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Surface and subsurface reworking by storms on a Cambrian carbonate platform: evidence from limestone breccias and conglomerates

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Abstract

Some limestone breccias and conglomerates from the Furongian (Late Cambrian) Chaomidian Formation (Shandong Province, China) were investigated in order to understand the depositional and deformational processes induced by storms. The sediments under study occur in a hummocky cross-stratified peloidal grainstone layer. The limestone conglomerates consist of well-rounded clasts that are mostly flat-lying or imbricated, and have erosional bases. They formed by surface reworking (erosion and rip-up) of thin-bedded grainstones by storm waves and currents. The limestone breccias consist of subangular to subrounded clasts of grainstone, which are often associated with small-scale grainstone clastic dykes. The breccias and dykes resulted from subsurface soft-sediment deformation (i.e., differential liquefaction and fluidization of heterogeneously cemented carbonate grains), most likely triggered by storm-wave loading. The limestone breccias and conglomerates bear important implications for understanding the reworking mechanisms of storms on ancient carbonate platforms.

Keywords: limestone breccia, limestone conglomerate, soft-sediment deformation, clastic dyke, North China Platform

1. Introduction

Intraformational limestone breccias and conglomerates are a common phenomenon in mixed carbonate and siliciclastic deposits of Cambrian-Ordovician successions (Sepkoski et al., 1991). They are generally interpreted as a result of rip-up and reworking of thin-bedded limestones by strong currents and waves, most likely induced by storms (e.g., Mount & Kidder, 1993; Meng et al., 1997; Myrow et al., 2004). However, the vertical orientation of so many clasts in breccias and conglomerates remained a puzzle for a long time, and some discordant geometries (fissure-, funnel-, and mound-like, and less easily defined geometries) cannot be well explained by primary processes. Various secondary processes (i.e., soft-sediment defor-

mation) were recently proposed to explain such features as vertical orientation of clasts and discordant geometries of beds (Bouchette et al., 2001; Chough et al., 2001; Kwon et al., 2002; Pratt, 2002; Myrow et al., 2004; Chen et al., 2009a,b, 2010, 2011; Van Loon et al., 2012, 2013; Chen & Lee, 2013; Chough & Chen, 2013).

The Furongian (Late Cambrian) Chaomidian Formation in Shandong Province, North China, consists of numerous levels of limestone breccias and conglomerates, many of which have recently been under study (Chen et al., 2009a, b, 2010, 2011; Van Loon et al., 2012, 2013; Chen & Lee, 2013; Chough & Chen, 2013). Here some closely related limestone breccias and conglomerates are presented that occur in a grainstone horizon in the middle part of the Chaomidian Formation in the Jiulongshan

section, Shandong Province, China (Fig. 1). The breccias and conglomerates look similar with respect to their clasts and matrix (both being composed of grainstone), but they bear certain differences in texture and fabric of the clasts and the bed geometry. Although the limestone breccias were described and genetically interpreted in previous studies, the limestone conglomerates, their relationship with breccias, and other storm-induced structures (e.g., gutter casts) were not dealt with in detail, although they are critical for understanding the storm-induced mechanisms that affected ancient carbonate platforms.

The primary objective of the present contribution is therefore to describe in detail the characteristics and relationship of these breccias and conglomerates, as well as other sedimentary structures, in order to make their formative processes clear, and thus to deepen the insights into surface and subsurface reworking of penecontemporaneous carbonate sediments by storm waves and currents.

2. Geological setting

The North China Platform was, during the early Palaeozoic, a typical epicontinental basin formed on a stable craton, the Sino-Korean Block, which covers an area of about 1500 km from East to West and 1000 km from North to South (Meng et al., 1997) (Fig. 1). The Cambrian succession contains in Shandong Province a thick succession (approx. 800 m) of mixed carbonate and siliciclastic deposits; this succession consists of six lithostratigraphic units (Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian Formations in ascending order) (Fig. 2A). It unconformably overlies a Precambrian granite and metasedimentary rocks, and is overlain by Ordovician dolostones and limestones (Chough et al., 2010; Chen et al., 2012).

The Chaomidian Formation (approx. 200~300 m thick) is assigned to the uppermost lithostratigraphical unit of the Cambrian in Shandong Province (Fig. 2A). It consists mostly of carbonate deposits with minor shales, including limestone and shale/marlstone alternations, thin-bedded lime mudstones, bioturbated wackestones, cross-stratified grainstones, microbialites, and limestone breccias and conglomerates (Chen et al., 2009a, b; Chough et al., 2010; Lee et al., 2010, 2012). The Chaomidian Formation was generally deposited in shallow-marine environments affected by storms that left frequent structures and deposits such as gutter casts, scoured bases, hummocky cross-stratification, and stratified limestone conglomerates (Chen et al., 2011, 2012).
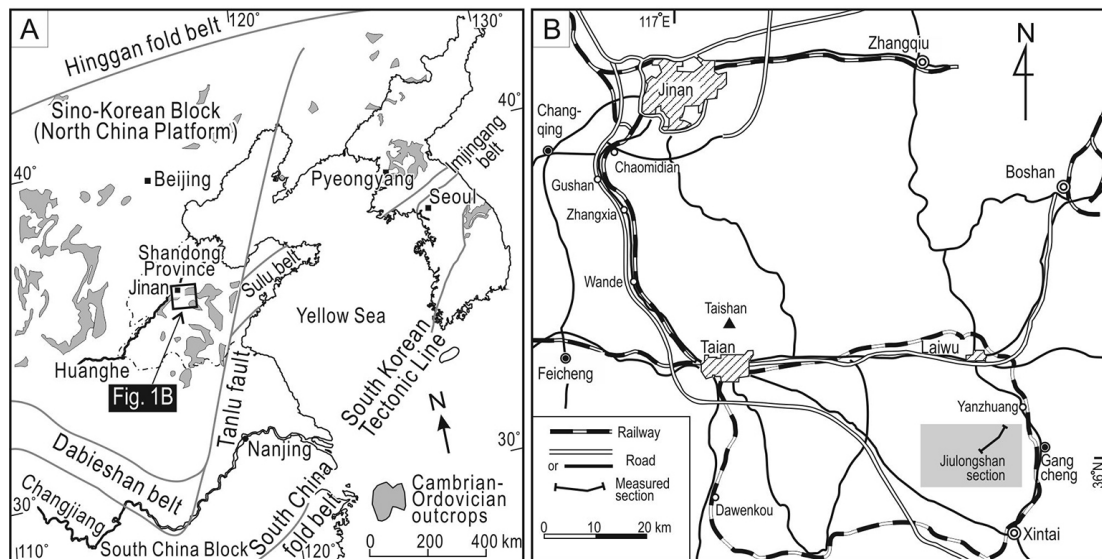

Fig. 1. Location map of the studied section.
  A: Schematic geological map of the North China Platform with major tectonic boundaries and distribution of Cambrian-Ordovician outcrops; **B:** Location of the Jiulongshan section in Shandong Province, China. For location, see Figure 1A.

3. Limestone breccias and conglomerates

The limestone breccias and conglomerates under study occur in a grainstone level (some 1.8 m thick) in the middle part of the Chaomidian Formation (Fig. 2), which can be laterally traced for at least several kilometres. The level is dominated by hummocky cross-stratified peloidal grainstones (Fig. 2B), which are composed mainly of coarse silt- to very fine sand-size peloids and a small amount of fossil fragments, with a cement of sparry calcite. The grainstone beds are partly laterally continuous, partly discontinuous, and vary in thickness from a few decimetres to two metres. The thick grainstone beds are commonly amalgamated with internal truncational boundaries (Fig. 3A). Individual grainstone layers are undulatory or wavy, and vary in thickness later-

ally from a few mm to two centimetres. The grainstone beds are partly bioturbated with vertical burrows (*Skolithos*, 1–5 cm deep). The limestone breccias and conglomerates are described and interpreted in detail below.

3.1. Limestone conglomerates

3.1.1. Description

The limestone conglomerates have a framework of monomictic to oligomictic clasts of peloidal grainstone (Fig. 3). The beds are intercalated between hummocky cross-stratified peloidal grainstones, and are laterally traceable for at least several tens of metres. The conglomerates are either clast-supported or matrix-supported, and sometimes show low-angle cross-stratification. Cross-stratified conglomerates are commonly matrix-support-
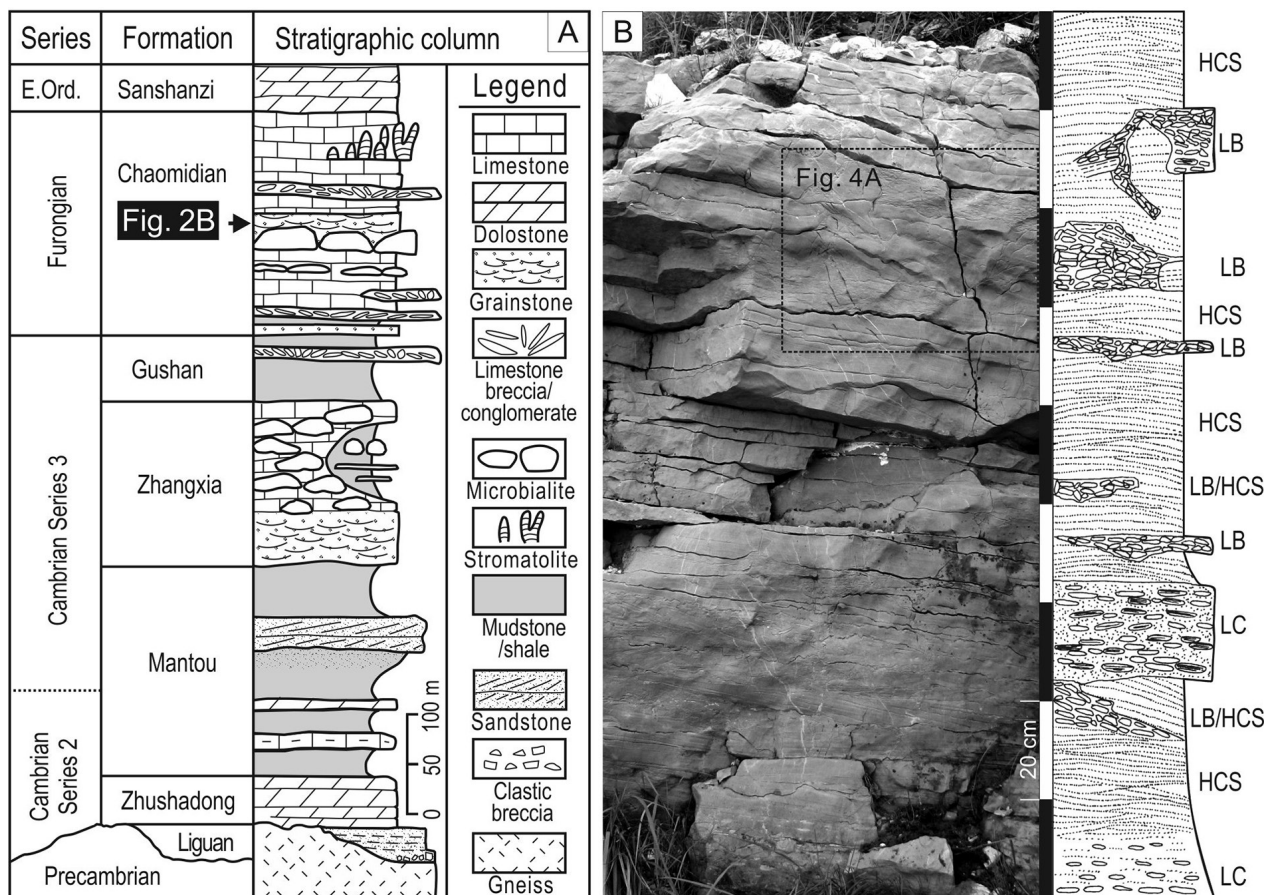

Fig. 2. Schematic stratigraphy of the Cambrian in Shandong Province and sedimentary log of the interval under study. **A:** Chrono- and lithostratigraphy of the Cambrian succession; **B:** Photograph and detailed sedimentary log of the grainstone-dominated interval under study. For stratigraphic position, see Figure 2A. HCS = hummocky cross-stratified grainstone; LB = limestone breccia; LC = limestone conglomerate.
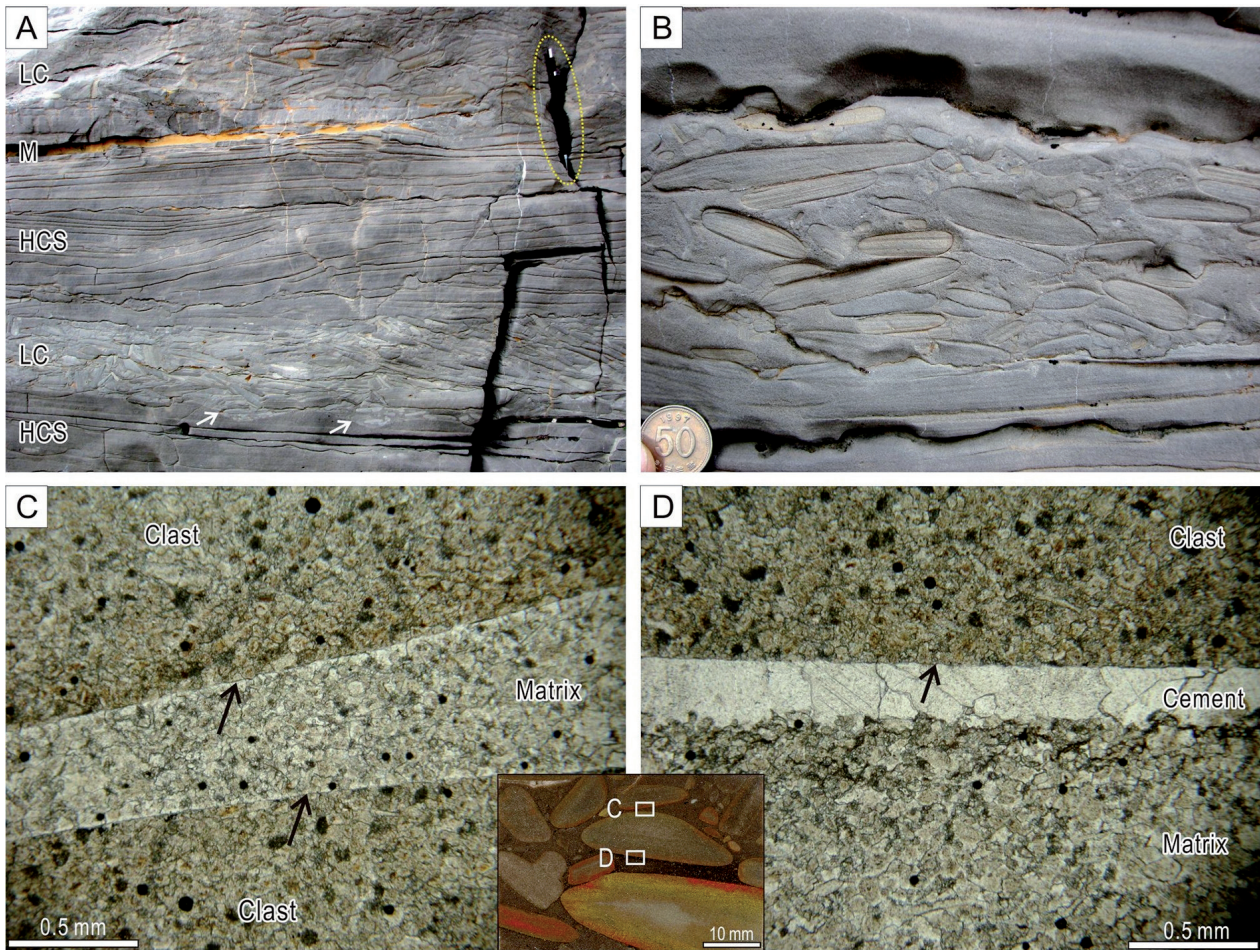
Fig. 3. Limestone conglomerates within hummocky cross-stratified grainstones.
A: Alternation of limestone conglomerate (LC) layers and hummocky cross-stratified grainstone (HCS) layers, lo-
cally intercalated between thin dolomitic marlstone (M) layers. The lower limestone conglomerate layer contains
imbricated clasts and shows a sharp, erosional boundary (arrows); **B:** Close-up of well-rounded flat-pebble clasts
of a limestone conglomerate; **C:** Thin section of a well-rounded flat-pebble conglomerate. Note that the matrix has
a similar microscopic texture as the clasts. Arrows indicate the sharp boundaries between clasts and matrix; **D:** Thin
section of sparry calcite cement below a well-rounded pebble. **Inset:** Polished slab used for preparing the thin sec-
tions, showing the location of Figures 3C and 3D.

ed, with clasts parallel to the forests of the
cross-stratification. The conglomerate beds are
underlain by peloidal grainstone with a sharp
irregular lower boundary and overlain by pe-
loidal grainstone with either a gradational or
a sharp boundary (Fig. 3A).

The clasts have long axes of a few centime-
tres and consist of laminated peloidal grain-
stone (Fig. 3B); they are well rounded and
sorted, and mostly flat-lying or imbricated and
rarely edgewise (Fig. 3A, B). The matrix has
the same texture as the clasts and the hum-
mocky cross-stratified grainstones, which are
composed mainly of peloids, fossil fragments
(among other fossils trilobites and echino-

derms), and sparry calcite cement (Fig. 3C, D).
Sparry calcite cement is sometimes present be-
low the clasts (Fig. 3D).

3.1.2. Interpretation

The limestone conglomerates formed by
transportation and deposition of rip-ups of
(semi)consolidated limestone layers (cf. Kreisa,
1981; Markello & Read, 1981; Sepkoski, 1982;
Sepkoski et al., 1991; Mount & Kidder, 1993;
Vierek, 2007, 2010). The stratified conglomer-
ates were probably reworked by strong cur-
rents and/or waves that were most likely in-
duced by storms. The coarse-grained matrix is
also suggestive of high-energy conditions.

The imbrication of the clasts resulted from modification by unidirectional currents, whereas flat-lying clasts were reworked by waves. The sporadic edgewise orientation of pebbles might have resulted from powerful oscillatory currents (Futterer, 1982) or storm-generated combined flows (Mount & Kidder, 1993).

The sharp contact between clasts and matrix indicates that the clasts were well cemented prior to brecciation and re-deposition. The sparry calcite cement below the clasts formed during early diagenesis in cavities sheltered by re-deposited clasts.

3.2. Limestone breccias

In addition to the limestone breccias (grainstone-matrix breccias) under study, it should be noted here that another type of breccias (marlstone-matrix breccias) also occurs locally in the level under study (Chen & Lee, 2013). These breccias are characterised by pebble- to cobble-sized peloidal grainstone clasts in a dolomitic marlstone and/or laminated wackestone matrix; they have commonly mound-shaped bed geometries, which makes them clearly distinguishable from the breccias under study.

These breccias have been the object of several studies, and were interpreted as a result of heterogeneous deformation of carbonate sediments and argillaceous sediments (Chen & Lee, 2013; Chough & Chen, 2013; Van Loon et al., 2013), and therefore will not be dealt with in the present study; the present study deals exclusively with the breccias that have a grainstone matrix and that are dealt with below.

3.2.1. Description

The limestone breccias are either clast-supported or matrix-supported. They consist of monomictic grainstone clasts with a disorganised fabric in a grainstone matrix (Fig. 4A). The clasts are identical in colour, texture, structures and composition to the adjacent hummocky cross-stratified grainstone. The grainstone clasts are mainly composed of peloids, small amounts of fossil fragments (trilobites, algae, and brachiopods) and mosaic sparry calcite. The peloids and fossil fragments are

about 0.05 to 0.15 mm in size (coarse silt to fine sand). The grainstone matrix is mainly composed of elongated sparry calcite grains which are mostly aligned parallel to each other (Fig. 4B). The calcite grains are partly present in the groundmass of micro-sparry calcite. Rhombic dolomite crystals occasionally occur in the matrix. The clasts are mostly of granule to pebble size (long axes of several mm to cm) and rarely of cobble size; they are generally poorly sorted and show elongated or irregular shapes with subangular to subrounded edges. Well preserved lamination is present in some relatively large clasts (Fig. 4A, C, D).

Discordant breccia bodies are usually centimetre to decimetre wide in cross-section, and commonly change into grainstones with distinct, irregular boundaries (Fig. 4A, C). They show various geometries such as funnel, channel, fissure (crack), and less easily defined shapes, and are locally connected, forming a reticulate network (Fig. 4A, C).

Small-scale clastic dykes are often associated with these breccias (Fig. 4E, F). In several cases, they extend upward and are connected with discordant breccias (Fig. 4E). The source of the dykes is hardly traceable; in many cases they demise downwards within the grainstone. They are steeply inclined to vertical pipe-shaped structures and occasionally are bifurcated or branched in vertical section. The walls of the dykes which cut through adjacent undeformed grainstone are generally straight to slightly sinuous. The dykes are several millimetres wide and a centimetre to a decimetre thick. Inside the clastic dykes massive or crudely laminated fine grainstone is present (Fig. 4F). Grainstone clasts are locally present in the dykes.

3.2.2. Interpretation

The limestone breccias were formed by differential liquefaction and fluidisation during early diagenesis (Chen et al., 2009b, 2011; Chen & Lee, 2013). Under external force, carbonate grains experience selective liquefaction and subsequent fluidisation due to heterogeneous cementation (Chen et al., 2009b; Chen & Lee, 2013). Increased pore-fluid pressure broke-up the weakly cemented aggregates of grains, and
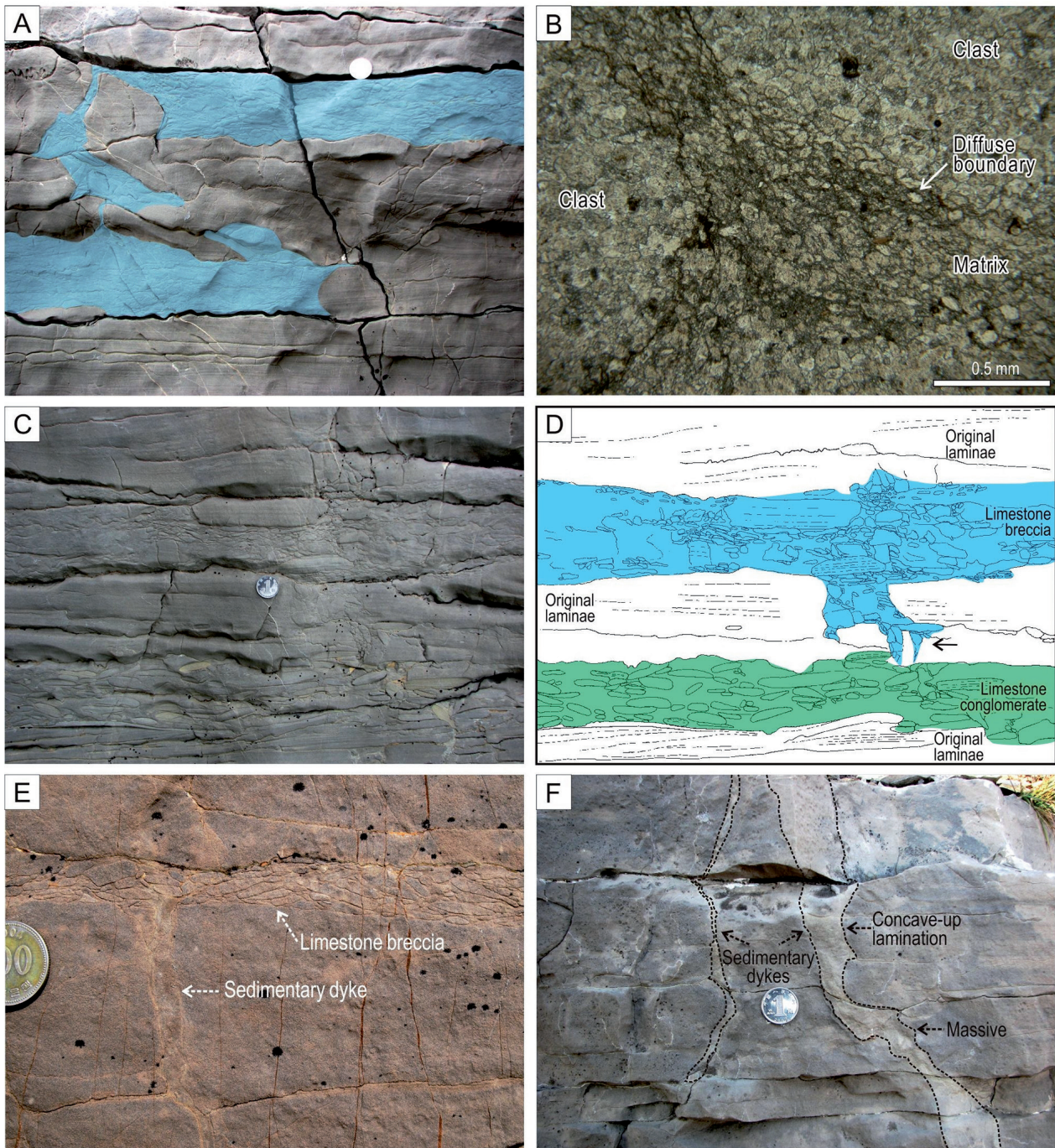
Fig. 4. Limestone breccias.
   A: Limestone breccias (shaded colour) with discordant geometry, which end abruptly to laminated grainstone; **B:** Thin section showing diffuse boundary between clast and matrix of elongated calcite grains with a micro-sparite groundmass; **C-D:** Field photograph and line drawing of discordant limestone breccias in the upper part and well-rounded pebble limestone conglomerates in the lower part. The arrow in Figure 4D shows a dyke-like conduit between the conglomerates and breccias; **E:** Clastic dyke connected with limestone breccia; **F:** Clastic dykes with either massive or crudely laminated sediment inside.

resulted in liquefaction. The liquefied sediments and pore water became under increasing pressure, and finally escaped upwards due to the increased pressure by an external force. Consequently, the upward influx of liquefied sediments and pore water led to restricted flu-

idization of the sediments. Clastic dykes resulted from upward flowage of either liquefied or fluidized sediments that came most likely from below. The upward injection of the fluid produced various crude laminae inside the dykes due to fluid drag and intrusion. Discordant breccias formed due to differential liquefaction or fluidisation of the heterogeneously cemented sediment: liquefied/fluidised portions formed matrix material, whereas unliquefied, well-cemented sediment formed clasts. The upward escape of pore water and fluidised sediment under increased stress by external force resulted in random dislocation of the clasts, which formed a disorganised internal fabric (horizontal, inclined, or vertical).

4. Discussion: deposition, erosion, and deformation by storm waves and currents

Storm-induced waves and currents are important sedimentary agents that episodically and catastrophically erode, deposit, and deform sedimentary strata. The dynamics of storm-induced currents are complex and such currents may form a wide range of sedimentary structures such as hummocky cross-stratification, flat pebbles, and pot and gutter casts (e.g., Aigner, 1985; Myrow & Southard, 1991, 1996; Myrow, 1992; Molina et al., 1997) (Figs 5 and 6). Hummocky cross-stratification is a rep-
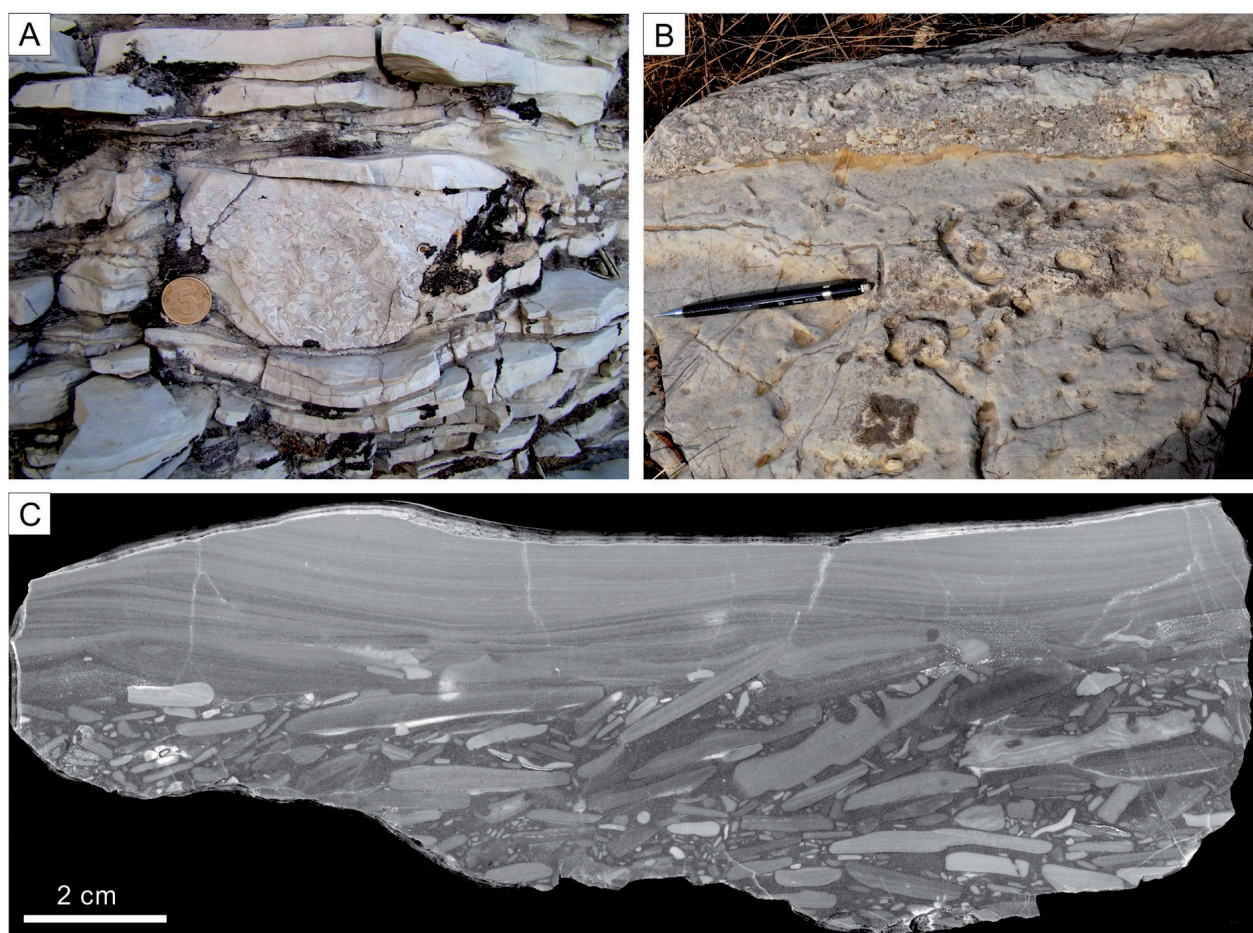

Fig. 5. Other sedimentary structures formed by storm-induced currents in relatively deeper settings (most likely below storm-wave base) of the Chaomidian Formation. These structures occur stratigraphically below the studied interval. **A:** Vertical section of a gutter cast filled with intraclasts and coarse-grained matrix. The gutter cast shows a channel-like geometry in thin-bedded lime-mudstone; **B:** Lower bedding plane of a gutter cast in thin-bedded lime-mudstone, filled with intraclasts and a coarse-grained matrix; **C:** Imbricated limestone conglomerate capped by fine ripple cross-lamination.
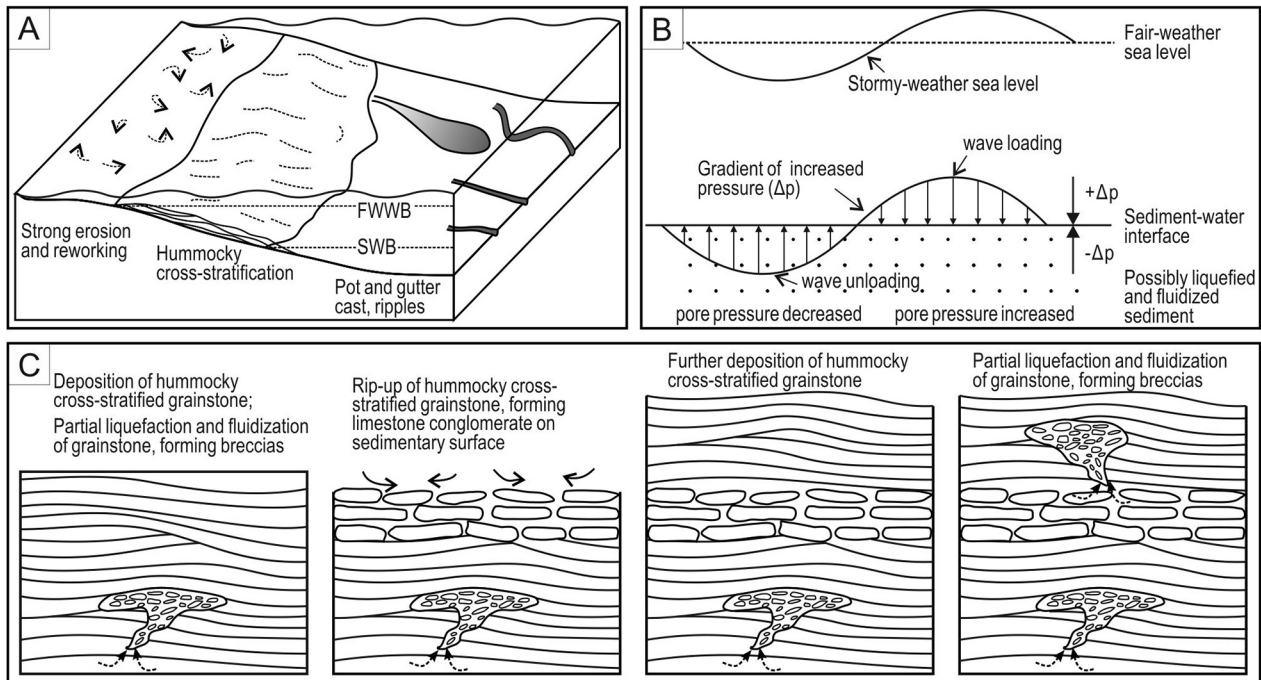
Fig. 6. Schematic model of storm-induced erosion, deposition, and deformation.
   A: Schematic depositional model during storms; **B:** Cyclically fluctuating pressure during storm waves (modified after Tsui & Helfrich, 1983; Alfaro et al., 2002); **C:** Genetic model of the limestone conglomerates and breccias by surface erosion and rip-up and subsurface soft-sediment deformation, respectively.

resentative sedimentary structure formed by storm-induced combined flows (Allen, 1985; Nøttvedt & Kreisa, 1987; Arnott & Southard 1990; Cheel & Leckie, 1993).

Storm waves and currents may erode and transport coarse-grained sediments (e.g., intraclasts and carbonate grains) from the shoreline and upper shoreface to relatively deep environments that are usually below the fair-weather wave base and above the storm-wave base (Fig. 6A). Hummocky cross-stratified grainstone beds were formed by oscillatory wave-dominated combined currents with waning currents during accumulation of sediments. Thick hummocky cross-stratified grainstone units are suggestive of energetic and frequent storms and proximal depositional environments close to the sources of sediments (Duke, 1990). The local occurrence of *Skolithos* is suggestive of post-storm colonization of organisms on the coarse-grained substrate of the shoreface (Posamentier & Walker, 2006). During severe storms, erosion may also occur, reworking the previously deposited peloidal grainstones that were re-deposited as limestone conglomerates (Fig. 6C). Further basinwards, gutter casts,

limestone conglomerates, and small-scale ripple-cross-lamination formed by erosion and deposition by sediment gravity flows (Figs 5 and 6A).

On the other hand, during stormy-weather conditions, when a wave (up to several hundreds of metres in wave length and decimetres in wave height) passes over sediments, the overburden pressure to the sediments is incrementally increased (Tsui & Helfrich, 1983). The increased pressure gradient fluctuates with the same period as the waves with a phase lag which is maximum at the sediment/water interface and decreases downwards within the sediment column (Fig. 6B). Soft sediments near the sediment/water interface that are not well compacted or cemented can be substantially eroded and suspended in the water column. The relatively deeper-buried sediment (centimetres to metres below the sediment/water interface where early cementation occurs), however, will be liquefied when the pore-fluid pressure passes the failure threshold (e.g., Molina et al., 1998; Alfaro et al., 2002). Subsequent fluidisation can be triggered by the influx of pore water and liquefied sediments.

In carbonate settings, liquefaction and fluidisation will be heterogeneous, due to partial cementation of carbonate sediments: unce-mented or weakly cemented sediments will be liquefied and fluidised, forming a matrix for the breccias, whereas well cemented sediments will not be liquefied, forming the clasts of the breccias (e.g., Bouchette et al., 2001; Chen et al., 2009b; Chen & Lee, 2013) (Fig. 6C).

One cannot rule out that catastrophic events such as earthquakes may have coincidently oc-curred during storms and that resulting shock waves also have deformed the sediments. However, earthquakes are for the breccias under study not a likely trigger mechanism for the following reasons: (1) the North Chi-na Platform formed on a stable craton during the Late Cambrian, which was tectonically and seismically quiet (Meng et al., 1997); (2) the limestone breccias and the associated clastic dykes, which resulted from differential lique-faction and fluidisation, occur only in hum-mocky cross-stratified peloidal grainstones (facies-dependent) (cf. Molina et al., 1998; Al-faro et al., 2002; Owen et al., 2011). In addition, the characteristics of the deformation struc-tures are different from those of seismically induced soft-sediment deformation structures such as convolute folds, ball-and-pillow struc-tures, and dish-and-pillars (e.g., Van Loon, 2009; Gibert et al., 2011). Nor is there any evi-dence of substantial gravity-induced sediment failure on a slope. Instead, the subtropical to tropical climate conditions of the North China Platform during the Cambrian, the common occurrence of storm-related features (i.e., hum-mocky cross-stratified grainstones, stratified limestone conglomerates, and erosional bases), and the relatively small-scale (cm to dm) and restricted (a few km^2 in surface area) presence of deformation structures suggest that storm events were the most probable triggers.

5. Conclusions

Limestone breccias and conglomerates oc-cur abundantly in the Furongian Chaomidian Formation of the North China Platform. Some grainstone breccias and conglomerates co-oc-cur in a hummocky cross-stratified grainstone interval in the middle part of the formation. The limestone conglomerates contain either flat-ly-ing or imbricated clasts with rounded edges, which were formed by surface erosion and rip-up of thin grainstone layers by storm-induced waves and currents. The limestone breccias contain subangular clasts and show discordant geometries (fissure-, funnel-, and mound-like, and less easily defined geometries); they are of-ten associated with clastic dykes. The breccias and dykes are characteristic of early-diagene-tic soft-sediment deformation structures that were formed by local differential liquefaction and fluidisation of heterogeneously cemented carbonate grains. The subtropical to tropical climate conditions of the North China Platform and the common occurrence of storm deposits suggest that storm-wave loading (subsurface reworking) was the most probable trigger ac-counting for the sediment deformation. This deepens the insight into not only the genesis of limestone breccias and conglomerates, but also the reworking mechanisms of storm waves on platform carbonates.

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