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Dinosaur track-bearing deposits in the Cretaceous Jindong Formation, Korea: occurrence, palaeoenvironments and preservation

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Dinosaur track deposits of the Upper Cretaceous Jindong Formation, Korea, were examined from a sedimentological viewpoint to interpret their palaeoenvironments and conditions of preservation. The general depositional environment of the Jindong Formation was lake-margin to shallow lacustrine. Lake-margin deposits comprise most of it but the stable isotope values of the carbonates suggest an open lake. There are two types of dinosaur track beds. One is a discrete trackway deposit and the other is a dinoturbated deposit. All of the dinosaur trackways in the formation are preserved in interlaminated fine-grained sandstone to siltstone-mudstone deposits, which were deposited on a dry mudflat at the lake margin by sheetfloods and then underwent calcareous pedogenesis. The dinoturbated deposit was originally calcareous silty mud, reflecting deposition in a shallow lake of low energy. It was also modified later by calcareous pedogenesis. The trampling traces of dinosaurs in the Jindong Formation are recognized both on bedding surfaces and in sections. In places dinosaur tracks occur as 'overtracks' which are preserved in layers above the true tracks. The Jindong dinosaur track deposits are usually associated with pedogenic calcretes, which indicates that the climate at the time was seasonal and arid. Consequently, it is interpreted that the extensive and frequent preservation of dinosaur tracks in the Jindong Formation is the result of repeated deposition by sheetfloods on a mudflat associated with a perennial lake, which was utilized by dinosaurs as a persistent water source during drought, and subsequent development of calcareous pedogenesis in an arid climate.
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KEY WORDS: dinosaur tracks; Jindong Formation; palaeoenvironments; preservation; calcareous pedogenesis.

1. Introduction

Mesozoic deposits containing dinosaur footprints occur in many parts in the world, and their taxonomy classification, palaeoecology, biostratigraphy, palaeobiogeography, and palaeoenvironment of formation have all been considered previously (e.g., Gillette and Lockley, 1989; Lockley, 1991). There have been comparatively few sedimentologic and taphonomic studies of dinosaur tracks and track-bearing deposits despite their significance for palaeoenvironmental interpretation and understanding track preservation. Lockley and Conrad (1989) examined the palaeoenvironmental context, preservation and palaeoecological significance of dinosaur tracksites in the western USA on the basis of depositional setting of track-bearing deposits. Lockley *et al.* (1994) described the relationships between track assemblages and facies-defining vertebrate ichnofacies. Avanzini *et al.* (1997) reconstructed the palaeoenvironment of an Early Liassic tidal flat in northern Italy and interpreted track preservation from the sedimentology and geochemistry of a dinosaur tracksite.

In Korea, Cretaceous nonmarine deposits are distributed in several sedimentary basins including the largest and the thickest (over 9000 m thick) Gyeongsang Basin (Figure 1), and they contain many dinosaur footprints (Choi, 1999). Among them the Jindong Formation contains the largest number (Yang, 1982; Lim *et al.*, 1989). The Samcheonpo site (Figure 1), which is one of the most famous dinosaur tracksites in the world (Lockley, 1991; Lim *et al.*, 1994), is within the formation. Since the first report of dinosaur footprints at this site (Yang, 1982), many more tracks have been discovered in this formation. It is thus a very useful deposit for understanding preservational modes and conditions of dinosaur track

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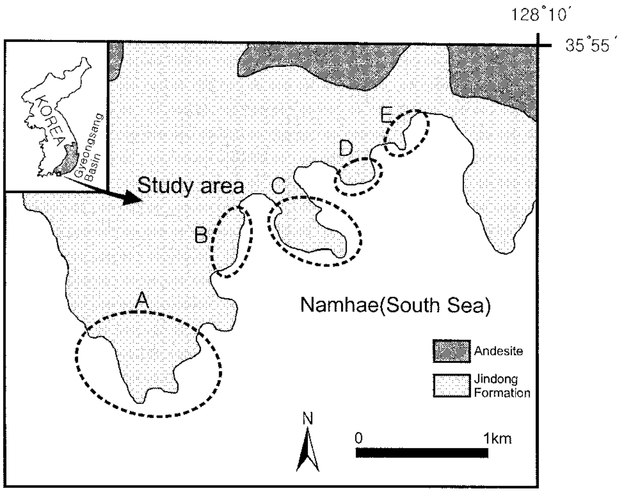

Figure 1. Location map of study area (Samcheonpo site). Measured sites: A, Silbawi; B, Bonghwagol; C, Dukmyeongri; D, Sangjokam; E, Jejeonmaeul.

registration. It has been interpreted as a succession of lacustrine deposits (Um *et al.*, 1983).

The objectives of this paper are to document various modes of track occurrences from a sedimentological viewpoint and to interpret the palaeoenvironments and preservational conditions of the tracks, based on the study of the general palaeoenvironments indicated by the Jindong Formation, the lithology of the Jindong dinosaur track-bearing deposits, and the occurrence of the dinosaur tracks in sections.

2. Geological setting

The Cretaceous non-marine deposits of the Gyeongsang Basin comprise the Gyeongsang Supergroup, which is divided into the Sindong, Hayang, and Yucheon groups in ascending order. These are interpreted as sedimentary successions that were deposited cyclically in alluvial fan, fluvial, and lacustrine environments (Um *et al.*, 1983; Choi, 1985).

The Jindong Formation (Late Cretaceous) is the uppermost section of the Hayang Group, and is over 2400 m thick. It is characterized by the frequent occurrence of dark grey and thinly interlaminated fine-grained sandstones and siltstones-mudstones (Figure 2) and by the repeated occurrence of mudcracks and small-scale symmetrical ripples (Figure 3). The general depositional environments represented in the study area are shallow lacustrine and lake margin. The deposits of the latter consist of calcrete-intraclast pebble conglomerate and pedogenic carbonate, in addition to the interlaminated sandstones, siltstones, and mudstones. Stromatolitic beds were described from the formations by Lim *et al.* (1989), but these are recognized here as partially calcretized, thinly interlaminated, siliciclastic beds. The shallow lacustrine deposits are composed of planar- and cross-laminated sandstones, flaser to lenticular bedded sandstones-mudstones and marlstones. Gastropod and ostracod shells and charophyte fragments are preserved in some of the marlstones; overall, however, fauna and flora are extremely rare throughout the formation. The general characteristics of the lithofacies are summarized in Table 1.

Rhythmic sedimentation, which is characterized by an alternation of calcrete-dominated beds and non-calcrete beds, is well developed in a few metre- to decimetre-scale units throughout the formation. The calcretes are mostly pedogenic palustrine carbonates. They occur as nodules, lenses, and beds. Such rhythmic sedimentation is interpreted to have resulted from alternating of wet and dry periods during deposition of the formation. Most of the tracks are preserved on these calcrete-dominated beds; the occurrences are summarized in Figure 4.

3. Jindong dinosaur track beds

The dinosaur track beds of the Jindong Formation are here separated into two types. One is the discrete trackway deposit and the other is a ‘dinoturbated’ deposit.

3.1. *Trackway deposits*

Most of the dinosaur track deposits observed are of the discrete trackway type. This means that each individual trackway is easily recognized and that trackway density is low enough to have prevented much overlap or extensive dinoturbation. They are recognized by the oriented distribution of subcircular or tridactyl depressions on bedding surfaces and some selective filling of breccias in these depressions (Figure 5). Without exception, this type of discrete trackway deposit in the Jindong Formation is in medium to dark grey fine sandstone (usually subarkosic) interlaminated with quartz siltstone-mudstone deposits; most of the underlying and overlying deposits also consist of the same lithofacies. The coarser laminae contain mudstone and/or lime-mudstone intraclasts in places, and mica flakes are commonly scattered through the siltstones and mudstones. In some mudstone laminae sand-filled evaporite mineral casts (Paik & Kim, 1998) are present (Figure 6A). The couplets of fine sandstone-siltstone and mudstone laminae usually show normal micro-grading, with a sharp lower contact and a gradational upper contact with coarser laminae.

Table 1. Lithofacies of the Jindong Formation.

Lithofacies	Characteristics	Depositional environment
Interlaminated to thinly interbedded fine sandstone–siltstone-mudstone	Graded within each layer with sharp lower contact; planar- to cross-laminated in sandstone layers; ripples occasionally present; mudcracks common; teepee structures associated in places; dinosaur tracks common	Lake margin (mudflat)
Planar- to cross-laminated sandstone-siltstone	Thin- to medium-bedded; graded; ripples present; burrows occasionally present; occasional mudstone flakes	Shallow lake
Megarippled sandstone	Thick-bedded; graded; planar- to cross-laminated; erosive base; mudstone chips common	Shallow lake
Graded sandstone	Medium- to thick-bedded; graded; erosive base; mudstone drapes common; mudcracks present in places	Shallow lake to lake margin
Marly siltstone	Thin-bedded; graded; burrows occasionally present; gastropods in places	Shallow lake
Planar- to cross-laminated siltstone-mudstone	Thin-bedded; graded; wavy-laminated in places	Shallow lake
Climbing-rippled, fine-grained sandstone-siltstone	Thin-bedded; long wavelength (over 50 cm); graded; aggraded	Shallow lake
Flaser- to lenticular-bedded fine-grained sandstone–siltstone-mudstone	Thin-bedded; planar- to cross-laminated; wave and current ripples present, bidirectional; mudcracks in places	Shallow lake
Pebbly coarse-grained sandstone	Thin-bedded; graded; pyroclastic	Lake margin
Intraclastic conglomerate	Thin-bedded; erosive base; graded; channel-filled in places; pebbles edgewise oriented in places	Lake margin to shallow lake
Pedogenic carbonate	Nodular, lenticular, and bedded; micritic; circum-granular cracks, peloids, tubular fenestrae present; brecciated in places	Lake margin

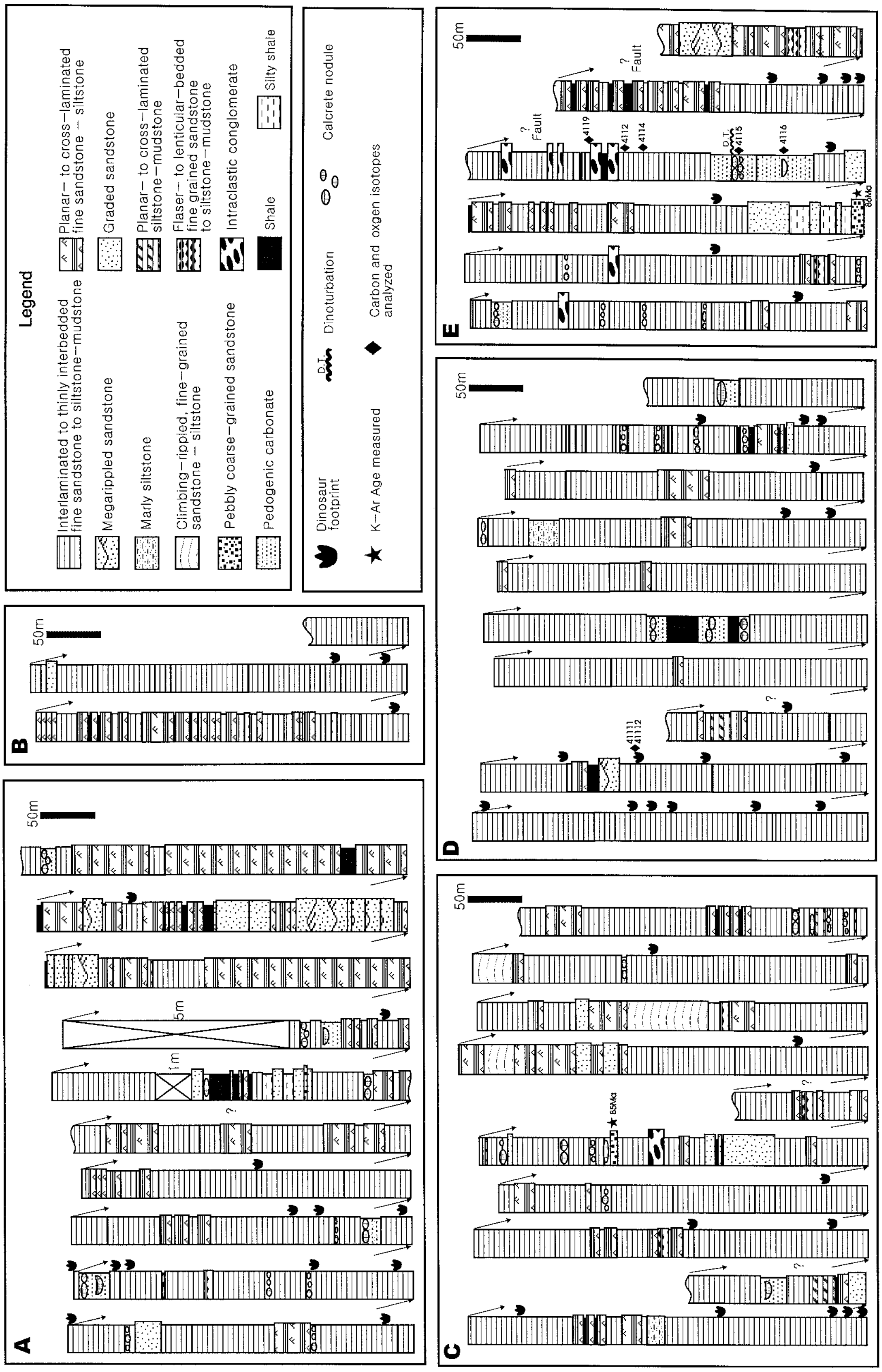

Figure 2. Stratigraphic sections of the measured sites shown in Figure 1.

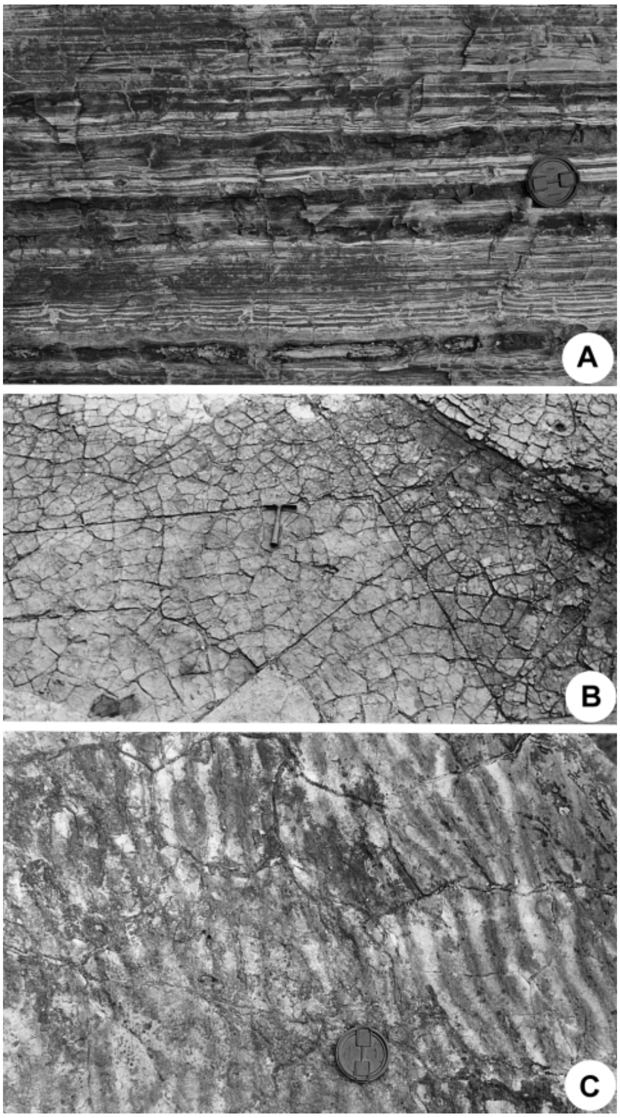

Figure 3. Sedimentological features of the Jindong Formation. A, section of thinly interlaminated fine-grained sandstone–siltstone-mudstone facies, the most common facies in the Jindong Formation. B, completely developed polygonal mudcracks formed on the surface of thinly interlaminated fine-grained sandstone–siltstone-mudstone facies. C, Polygonal mudcracks formed on the rippled sediments of thinly interlaminated fine-grained sandstone–siltstone-mudstone facies.

The fine sandstones are partially cemented by calcite, and pedogenic calcrete nodules are present in some trackway deposits. Characteristically some trackway deposits are partially calcified. Calcification has occurred in two ways: (1) by micritization of the surface of track deposits (a few mm to a few cm deep; Figure 6B); (2) by deposition of calcite rinds (less than 1 mm thick) around intraclasts and on eroded surfaces (Figure 6A). The intraclasts are usually mudstone flakes, some of which have been completely replaced by micrite. They are deformed and partially fragmented. The calcite rinds on the eroded surfaces are discontinuous. They usually consist of two laminae, a micritic inner layer overlain by fibrous calcite.

Mudcracks are commonly present on the bedding surfaces of trackway deposits. Ripples and some invertebrate trace fossils are typically associated with them. The mudcracks are usually polygonal on undisturbed surfaces, but some are concentric within and around subcircular footprints (Figure 7). In places, teepee structures are present. The ripples are generally small-scale, and mostly symmetrical and slightly sinuous. The invertebrate trace fossils include trails that are generally a few millimetres in diameter, and circular resting marks about 1 cm in diameter and a few mm deep. Bird tracks occur in places (Lockley *et al.*, 1992). In general, the degree of bioturbation is very low.

3.2. Dinoturbated deposits

Lim (1990) reported a few dinoturbated deposits from the Jindong Formation. Among them only one, which was mentioned by Lockley (1991), is considered here. The deposit concerned is about 50 cm thick and exposed as a coastal platform with a surface of over 400 m^2 (Figure 8A). It is distinguished by its very rugged surface and buff-weathering colour. The dinoturbated surface comprises over 80% of its areal extent. On the bedding surface, however, footprints are indistinct and appear as randomly distributed, irregular depressions at least 10 cm deep. It is not certain that the depressions resulted from dinoturbation, but it is quite likely. They are not a weathering feature and clearly predated the deposition of the overlying sediments. Some depressions are circular, and dinosaur footprints are common in layers below and above this deposit. Polygonal mudcracks occur on both presumed dinoturbated and clearly non-dinoturbated flat surfaces.

It is characteristic of this presumed dinoturbated deposit that pedogenic calcrete occurs in the form of massive hardpan about 40 cm thick (Figure 8B). The original lithology of the deposit was calcareous, quartzose, silty mudstone with some ostracod and charophyte fragments. The pedogenic features include downward calcretization that resulted in a sharp upper contact and a gradational lower contact, circumgranular cracks, fitted peloids, brecciation, microstromatactis cavities, and irregular fenestrae. These are characteristic of alpha-calcrete (Wright & Tucker,

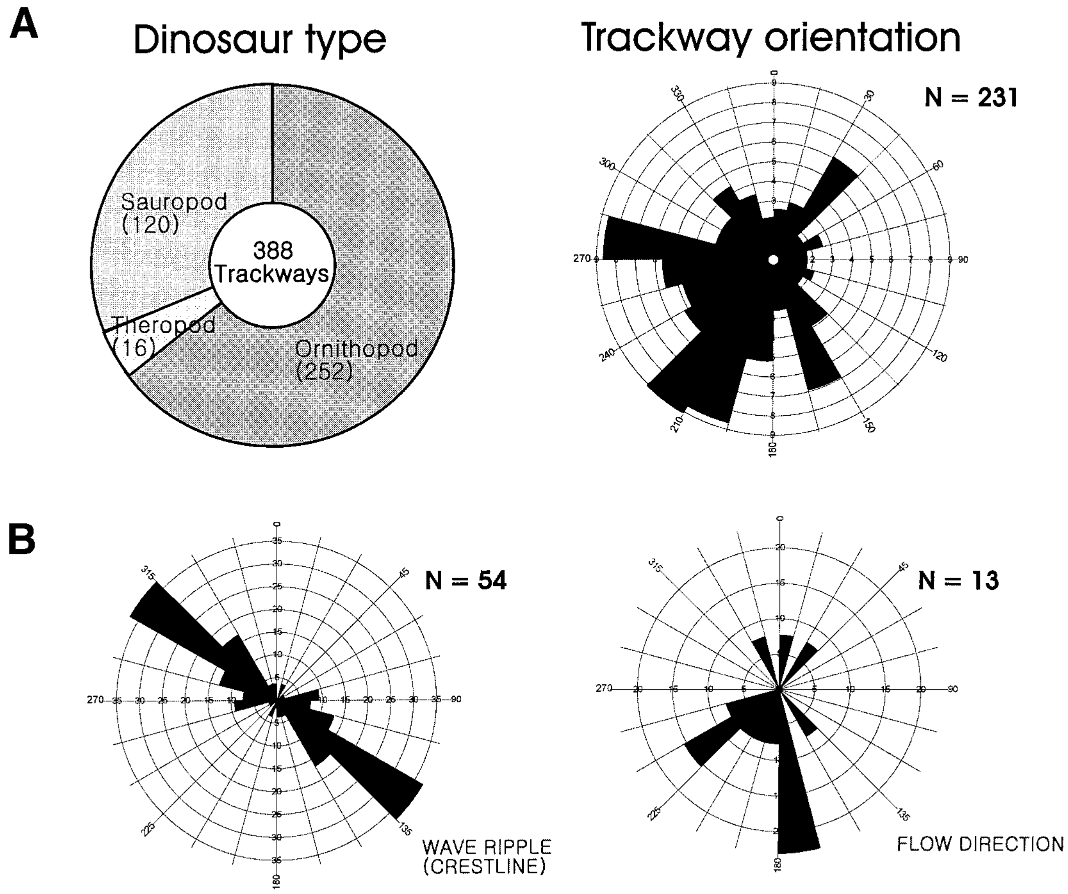

Figure 4. Summary of the occurrence of Jindong dinosaur tracks (after Lim, 1990; Lim *et al.*, 1994).

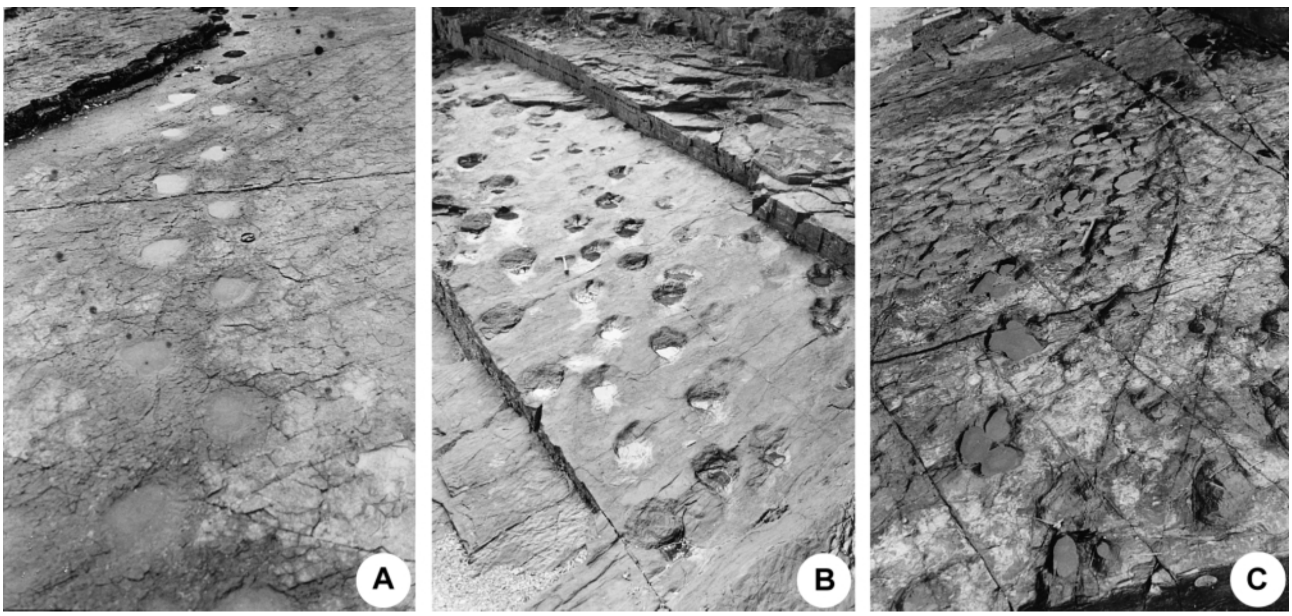

Figure 5. Surface views of dinosaur trackways. A, subcircular depressions. B, subcircular to semi-tridactyl depressions generated by tracking of several dinosaurs. C, tridactyl depressions.

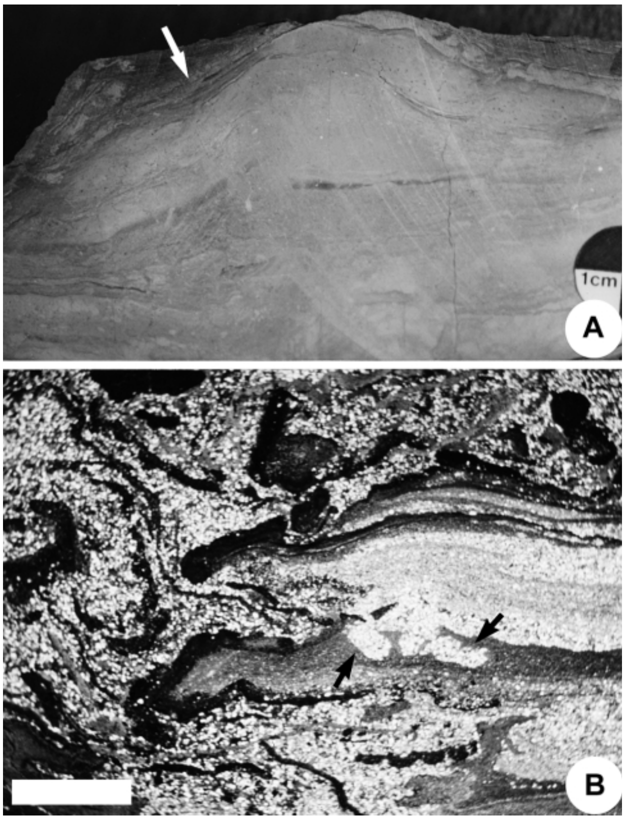

Figure 6. A, calcified crust (arrow) formed on the upper surface of dinosaur track deposit, sawed rock slab. B, thin-section photomicrograph. Calcite rinds on the trampled surface and spalled-off flakes. Hemibipyramidal casts (pseudomorphs after evaporite minerals: arrows) occur in the trampled deposit (thinly interlaminated fine-grained sandstone–siltstone-mudstone). Scale bar represents 2.5 mm.

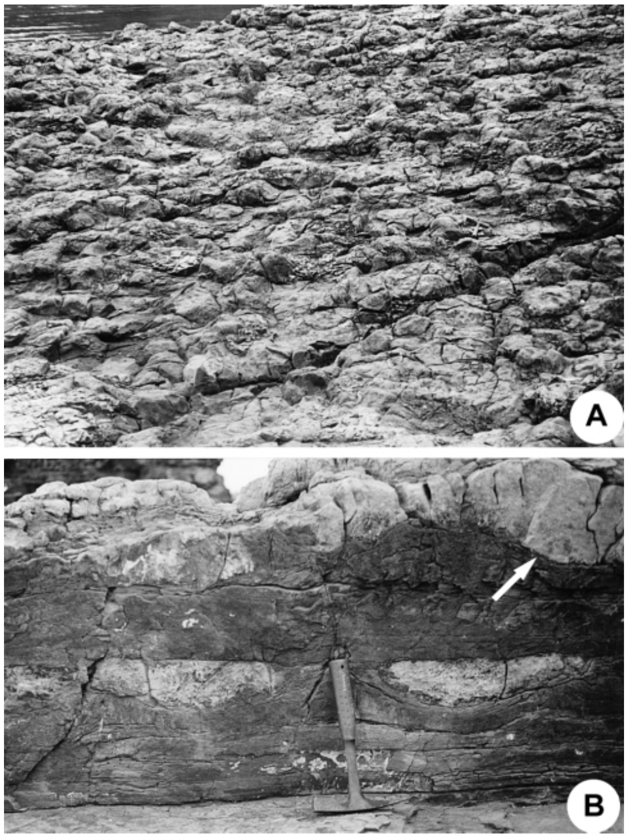

Figure 8. Surface overview (A) and sectional view (B) of dinoturbated deposit. A, preservation of rugged surface resulting from calcretization of dinoturbated surface. Polygonal mudcracks occur on the surface. B, pedogenic nodular to bedded calcrete (arrow) formed in the upper layers of dinoturbated deposit. The lenticular calcrete nodules occurring in the underlying layers are also pedogenic.

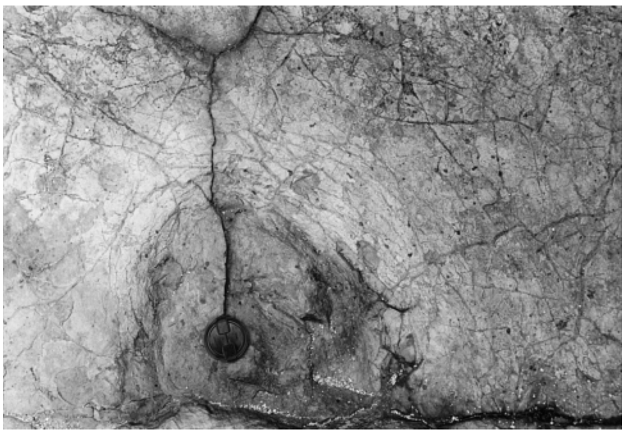

Figure 7. Concentric desiccation cracks formed around dinosaur footprint. Mudcracks beyond the footprint are polygonal (camera lens cap for scale).

1991), and have been documented in other pedogenic calcretes (Read, 1976; Freytet & Plaziat, 1982; Esteban & Klappa, 1983; Ettensohn *et al.*, 1988; Retallack, 1988; Paik *et al.*, 1997). The presence of calcrete intraclasts in overlying layers underpins the pedogenic origin of the calcretization. In places subrhombic to subrectangular or bipyramidal pores filled with sparite are present within the calcrete. These pores are deemed to be evaporite casts resulting from dissolution of minerals such as gypsum.

The calcrete development of the presumed dinoturbated deposit is greatest through the section of the Jindong Formation examined. A nodular calcrete layer (10 cm thick), which is also pedogenic, occurs just beneath the presumed dinoturbated deposit. Siliciclastic deposits consisting of planar- to cross-laminated fine-grained sandstones and silty shales

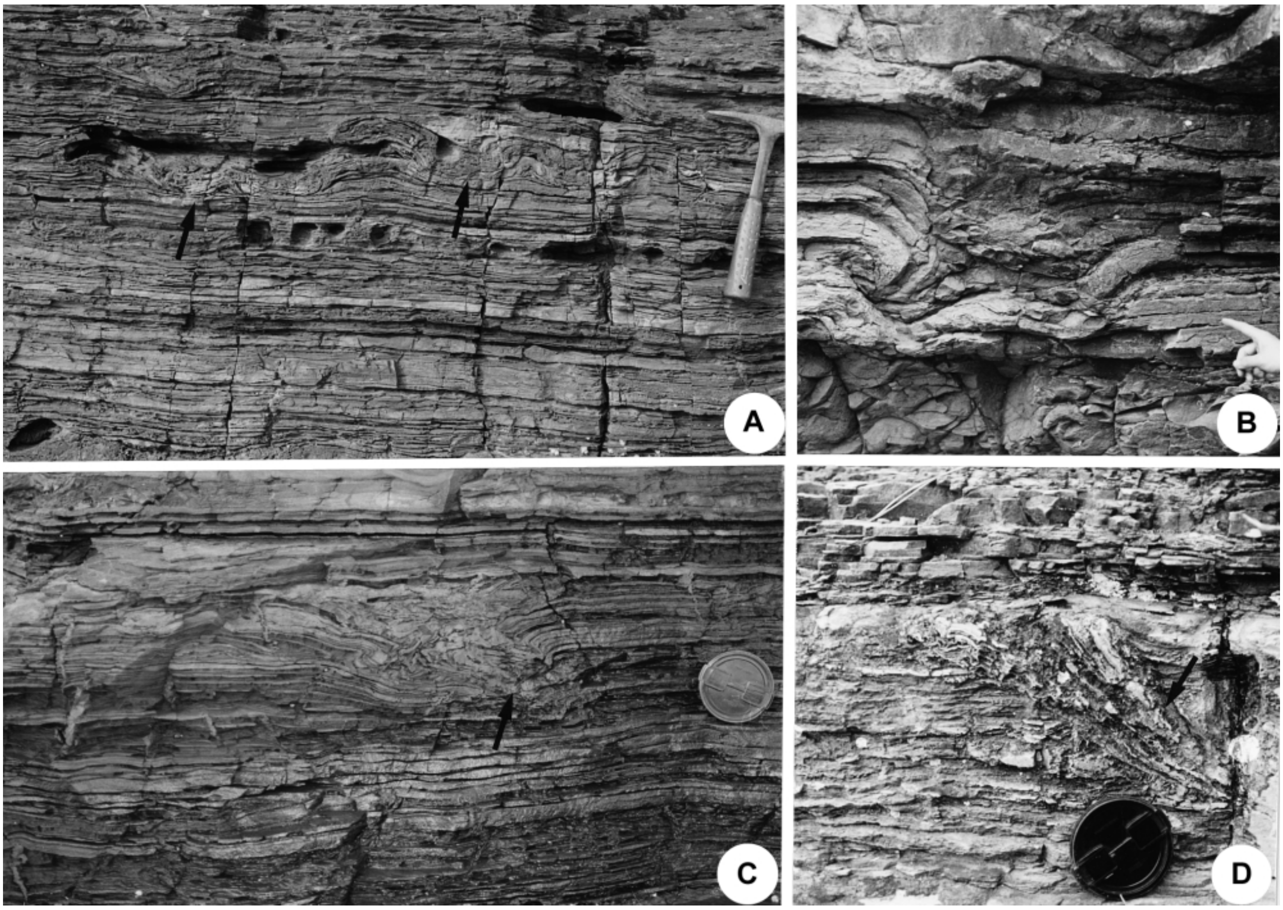

Figure 9. Sectional views of dinosaur tracks preserved in the Jindong Formation as diverse modes of depressions. A, low-angle and shallow depressions (arrows). B, subvertical, deep depression. C, D, pointed depressions (arrows).

with mudcracks are present below this; there is no calcrete development within these. Above the presumed dinoturbated deposit, calcrete layers a few centimetres thick are commonly intercalated with calcareous silty shales.

4. Sectional traces of footprints

Most dinosaur tracks are observed on bedding surfaces. Hence, their descriptions are usually based on surface features (Gillette & Lockley, 1989), although trampling by dinosaurs can leave impressions not only on depositional surfaces but also on subjacent deposits. Such impressions on underlayers are called undertracks or underprints (Lockley, 1991). Even with undertracks, two dimensional surface features are often conspicuous and command attention. Trampling traces of dinosaurs can be recognized in the profiles of underlayers, and many traces, which are deemed to be dinosaur tracks, are exposed in diverse forms in cross-section exposures of the Jindong Formation.

These sectional traces occur in interlaminated fine-grained sandstones and siltstones-mudstones in common with the trackway deposits, and are recognized by asymmetrical depression and syndepositional deformation. There are three types of asymmetrical depressions: (1) low-angle, shallow depressions (Figure 9A); (2) subvertical, deep depressions (Figure 9B); and (3) pointed depressions (Figure 9C).

Type 1 depressions are generally 20–40 cm wide and mostly less than 10 cm deep. The central parts of the underlayers are downwarped and their rims are bulged. In places the less steep rims show kinked deformation. Type 2 depressions are generally 40 cm wide and deep. The steeper sides of these depressions, which are nearly vertical, have formed faulted walls with drag folds in the underlayers. The upper parts of less steep sides also have faulted walls, but the underlayers of lower parts are downwarped, and the central parts are rarely deformed. Type 3 depressions are characteristically wedge-shaped and about 10 cm deep. Their steeper sides have formed

Figure 10. Preservation of dinosaur track by trapping sediments (arrow). Trampled layers are deformed (camera lens cap for scale).

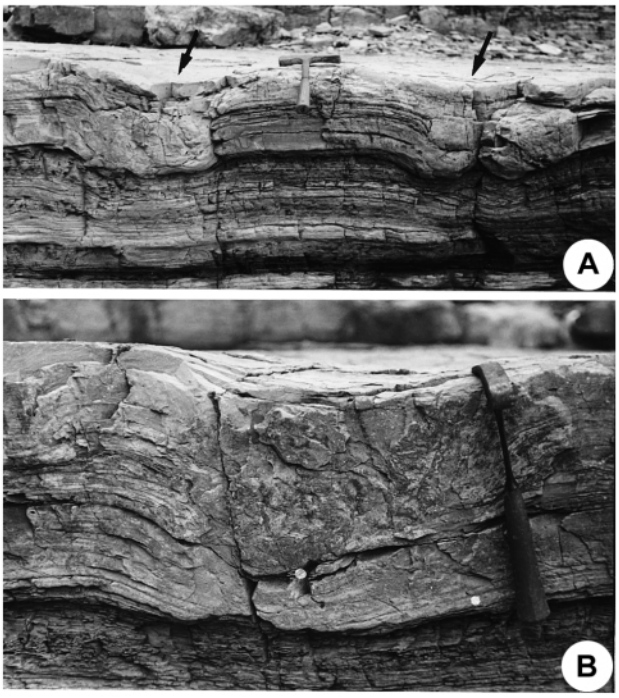

Figure 11. A, B, sectional views of 'overtracks' (B is close-up). The depressed upper layers are formed by the draping of trapping sediments over dinosaur tracks (geological hammer for scale).

faulted walls in the underlayers and drag folds as in type 2, whereas the underlayers of less steep sides are folded.

The preservation of footprints as track infilling is recognized in some profiles of depressions (Figure 10). The trapping sediments occur as downward-convex lenses. These commonly occur in couples about 20–30 cm apart, and are deemed to be transverse sections of trackway deposits. The trapping sediments are planar stratified, and some drape over the depressions. These draped trap sediments form subcircular depressions on some weathered bedding surfaces (Figure 11). Such depressions made on overlayers of the tracks can be called 'overprints' or 'overtracks', and their mode of preservation is illustrated in Figure 12. If the profiles of these track deposits are not seen, they may be misinterpreted as undertracks.

5. Geochemistry

A total of 17 carbon and oxygen stable-isotope analyses were performed on selected palustrine carbonates from the Jindong Formation (Figure 13). Sample powder ($\sim$10 mg) was drilled out under the microscope from the polished slabs using a dental drill. The drilling sites were checked by petrographic observation of thin sections. Powder samples were roasted under vacuum before reaction with phosphoric acids. Isotopic data were obtained by conventional techniques at the Korea Basic Science Institute. The results are expressed in parts per thousand with reference to the PDB standard. The reproducibility of carbon and oxygen isotopic values is ± 0.05‰ and ± 0.1‰, respectively.

Carbon and oxygen stable-isotope values for the Jindong Formation (Table 2, Figure 13) all plot clustered around -3.4‰ and -16.3‰ respectively, with spreads of $\delta^{13}C$ from -2 to -5‰ and of $\delta^{18}O$ from -15 to -17‰. The $\delta^{13}C$–$\delta^{18}O$ was held relatively constant, which is consistent with a stabilized lake environment (Arenas *et al.*, 1997).

The isotopic composition of carbonates in the ancient record can be used to distinguish between open and closed lakes (Talbot, 1990). The relatively small variations in $\delta^{18}O$ values of Jindong carbonates suggest that the carbonates originated in open lakes. The Jindong calcites with strongly negative $\delta^{18}O$ values could represent precipitation during a diluted stage, probably reflecting the input of $\delta^{16}O$-enriched waters of meteoric origin (Craig & Gordon, 1965). The low $\delta^{18}O$ values indicate that during precipitation of these calcites the lake water was undergoing little evaporation, which reflects a short residence time for the water. However, the inferred meteoric water composition is much depleted in ^{18}O compared to the estimated composition (-6 to -8‰ SMOW) of Early Cretaceous meteoric water in the Gyeongsang Basin (Lee, 1999). The alternative would be that the carbonates had experienced recrystallization at high temperatures (61–76°C; Friedman & O'Neil, 1977).

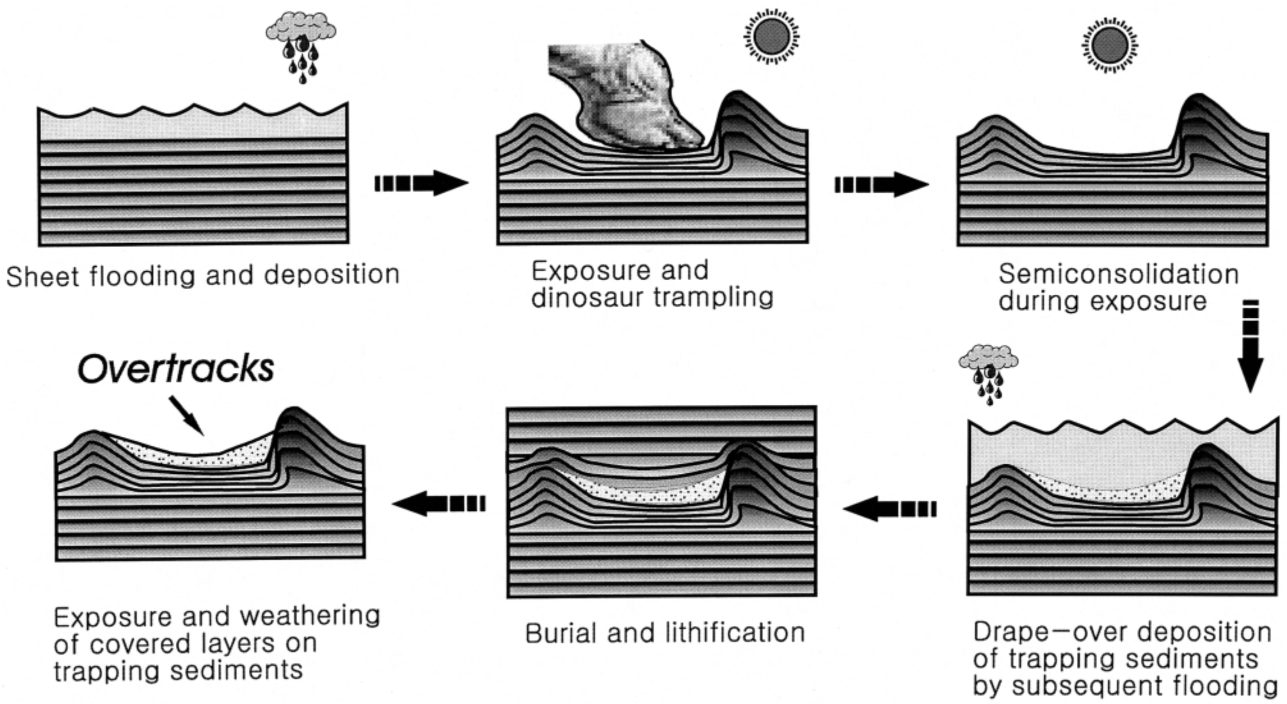

Figure 12. Schematic diagram showing the process of 'overtrack' development.

Table 2. Stable isotope compositions of Jindong carbonates.

Sample no.	$\delta^{13}C$	$\delta^{18}O$	Remarks
4112	− 3.5	− 16.2	limestone matrix
4114	− 2.6	− 16.3	limestone matrix
41111	− 2.0	− 15.5	limestone matrix
41112	− 3.4	− 15.7	limestone matrix
4115(1)	− 4.3	− 16.4	limestone matrix
4115(2)	− 4.5	− 16.6	limestone matrix
4115(3)	− 5.0	− 17.0	crack-fill marl
4115(4)	− 4.4	− 16.3	limestone matrix
4115(5)	− 4.1	− 16.4	limestone matrix
4115(6)	− 4.3	− 16.7	limestone matrix
4116(1)	− 3.4	− 16.4	limestone matrix
4116(2)	− 2.9	− 16.7	limestone matrix
4116(3)	− 3.8	− 16.4	crack-fill marl
4116(4)	− 2.5	− 16.2	limestone matrix
4119(1)	− 2.4	− 16.1	micrite pebble
4119(2)	− 2.2	− 16.3	micrite pebble
4119(3)	− 3.3	− 16.5	limestone matrix
average	− 3.4 ± 0.9	− 16.3 ± 0.3	

Considering calcite precipitation in lakes that became saline as a result of evaporative concentration under arid or semi-arid climatic conditions, as indicated by the presence of evaporite minerals, temperatures would have been higher than those calculated here.

Carbon isotope fractionation between dissolved carbonate (HCO_3^- and CO_2) is 8–10‰ at 25°C. Under isotopic equilibrium with atmospheric CO_2, which normally has a $\delta^{13}C$ of − 7‰, the lacustrine carbonate would have precipitated with a $\delta^{13}C$ composition of +1 to +3‰ (Romanek *et al.*, 1992) unless it was modified by photosynthetic activities of the vegetation in the lake. However, the lower carbon isotopic values of the Jindong carbonates record the

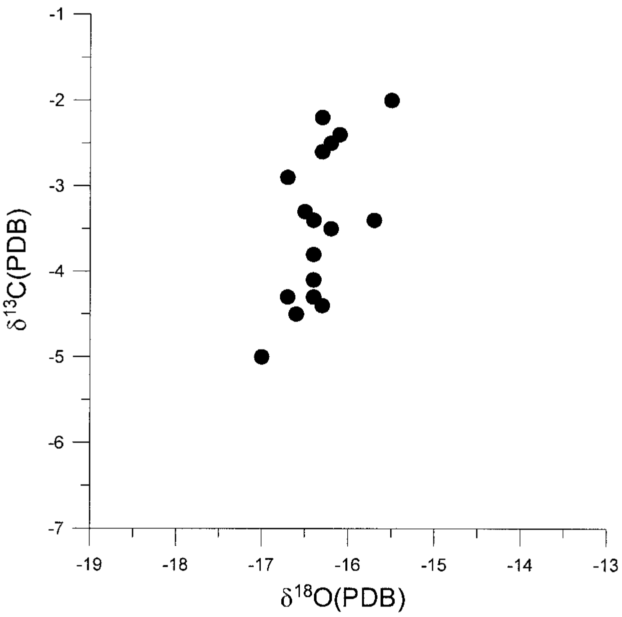

Figure 13. Isotopic compositions of the Jindong carbonates.

input of light CO_2 produced by the decay of organic matter. Although the spread of $\delta^{13}C$ is rather small, samples from the dinoturbated bed (sample number 4115) recorded the lightest isotopic compositions (-4.1 to -5.0‰). The more negative $\delta^{13}C$ values of the dinoturbated bed reflect greater pedogenic modification as mentioned above, recording more contact with isotopically light soil-derived CO_2.

6. Palaeoenvironments

The micrograding of sand laminae into mud laminae and the common presence of polygonal mud cracks in the Jindong dinosaurian trackway deposits indicate that they are consistent with sheetflood deposits on a dry mudflat at the margin of a lake (Smoot, 1983; Sanz *et al.*, 1994; Gierlowski-Kordesch & Rust, 1994). The presence of small-scale symmetrical ripples in the deposits suggests the influence of waves generated by subsequent lake expansion. The absence of any body fossils implies a hostile physico-chemical environment (Lim *et al.*, 1989). However, the common presence of invertebrate trace fossils and the dark grey colour of the discrete trackway deposits indicate that they contain organic matter, which might have been derived from the vegetation in the vicinity of the lake basin. Tiny carbonized plant fragments are observed in places. The abundance of herbivorous dinosaur tracks (Lim, 1990) supports the former existence of a vegetated area around the lake.

The repeated occurrence of mudcracks and wave ripples on a lamina scale indicates that inundation of the mudflat was brief and exposure was lengthy. Such a seasonal, semi-arid climate at the time of trackway formation is also indicated by the common presence of pedogenic calcretes in trackway deposits, as noted above. The calcareous lithology of the deposits and the presence of teepee structures and evaporite mineral casts also support this interpretation.

The depositional environment of the dinoturbated deposit differs slightly from that of the discrete trackway deposits. The presence of ostracod and charophyte fragments in the former and its marly composition suggest that it reflects shallow, low energy, lacustrine conditions. It is interpreted that the depth of water was shallow enough for dinosaurs to trample submerged substrates. The occurrence of marginal lake beds above and below the dinoturbated level, and its thickness of 50 cm, support this interpretation. The presence of polygonal mudcracks post-dating dinoturbation on the surface indicates, however, that the original deposit was subaerially exposed after being trampled. The mature development of pedogenic calcrete and the presence of evaporite mineral casts again suggest an arid climate; indeed, the advanced development of pedogenic calcrete in the dinoturbated deposit examined indicates that it was produced during one of the most arid periods of deposition identified within the Jindong Formation. Such mature petrocalcic horizons may have taken 6000 years or more to form (Retallack, 1983). The mean annual precipitation in the southwestern USA where such mature calcic palaeosols develop, ranges from 200–300 mm (Machette, 1985).

The arid climate and scarcity of plant remains preserved in the Jindong dinosaur track deposits contrast with the dinosaur track deposits of NE China and Tetori, Japan (Early Cretaceous), in the same palaeobiogeographical province, where the climate was humid and abundant plant fossils have been preserved (Matsukawa *et al.*, 1995). Nevertheless, the number of track beds greatly exceeds those of NE China and Japan. Such conflicting occurrences of evidence of the presence of a herbivore-dominated fauna in an arid setting with a scarcity of plant remains in the Jindong track deposits may be resolved by invoking drought. This occurred frequently in periodic and cyclic episodes, and many of the dinosaurs that inhabited vegetated land in the vicinity of the Jindong Lake probably frequented the persistent source of water during times of drought. Jindong Lake was likely to have been a perennial lake, considering the absence of bedded evaporite deposits and the presence of a thick succession of marginal lake deposits. The stable isotope values of the Jindong carbonates, suggestive of open-lake type, support this interpretation. The lake may also, or alternatively, have been a route used by dinosaurs that connected vegetated lands, as Avanzini *et al.* (1997) proposed for an Early Jurassic tracksite at Lavini di Marco, Italy. The repeated occurrence of dinosaur tracks in the succession of the Jindong Formation suggests, however, that the lake was mostly used as an inexhaustible water supply rather than merely as a travel-stop. Such an assumption is also supported by the fact that main direction of the trackways is NE-SW (Lim, 1990), which was apparently at right-angles to the shoreline (NW-SE) as inferred from the prevailing orientation of the crests of the wave ripples.

The dinosaurs must have congregated around the lake, and some could have died from drought-related hardship, although there is no evidence of this. The calcareous deposits would have been suitable for bone preservation (Retallack, 1997), but none has been found so far. This might have been a result of the very low rate of deposition of the track-bearing deposits. If dinosaur carcasses lay on a dry mudflat adjacent to the Jindong Lake and were not buried quickly, they might have been exposed long enough (hundreds to thousands of years) to have allowed development of pedogenic calcrete, leaving ample time for the complete weathering and disaggregation of bones.

7. Preservation

The presence of clay drapes and the desiccation or hardening of trampled substrates are considered to be important factors in the preservation of dinosaur footprints (Lockley & Conrad, 1989; Lockley, 1991; Avanzini *et al.*, 1997). The trackway deposits of the Jindong Formation reflect all of the prerequisites for preservation; hence, the numerous occurrences of footprints in the succession.

On the mudflats of the Jindong Lake dinosaurs trampled interlaminated deposits of sand and mud, which were partially to entirely saturated after sheet-flooding. The interlaminated nature with clay drapes enabled tracks to be impressed on the substrates. The clay drapes provided a suitable medium for preservation of the tracks, and the interlaminated sands underpinned the impressions so that they would not disintegrate. Lockley (1991) suggested that good tracks are commonly preserved after waning flood. Following trampling, the substrates dried and were exposed for long periods. Evidence of desiccation after trampling is indicated by the occurrence of mudcracks that cut across the footprints. However, the selective filling of breccias in some tracks suggests that in places trampling post-dated desiccation of the substrates. Prolonged exposure of the trackway deposits meant that they were subsequently cemented and influenced by calcareous pedogenesis under an arid climate, resulting in surface hardening. Subsequent floods would therefore have buried the trampled deposits without destroying the footprints.

The preservation of the Jindong dinoturbated deposits is interpreted in a similar way to that of discrete trackway deposits, the only difference being the nature of substrate. The tracks in the dinoturbated deposits seem to have been made on very soft substrates consisting of unlaminated muds distinct from those of the discrete trackway beds; this resulted in the formation of irregular and rugged impressions, which subsequently suffered from long exposure and were lithified subaerially by calcareous pedogeneis to form massive nodules and lenses. Such pedogenic growth of calcretes might have contributed to the destruction of track shapes.

It is concluded that repeated deposition by sheet-floods on the mudflats adjacent to a perennial lake, which was utilized by dinosaurs as a persistent water source during drought, and the subsequent development of calcareous pedogenesis in an arid climate, are the main reasons for the extensive and abundant preservation of dinosaur footprints in the Jindong Formation (Figure 14). It is probable that calcareous pedogenesis played a significant role in track preservation in many other Mesozoic dinosaur track-bearing deposits formed under arid climatic regimes; for example, those in the Jurassic Morrison Formation of Dinosaur Lake, Colorado, USA (Lockley, 1991) and in the Lower Liassic tidal flat deposits of Lavini di Marco in northern Italy (Avanzini *et al.*, 1997).

8. Conclusions

1. Dinosaur track beds of the Jindong Formation can be divided into two types; discrete trackway and dinoturbated.
2. All of the trackways in the formation are preserved in interlaminated fine-grained sandstones and siltstone-mudstones, which were deposited on the dry mudflats of a lake margin by sheetfloods and subsequently experienced calcareous pedogenesis. The dinoturbated deposit was originally a calcareous silty mudstone, which reflects low energy deposition in shallow lake and was similarly modified later by calcareous pedogenesis.
3. The trampling traces of dinosaurs in the formation are also recognized in profile. They occur in diverse forms: (1) low-angle and shallow depressions;

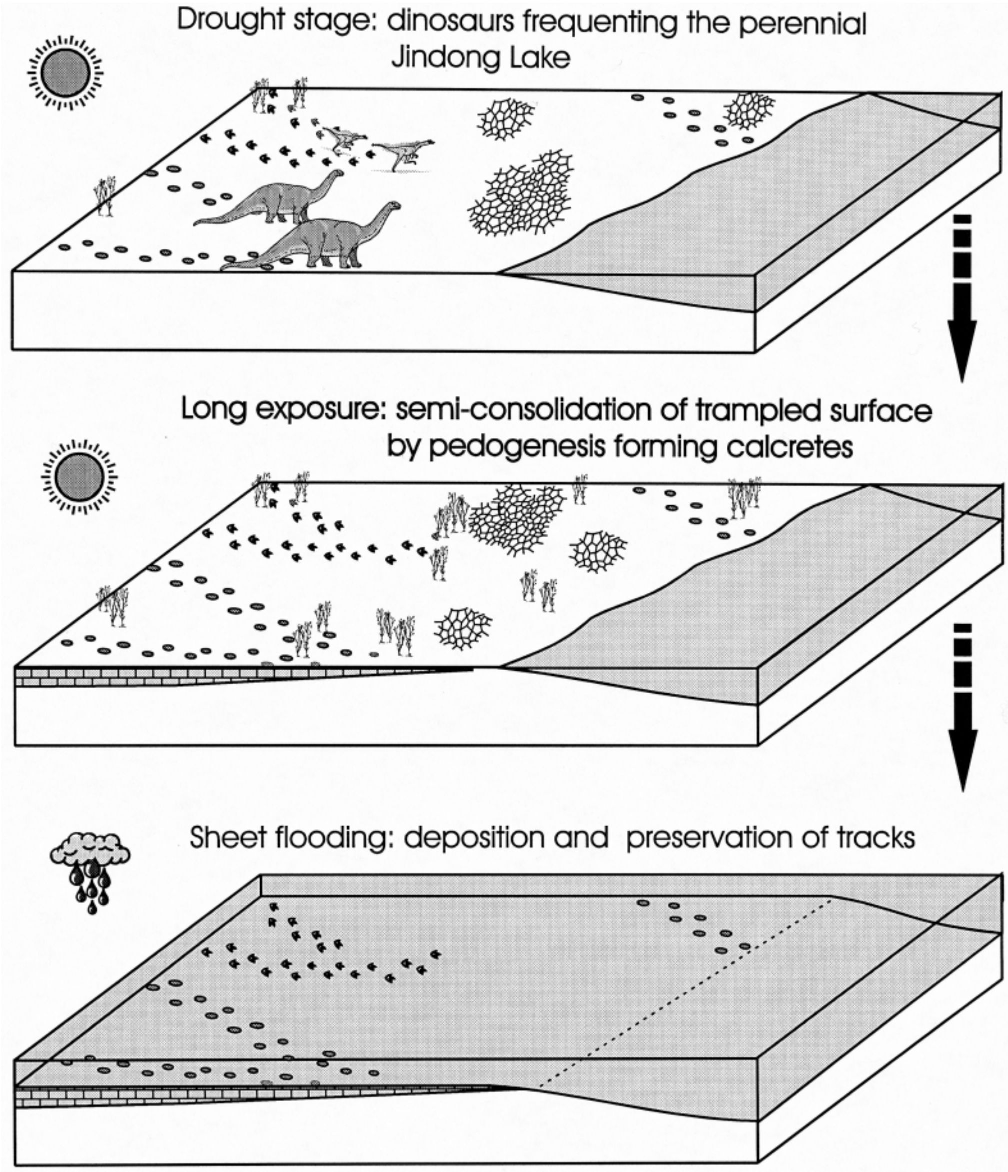

Figure 14. Schematic diagram showing the process of preservation of the Jindong dinosaur tracks.

(2) subvertical and deep depressions; and (3) pointed depressions. These may generally suggest the touch-down, weight-bearing, and kick-off phases identified in some footprints. In places dinosaur tracks occur as 'overtracks', which are preserved in layers above the true tracks.

4. The widespread preservation of pedogenic calcretes in the dinosaur track deposits indicates that the climate during their formation was seasonal and arid. It is thus inferred that repeated deposition by sheet-floods on the mudflats adjacent to a perennial lake, which was used by dinosaurs as a persistent water source during droughts, and the subsequent development of calcareous pedogenesis, were the main reasons for the extensive preservation of dinosaur tracks in the Jindong Formation.

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