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The Jangsan and Myeonsan formations (Early Cambrian) of the Taebaek Group, mideast Korea: depositional processes and environments

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ABSTRACT: The present study focuses on the depositional processes and environments of the lower part of the Taebaek Group (Cambrian-Ordovician) during the initial basin-forming inundation of the Taebaeksan Basin, an eastern margin of the North China platform. The lowermost part of the Taebaek Group is represented by two contrasting lithologic units, the Jangsan and Myeonsan formations. The Jangsan Formation consists of cross-bedded, massive, and foreset-bedded quartzose sandstone (quartzite) interpreted as shallow marine deposits ranging from inner shelf to nearshore environments. Deposition occurred in a stable cratonic basin where continuous subsidence and the accompanied sea-level rise accommodated large supply of sediments. The Myeonsan Formation comprises basal disorganized conglomerate, cross-bedded and laminated sandstone, and homogeneous or laminated mudstone, which largely formed in a tidally influenced restricted embayment. The formation is localized in the margin of the basin, as represented by the basal mass-flow conglomerate and the rapid transition to the tide-influenced marine succession. In the Early Cambrian, initial sedimentation in the Taebaeksan Basin was largely controlled by abundant sediment supply, accompanied with sea-level rise.

Key words: Depositional environments, Jangsan Formation, Myeonsan Formation, Taebaeksan Basin, North China platform

1. INTRODUCTION

The mixed siliciclastic-carbonate sequence of the Joseon Supergroup represents the first Phanerozoic sedimentation in the Korean peninsula. The lower part of the sequence consists of laterally extensive thick (ca. 200 m thick) quartzose sandstone (Jangsan Formation) and localized conglomerate and sandstone (Myeonsan Formation) which are overlain by thick mudrock (Myobong Formation). The Jangsan and Myeonsan formations are unfossiliferous, whereas the Myobong Formation contains trilobites of Middle Cambrian age (*Redlichia*, *Elrathia, Mapania*, and *Bailiella*) (Kobayashi, 1966). The sequence marks the major unconformity in the Taebaeksan Basin, overlying the Precambrian massif of granitic gneiss (1714–1825 Ma) (Kim, 1982). The quartzose sandstone of the Jangsan Formation is rather well-sorted, characterized by cross-bedded, stratified, and massive sandstones. The Myeonsan Formation consists of ca. 60-m-thick sequence of conglomerate, sandstone, and mudrock. It is stratigraphically equivalent to the Jangsan Formation, bounded by a dextral fault (Fig. 1).

Based on the cursory description of the outcrop sections of the Jangsan and Myeonsan formations in the Taebaek–Samcheok area, Son and Cheong (1965), Yun (1978), Kim and Cheong (1987), and Kim (1991) outlined the occurrence and stratigraphic relations and suggested that the deposits were largely formed in nearshore environments such as beach and tidal flat. A detailed study of sedimentary facies warrants to understand depositional environments and basin-fill processes during the initial stage of the basin formation. This paper presents the results of a detailed description of the outcrop sections in the Jeongseon–Taebaek area (Fig. 2), aiming at an interpretation of sedimentary processes and depositional environments. Since the equivalent sequences occur in North Korea and China, this study will help delineate the early evolutionary history of the North China Platform.

2. PREVIOUS WORKS

The Taebaeksan Basin occupies the mid-eastern part of the Korean peninsula and consists of mixed carbonate-siliciclastic rocks (Joseon Supergroup, Cambrian – Ordovician), and the unconformably overlying siliciclastic rocks (Pyeongan Supergroup, Permo-Carboniferous) (Fig. 1). The supergroup can be divided into five lithologic units: Taebaek, Yeongwol, Yongtan, Pyeongchang, and Mungyeong groups (Choi, 1998). The Taebaek Group consists of 11 lithologic units (about 1000–1400 m thick), which are subdivided into the Jikdong Subgroup (Cambrian) and the Sangdong Subgroup (Ordovician) (Table 1). The Jikdong Subgroup contains six formations: Jangsan (Js), Myeonsan (Ms), Myobong (Mb), Daegi (Dg), Sesong (Ss), and Hwajeol (Hj) formations, whereas the Sangdong Subgroup consists of Dongjeom (Dj), Dumugol (Dm), Makgol (Mg), Jigunsan (Jg), and Duwibong (Dw) formations, in ascending order (Table 1) (Choi,

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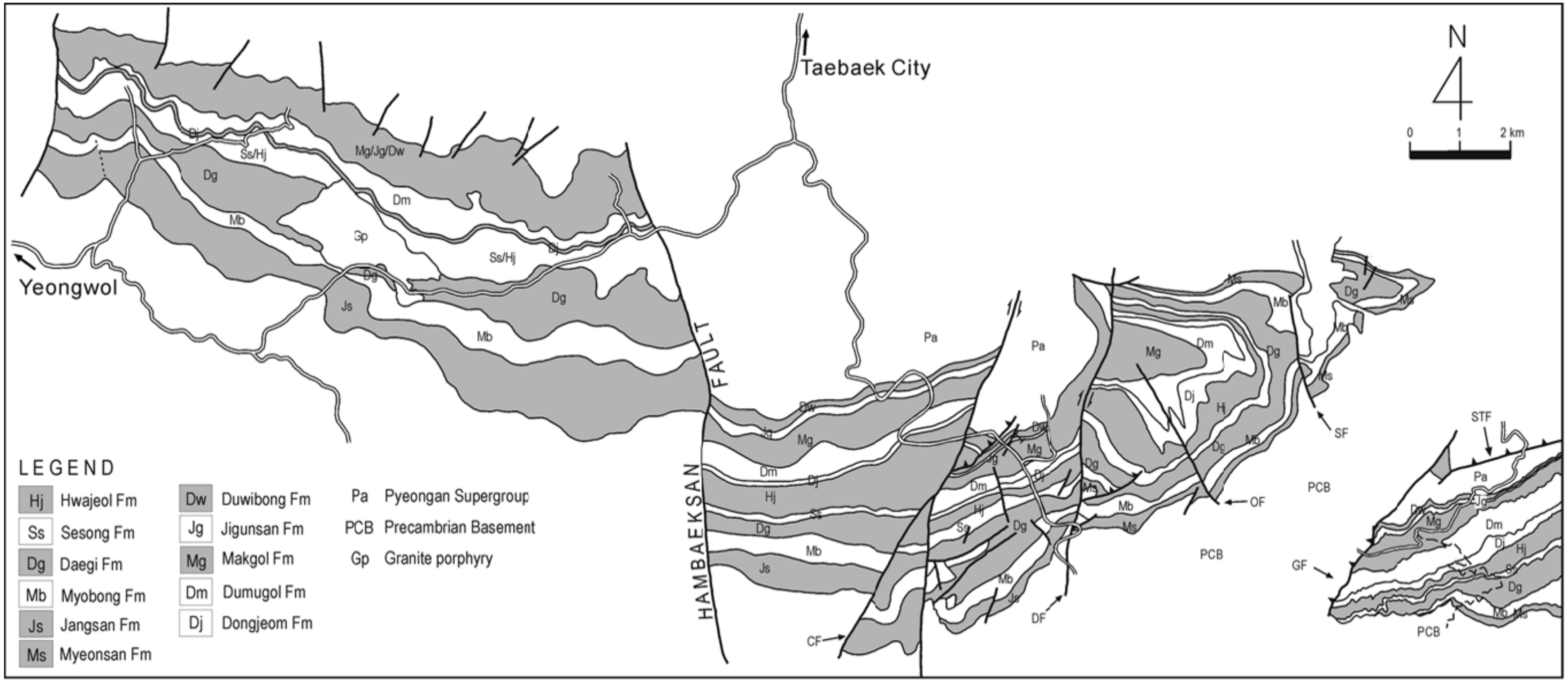


Fig. 1. Geologic map of the Taebaek area showing spatial distribution of the Taebaek Group. The Jangsan and Myeonsan formations are bounded by the Dongjeom Fault. CF= Cheolam fault, DF= Dongjeom fault, OF=Ohongol fault, SF=Seonwol fault, STF=Sambang thrust fault, GF=Gwanghwalri fault. Modified from GICTR (1962) and Chough et al. (2000).

Table 1. Stratigraphic nomenclature of the Cambro-Ordovician Joseon Supergroup in the Taebaeksan Basin (after Choi, 1998).

Geologic Age		Distribution									
		Yeongwol		Taebaek-Samcheok			Jeongseon		Pyeongchang	Mungyeong	
Ord.	Ashgill										
	Caradoc	Yeongwol Group	Yeongheung Fm				Yongtan Group	Haengmae Fm	Pyeongchang Group	Mungyeong Group	carbonate strata
	Llanvirn			Taebaek Group	Sangdong Subgroup	Duwibong Fm Jigunsan Fm Makgol Fm		Jeongseon Fm			
	Arenig										
	Tremadoc		Mungok Fm			Dumugol Fm Dongjeom Fm					
Cam.	Late		Wagok Fm Machari Fm		Jikdong Subgroup	Hwajeol Fm Sesong Fm					
	Middle		Sambangsan Fm			Daegi Fm Myobong Fm					
	Early					Jangsan/ Myeonsan fms					Gurangri Fm

1998; Choi et al., 2004).

The Taebaek Group consists mainly of sandstone (Js, Ms, and Dj fms), shale (Mb, Ss, lower Dm, and Jg fms), and carbonates (Dg, Hj, upper Dm, Mg, and Dw fms). The sandstone formed in offshore and shoreface environments (Yun, 1978; Woo and Park, 1989; Kwon et al., in press), whereas the shale and carbonate formed in deep and shallow ramp environments, respectively (Lee and Kim, 1992; Woo, 1999; Chough et al., 2000; Choi et al., 2004; Kwon et al., in press). The lowermost lithologic unit is represented by the laterally equivalent Jangsan and Myeonsan formations, bounded by the Dongjeom Fault (Kim and Cheong, 1987; Kim,1991; Chough et al., 2000; Choi et al., 2004). The Jangsan Formation (200–300 m thick) unconformably overlies the Precambrian granitic gneiss and metasedimentary rocks of the Yulli Group in the western part of the Dongjeom Fault (Chough et al., 2000), whereas the Myeonsan Formation (ca. 90 m thick) is well exposed in the eastern part and also unconformably overlies the Precambrian crystalline basement of granitic gneiss (Kim, 1982; Choi et al., 2004). The crystalline basement rocks range in isotopic age from 730 to 1925 Ma (Kim, 1982). Both the Jangsan and Myeonsan formations are underlain conformably by slate and shale of the Myobong Formation (80–250 m thick) which was assigned to the late Early Cambrian to the early Middle Cambrian (Kobayashi, 1966).

The Jangsan Formation consists of unfossiliferous milky white to light brown coarse-grained quartzose sandstone (quartzite) with quartzite and gneiss pebbles (Yun, 1978; Chough et al., 2000). On the other hand, the Myeonsan Formation is mainly composed of laminated sandstone, cross-bedded sandstone, mudstone, and thin basal conglomerate (Kim, 1991). The basal conglomerate bed of the Myeonsan Formation comprises well rounded, pebble-to-cobble-grade clasts of quartzite, slate, and granitic gneiss that are similar in lithology and geologic age to the basement rocks (Kim and Cheong, 1987). According to the petrographic study of the conglomerate, clasts were derived from the underlying basements rocks (Kim, 1991).

3. LITHOFACIES DESCRIPTION AND INTERPRETATION

3.1. Jangsan Formation

The outcrop sections were measured in well exposed road and stream cuts in order to describe the characteristics of sedimentary structures and texture. Table 2 summarizes the sedimentary features and interpretation of each facies of the Jangsan Formation. Both the occurrence of chlorite and sericite of low- to medium-grade metamorphism (Yun, 1978) and the quartz overgrowth are suggestive of post-depositional modification by diagenesis, metamorphism, and tectonic deformation.

3.1.1. Thin pebble layer (facies P)

This facies consists of a single-clast-thick layer of pebbles (Fig. 3A). The layer is mostly horizontal and occurs patchily on bedding plane (Fig. 3B). Pebble-grade clasts are common within the horizontally stratified sandstone. The layer is located in the middle of the sandstone facies with rare facies change across the pebble layer. Well rounded pebbles are composed of quartzite and metasedimentary rocks, and compositionally same as those dispersed in the sandstone.

The similarity of the pebbles to those in the massive or stratified sandstone and the frequent association with these facies are suggestive of a close relationship between the thin pebble layer and the sandstone facies. This facies formed probably by winnowing of pebble-bearing sands under agitating conditions. Similar accumulation of pebbles has been interpreted as a lag deposit winnowed by strong storm surges (e.g., Richards, 1986; Lindsey and Gaylord, 1992).

3.1.2. Massive sandstone (facies Sm)

This facies comprises well-sorted medium-to-very coarse quartzose massive sandstone (Fig. 4A). Sand grains comprise commonly spherical and angular quartz and heavy mineral grains (zircon and tourmaline), whereas fragments of metasedimentary rocks occur in minor amounts (Fig. 4B). Each facies unit is usually tabular and varies in thickness from tens of centimeters to several meters.

The lack of primary sedimentary structures can be ascribed generally to reworking of sediments by biogenic disruption, physical deformation or sedimentary processes such as rapid deposition (Tucker, 2003). The absence of remnants of bioturbation and water escape structures implicitly implies that the massive sandstone formed by primary depositional processes. The relaxation of sediment-laden storm currents could have resulted in rapid sedimentation of suspended sands (e.g., Levell, 1980; Soegaard and Eriksson, 1985; Simpson et al., 2002).

3.1.3. Trough cross-stratified sandstone (facies St)

It comprises well-sorted medium-to-very coarse sandstone with pebble clasts. The alignments of minerals such as biotite and the grain-size variations form the laminae. The cross-stratification shows low-angle and long-wavelength (about tens of centimeters) troughs (Fig. 5A). The height of the cross-sets is about 20–30 cm on average. The trough cross-beds are mostly unidirectional to weakly bidirectional. The small-scale cross-beds dip obliquely to the dominant current directions, and occur on the larger set boundary. The small-scale subordinate sets are relatively tabular (Fig. 5A). Some internal stratifications are discordant to the lower boundary of the cross-sets with a wedgewise geometry.

The trough cross-bedded sandstone most likely formed by migration of small 3D dunes (Harms et al., 1975). On the other hand, the smaller tabular cross-sets on the trough cross-sets resulted from the migration of smaller sandwaves or 2D dunes. This implies the presence of fluctuations in both flow strength and direction between major 3D dunes and subordinate 2D dunes. There was minor backflow on the lee side of the dunes by flow separation forming small-scale cross-sets.

3.1.4. Horizontally stratified sandstone (facies Sh)

This facies is characterized by horizontal stratification of well-sorted medium-to-very coarse sandstone. Well-sorted

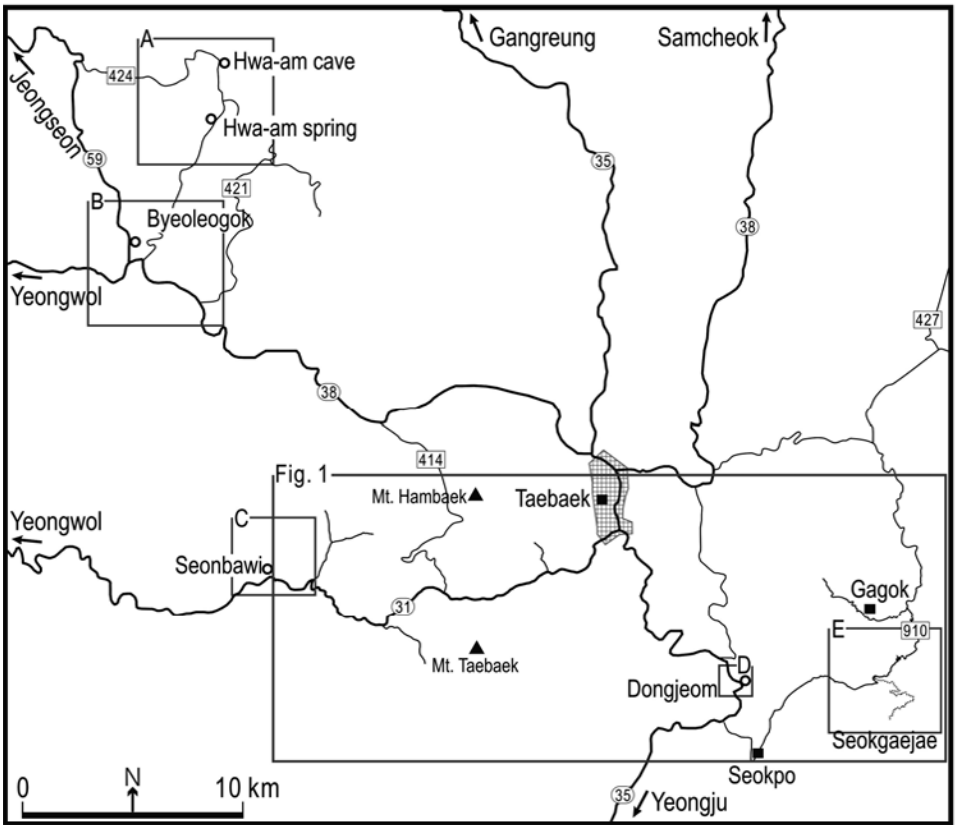


Fig. 2. Road map of the study area showing location of the outcrops. Geologic maps modified from GICTR (1962) and Chough et al. (2000)

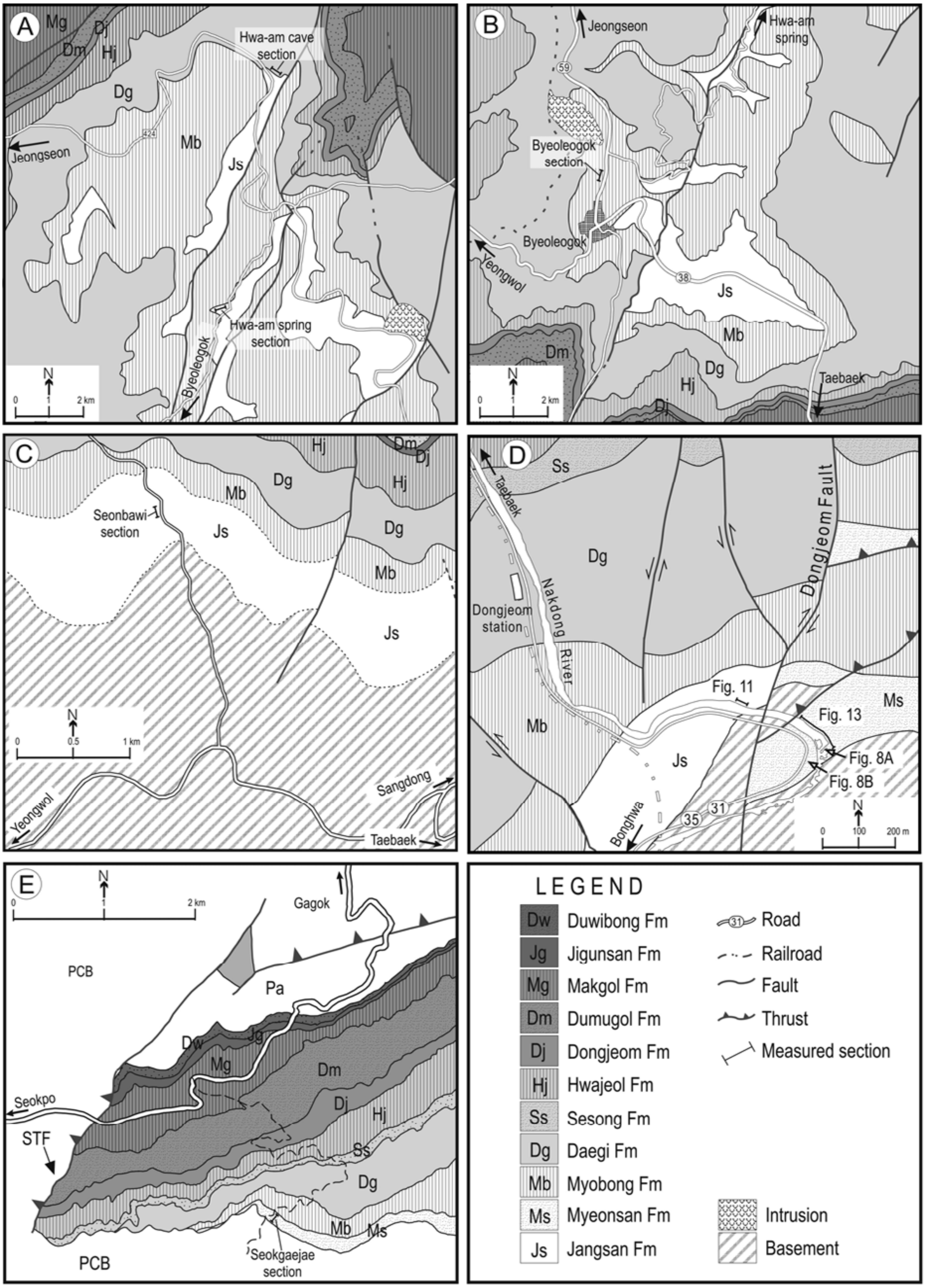


Fig. 2. (Continued) (A) Hwa-am area. (B) Byeoleogok area. (C) Seonbawi section. (D) Dongjeom section. (E) Seokgaejae section.

Table 2. Description and interpretation of sedimentary facies of the Jangsan Formation

Sedimentary facies	Description	Interpretation
Thin pebble layer *(facies P)*	One-clast-thick layered pebbles; discontinuous and patchy on bedding plane; round fine- to coarse-grained quartzite, and dark colored metamorphic clasts; associated with massive or stratified sandstone	Winnowing by strong currents e.g., induced by storm (Richards, 1986)
Massive sandstone *(facies Sm)*	Medium to very coarse massive quartzose sandstone; spherical and angular sand grains; well sorted; accessory grains of heavy minerals and small rock fragments of metasedimentary rocks	Rapid sedimentation by relaxation of heavy sediment-laden flow (Levell, 1980; Soegaard and Eriksson, 1985; Simpson et al., 2002) or post-depositional modification
Trough cross-stratified sandstone *(facies St)*	Low-angle and long-wave length, about tens of centimeters; cross-sets fanning with lateral change in thickness; partly bidirectional; finer grained sediments between cross-sets; small-scale scour and fills	Migration of 3D dune (Harms et al., 1975)
Horizontally stratified sandstone *(facies Sh)*	Well-sorted medium to very coarse sandstone; decimeters to a few meters thick; tabular and continuous bed; sharp upper and lower boundaries; small-scale scours; associated with low-angle trough cross-stratified sandstone, foreset bedded sandstone, and massive sandstone	Upper flow regime plane bed formed by high-speed unidirectional current or strongly oscillatory wave action (Harms et al., 1982)
Foreset bedded sandstone *(facies Sf)*	Medium to coarse sandstone; tabular and laterally extensive; about 1.3 m thick; slightly tangential to the base of the set; unidirectional; associated with pebbly sandstone/conglomerate, and horizontally stratified coarse sandstone; ripples on top of some foreset bed	Migration of large-scale 2D dune (Harms et al., 1975) and superimposed oscillatory waves (Allen, 1984; Greb and Archer, 1995)
Tabular cross-stratified sandstone *(facies Sx)*	Tabular or tapering cross-set with relatively high angle cross-lamination; about 10 cm high cross-set; tangential cross-laminae to the lower surface of the set; fine-to-medium sandstone	Migration of 2D mega ripple or dune (Harms et al., 1975)

sands are aligned or interlaminated with thin mica-rich layers (Fig. 5B, C). Occasionally, the laminae form very low-angle cross-set (Fig. 5B). Each unit is about decimeters to a few meters thick and tabular. The upper and lower boundaries of the facies are sharp. Small-scale scours, less than 15 cm in depth and about 30 cm in width, are filled with coarser-grained sediments (Fig. 5C). The scour surface is covered with a thin layer of dark minerals. It is associated with low-angle trough cross-stratified sandstone, foreset-bedded sandstone, and massive sandstone.

The well-sorted coarse sandstone with horizontal stratification has been commonly interpreted as the upper flow regime plane bed. The planar stratification in the upper flow regime might have formed by high-speed unidirectional currents or strong oscillatory wave action (Harms et al., 1982). In shallow marine environments, such conditions occur nearshore under strong shoaling conditions or beaches (Hein, 1987). The small-scale scours filled with reworked lag deposits were due to strong currents, generated most likely by storms.

3.1.5. Foreset-bedded sandstone (facies Sf)

This facies comprises medium-to-coarse quartzose sandstone, occurring as tabular foreset-beds about 1–1.3 m in height (Fig. 6A, B, D). The foreset dips to the southwest (about 15°). The cross-bed is slightly tangential to the base, whereas the upper contact is angular. There are thin layers of laminated or massive finer sandstone between some foreset units (Fig. 6A, B). Symmetrical ripples (wavelength of about 5 cm) occur on the surface of some foreset beds (Fig. 6C). The round ripple-crests are straight and orientated slightly oblique to those of the foreset beds. This facies is alternated with tabular unit of massive sandstone and crudely horizontally stratified (pebbly) coarse sandstone.

This facies probably formed by migration of subaqueous dunes (e.g., Greb and Archer, 1995). The tabular bed of the unidirectional cross-sets was deposited by 2D dune migrations under the influence of offshore-ward currents. The consistent southwestward dip angle reflects the dominance of unidirectional currents. The finer sand layers between the foreset units are suggestive of intermittent slack conditions between the periods of unidirectional currents. The symmetric and round-crested ripples on the surface of the foreset bed are suggestive of wave-generated structures that were probably superimposed on the surface of unidirectional cross-beds of 2D dunes, most likely formed by oscillatory flows (Allen, 1984; Greb and Archer, 1995).

3.1.6. Tabular cross-stratified sandstone (facies Sx)

This facies is characterized by tabular or tapering cross-set with relatively high-angle (about 20°) cross-lamination (Fig. 7A). The cross-set is relatively small scale, about 10 cm in height. The cross-laminae are tangential to the lower surface of the set. In some cases, the sigmoidal cross-laminae with well developed topset occur (Fig. 7C). The base is a low-angle concave-up truncation surface.

Fig. 3. Outcrop photographs of thin pebble layer near the Hwa-am cave. (A) Pebbles form a thin horizontal layer. Lens cap is 5.2 cm in diameter. (B) Plan view of a pebble layer. For location, see Figure 2A.

The tabular cross-stratification formed by migration of 2D mega-ripples or dunes (Harms et al., 1975). The consistent trend of the cross-laminae is suggestive of movement of 2D dunes by unidirectional currents. On the other hand, some tabular cross-stratified sandstone units, superimposed on the trough cross-beds, formed by subordinate currents. The sigmoidal cross-laminae imply high rate of sedimentation outpacing the migration of the bedforms.

3.2. Myeonsan Formation

Two outcrop sections were measured. Six lithofacies are identified on the basis of physical sedimentary structures and lithology (Table 3).

3.2.1. Disorganized conglomerate (facies Cd)

This facies occurs in the lowermost part of the Myeonsan Formation, unconformably overlying the Precambrian basement rocks (Fig. 8A). It is commonly disorganized and composed of pebble- to cobble-grade clasts of quartzite, slate and granitic gneiss that were derived from the basement rock (Kim and Cheong, 1987). The main bedding style in the Dongjeom section is represented by alternation of two subfacies; clast-rich and matrix-rich conglomerates (Fig. 8B). The clast-rich subfacies predominantly contains clast-supported conglomerate with matrices of medium to coarse sand grains (Fig. 9A). The muddy matrix is rare except in several thin (< 5 cm in thickness) mudstone layers. The poorly sorted and subrounded clasts (Fig. 9A) are alingned to bedding plane and partly imbricated. The quartzite and gneiss clasts are common and the largest ones are granitic gneiss (< 1 m in length). The thin layers of remnant mudstone are aligned parallel to bedding plane. The matrix-rich subfacies comprises disorganized conglomerate with sandstone stone matrix (Fig. 9B). It is alternated with clast-rich conglomerate with diffuse boundaries. Discontinuous lenticular gravel patches partly occur.

The weak stratification, poor sorting, and the dominance

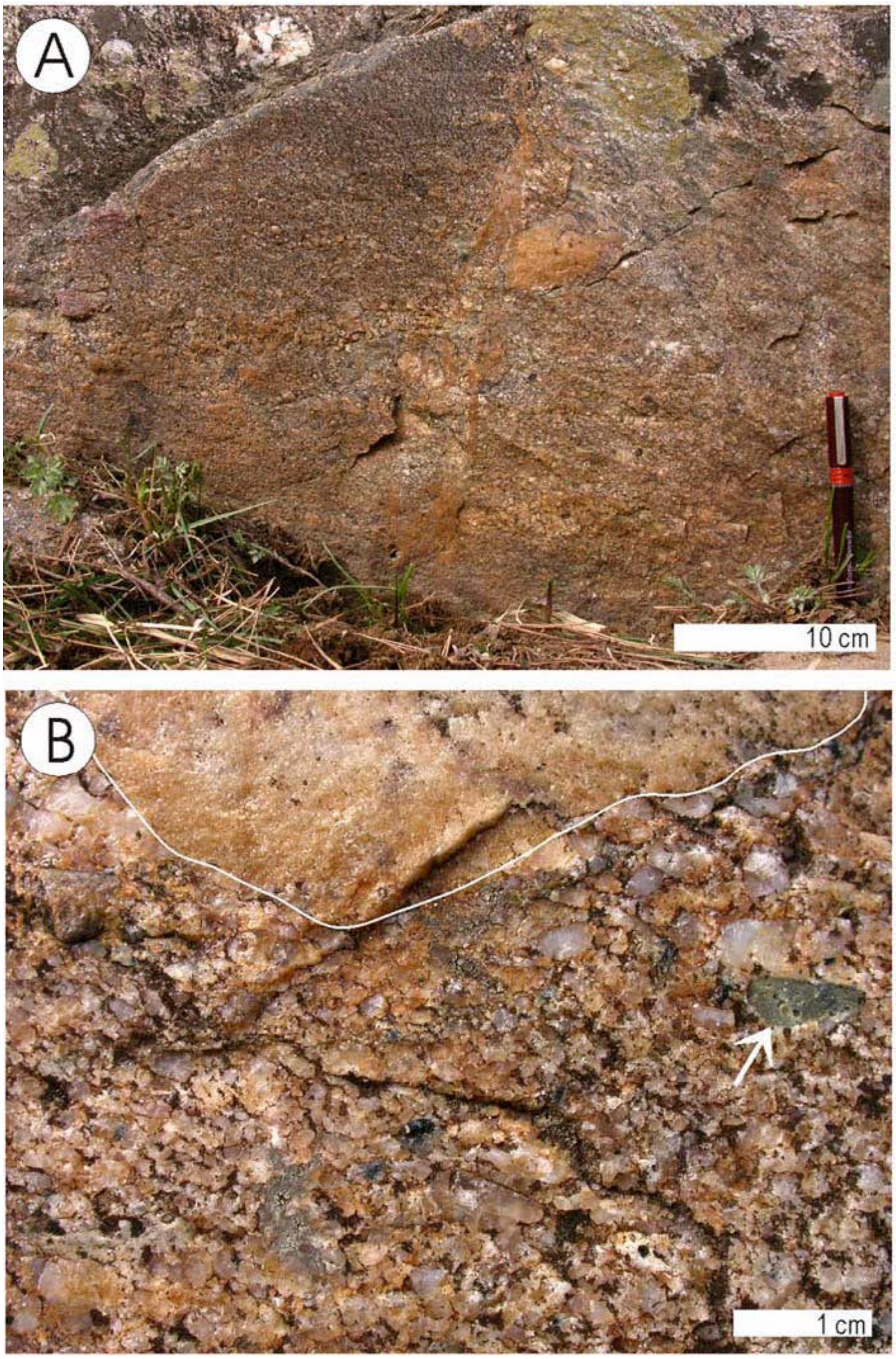


Fig. 4. Photographs of massive sandstone (quartzite) near the Hwa-am cave. (A) Massive sandstone with pebble clasts. (B) Close-up of massive sandstone. Note pebble clasts in the upper part of the photograph and a metasedimentary rock fragment (arrow). For location, see Figure 2A.

of sandstone matrix generally represent deposition from sandy debris flows (Costa, 1988; Shanmugam, 1996). The alternation of clast- and matrix-rich units probably represents repetition of accelerating and decelerating mass-flows (Lowe, 1982).

3.2.2. Thin-bedded conglomerate of mudstone rip-ups (facies Cb)

This facies consists mainly of granule to pebble-grade mudstone clasts and quartz grains with sandy matrix (Fig. 10A). The clasts are subrounded to angular, poorly sorted, and slightly parallel to bedding plane. A conglomerate bed occurs as channel-shaped body (2–8 cm in thickness and tens of meters in width). The scour walls are commonly steep and exhibit a sharp erosional base and a gradual transition to the trough cross-bedded (gravelly) sandstone.

The concentrated mud clasts at the erosional base are interpreted as the lag deposits of tidal-channel scours (Clifton, 1983). Some discontinuous pebble layers represent scour pits of sandwaves or dunes.

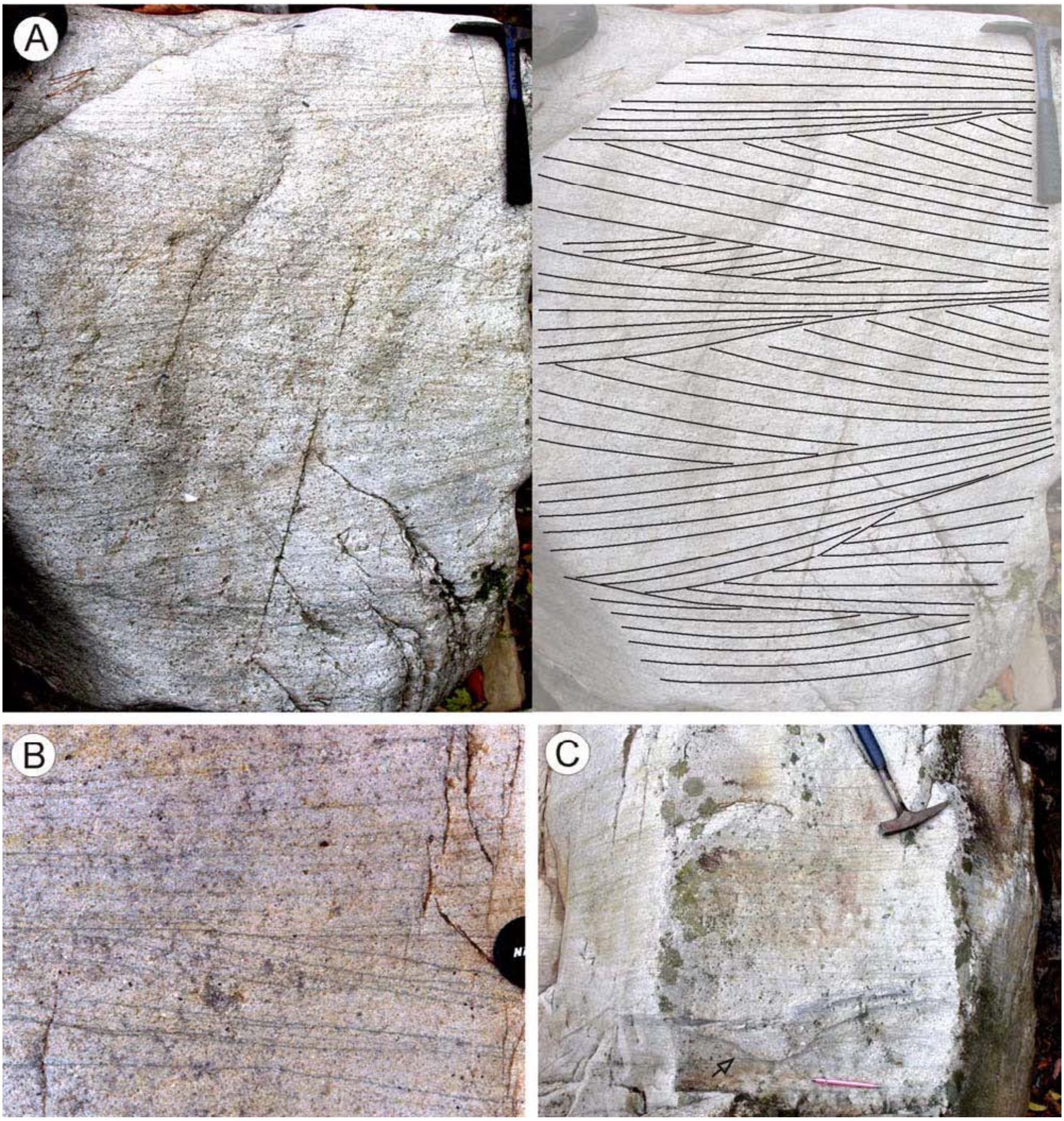


Fig. 5. Photographs of the Jangsan Formation in the Seonbawi section. (A) Trough cross-stratified sandstone. Note small-scale cross set with reverse dip direction. Hammer is 27.5 cm in length. (B) Horizontally and low-angle cross-stratified sandstone. Lens cap for scale is 5.2 cm in diameter. (C) Horizontally stratified sandstone. Note a small scale scour-and-fill (arrow). Pen for scale is 14 cm. For location, see Figure 2C.

3.2.3. Trough cross-bedded sandstone (facies Stx)

This facies consists of relatively thick (0.1–0.5 m) sandstone beds composed mainly of poorly sorted, medium-to-very coarse sandstone and pebbly sandstone. The sandstone is dominantly arkosic arenite and contains <41% feldspar and detrital grains of hematite and ilmenite with average content of 36 % (Kim, 1991). This facies displays small-to medium-scale sets of cross-beds (with an average thickness of 0.1 m and the maximum of 0.2 m) (Fig. 10B, C). The amounts of granule- and pebble-grade clasts are variable. Cross-beds are separated by mud drapes with a tangential contact to the base of the cross-bedded set (Fig. 10B, C). Some cross-beds are represented by grain size variation of quartz. The granule-grade, rip-up mudstone clasts are dis-

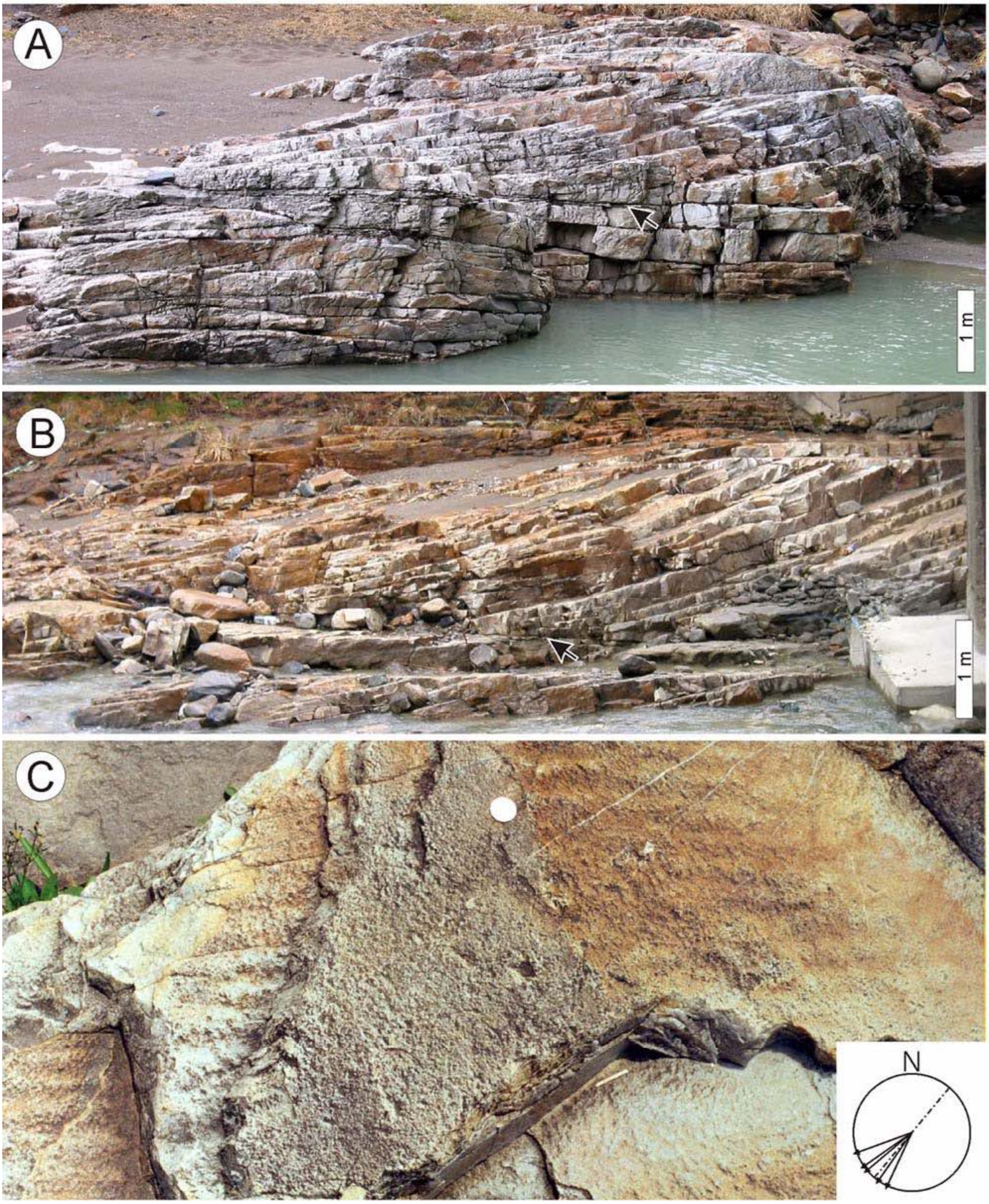


Fig. 6. Photographs of the Jangsan Formation near Byeoleogok. (A, B) Prograding foreset bedding. The contact to the lower surface is tangential. Note thin fine sandstone layers between the foreset bedded units (arrows). (C) Ripples on the surface of the foreset beds. Coin is about 2.2 cm in diameter. Inset shows comparison of foreset dip direction (arrows) and orientation of ripple (broken line). (D) Lowermost part of the Jangsan Formation in the Hwa-am spring section, characterized by tabular foreset-beds underlain by a conglomeratic unit. For location, see Figure 2B.

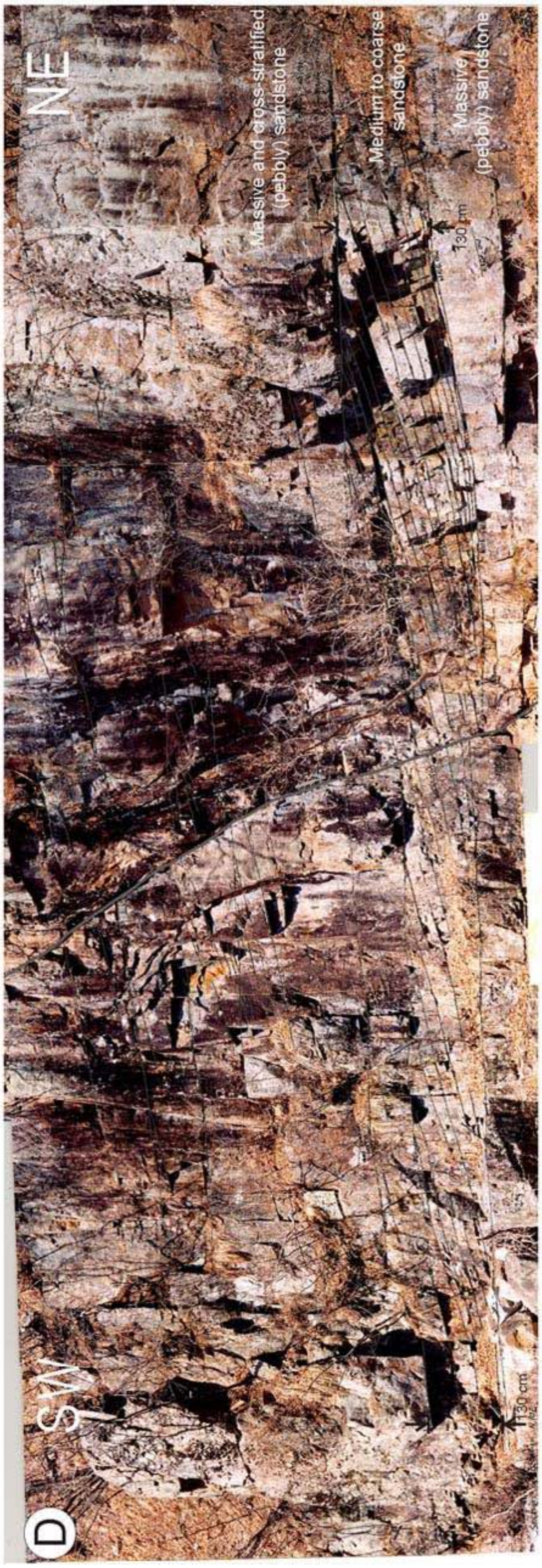


Fig. 6. (Continued). (D) Lowermost part of the Jangsan Formation in the Hwa-am spring section, characterized by tabular foreset-beds underlain by a conglomeratic unit. For location, see Figure 2A.

persed and occasionally aligned to the cross-beds. The cross-beds generally dip northwestward. Each cross-bedded set is bounded by thin mud drape and overlain by other mud-draped cross-beds (Fig. 10B, C). The lenticular patches of sands and pebbles commonly occur at the set boundaries. Some cross-beds are associated with flaser, wavy, and lenticular beds (Fig. 10B, C). The relatively thick intervals of pebbly sandstones with faint cross-beds are present.

The mud-draped cross-beds indicate fluctuating flow conditions with suspension settling of mud during the periods of slack water (Nio and Yang, 1991). The unidirectional pattern of the cross-bed indicates that the main currents of ebb or flood flows influenced net sand migration. The relatively thick mud drapes on the set boundary, together with thin lenses of ripple beds, reflect deposition from relatively weak, subordinate tidal currents. The small- to medium-scale trough cross-beds associated with the flaser to lenticular bedding suggest that this facies represents deposition from ebb- or flood-dominated bedform migration (e.g., Myrow, 1998), possibly in tidal channels or distributaries (Visser, 1980; Terwindt, 1988).

3.2.4. Ripple cross-laminated sandstone (facies Slr)

This facies is characterized by fine to coarse-grained sandstone with thin intercalation of laminated mudstone (Fig. 10D, E). A sandstone bed ranges in thickness from 1 to 12 cm and is frequently interbedded with centimeter-thick siltstones or very fine sandstones. The lower boundary of the bed appears to be sharp and erosional, partly with lag deposits, whereas the upper boundary is gradational. Internal structures are characterized by thin mud drapes and irregularly undulating lamination. Some symmetrical wave ripples on the top of the bed (<6 cm in wave length, <1 cm in height) display form-discordant lamination (Fig. 10E). The granule-grade sand grains and mudstone chips are frequently concentrated on the erosional base and ripple trough. The sandstone bed changes laterally into sandy layers or patches. The grain size of the facies decreases upward with upward-thickening of intercalated mud layers.

The wavy to lenticular beds with ripple cross-lamination are interpreted to reflect alternating period of ripple migration and deposition from suspension during tidal cycle (Reineck and Singh, 1980). The sheet-like sandstone beds associated with thin-interbedded mudstone are suggestive of small-scale bedform migration. The wave- or current-generated ripple beds are common in sandy tidal flats or relatively shallow tidal channel margin (Meyer et al., 1998).

3.2.5. Planar to wavy laminated sandstone (facies Slp)

This facies consists of parallel-laminated fine sandstone, characterized by centimeter-scale irregular alternation of sandstone and mudstone (Fig. 10F). The sandstone layers are generally thin to medium-bedded with some distinct lower intra-boundary. The alternating thin mudstone layer

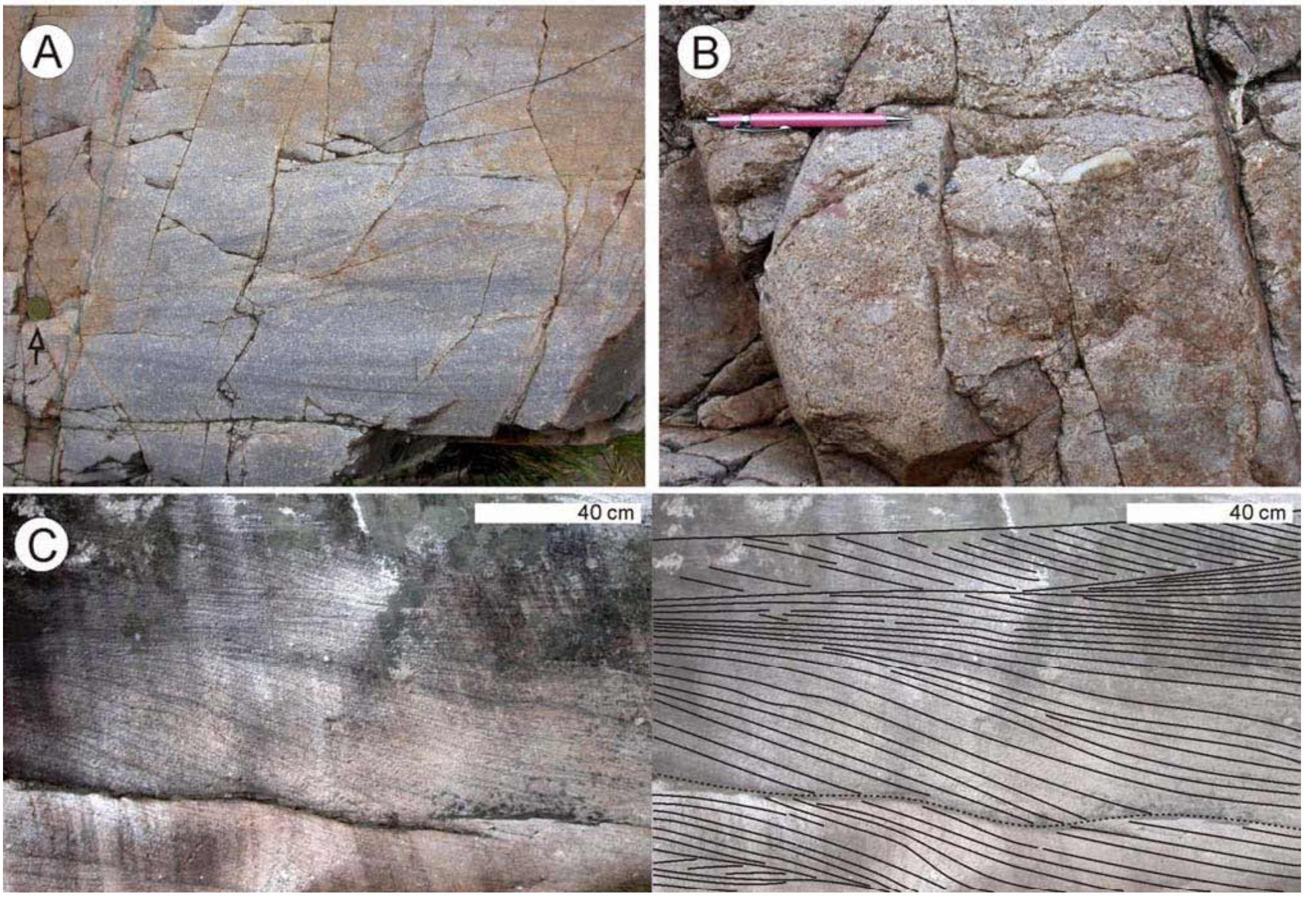


Fig. 7. Photographs of tabular cross-stratified sandstone. (A) Tabular planar cross-stratified sandstone in the Dongjeom section. Note low-angle truncation in the lower part. Coin for scale (arrow) is 2.2 cm in diameter. (B) Massive sandstone with pebble clasts, usually forming depositional unit with tabular cross-stratified sandstone. Pen for scale is 14 cm in length. For location, see Figure 11. (C) Tabular cross-stratified sandstone in the Seonbawi section. Note sigmoidal cross laminae. For location, see Figure 2C.

which forms the appearance of the parallel lamination is characterized by millimeter-scale laminae that are rather discontinuous. Individual lamina is slightly wavy to irregular and can be traced laterally for a few meters. In some case, thin sandstone layers are bounded below by a sharp erosional boundary, which occasionally form a depression filled with graded sediments (Fig. 10F).

The general lack of distinct primary structures in the sandstone suggests that sands were reworked in deep-water environments below normal wave base. The distinct alternation of laminated mudstone layer is suggestive of suspension settling of mud during intermittent pause of wave- or wind-generated currents (Walker and Plint, 1992).

3.2.6. Dark gray mudstone (facies M)

This facies consists of shale, siltstone, and minor portion of fine to coarse-grained sandstone. Sedimentary structures include millimeter- to a few centimeter-thick laminae of siltstone to fine-grained sandstone and homogeneous part of mudstone (Fig. 10F). Each facies unit ranges in thickness from 2 to 8 cm. Fine to coarse-grained sands are scattered within the bed and occasionally form nodular patches or thin layers. It overlies either the ripple cross-laminated sandstone or planar to wavy sandstone.

The homogeneous mudstone contains little evidence of bedload deposition and is interpreted as deposition from suspension.

4. FACIES ASSEMBLAGES AND DEPOSITIONAL ENVIRONMENTS

4.1. Jangsan Formation

In the Jeongseon area (Fig. 2A, B), the Jangsan Formation is characterized by tabular units of foreset beds (Sf) and pebble-bearing coarse sandstone (Sm, Sh, and P) (Figs. 3 and 6). The foreset beds are alternated with horizontally stratified or massive coarser units (Sm and Sh) (Fig. 6). In the Byeoleogok section (Fig. 2A), the tabular cross-sets of meter-scale foreset beds are alternated with the horizontally

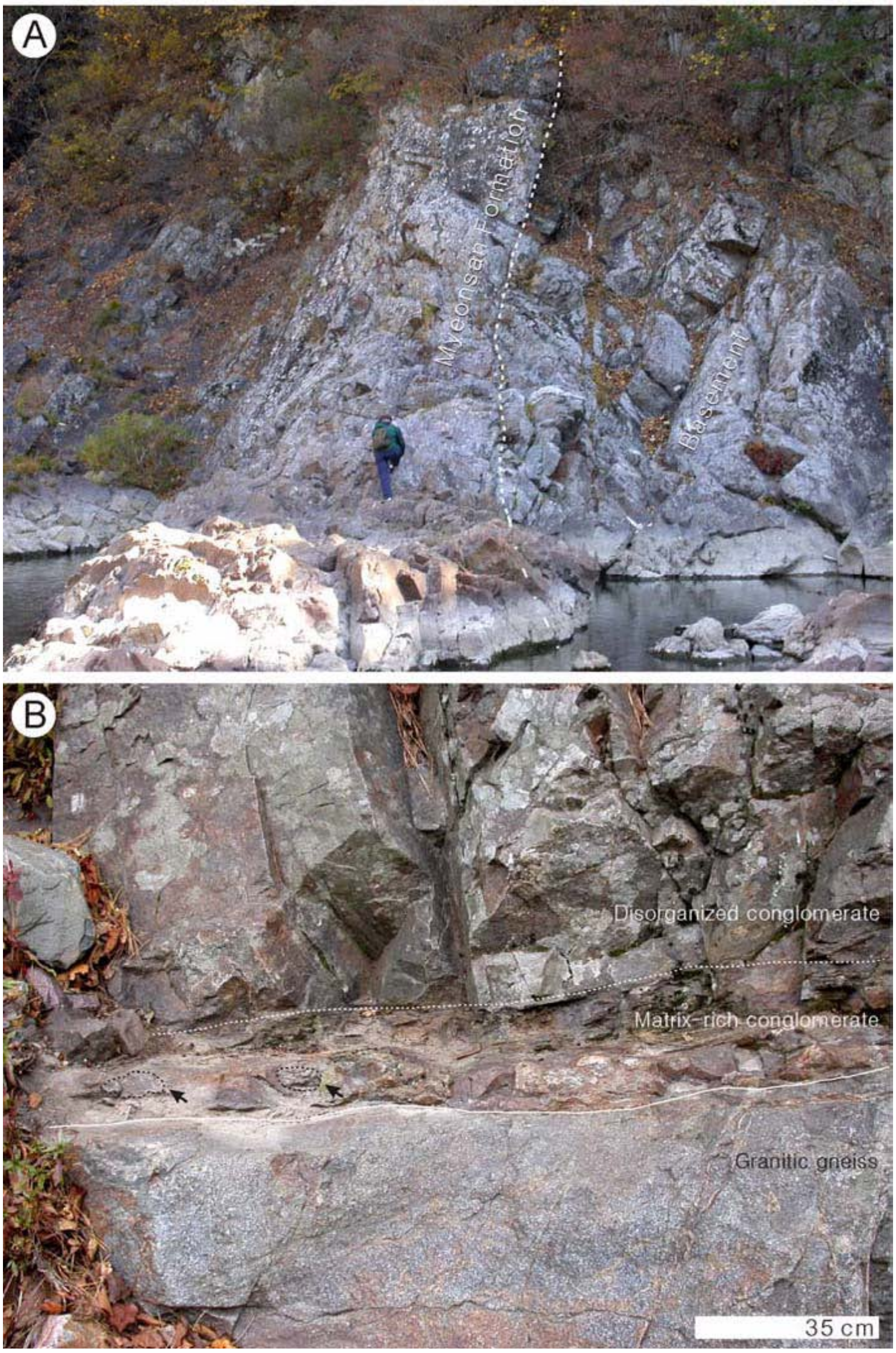


Fig. 8. (A) Photographs of the Myeonsan Formation overlying the Precambrian basement (granitic gneiss). (B) The lowermost unit of the Myeonsan Formation overlying the Precambrian basement rock. The matrix-rich unit with sparse clasts (arrows) is overlain by a clast-rich unit with indistinct boundary. For location, see Figure 2D.

bedded massive sandstone (Fig. 6A, B). In the Hwa-am spring section (Fig. 2B), the tabular foreset-bedded sandstone beds are laterally continuous for 200 m (Fig. 6D) and are alternated with massive (Sm) and horizontally stratified sandstone (Sh). The massive sandstone is characterized by abundant angular pebble-grade clasts and wedge-shaped geometry of the facies unit (Fig. 6D). The section is about 30 m in height and consists of repetition of tabular foreset beds and massive or stratified sandstone units with a consistent southwestward dip direction. The Hwa-am cave section (Fig. 2B) also consists of tabular foreset-bedded sandstone (Sf), pebble layers (P) and pebble bearing massive (Sm) or stratified sandstone (Sh). Round pebbles form one or several clasts thick planar layer, or are dispersed in the sandstone. The pebble layers are discontinuous and patchy on bedding plane. Most of the facies units are tabular and continuous in outcrop scale.

The pebble-bearing sandstone facies in the lower part of the Hwa-am spring and Hwa-am cave sections represent shoreface deposit, formed in the early stage of the basin

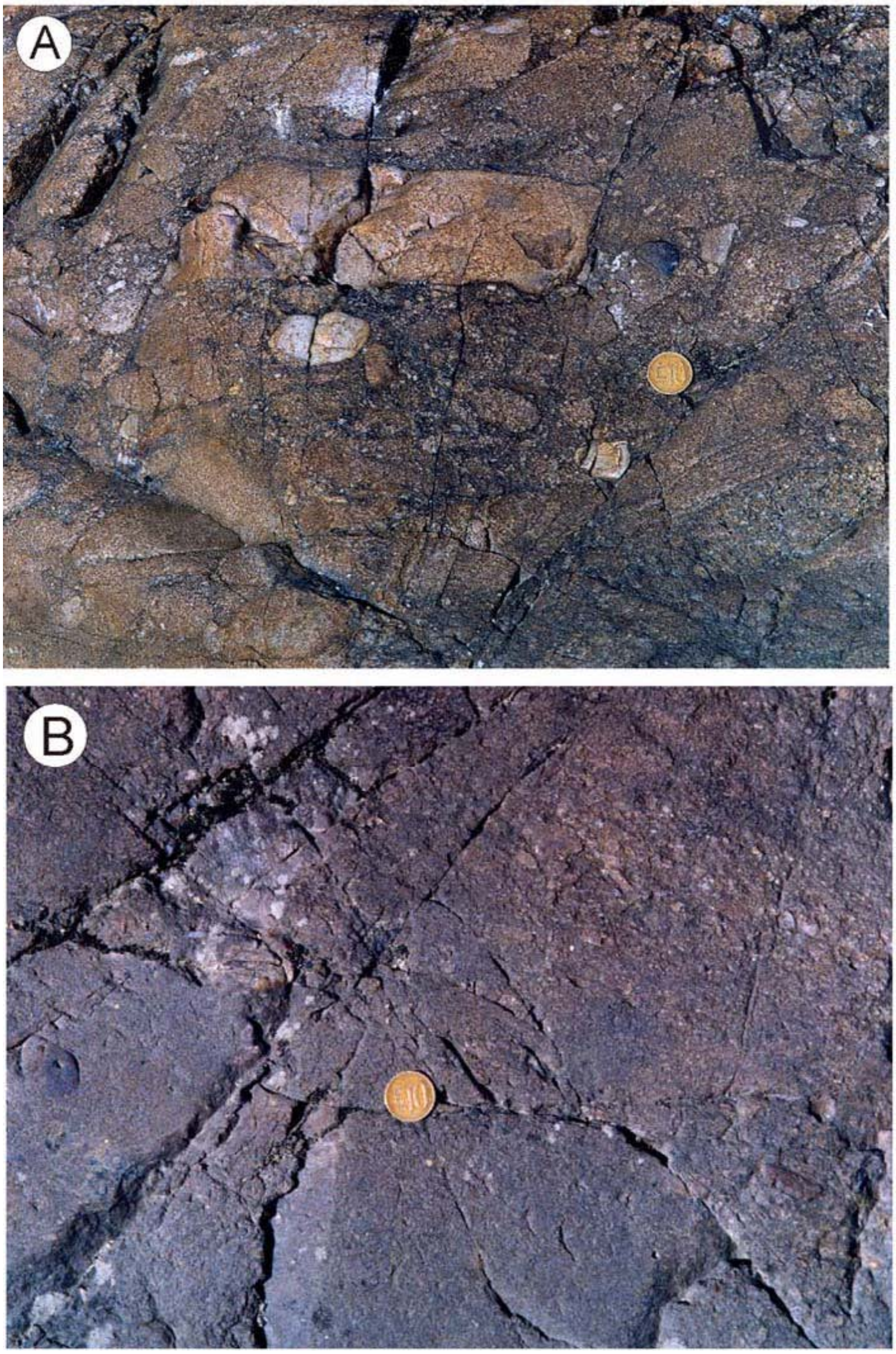


Fig. 9. Photograph of two types of conglomerate in the lowermost part of the Myeonsan Formation. (A) Clast-rich conglomerate. (B) Matrix-rich conglomerate. Coin for scale is 2.2 cm in diameter. For location, see Figure 8A.

inundation. The overlying tabular foreset-bedded sandstone and the alternating massive sandstone facies are suggestive of lower shoreface to inner shelf where active migration of the 2D dunes was prevalent (Fig. 12). The dip direction of the foreset bed is suggestive of consistent west- to southwestward currents, although the relation between the paleoshoreline and the basin physiography is uncertain. The extensive tabular sets of the foreset-bedded sandstone, however, suggest that currents lasted for considerable duration. The unidirectional current in the shallow marine environments probably was wave- or storm-generated currents such as longshore current and geostrophic flow (Walker and Plint, 1992).

The facies assemblages of the Seonbawi section (Fig. 2C) are characterized by low-angle trough cross-stratified sandstone and horizontally stratified sandstone (Fig. 5). The frequent occurrence of trough cross-beds is suggestive of shoreface dominated by 3D subaqueous dunes (Fig. 12). The consistent unidirectional trough cross-stratification with subordinate ripples is indicative of wave-generated

Table 3. Description and interpretation of sedimentary facies of the Myeonsan Formation

Sedimentary facies	Description	Interpretation
Disorganized conglomerate *(facies Cd)*	Disorganized, poorly-sorted; subrounded clasts (<1 m in length); sand matrix; weak stratification by alternation of clast- and matrix-rich subfacies	Cohesionless, mass-flow deposits (Lowe, 1982; Costa, 1988; Shanmugam, 1996)
Thin-bedded conglomerate of mudstone rip-ups *(facies Cb)*	A thin bed (2–8 cm thick); granule to pebble-grade mud clast and quartz granules; sharp erosive base	Channel lag
Trough cross-bedded sandstone *(facies Stx)*	Medium- to very coarse-grained; mud drape on cross-bed surface with tangential contact to bottom set; unimodal current distribution of trough and cross-beds; small-pebble concentration on trough; alignment of mud clast along cross-bed	Tidal sand dunes or sand waves (Terwindt, 1988; Dalrymple et al., 1990; Myrow, 1998)
Ripple cross-laminated sandstone *(facies Slr)*	Very thin- to thin-bedded; fine- to very coarse-grained; lateral and vertical change to wavy or flaser bedding; form-discordant wave ripple, ripple-cross, and irregular undulating laminations	Wave- or current-generated ripple during tidal cycle (Reineck and Wunderlich, 1968; Dalrymple et al., 1991)
Planar to wavy laminated sandstone *(facies Slp)*	Fine- to medium-grained; millimeter-scale laminae; wavy- to- horizontal silt lamination; crudely laminated; thin sandstone layer with grading	Suspension load and storm-generated wave
Dark gray mudstone *(facies M)*	Dark gray in color; wide range of bed thickness; interbedded massive and laminated subfacies; alternation of millimeter-thick silt laminae; parallel, wavy, discontinuous streaky laminae; graded laminae	Suspension load

longshore currents. Sporadic offshore currents of storms may also cause migration of shoreface dunes. The horizontally stratified sandstone represents (upper) shoreface setting where strong oscillatory wave action is common. The well-sorted planar stratified sandstone with very low-angle set boundary probably is suggestive of deposition in swash zone of foreshore environments (Harms et al., 1982) (Fig. 12).

The Jangsan Formation occurs in the Dongjeom area (Fig. 2D) in the west of the Dongjeom fault. The stream section consists of alternating massive (pebbly) very coarse sandstone, horizontally stratified sandstone, and cross-stratified medium to coarse sandstone (Fig. 11). The cross-stratified medium-to-coarse sandstone is characterized by small-scale (about 10 cm in height) tabular or tapering cross-sets. Cross-laminae are relatively steep with dip angle of 20°. These cross-sets are alternated with low-angle cross-laminated sets with an erosional contact. Larger-scale medium-to-coarse tabular cross-sets (about 70 cm in height) also occur in this section. These finer cross-stratified units gradually change into the overlying massive pebbly very coarse sandstone. The finer cross-bedded facies formed by migration of various dunes on inner shelf or lower shoreface (Fig. 12), whereas the overlying coarser massive pebbly sandstone units were deposited by storm activity. The alternation of these facies is suggestive of frequent reworking of sediment and incursion of sediment-laden flow during storms.

The dominant influence of waves, storms, and related currents to the sedimentation of the Jangsan Formation are suggestive of open marine conditions (Fig. 12). The lack of discernable fining- or coarsening-upward trends in the thick succession is probably suggestive of aggradation (e.g., Cant and Hein, 1986, Johnson and Baldwin, 1996). Because of relatively rapid subsidence in the initial stage of the basin evolution and ensued eustatic rise in sea level in the Early Cambrian, the aggradation most likely implies large sediment input. The large amounts of sediments could have been dispersed on the platform by waves, tides, coastal and oceanic currents, and storms. There was a balance between an increase in accommodation space and sediment supply, which resulted in thick accumulation of sandstone. Similar basal sandstone beds formed commonly in passive margin or interior cratonic basins of the Late Precambrian and Cambrian (Johnson and Baldwin, 1996).

4.2. Myeonsan Formation

The Myeonsan Formation comprises a small-scale conglomeratic deposit and the overlying unit of tide-influenced shallow marine depositional unit (Fig. 13). The latter is organized into three lithofacies assemblages of subtidal channels, tidal flat, and outer shelf subenvironments.

The basal conglomerate bed (< 9 m in thickness) is variable in thickness and intermittently rests on the basement rock. The ungraded conglomerates with poorly-sorted clasts and sandy matrix suggest that cohesive strength was less important, probably indicating deposition from cohesionless, mass-flow deposits (Middleton and Hampton, 1973; Nemec, 1990; Kim et al., 1995) formed by avalanching of gravels and sands. The weak stratification, defined by alternating matrix-rich and clast-rich subfacies without discernable erosion would reflect fluctuations in sediment gravity flows (Lowe, 1982). The poor lateral discontinuity and the highly variable

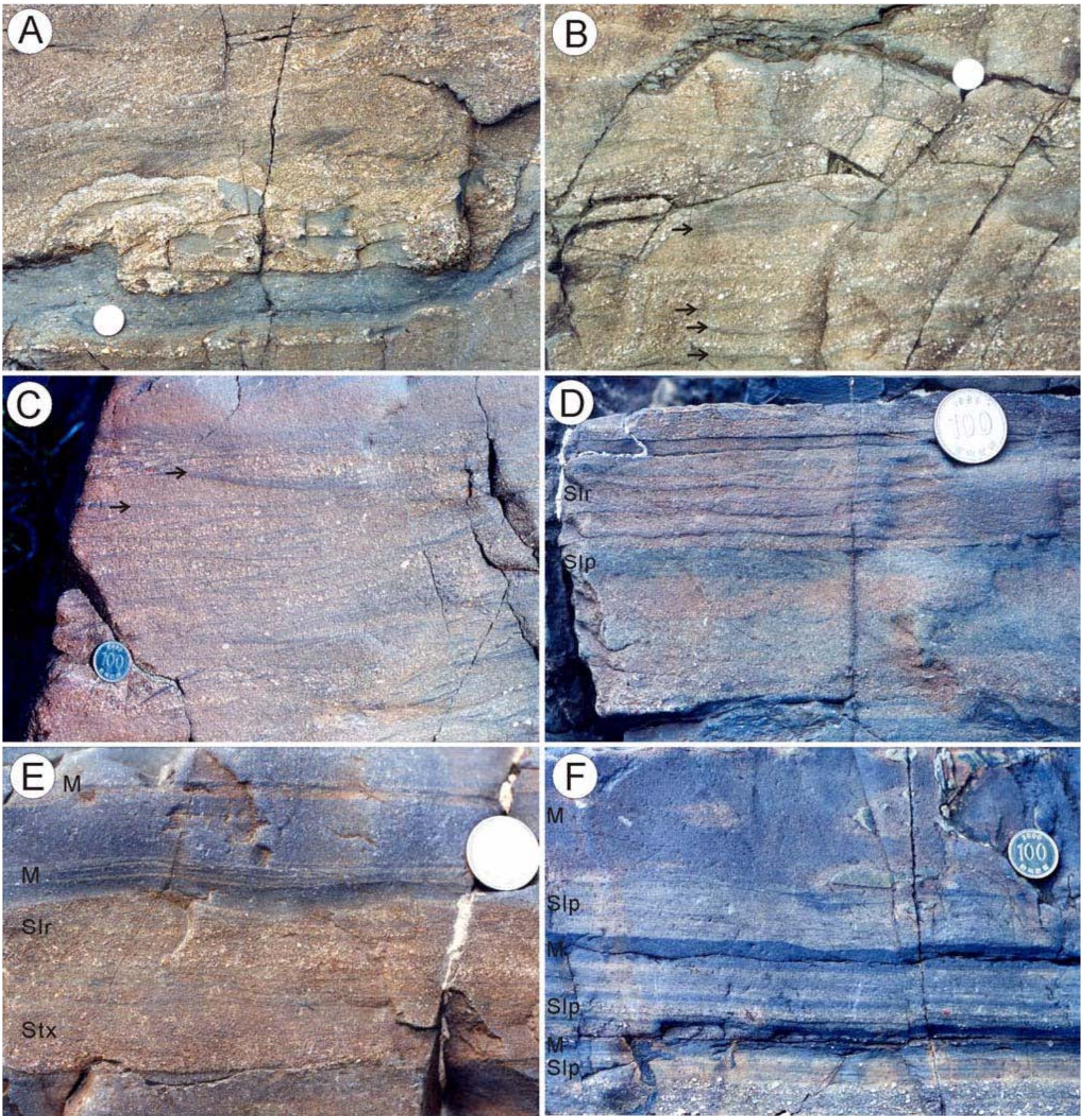


Fig. 10. (A) Outcrop photograph of thin-bedded conglomerate of mudstone rip-ups (Cb). (B–C) Vertical succession of trough cross-bedded sandstones (Stx). Cross-beds are separated by thin mud drapes showing unidirectional flow from right to left. Note the set boundaries represented by relatively thick mud layer and closely-spaced mud drapes (arrows). (D–E) Ripple cross-bedded sandstone (Slr) associated with planar to wavy sandstone (Slp) and massive mudstone (M). (D) Ripple cross-beds display a sharp, erosional base and a gradational top, separated by a thin bed of mud drape. (E) Top surface is wave rippled and displays form-discordant laminations. (F) Planar to wavy sandstone (Slp) and massive mudstone (Mm) of the Myeonsan Formation. Coin for scale is 2.2 cm in diameter.

thickness of the conglomerate unit are ascribed to localized mass-flow events.

The subtidal channel assemblage is characterized by the upward-fining succession of thin-bedded conglomerate (facies Cb) on the erosional base, trough cross-bedded (gravelly) sandstone (facies Stx), and ripple cross-laminated sandstone (facies Slr) at top (Fig. 14A). The granule-to-pebble lags on the erosional base and the stacked mud draped cross-beds are interpreted as subtidal channel deposits (Plint, 1983; Brownridge and Moslow, 1991; Hamberg, 1991). The uni-

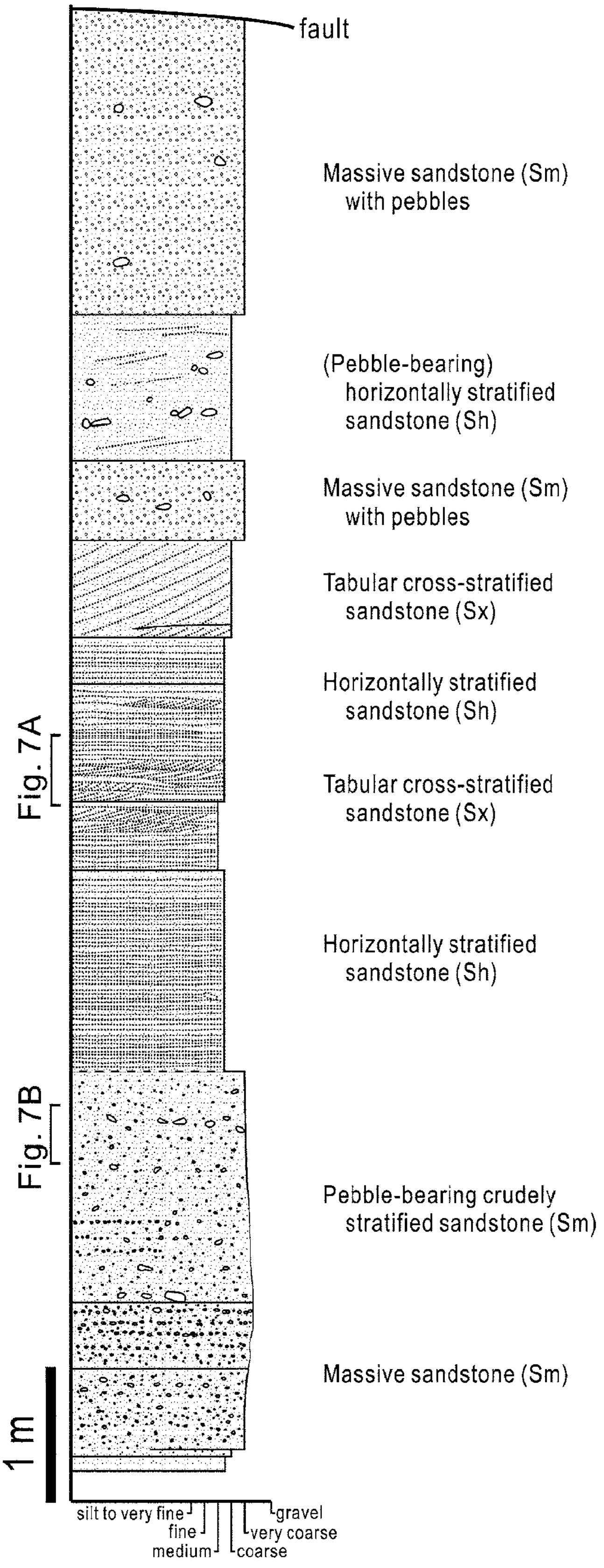


Fig. 11. Columnar description of the Jangsan Formation, Dongjeom section. For location, see Figure 2D.

directional dune cross-beds of various scales were produced by ebb- or flood-dominant tidal currents developed mainly in tidal channels (Fig. 15). The ripple-topped sandstone beds were most likely deposited during upward growth of dune crests (e.g., Dalrymple et al., 1990), indicating a shoaling-upward transition. The vertical succession resulted from infilling of tidal channels with tidal sand dunes and aggradation of an adjacent sandy tidal flat (e.g., Meyer et al., 1998). The lower part of the formation is commonly associated with the amalgamated beds of trough cross-bedded (gravelly) sandstone with rare ripple-topped sandstone bed (Fig. 13). The thick-bedded amalgamated sandstones are less mature in composition than those of the upper part of the formation. The amalgamated attribute is indicative of active deposition in relatively deep subtidal area, probably in main channels.

The tidal flat assemblage consists largely of interbedded sandstone and mudstone (facies Slp, Slr, and M) (Fig. 14). This assemblage occurs in beds a few centimeters to tens of centimeters thick which are laterally persistent. A thin sandstone bed shows a variety of small-scale sedimentary structures including ripple cross-beds, wavy-to-parallel lamination, and discontinuous lenses of ripple beds. It is commonly alternated with a thin bed of laminated or massive mudstone, which represents ‘sand-mud couplets’ of tidal origin (e.g., Dalrymple et al., 1991). As the mudstone bed is thick (>5 cm), the wavy-to-parallel sand-mud couplets become dominant. The tidal flat assemblage is commonly alternated with the decimeter-scale subtidal channel assemblage, which reflects lateral coexistence of the tidal flat and channel in tide-influenced environments (Fig. 13). Some trough cross-bedded gravely sandstones with a large number of pebble-grade mudstone clasts in channel-shaped beds (Fig. 14A) are interpreted as small-scale tidal gully with megaripples (Clifton, 1983). The limited lateral continuity and the isolated occurrence are suggestive of ephemeral runoff channels crossing the tidal flat (e.g., Clifton, 1983). The presence of mud cracks probably indicates intertidal flat for a certain interval (cf., Kim, 1991). The discrimination between intertidal and subtidal deposition is, however, uncertain due to the lack of recognizable trace and body fossils.

The outer shelf subenvironment is represented by interbeds of planar to wavy very fine sandstone (facies Slp) and mudstone (facies M) (Fig. 14B). In contrast to other facies assemblages, it is characterized by rare occurrence of mudstone rip-ups, mud-draped cross-beds and wave-generated structures, which suggests deposition in deep subtidal to shelf environments (Fig. 15). The intermittent inclusion of coarse-grained sandy layers is possibly ascribed to the storm events. This facies assemblage mainly constitutes the upper part of the Myeonsan Formation (Fig. 13) and gradually transforms into the mudstone-dominant Myobong Formation. It represents a transition from a tide-influenced coastal to an open marine shelf environment, mostly below

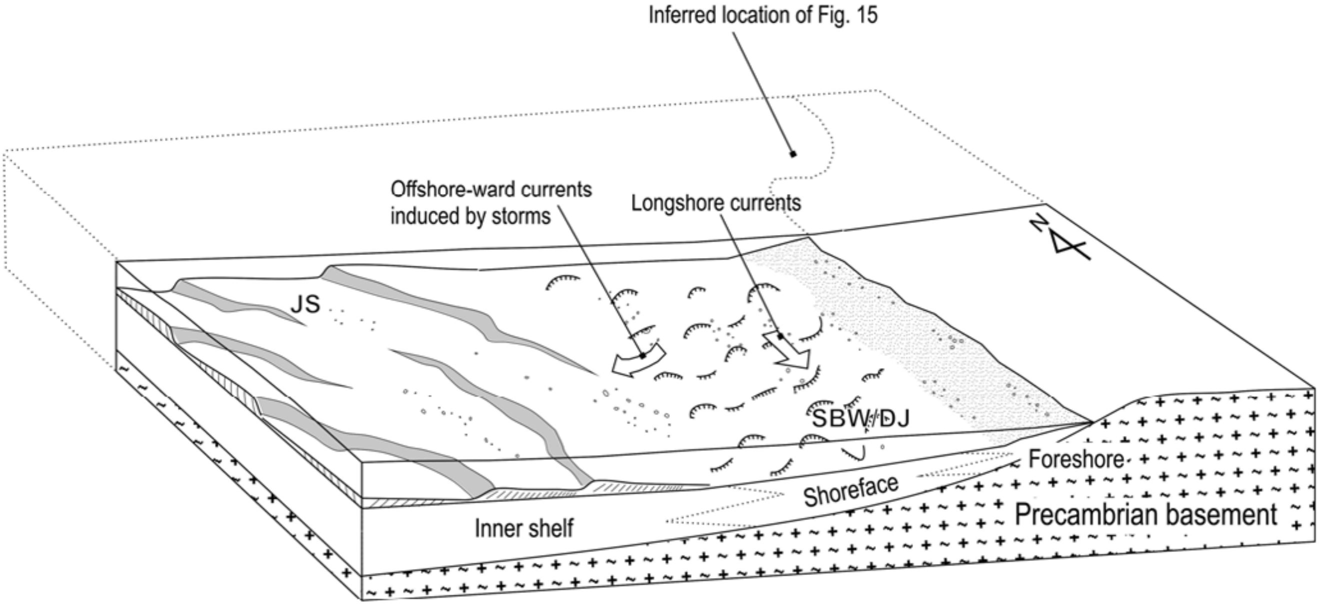


Fig. 12. A model for depositional environments of the Jangsan Formation. JS: Jeongseon, SBW: Seonbawi, DJ: Dongjeom.

fair-weather wave-base, but influenced by occasional storm waves.

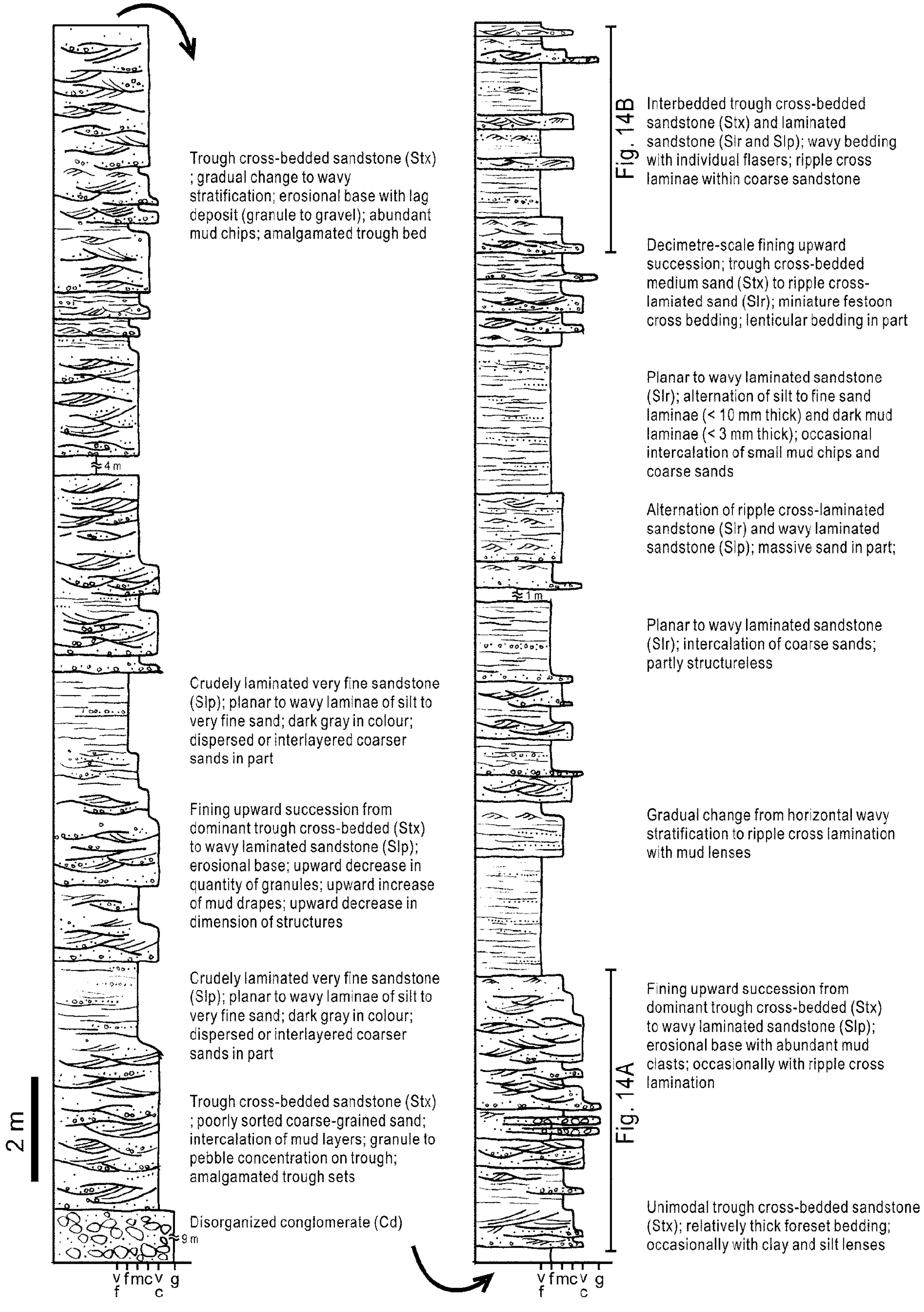
The lithofacies assemblages provide evidence for tidal deposition for the Myeonsan Formation. The tide-influenced shallow marine succession largely comprises tidal flat/channel assemblage in the lower part and outer shelf assemblage upward (Fig. 13). The repetitive fining-upward subtidal channel to tidal flat successions reflect lateral heterogeneity and complexity of tidal environment, rather than vertical sedimentary cycles created by the shoreline shift (Fig. 15). There is a gradual upward decrease in proportion of trough cross-bedded channel deposits and an increase in mudstone facies. The overall transition is characteristic of transgressive sequence with an upward-deepening trend. The lower part of the transgressive sequence is floored by basal conglomerate beds. It represents transgression onto the marginal marine shelf, lacking significant fluvial systems. Tidal deposition was gradually terminated when the rate of relative sea-level rise exceeded accommodation-fill, which was, in turn, overlain by open marine shale (Myobong Formation). The transgressive record represents the early part of the second-order sea-level rise in the Cambrian–Ordovician (Kwon et al., 2006).

The Myeonsan Formation contains small-scale basal conglomerate bodies and transgressive tidal deposits with significant amounts of fine-grained deposits, compared to the Jangsan Formation. It formed in a restricted depositional environment where tidal currents were dominant. The limited occurrence of the conglomerate possibly attests to the local uplift of hinterland. It is supported by the lithofacies characteristics of the basal conglomerate, representing downslope sediment gravity flows, shedding onto the basement. An abrupt transition to the overlying shallow marine succession would represent sedimentary response to an immediate increase in accommodation space due to the possible uplift and the accompanied subsidence of the basin. The dominance of tidal influence on the shallow marine deposits would also represent a restricted shoreline configuration.

5. COMPARISON WITH NORTH CHINA PLATFORM

A paleogeographic reconstruction of the East Asia suggests that the Pyeongnam and Taebaeksan basins were located in the eastern margin of the North China Platform in the Early Paleozoic (Chough et al., 2000; Choi et al., 2001). The lowermost part of the Early Paleozoic succession of the North China Platform can be grouped into four localities (Fig. 16). The Xinji Formation in the southern part of the platform consists mainly of phosphoritic and glauconitic sandstone and rare conglomerate. In the northern part, the fine-grained carbonates of the Changping Formation occur. These units change upward into dolomitic fenestrae and desiccated microbial laminite. On the western part of the platform near the Ordos oldland, the basal deposit is characterized by hypersaline shallow facies of the Zhushadong Formation (Meng et al., 1997). The lowermost part of the Pyeongnam Basin is characterized by siliciclastic fines (Paek et al., 1996). These varieties were probably due to the interplay among the paleobathymetry, rate of sea-level rise, and the amounts of sediment supply.

The Xinji Formation formed in a shallow-to-moderate depth, marine sand-wave environment (Meng et al., 1997). The phosphorite of the formation represents deep weathering of the Precambrian basement and erosion, coupled with



Trough cross-bedded sandstone (Stx) ; gradual change to wavy stratification; erosional base with lag deposit (granule to gravel); abundant mud chips; amalgamated trough bed

Crudely laminated very fine sandstone (Slp); planar to wavy laminae of silt to very fine sand; dark gray in colour; dispersed or interlayered coarser sands in part

Fining upward succession from dominant trough cross-bedded (Stx) to wavy laminated sandstone (Slp); erosional base; upward decrease in quantity of granules; upward increase of mud drapes; upward decrease in dimension of structures

Crudely laminated very fine sandstone (Slp); planar to wavy laminae of silt to very fine sand; dark gray in colour; dispersed or interlayered coarser sands in part

Trough cross-bedded sandstone (Stx) ; poorly sorted coarse-grained sand; intercalation of mud layers; granule to pebble concentration on trough; amalgamated trough sets

Disorganized conglomerate (Cd)

Interbedded trough cross-bedded sandstone (Stx) and laminated sandstone (Slr and Slp); wavy bedding with individual flasers; ripple cross laminae within coarse sandstone

Decimetre-scale fining upward succession; trough cross-bedded medium sand (Stx) to ripple cross-lamiated sand (Slr); miniature festoon cross bedding; lenticular bedding in part

Planar to wavy laminated sandstone (Slr); alternation of silt to fine sand laminae (< 10 mm thick) and dark mud laminae (< 3 mm thick); occasional intercalation of small mud chips and coarse sands

Alternation of ripple cross-laminated sandstone (Slr) and wavy laminated sandstone (Slp); massive sand in part;

Planar to wavy laminated sandstone (Slr); intercalation of coarse sands; partly structureless

Gradual change from horizontal wavy stratification to ripple cross lamination with mud lenses

Fining upward succession from dominant trough cross-bedded (Stx) to wavy laminated sandstone (Slp); erosional base with abundant mud clasts; occasionally with ripple cross lamination

Unimodal trough cross-bedded sandstone (Stx); relatively thick foreset bedding; occasionally with clay and silt lenses

Fig. 13. Columnar log of the Myeonsan Formation in the Dongjeom section. For location, see Figure 2D.

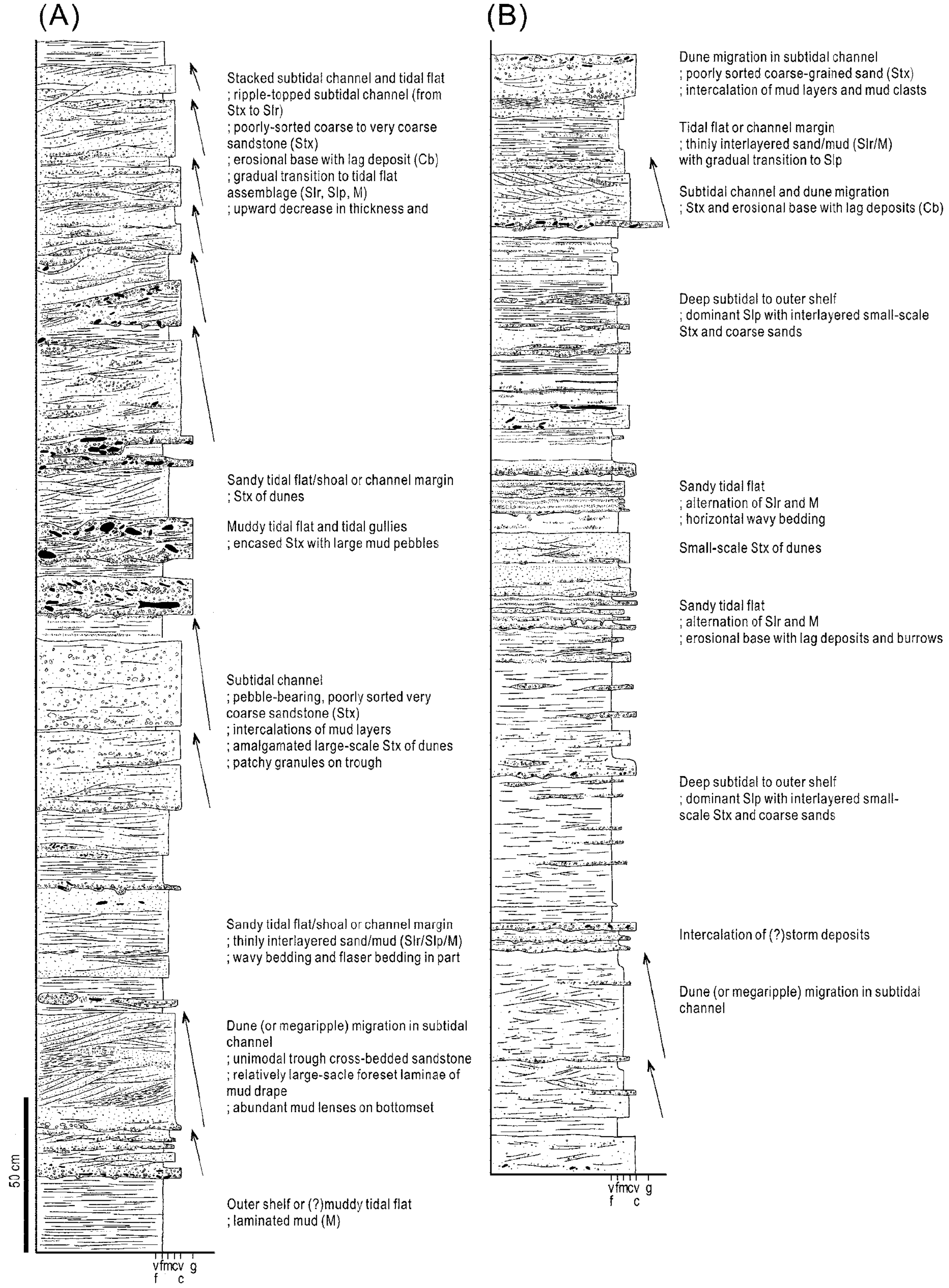


Fig. 14. Columnar log showing vertical succession of subtidal channel, tidal flat, and outer shelf facies assemblage. (A) Dominant facies assemblage in the Myeonsan Formation comprising subtidal channel and tidal flat (tidal shoal/channel margin) facies. (B) The upper part of the Myeonsan Formation is dominated by deep subtidal to outer shelf facies assemblage. Arrows indicate upward fining trends. For location, see Figure 13.

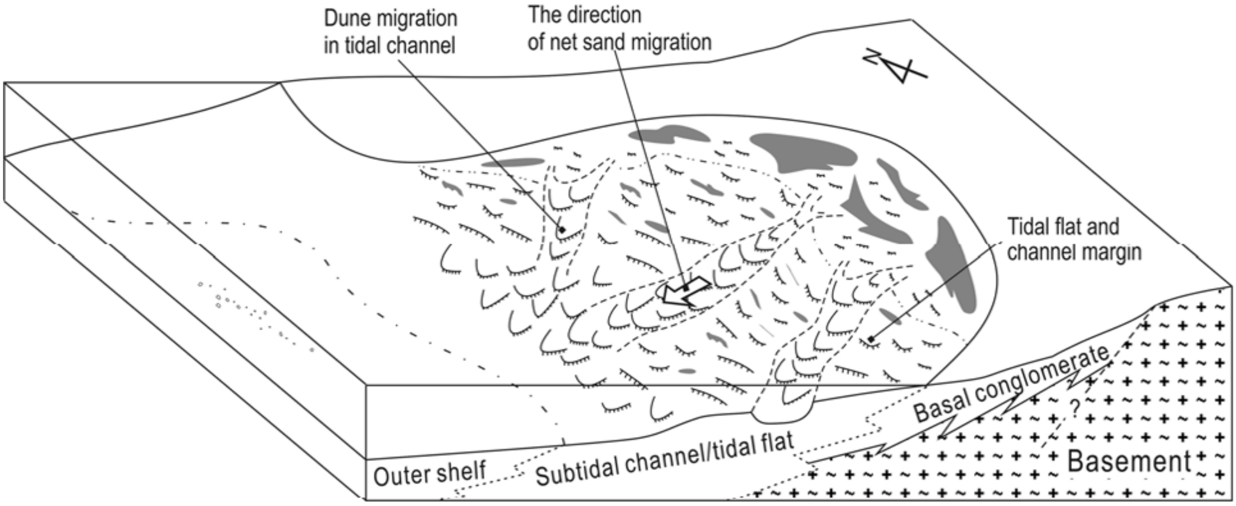


Fig. 15. A model for depositional environments of the Myeonsan Formation.

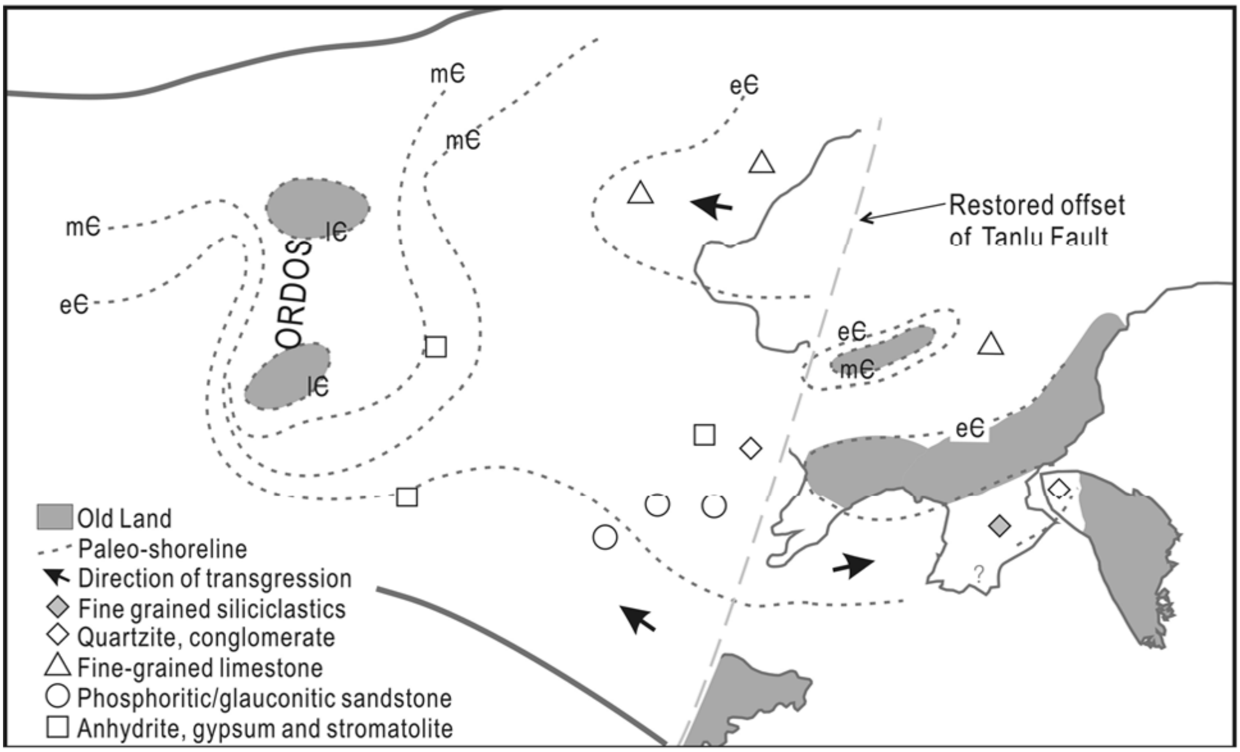


Fig. 16. Map showing direction of transgression and lithologic distribution of the basal units of the North China Platform during the Cambrian (Modified from Meng et al., 1997).

high nutrient supply in the transgressive marine condition (Meng et al., 1997). The phosphorite, glauconite, and pebble conglomerate are interpreted as deposits representing sediment starvation (Meng et al., 1997). The upwelling of phosphate-supplying cold water, related to the transgression, probably suppressed carbonate deposition. The fine-grained carbonates of the northern part of the platform (Changping Formation) represent subtidal deposition. There possibly were favorable conditions for carbonate deposition, such as clear and warm seawater. An upward transition to the supratidal sediment might be attributed to decrease in rate of sea-level change and consequent shallowing. Because the transgression proceeded generally from the east towards the Ordos oldland, the western part of the platform was submerged in the later stage. The successions of evaporate deposits of the Zhushadong Formation most likely resulted from slowed sea-level rise.

The dominance of coarse-grained siliciclastic basal units in the Korean peninsula would represent the early stage of the inundation. The eastern part of the platform was likely supplied with abundant sandy sediments. Relatively rapid rise in sea level in the early transgressive stage was most likely accompanied with high sediment input and oceanic currents that played a major role on sedimentation in shoreface to shelf environments. On the other hand, the conglomerate in the basal part of the Myeonsan Formation was probably related to localized structural motions, forming a downslope wedge in a subsiding basin margin.

6. CONCLUSIONS

1. The lowermost part of the Taebaek Group consists of Jangsan and Myeonsan formations. The Jangsan Formation consists of six sedimentary facies (thin pebble layer, massive sandstone, trough cross-stratified sandstone, horizontally stratified sandstone, foreset-bedded sandstone, and tabular cross-stratified sandstone), formed in shallow marine environments ranging from inner shelf to nearshore. Wave-generated nearshore currents, storm activity, and tidal currents played a major role for the deposition.
2. The Myeonsan Formation consists of six sedimentary facies (disorganized conglomerate, thinly-bedded conglomerate of mudstone rip-ups, trough cross-bedded sandstone, ripple cross-laminated sandstone, planar to wavy laminated sandstone, and dark gray mudstone), representing deposition in a small-scale slope and tide-influenced coastal embayments.
3. The Jangsan and Myeonsan formations represent deposition in the easternmost part of the North China Platform, controlled by eustatic rise in sea level and large siliciclastic input.

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