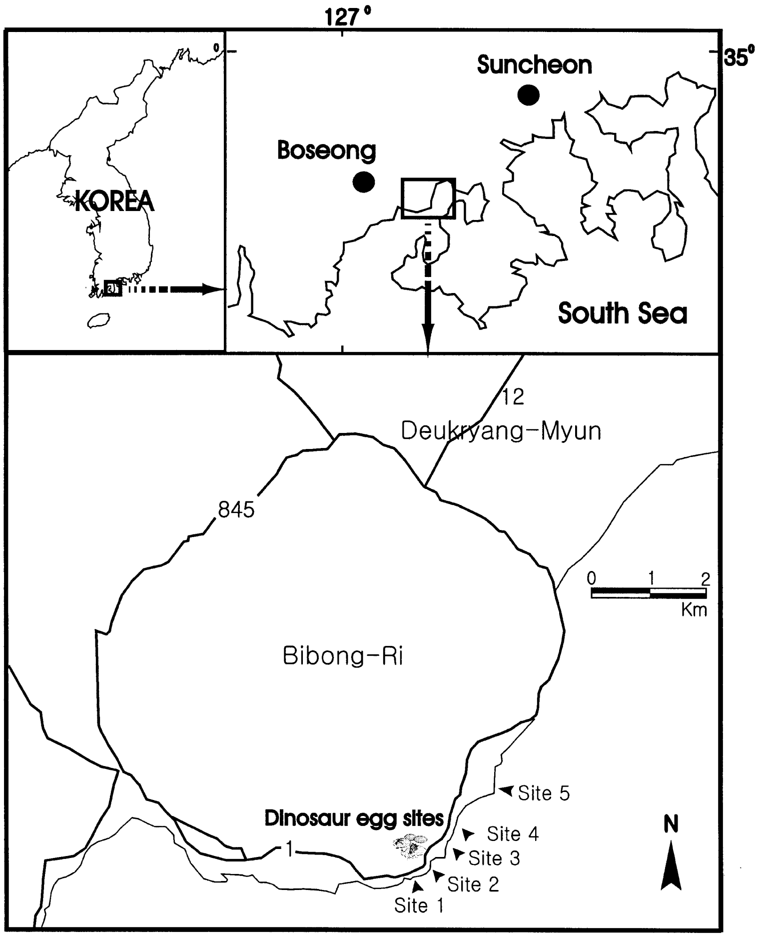

Fig. 1. Location maps of study area.

regional tectonism, climate, and volcanic activity. The sediments are all nonmarine and consist of alluvial fan, fluvial plain, lacustrine, and volcanic deposits. The Gyeongsang Basin is the largest transtensional basin and consists of a 9000-m-thick sequence of deposits assigned to the Gyeongsang Supergroup, which is subdivided into the Sindong, Hayang, and Yucheon groups, in ascending stratigraphic order (Chang, 1975). The Sindong and Hayang groups consist of a stacked sequence of alluvial fan, fluvial, and lacustrine deposits, whereas the Yucheon Group is composed of volcanic rocks and pyroclastic deposits, with intercalated alluvial and lacustrine deposits (Um et al., 1983; Choi, 1985).

Outside of the western part of the Gyeongang Basin are several subordinate basins that trend in a NE–SW direction and some of cauldron basins which include a small isolated basin that contains the Boseong dinosaur egg sites. The sedimentary sequences at the Boseong sites consist of epiclastic, pyroclastic, and intermediate to acidic volcanic rocks, and are divided into the Seonso Conglomerate, Seonso Formation, Pilbong Rhyolite, Mudeungsan Flow, Obongsan Brecciated Tuff, and Docheonri Rhyolite, in ascending stratigraphic order (Hwang and Cheong, 1968). The egg-bearing Seonso Conglomerate and the overlying Seonso Formation are primarily clastic and consist of conglomerates, sandstones, and mudstones,

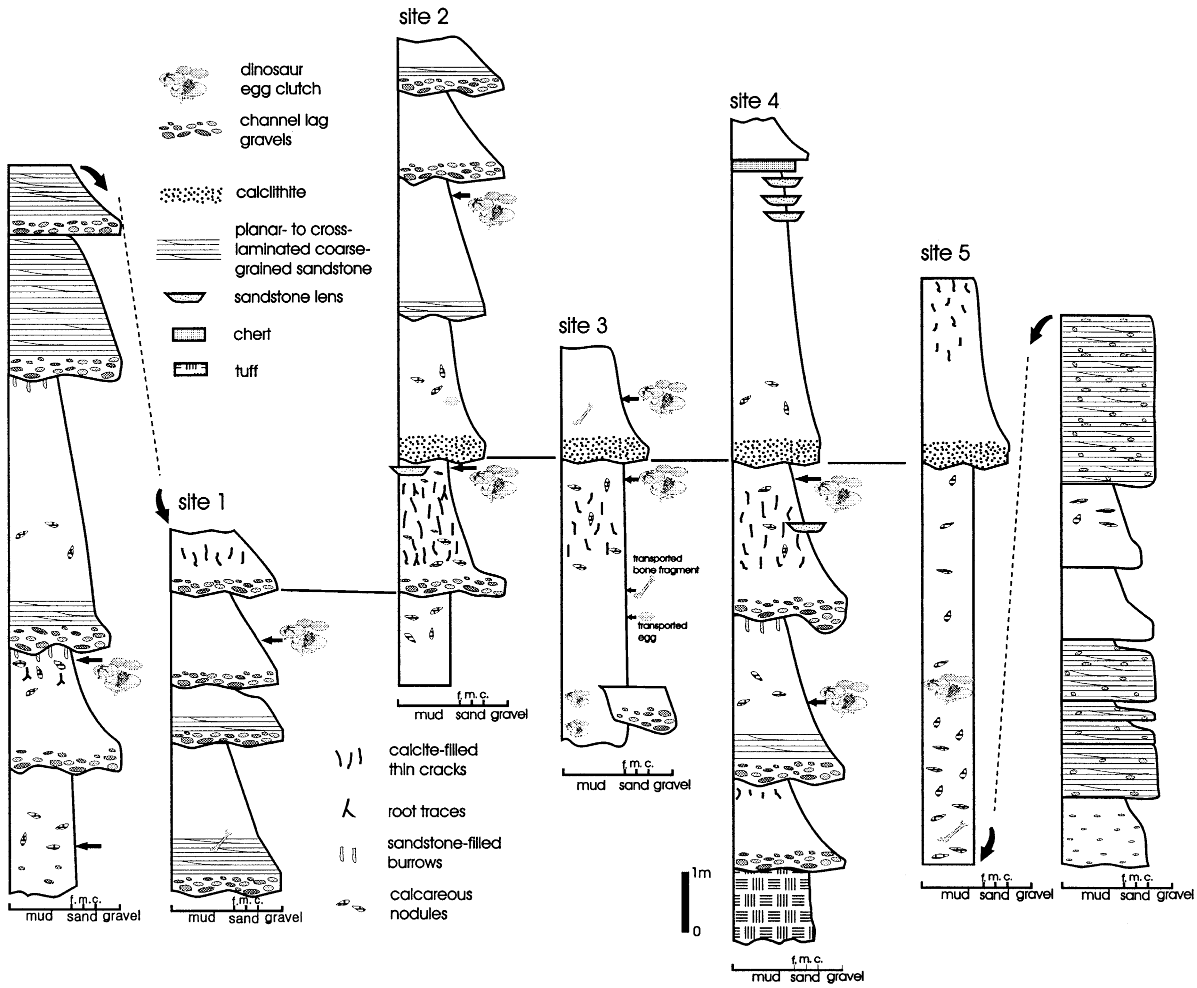

Fig. 2. Stratigraphic sections of Boseong dinosaur egg-bearing deposits.

and alternating sandstones and mudstones, respectively. Lapilli tuff occurs in the lowermost part of the Seonso Conglomerate. The general abundance of volcanic rocks and pyroclastic deposits in sequences of this isolated basin suggests that they can be time-correlated with the Yucheon Group (Upper Cretaceous) of the Gyeongsang Supergroup (Kang et al., 1995), in which volcanic activity was common.

During the Cretaceous, the Korean Peninsula was situated in midlatitudes as it is today (Lee et al., 1987; Kim et al., 1993). Based on palynological records (Choi, 1985), calcisol develoment (Paik and Kim, 1995; Paik and Lee, 1998; Paik et al., 1997), and evaporite mineral casts (Paik and Kim, 1998), the general palaeoclimatic regime during deposition of the Gyeongsang Supergroup is interpreted to have been warm and dry.

3. Occurrences

3.1. Dinosaur eggs

Dinosaur eggs occur at five sites located along a 3-km stretch of the coast of Bibongri of Boseong-Gun (Fig. 1). Seventeen egg clutches, several isolated eggs, as well as numerous shell fragments have been collected from or located within sedimentary deposits

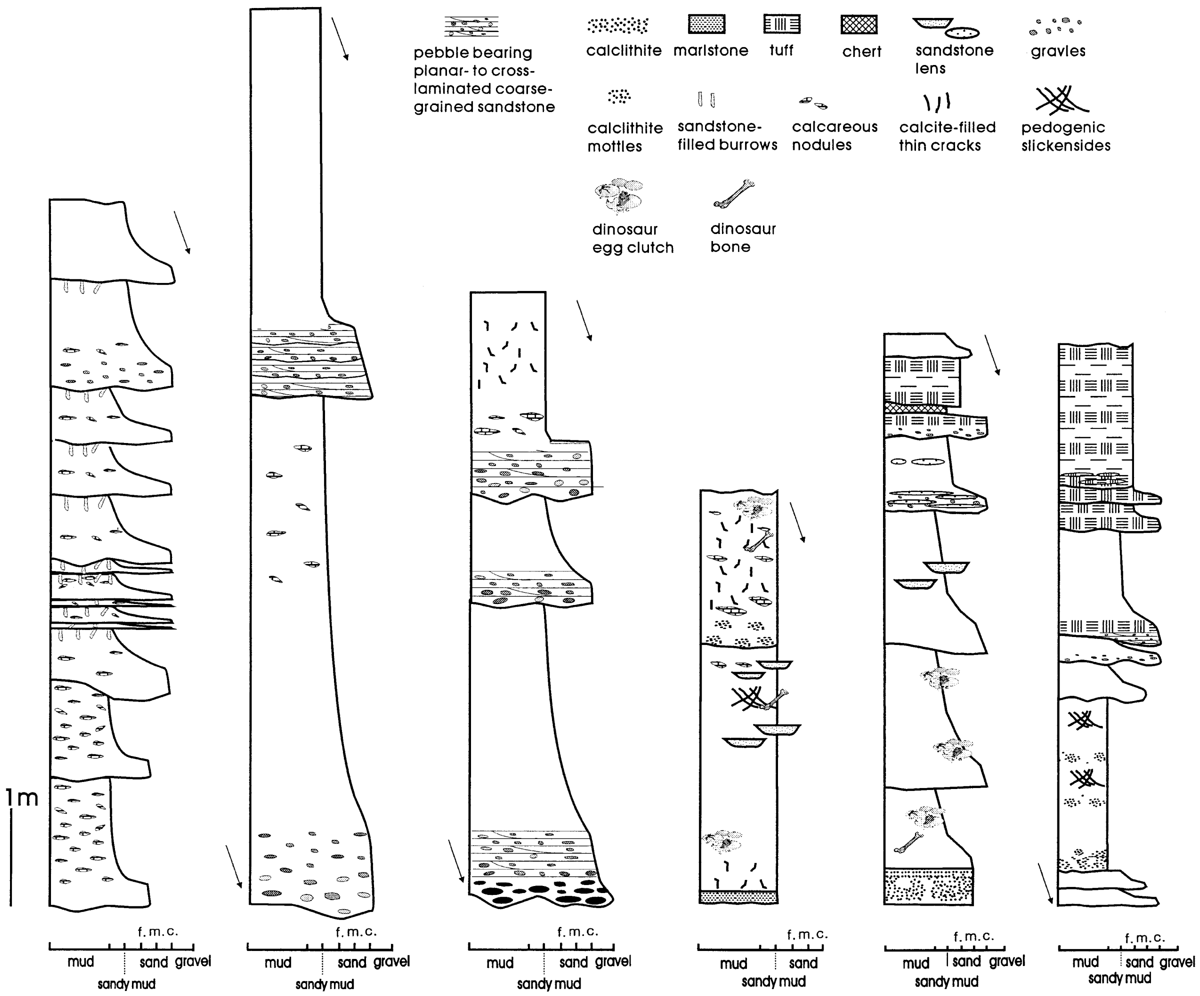

Fig. 3. Stratigraphic sections at site 3.

of this site. Eggs found in situ occur in at least six separate horizons (Figs. 2 and 3), although eggs are also found in blocks detached from the cliff face, and within unconsolidated beach deposits.

The clutches tend to occur about 30 m apart laterally in cross-section. At site 2, two clutches occur in the same section with a vertical separation of 30 cm (Fig. 4B). Two structural types of dinosaur eggs are known from the Boseong sites (Huh and Zelenitsky, 2002). The smaller eggs are spheroolithids (7–9 cm in diameter) while the larger eggs are faveoolithids (15–20 cm in diameter). Spheroolithid clutches contain up to eight eggs, whereas faveoolithid clutches contain up to 16 eggs. All clutches consist of unarranged eggs in a single layer and have been affected by postexposure weathering, and it is possible that the original clutch sizes may have been larger. Most of the eggs within clutches lack the

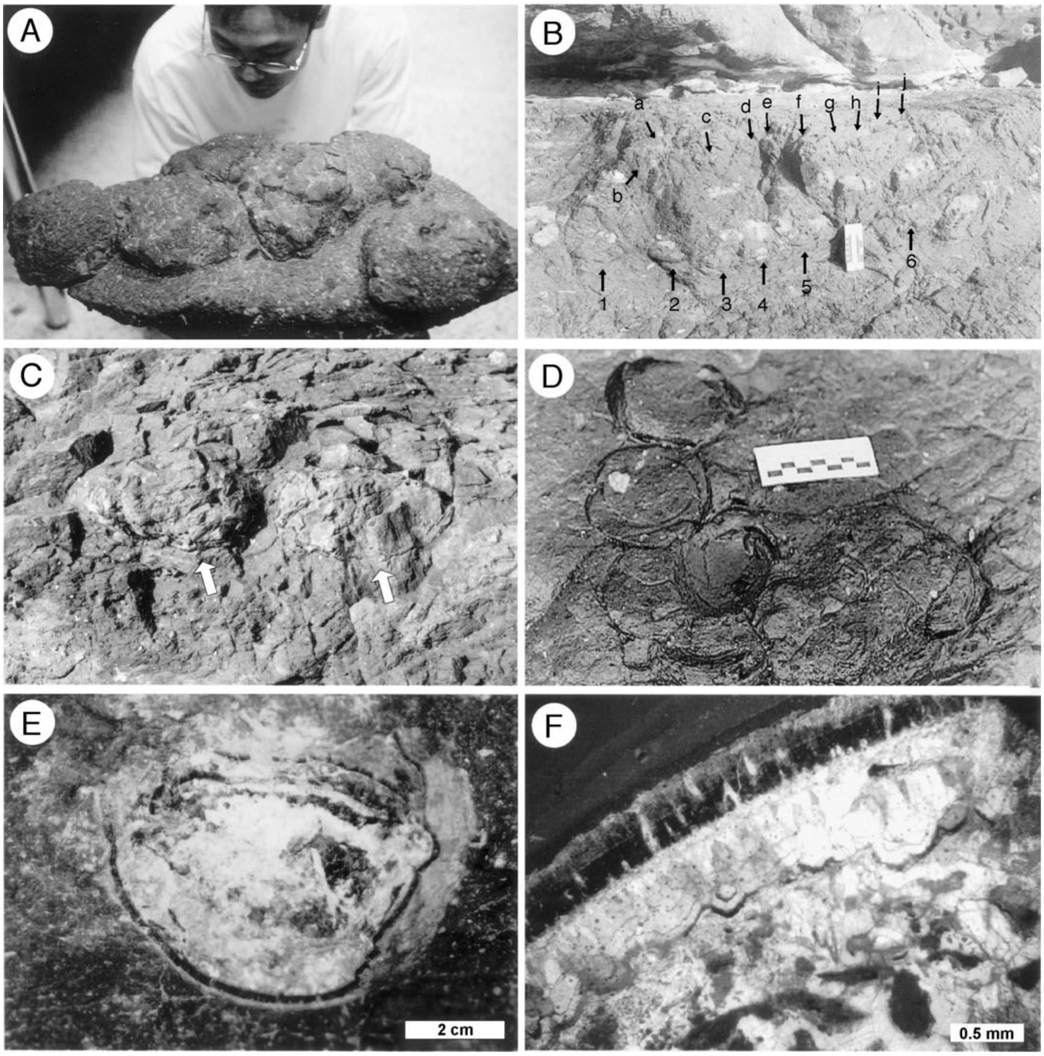

Fig. 4. Occurrence of dinosaur eggs at the Boseong sites. (A) Egg clutch preserved in sandy mudstone (site 1). (B) Partially exposed egg clutches preserved in two adjacent stratigraphic horizons (site 2). (C) Closeup of partial clutch showing the eggs with their tops removed (arrows). (D) Egg clutch showing subparallel distribution of shell fragments inside the eggs (site 2). (E) Isolated egg filled with calcite cement. (F) Thin-section photomicrograph of Panel E.

upper portion of the eggshell and may represent collapsed and/or hatched eggs (Fig. 4A,B,C and D). These ‘‘topless’’ eggs are sediment in-filled and often contain eggshell fragments stacked within, in a concave upward or inward orientation (Fig. 4D). One egg has 11 such layers of eggshell.

In places, isolated and unhatched eggs are also present. Some of isolated top-broken eggs are capped by concave downward eggshells (Fig. 4E). These eggs are not filled with sediment but with calcite cement (Fig. 4F). Such occurrence might have been attributed to the shelter effect of topping eggshells against sediment infiltration.

3.2. Dinosaur egg-bearing deposits

At the Boseong egg site, outcrops of the Seonso Conglomerate consist of pebble to cobble-bearing

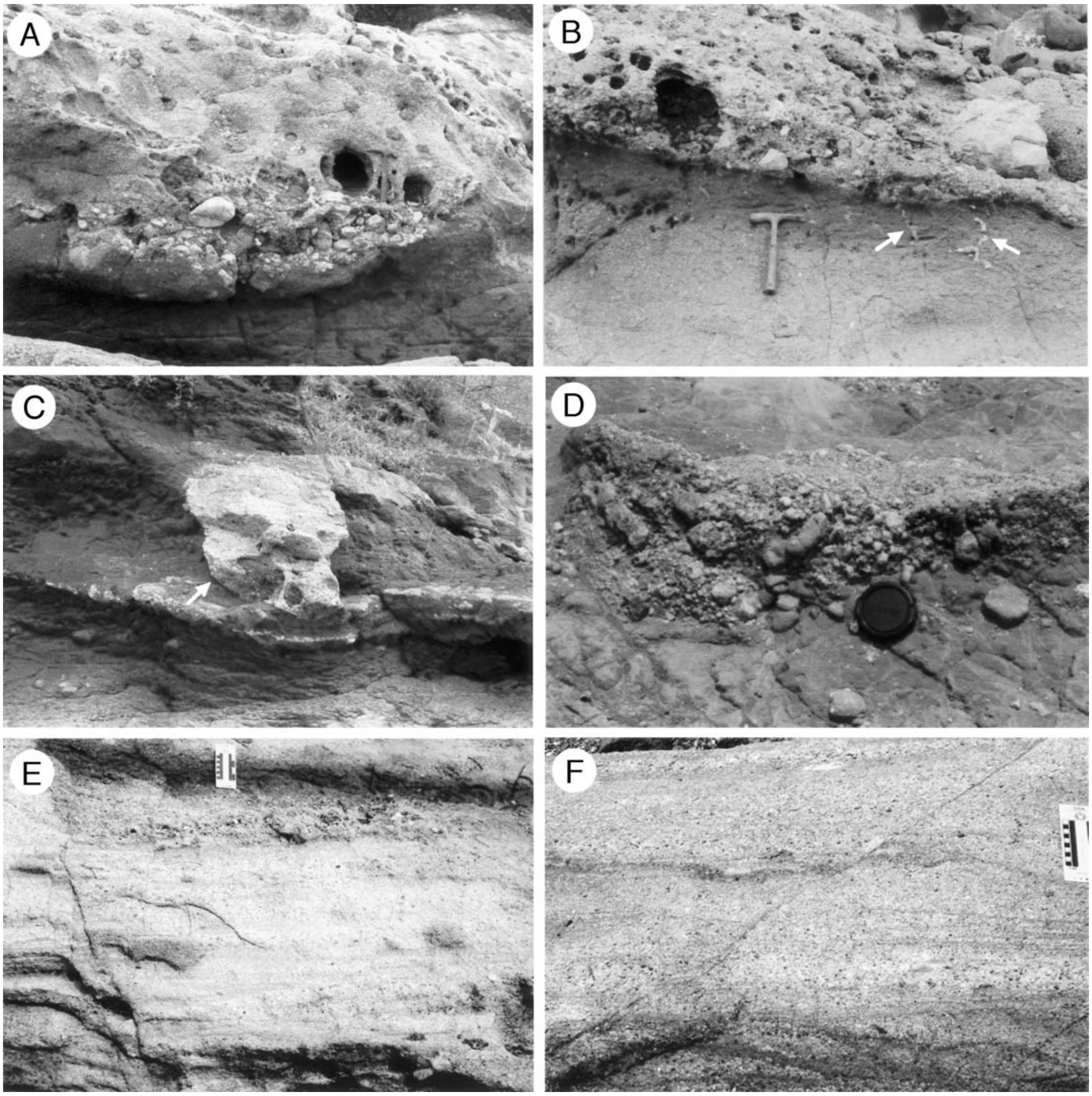

Fig. 5. Gravel-bearing coarse-grained sandstone. (A) Lag-gravels on erosive base. (B) Sandstone-filled burrows (arrows) below the sandstone. (C) U-shaped narrow channel deposit (arrow) formed on mudstone. (D) Lenticular channel deposit with lag-gravels. (E) Planar bedding and cross-bedding formed in the sandstone. (F) Planar bedded couplets consisting of pebbly coarse-grained sandstone and sandstone.

coarse-grained sandstone (greenish grey to variegated) that grades upwards into sandy mudstone to mudstone (purple), and the prevailing lithology changes vertically and laterally (Figs. 2 and 3). The gravel-bearing sandstones are dominated in the lower part, whereas mudstones are dominated in the middle part where the eggs are concentrated. In the upper part, tuffaceous deposits are common. The thickness of mudstones in the middle part increases eastwards. The gravels, sands, and muds comprising these rocks are primarily epiclastic, but partially tuffaceous. The coarse-grained sandstone beds commonly overlie the mudstone beds with a few cm to 2 m relief on the erosive contact. Lag gravels are usually present on the erosive surfaces (Fig. 5A,B,C, and D) and are generally poorly sorted and subangular to subrounded. Planar bedding and cross-bedding are common in the sandstone (Fig. 5E). Planar bedded couplets consisting of pebbly coarse-grained sandstone and sandstone are often observed (Fig. 5F). They are usually discontinuous and in places occur as U-shaped narrow channel fills (Fig. 5C) or lenses (Fig. 5D).

In contrast to the lateral discontinuity of most gravel-bearing, coarse-grained sandstones, one coarse-grained sandstone bed (Fig. 6A) extends 3 km and lies above the main egg-bearing deposits. It varies from a few cm to 30 cm in thickness and has abrupt contacts with an underlying mudstone bed and an overlying sandstone bed (Fig. 6B). Internal stratification is poor and, in places, flow-like texture is observed (Fig. 6C). Lithologically, this sandstone is calclithite that is primarily composed of irregularly shaped crystalline limestone fragments. The limestone fragments are moderately to poorly sorted and gener-

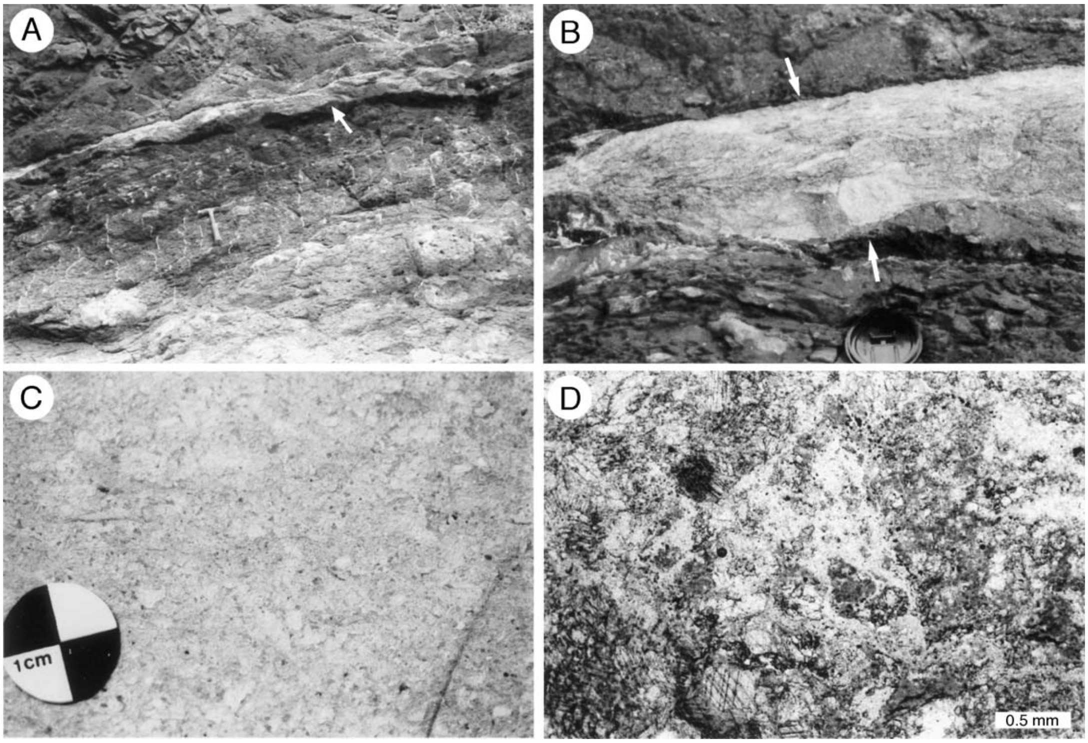

Fig. 6. Occurrence of calclithite. (A) Irregularly and continuously distributed calclithite bed (arrow) on the egg-bearing mudstone in which pedogenic calcrete nodules and calcite-filled desiccation cracks are well preserved. (B) Close view of Panel A showing sharp contacts (arrows) with both lower mudstone and upper sandstone. (C) Etched rock slab showing poor internal stratification with flow-like texture and irregular grain shape. Dark spots scattered throughout are hematite-coated grains. (D) Vesicular textures observed in the calcite grains. Thin-section photomicrographs.

ally subangular. Some grains have shard-like shapes, and flow or vesicular textures (Fig. 6D) are present in places. They show little evidence of compaction and are well cemented by calcite. Hematite-coated grains are scattered throughout the bed (Fig. 6C). This sandstone is used as a marker bed in this area due to its nearly homogeneous composition and extensive occurrence.

The mudstones are host to the dinosaur eggs and appear to show a variety of pedogenic features. Detrital grains in the mudstone exhibit calcite aureoles (Fig. 7A) and micrite rims, and these features are interpreted to reflect pedogenesis (Freytet and Plaziat, 1982). The micrite rims typically occur around crystalline limestone fragments (Fig. 7B). Pedogenic calcrete nodules (a few cm to 20 cm) are common in the mudstone. Some occur as rhizocretions (Fig. 7C), and circumnodular cracks are present around the nodules (Fig. 7D). Pedogenic circumgranular cracks (Fig. 7E) and peloids were observed in thin section. The pedogenic development of egg-bearing deposits varies both vertically and laterally. In one dinosaur egg deposit, in which clutches are mostly found, the degree of calcrete development varies laterally from stages 1 to 3 (Machette, 1985). Vertic features including pedogenic slickensides, pseudoanticlines (Fig. 7F), and calcite-filled deep desiccation cracks (Fig. 7G and H) (Paik and Lee, 1998) were also observed. Bioturbation in the mudstones is evidenced in the form of burrows (diameters of about 1 cm and lengths of a few cm) that lie immediately below sandstone beds (Fig. 5C). The burrows are perpendicular to subperpendicular to the bedding plane and filled with sandstone derived from the overlying sandstone.

Approximately 1 m below and above the calclithite bed, tubular or irregular mottles occur, in which calclithic grains are selectively concentrated (Figs. 8, 9A,B). The diameter of these mottles is circa 10 cm. The mottles are subparallel and subperpendicular to the bedding plane (Fig. 9B) and are interconnected in three dimensions. These mottles are presumed to have been resulted from a bioturbation. One invertebrate burrow filled with calclithite grains, which is intimately associated with the egg in the clutch, was also observed (Fig. 9C).

4. Palaeoenvironments, taphonomy and preservation

The absence of marine fossils and the common development of palaeosols within the Boseong egg deposits indicate that they are continental, and the abundance of channel deposits with erosive bases suggests that fluvial action was involved in their deposition. The upwards-fining units, which occur in repetition within Boseong egg deposits, may form in various alluvial environments such as alluvial fan, braided river, and meandering river (Miall, 1996; Reading, 1996). The common presence of narrow channel deposits filled with poorly stratified sandy conglomerate, the absence of multiple channel development, and the absence of point bar deposits indicate that they represent alluvial fan deposits (Nilsen, 1982; Blair and McPherson, 1994; Miall, 1996), although radial flow patterns and cone-shaped architecture can not be recognized due to limited outcrops. Their development in marginal area in the cauldron-type basin (Hwang and Cheong, 1968) supports an alluvial fan development.

Alluvial fans are characterized by a wide variety of depositional environments, including debris flow dominated fan, braided fluvial fan, and low-sinuosity/meandering fluvial fan (Stanistreet and McCarthy, 1993). The debris flow dominated fan has been divided into two types by Blair and McPherson (1994). One is dominated by sediment gravity flow deposits, and the other is dominated by sheetflow deposits. The absence of matrix-supported and unstructured or inverse-graded conglomerate beds, an abundance of planar laminated sandstones, the repetition of fining-upward intervals from conglomerate to mudstone, and the presence of calcic palaeosols and burrows in overbank mudstones indicate that sheetflooding was the dominant process during the formation of the Boseong egg deposits (Blair and McPherson, 1994; Galloway and Hobday, 1996). Sand- and mud-dominated alluvial fan deposits with a low portion of debris flow deposits, similar to those of the Boseong egg deposits, have been documented from the Miocene Seto Porcelain Clay Formation in Japan (Nakayama, 1999).

The successions of the Boseong egg deposits are comparable to those of terminal fan formed in arid to semiarid regions in the aspect of dominance by

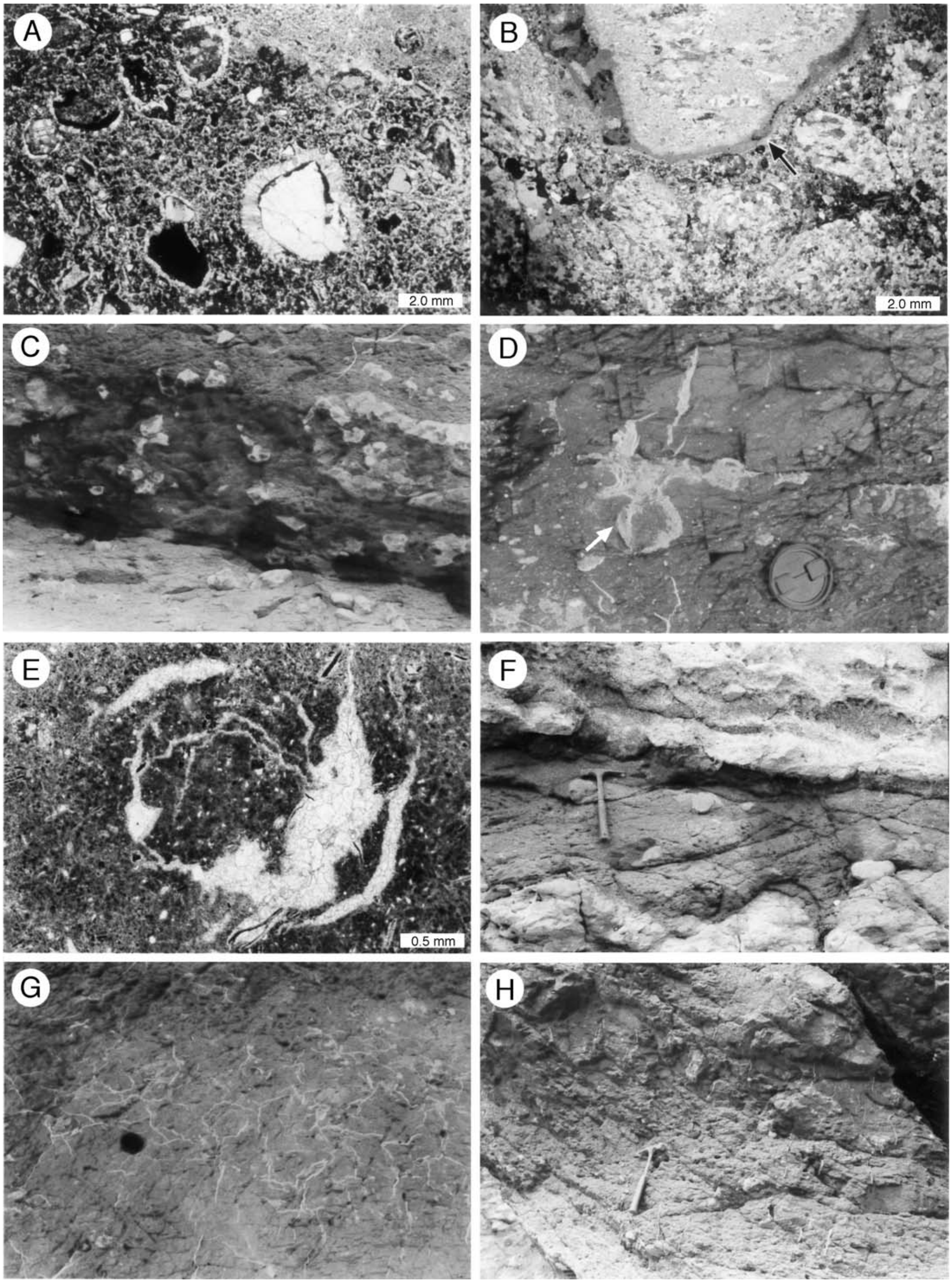

Fig. 7. Calcic and vertic palaeosols preserved in the egg-bearing mudstone. (A) Calcite aureoles around detrital grains, thin-section photomicrograph. (B) Micrite rim (arrow) on limestone fragment, thin-section photomicrograph. (C) Tubular to irregular pedogenic calcrete nodules. (D) circumnodular cracks (arrow). (E) Circumgranular cracks, thin-section photomicrograph. (F) Pseudoanticlines. Polygonal calcite-filled deep desiccation cracks on the surface (G) and in the section (H).

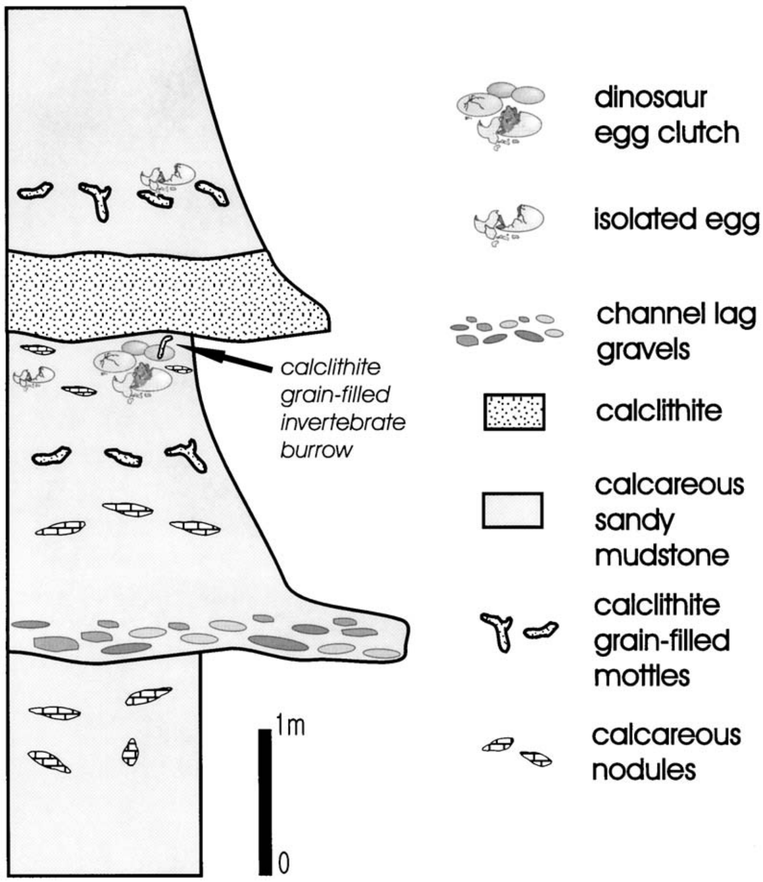

Fig. 8. Stratigraphic section of presumed bioturbation mottles occurring horizon at Boseong egg site 2.

fining-upwards units with sheetflood and overbank deposits (Kelly and Olsen, 1993). The common development of calcic palaeosols in the overbank deposits is characteristic feature in interchannel deposits of terminal fan (Reading, 1996). The common presence of narrow and shallow channel fills suggests that channel development was episodic and temporary, which is also indicative of terminal fan deposits (Kelly and Olsen, 1993; Miall, 1996; Reading, 1996). In general, terminal fan is divided into feeder, distributary, and basinal zones (Kelly and Olsen, 1993). The lower part of Boseong egg deposits is compared with feeder to distributary zone deposits, and the middle part is compared with distributary to basinal zone deposits.

Consequently, the nesting area is interpreted to have been situated on temporarily stable fan surfaces that were buried by sheetflood deposits. The lateral variation of peodogenic calcrete development in the egg-bearing deposits suggests that there was topographic relief in the nesting area.

The expansion of an arid flora into eastern Asia from the Albian to the Campanian (Vakhrameev, 1991) suggests arid palaeoclimatic condition during the Late Cretaceous on the Korean peninsula. The preservation of the dinosaur egg clutches in calcic and vertic palaeosols indicates that the palaeoclimate of the nested area was semiarid and seasonal with regard to water availability (Mack and James, 1994). The presence of hematite-coated grains in the calclithite supports a semiarid palaeoclimatic condition.

The common occurrence of dinosaur eggs in groups indicates that there was little postmortem disturbance of eggs at the Boseong site. The unar-

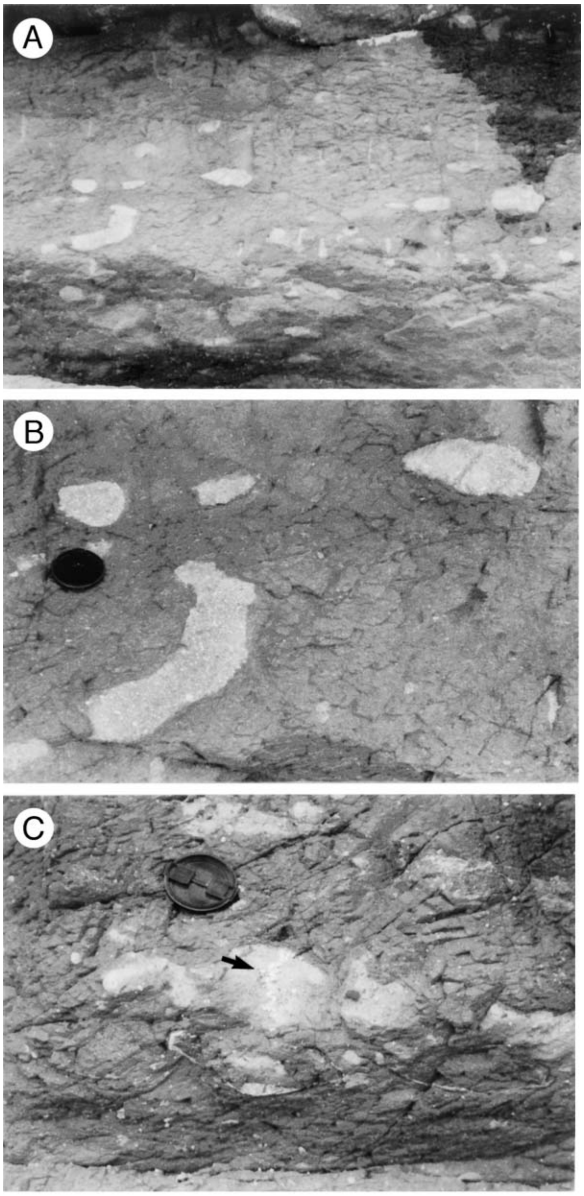

Fig. 9. (A) Calclithite grain-filled mottles (light gray) presumed to have been resulted from bioturbation. (B) Closeup of Panel A. (C) Calclithite grain-filled insect burrow (arrow) oriented into dinosaur egg in nest.

rangement of eggs in single or double layers in the clutch is typical of undisturbed clutches from other regions (Mikhailov et al., 1996). Futhermore, the preservation of most eggs with shell fragments inside and next to the eggs suggests that the eggs were not displaced after hatching. Such preservation can be explained in two ways: (1) the eggs were laid in above ground nests and later buried by eolian deposition as in some reports (Norell et al., 1995; Dong and Currie, 1996), or (2) the eggs were laid in nests excavated in the ground. The highly porous nature of the eggshells from Boseong (Huh and Zelenitsky, 2002) indicates that the eggs were buried during incubation (Seymour, 1979), although whether they were in mounds above or in excavation within the ground cannot be determined from the eggshells alone. It is certain, however, that the eggs at Boseong were buried by flooding events rather than by eolian processes. The lack of displacement of eggs and egg shells, the presence of some egg clutches 5–10 cm below flood deposits, and the porous nature of the eggshells suggest that the eggs were laid in excavated nests that were buried during incubation.

River floodplains have been documented as the best environments for the preservation of dinosaur eggs because proximity of nests to a body of water can result in their rapid burial (Carpenter et al., 1996; Martin, 2001). Based on the sedimentology, the Boseong dinosaur clutches were also located close to channels and could be buried readily by flooding. The development of vertic and calcic palaeosols, however, indicates that flooding was infrequent. After burial, the calcic soil condition likely contributed to the preservation of eggs. The extensive occurrence of calclithite associated with the egg clutches might have played a similar role in preserving the eggs. Calcic palaeosols also served as sites of egg preservation in the Upper Cretaceous of Southern France (Cousin et al., 1996), Uruguay (Faccio, 1996), Romania (Grigorescu et al., 1996), Mongolia (Mikhailov et al., 1996), and India (Sahni, 1997). Calcic palaeosols are also responsible for the preservation of dinosaur bones (Retallack, 1997; Paik et al., 2001b).

The preservation of numerous dinosaur clutches in several horizons of Boseong egg-bearing deposits suggests that Boseong site was exploited by dinosaurs as nesting sites. Such occurrence is comparable to a site fidelity that is habitual visitation of an area by a species of animal (Martin, 2001). The site fidelity of Boseong dinosaurs is deemed to have been related to the situation of Boseong site in a relatively arid region that had a low probability for eggs to be moved away by infrequent flooding. Consequently, Boseong site is considered to have been preferred by dinosaurs as nesting sites and to have been a suitable place for the preservation of eggs.

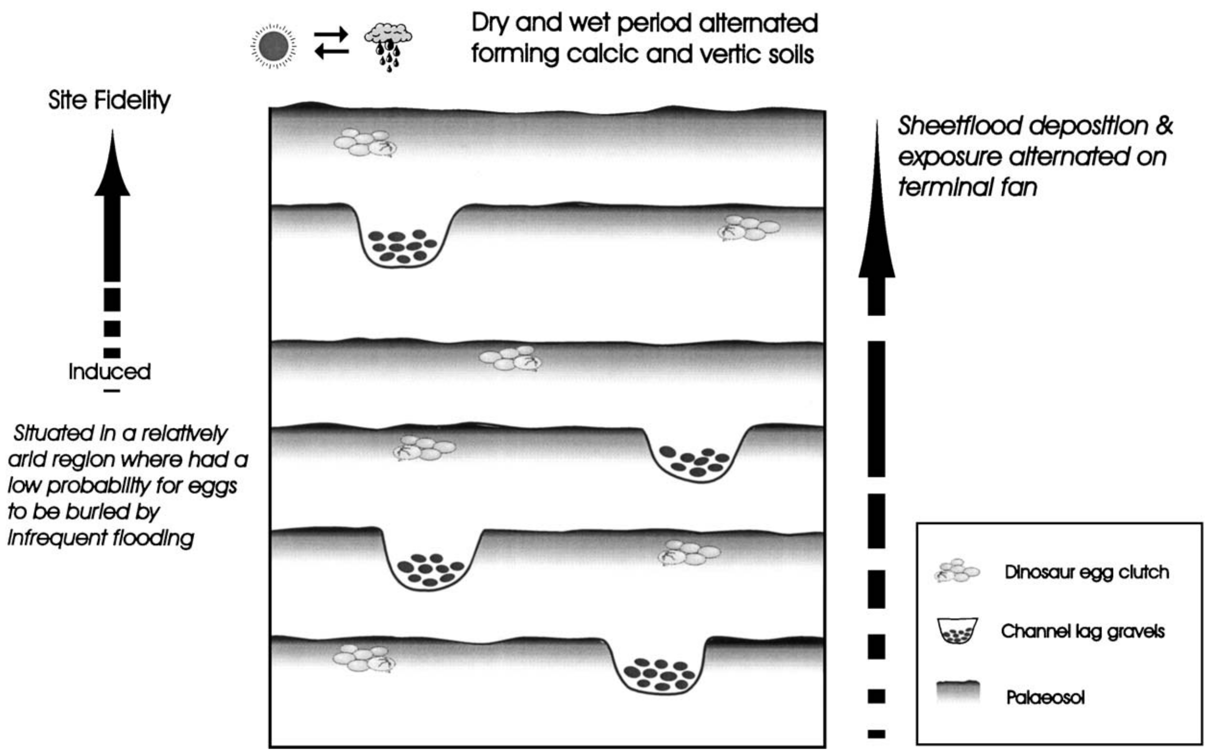

Fig. 10. Summarized diagram of palaeoenvironments and taphonomic preservation of Boseong dinosaur egg-bearing deposits.

5. Conclusions

(1) Dinosaur (sauropod and ornithopod) egg-bearing deposits of the Upper Cretaceous Seonso Conglomerate, Boseong, Korea are interpreted as terminal fan deposits.
(2) Boseong dinosaur eggs are preserved in calcic and vertic palaeosols, indicating that the palaeoclimate of the nesting area was semiarid.
(3) The preservation of numerous dinosaur clutches in several stratigraphic horizons of Boseong suggests that site fidelity may have typified dinosaur nesting in this region.
(4) Palaeoenvironments and taphonomic preservation of Boseong dinosaur egg-bearing deposits are summarized in Fig. 10.

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