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Sequence stratigraphy, sea-level changes and depositional systems in the Cambrian of the North China Platform: A case study of Kouquan section, Shanxi Province, China

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Abstract

This study is an attempt to reconsider the sequence stratigraphy of the Cambrian succession through field investigation of the deposited strata in the central part of the North China Platform. Contrary to the other parts of the North China Platform, the Kouquan section of Datong city, Shanxi province received a relatively late sedimentation i.e. during Middle Terreneuvian, resulting in the development of two-third of the total Cambrian succession in the study area. The strata outcropping in the section comprise of Xuzhuang, Zhangxia, Gushan, Changshan and Fengshan formations, having an angular unconformable contact with the underlying Archean metamorphic rocks and parallel unconformable contact with the overlying Ordovician Yeli Formation. Based on the facies stacking patterns and cyclicity in the chronostratigraphic context, the strata are subdivided into six third-order depositional sequences (DS_1-DS_6). The shift in sedimentary strata from the mixed tidal flat facies at the base of Xuzhuang Formation to the overlying ramp carbonate deposits shows retrogradation under the second-order transgressive process. The change from the depositional sequence “transgressive system tract → condensed section → high stand system tract” in Xuzhuang Formation to the drowning unconformity type in the overlying strata controlled by “condensed section → high stand system tract” sequence defines the evolution of carbonate platform from a developing to a mature stage in the north China during Cambrian time. The lithological change from oolitic grain banks during Cambrian Series 3 to bioherm bearing massive micrites and calcareous mudstone with lenses of edgewise conglomerates in Changshan and Fengshan formations represents the depositional pattern of the skeleton-poor stormy sea during the Furongian marked by an increase in microbial carbonate buildups.

Keywords: Cambrian Series 3; Furongian; Sequence stratigraphy; Drowning unconformity; North China Platform.

1. Introduction

Sequence stratigraphy emphasizes the significance of breaks in the stratigraphic record for the definition of sequences, and offers a framework for stratigraphic units and their bounding surfaces related to their origin (Catuneanu et al., 2010). As an integration of stratigraphy and sedimentology, the sequence stratigraphy is regarded as the latest conceptual revolution to refurbish the methodology of stratigraphic analysis (Miall, 1995). Since Sloss’s definition of "sequence" as "stratigraphic unit bounded by unconformities" (Sloss et al., 1949) to Vail′s concept of sedimentary sequence "stratigraphic unit defined by unconformity and comparable conformity surface" (Vail and Mitchum, 1977), the journey indicates the step-wise establishment of sequence stratigraphy. The sequence stratigraphy of the post Exxon era, evolved from maximum flooding surface as sequence boundary and the reason for formation of depositional sequences (Galloway, 1989) to "forced regressive wedge system tract" as revised Type 1 sequence (Hunt and Tucker, 1992; Helland-Hansen and Gjelberg, 1994). Catuneanu et al. (2009, 2010), emphasized the importance of the relationship between the stratigraphic superposition style and the sedimentary facies in sequence stratigraphic unit, and the recognition of the boundary. They defined the sequence as "A sequence of depositional systems formed in an integrated accommodating space or sediment supply cycle", and pointed out that there still exists no standardization (i.e. confusion of terminology) in sequence stratigraphy and it lacks conceptual harmony. However, it is undeniable that sequence stratigraphy has been widely applied, right from explaining the regional and global changes of paleogeography and the controlling factors of depositional processes to improving the success rate of oil and gas exploration.

Representing noteworthy sedimentary features and unique cyclicity in the deposited sediments, the Cambrian strata of the North China Platform are an area of great interest for the geologists. Previous workers made many important achievements in the course of describing the Cambrian strata of the North China Platform; Meng et al. (1986) described Late Cambrian storm deposits and their sequence patterns; Feng et al. (1990) carried out sedimentary facies analysis and paleogeography of Early Paleozoic; Fan (1990) studied breccia genesis of Mantou Formation; Wang et al. (1990) described the features of oolitic grainstone in Middle Cambrian Zhangxia Formation; all these studies laid foundation for developing basic understanding regarding sedimentary characteristics of Cambrian strata in the North China Platform. Mei (1992, 1993, 1996), based on the systematic study and in-depth discussion of the meter-scale cycle and drowning unconformity type, presented the sequence stratigraphic division of the Cambrian succession in North China Platform from the perspective of cyclicity in sediments; Shi et al. (1997) used the tools of biostratigraphy and depositional sequence to establish the chronological division of the Cambrian strata of North China Platform; Wang (1999) discussed the sequence stratigraphy of Cambrian Gushan Formation in Taihang Mountain area, which provided a reference for research on the Middle Cambrian sequence stratigraphic division in the North China Platform. Based on facies superposition model and depositional cycles, the current sequence stratigraphic division of the Cambrian strata in Kouquan section will provide a reference example for the exploration of Cambrian strata widely distributed in the North China Platform and clues for the comparative studies and correlation on regional scale. This study is aimed at describing the sequence stratigraphic framework toward improved geologic conceptual models of cyclic deposition in Kouquan section in North China Platform. The sequence stratigraphic attributes of the Cambrian strata in the studied section are studied to define paleodepositional sequences within the Cambrian succession in response to relative sea-level change.

2. Geological setting

The studied Kouquan section lies close to the Kouquan railway station in Datong city (Fig. 1). The section is located at the north-western margin of Taihang Mountain, which constitutes the middle part of the North China Platform. The North China Platform started receiving the sediment influx during mid-late Lower Cambrian (Middle Terreneuvian) transgression, which was confined to the southern, eastern and western margins of the North China Platform. The influx was mainly from Qin Ling Sea located in south and southeast, as obvious from paleoshoreline reconstruction based on facies distribution (Meng et al. 1997). A sum of seven formations can be defined within the Cambrian succession across the stretch of the North China Platform, which in stratigraphic order include Changping, Mantou, Maozhuang, Xuzhuang, Zhangxia, Gushan, Changshan and Fengshan formations. The Changping Formation is unconformably overlying the Precambrian basement composed of Archean gneiss or Neoproterozoic metasediments (Yang et al., 1986; Meng et al., 1997; Mei, 2011). Contrary to Meng et al. (1997), who reported from the study area the Cambrian strata initiating from Maozhuang Formation (Early Stage 5), the oldest outcropping sedimentary strata can be considered the Xuzhuang Formation (Late Stage 5), marking an unconformity with the underlying Archean metamorphic rocks. This is quite different form Xiaweidian section in Beijing, where a parallel unconformity exists between the Changping Formation (Series 2, Stage 4 of Cambrian, but older than Mantou Formation) and the underlying Jingeryu Formation of Neoproterozoic (Mei, 2011), and the Qijiayu section, where the Mantou Formation is in a parallel unconformity with the underlying Wumishan Formation of Mesoproterozoic (Xiao et al., 2017b).

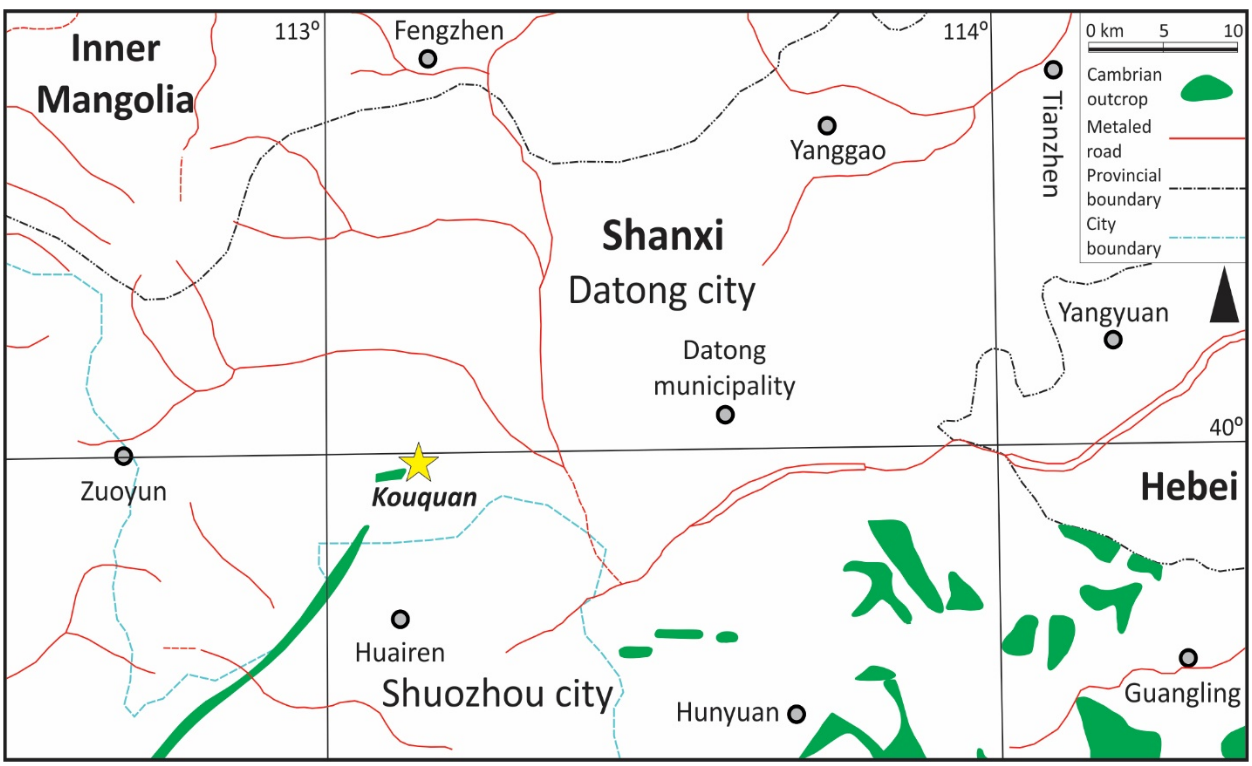

Fig. 1. Location map of the study area.

3. Sequence stratigraphic division and interpretation

The overall Cambrian succession of the North China Platform is not fully developed in the study area. Maozhuang Formation, forming the base of Series 3 in North China Platform is missing in the Kouquan section, and instead the Xuzhuang Formation, overlying the Archean metamorphic rocks, marks the base of Cambrian in the area. The exposed Cambrian strata can be subdivided into Series 3 and Furongian series; Xuzhuang, Zhangxia and Gushan formations (DS_1-DS_3) together represent Series 3 in the study area, whereas Furongian series is dividable into Changshan and Fengshan formations, which are the collective equivalent of the Furongian Chaomidian Formation (Lee et al., 2010; Lee et al., 2012, 2014a; Chen eta al., 2014), and are believed to be deposited in three third-order depositional sequences (DS_4-DS_6, Figs. 2-3,6). The overall sedimentary succession shows a facies change from the mixed tidal flat to the ramp carbonate deposits in response to retrogradation during second-order transgressive process.

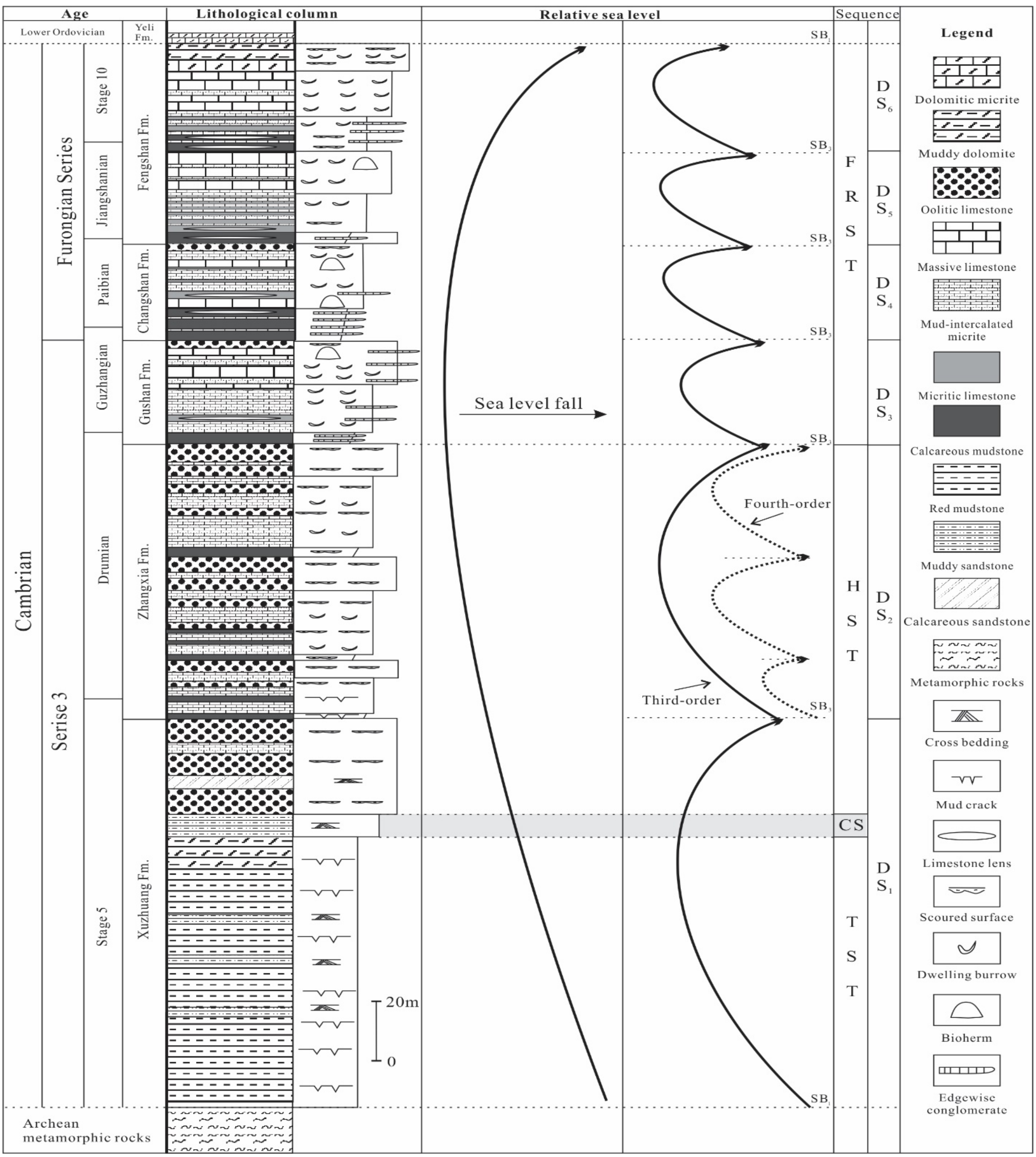

Fig. 2. Sequence stratigraphy of the exposed Cambrian succession (following Xiao et al., 2017a,b).

3.1. Sequence stratigraphy of Cambrian Series 3

3.1a. Xuzhuang Formation

The sedimentary facies analysis for Xuzhuang Formation (DS_1, Figs. 2-3) shows a shift from the mudstone of evaporative tidal flat facies in the lower part to the oolitic grain bank facies in the top part of the formation (Fig. 4a-b). The lower part of the Xuzhuang Formation (56m thickness), comprises of red colored massive mudstone of supratidal facies, which graduates into sandy to muddy dolomite of intertidal facies, and defines transgressive system tract (TST) within the formation. The overlying strata consist of gray-green silty calcareous shale in the middle part of the formation (2m thickness), which represent the shelf facies, and constitute the condensed section (CS) of the third-order sequence DS_1. The interbedding of the thin to medium bedded calcareous sandstone and the medium bedded oolitic grainstone in the upper part of the formation forms a subtidal type meter-scale cycle, which is composed of shallow ramp deposits (25m thickness). The top part of the formation is comprised of thin bedded mud-intercalated micritic limestone and massive oolitic grainstone of oolitic grain bank facies, forming subtidal type meter-scale cycle (35m thickness). The formation is bounded by Type 1 unconformity (sequence boundary one: SB_1) with the Achaean basement rocks on the bottom, while a drowning type unconformity (sequence boundary 3: SB_3) on its top with Zhangxia Formation.

3.1b. Zhangxia Formation

Zhangxia Formation is comprised of one third-order sequence DS_2 and three fourth-order sequences (Figs. 2-3). The development of thick beds of oolitic grain bank facies with middle and deep ramp facies of mud-intercalated micrite during high stand system tract (HST) and calcareous mudstone is the main feature of the formation, which reflect the internal cyclic change between shoaling and non-shoaling facies. The third-order sequence DS_2 from the bottom-lying shelf facies of calcareous mudstone to the top oolitic grain bank facies reflects a gradually upward shallowing sedimentary sequence (Figs. 4c-d). It can be subdivided into three fourth-order sequences bounded by flooding surfaces, and showing the abrupt transition (Mei and Ma, 2001) from shallow grain bank environment to deeper shelf during transgression, whereas the whole sequence is bounded by Type 3 sequence boundaries at top and bottom.

The details of sedimentary facies recognized for Zhangxia Formation is given in the following:

i. ***First fourth-order sequence***

Shelf facies: Calcareous mudstone with lenses of edgewise conglomerate, 4m thickness (forming CS).

Deep ramp facies: Thick bedded calcareous mudstone and thin bedded mud-intercalated micrite, forming L-M subtidal meter-scale cycle, thickness 20m (forming lower part of HST).

Middle to shallow ramp facies: Thick bedded calcareous mudstone with lenses of edgewise conglomerate, thin bedded mud-intercalated micrite and thin bedded oolitic grainstone, forming L-M subtidal meter-scale cycle, 10m thickness (forming upper part of HST).

Oolitic grain bank facies: Thin bedded mud-intercalated micrite and massive oolitic grainstone of oolitic grain bank facies, forming subtidal type meter-scale cycle, 15m thickness (forming upper part of HST).

ii. ***Second fourth-order sequence***

Shelf facies: Greenish-gray calcareous mudstone with lenses of edgewise conglomerate, 3m thickness (forming CS).

Deep ramp facies: Greenish-gray to green, thick bedded calcareous mudstone and thin bedded mud-intercalated micrite, forming L-M subtidal meter-scale cycle, 15m thickness (forming the lower part of HST).

Middle ramp facies: Thick bedded greenish gray calcareous mudstone with lenses of edgewise conglomerate, thin bedded strip mud limestone and thin bedded oolitic grainstone, forming L-M subtidal meter-scale cycle, 10m thickness (forming the upper part of HST).

Shallow ramp facies: Thin bedded mud-intercalated micrite and medium bedded oolitic grainstone, forming subtidal type meter-scale cycle, 10m thickness (forming lower part of HST).

Oolitic grain bank facies: Thin bedded mud-intercalated micrite and massive oolitic grainstone of oolitic grain bank facies, forming subtidal type meter-scale cycle, 24m thickness (forming upper part of HST).

iii. Third fourth-order sequence

Deep ramp facies: Greenish-gray, thick bedded calcareous mudstone with edgewise conglomerate lens, 5m thickness (forming CS).

Middle ramp facies: Thin bedded mud-intercalated micrite and thin bedded oolitic grainstone, forming L-M subtidal meter-scale cycle, 15m thickness (forming lower part of HST).

Shallow ramp facies: Thin bedded mud-intercalated micrite and medium bedded oolitic grainstone, forming subtidal type meter-scale cycle, 8m thickness (forming middle part of HST).

Oolitic grain bank facies: Thin bedded mud-intercalated micrite and massive oolitic grainstone of oolitic grain bank facies, forming subtidal type meter-scale cycle, 30m thickness (forming upper part of HST).

The fourth-order sequences, identified on the bases of variation in sedimentary facies, can be observed with "CS → HST" as the basic depositional sequence. The shelf facies of calcareous mudstone comprise CS unit, while the mud-intercalated micrite and oolitic grainstone comprise subtidal type meter-scale cycles and together with the thick bedded oolitic grainstone in the upper part form HST. The top and bottom boundaries of the fourth-order sequences are flooding surfaces, which are represented by the sediments' starvation resulted from the rapid rise of sea level.

The shelf facies of calcareous mudstone in Zhangxia Formation represents a rapid sea-level rise, which is believed to have provided basis for a submerged carbonate platform (Sattler et al., 2009) having suspended sediments, and the development of deeper water, thin bedded sedimentary strata. The HST inside DS_2 is directly covered by CS of DS_3, which represents SB_3 of typical drowning unconformity type (Mei and Mei, 1997) (Fig. 4d, 5a). The discontinuity of deposition itself represents the unconformity of this set of relatively integrated beds (Schlager, 1999), which represents that this type of sequence boundary is different from the Exxon model for Type I and Type II sequence boundaries (Mei and Mei, 1997).

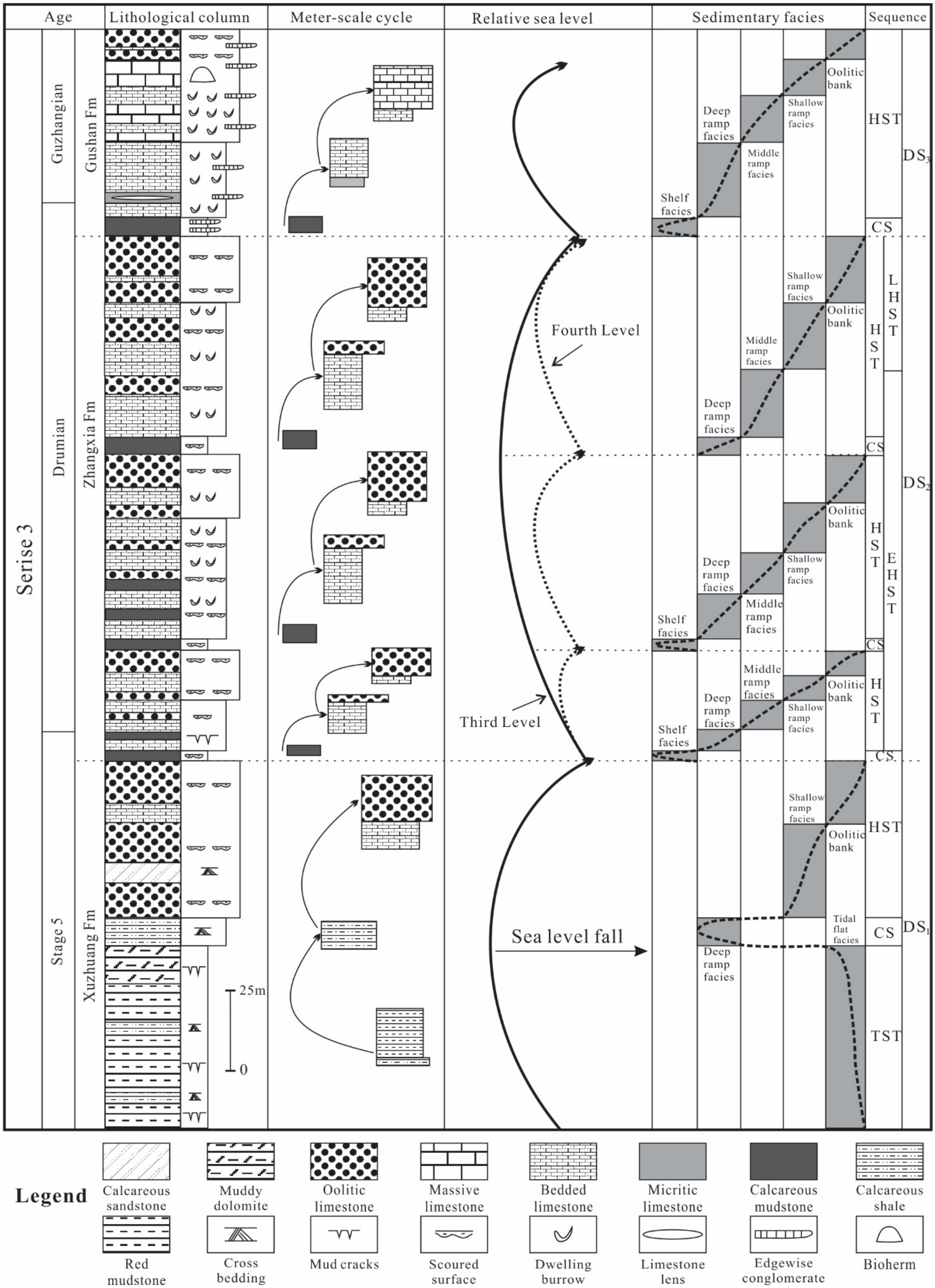

Fig. 3. Sequence stratigraphy of the Cambrian Series 3 strata (following Xiao et al., 2017a,b).

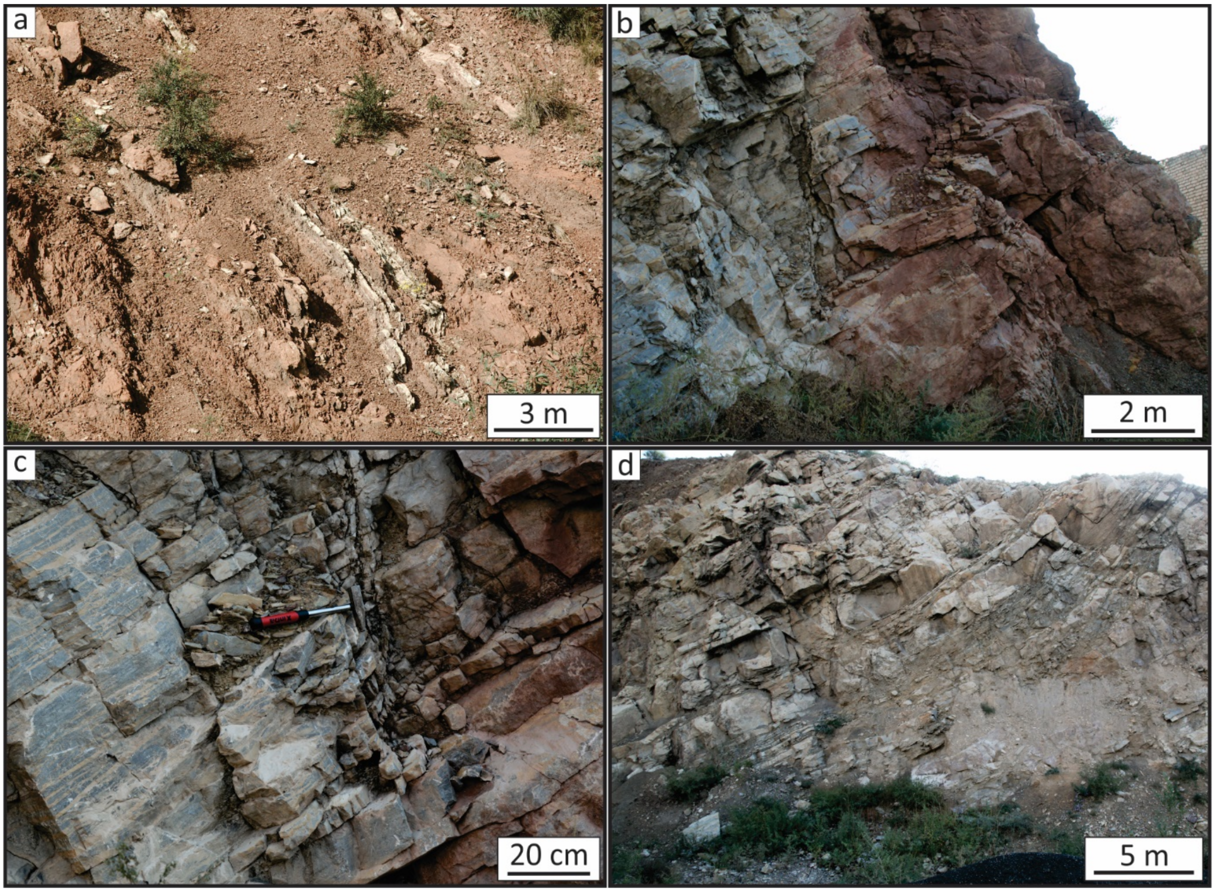

Fig. 4. Field photographs showing a-red beds of Xuzhuang Formation; b-condensed section at the bottom of Zhangxia Formation graduating into micritic limestone; c-massive oolitic grainstone of oolitic grain bank facies in Zhangxia Formation; d-thin bedded mud-intercalated micrite and medium bedded oolitic grainstone, graduating into thin bedded mud-intercalated micrite and massive oolitic grainstone in the upper part of Zhangxia Formation.

3.1c. Gushan Formation

Gushan Formation in the studied section comprises of one third-order sequence DS_3 (Figs. 2-3). The lower strata consist of shelf facies of calcareous mudstone (8m thickness), forming CS of DS_3. HST is comprised of deep ramp facies (6m thickness) of mud-intercalated micrite having edgewise conglomerate, overlain by the middle ramp facies (4m thickness) of thin bedded mud-intercalated micritic limestone and medium bedded (of massive type) micrite, then shallow ramp facies (3.5m thickness) of bioherm-bearing massive micrite with interbedded mud-intercalated micrite, and finally the massive oolitic grain bank facies (6m thickness) in the top part of the formation. The massive oolitic grainstone in top part of Gushan Formation is overlain by the calcareous mudstone of shelf facies at the bottom of Changshan Formation (DS_4), while the calcareous mudstone of shelf facies at the bottom of Gushan Formation overlies the top oolitic grainstone of Zhangxia Formation, showing typical "CS → HST" sequence of drowning unconformity type (Figs. 5a-d).

Summarizing, Cambrian Series 3 in Kouquan section represents the sedimentary characteristics of the red beds of tidal flat depositional setting at the base of Xuzhuang Formation, which progress into the oolitic grain bank facies in the overlying strata and represent the carbonate platform in north China from developing to mature stage (Xiao et al., 2017a,b). In the mature stage of carbonate platform, the development of oolitic grain bank facies shows HST (i.e. LHST), where the forming process is similar to the forced regression (FRST) (Hunt and Tucker, 1992) and falling-stage systems tract (FST) (Schlager and Warrlich, 2009), and therefore it cannot be simply classified as platform shoal product (Xiao et al., 2017a,b.).

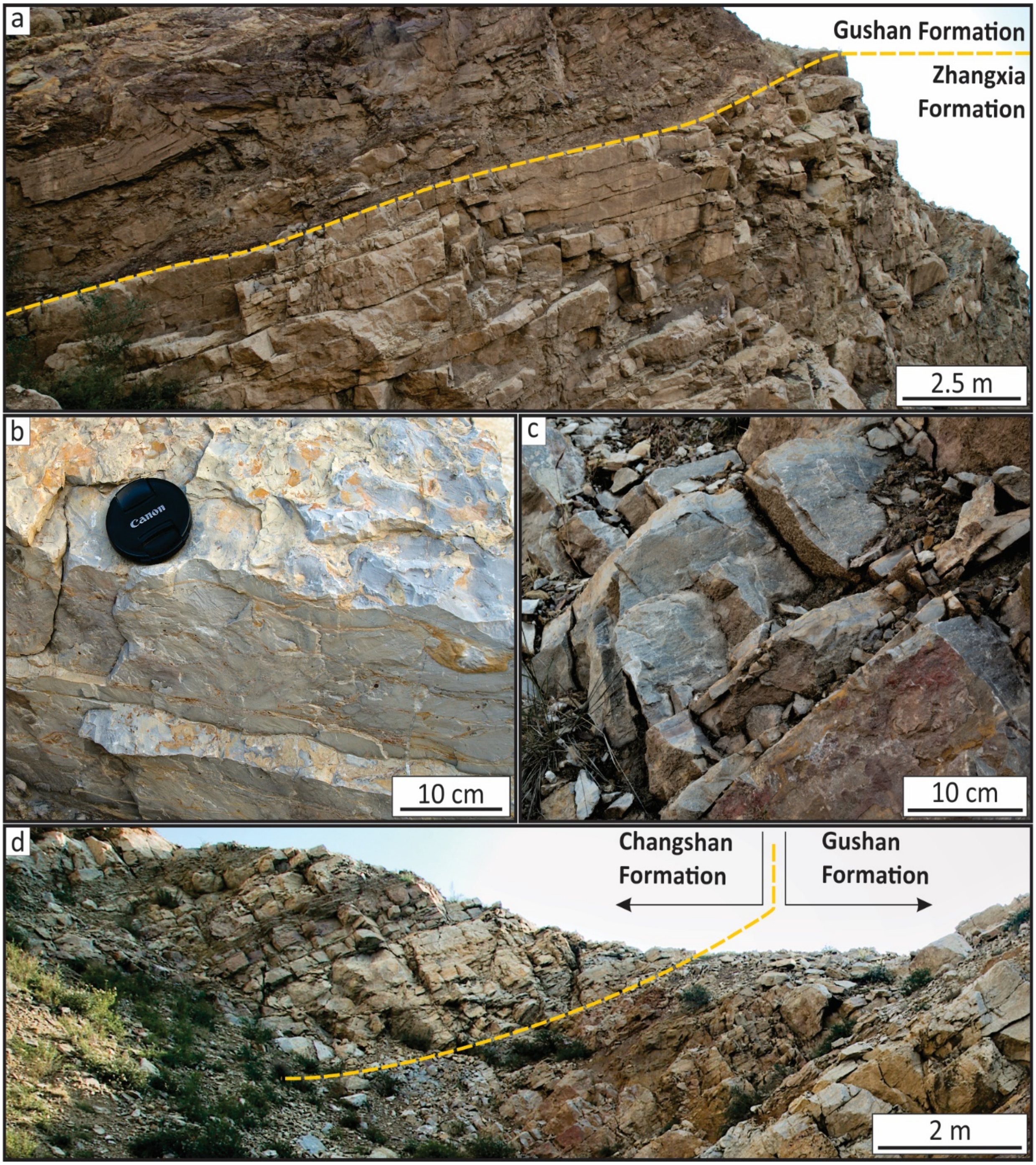

Fig. 5. Field photographs showing a-contact between Zhangxia and Gushan formations; b-massive limestone in Gushan Formation; c-oolitic grainstone in the upper part of Gushan Formation; d-contact between mudstone of Changshan Formation and oolitic grainstone of Gushan Formation.

3.2. Sequence stratigraphy of Furongian series

3.2a. Changshan Formation

Changshan Formation constitutes one third-order sequence DS_4 (Figs. 2,6). The bottom lying shelf facies (3m thickness) of calcareous mudstone constitutes condensed section of the third-order sequence, with conglomerate lenses developed as a result of storm events. The HST within the formation comprise of massive micritic limestone of deep ramp facies (2m thickness) having bioherms, followed by a series of thinning upward beds of intercalated shale and marl interbedded with thickening upward mud-intercalated micrite, comprising deep to middle ramp facies and constituting L-M type meter-scale cycle (11m thickness). The strata formed in HST is overlain by the bioherm-bearing massive micritic limestone with intercalated mudstone of middle ramp facies (8m thickness) and thin bedded mud-intercalated micrite overlain by thick bedded oolitic grainstone of shallow ramp facies (5m thickness), respectively (Figs. 7a-d). The middle and shallow ramp facies in the upper part of Changshan Formation determines the Forced Regressive System Tract (FRST) of third-order sequence of Hunt and Tucker (1992) and Mei (2010) which is equal to the Late Highstand System Tract (LHST) (Mei et al., 2015) and Falling-Stage Systems Tract (FST) (Mei et al., 2005; Mei, 2007; Schlager and Warrlich, 2009; Samanta et al. 2016), characterizing relative sea level fall in sedimentary record (Figs. 2,6). It differs from the Exxon model (Vail et al. 1977), which suggests that the deposition occurred during HST or sea level stagnation period, followed by successive erosional unconformities during forced regression.

The shelf facies of calcareous mudstone at the bottom of Changshan Formation overlies the shallow ramp facies of massive micritic and oolitic limestone in the upper part of Gushan Formation, while the shelf facies of calcareous mudstone at the bottom of Fengshan Formation covers the thick bedded oolitic grainstone of shallow ramp facies in the top part of Chnagshan Formation. These abrupt changes in depositional facies, commencing from Zhangxia Formation of Series 3, and continuing through Gushan Formation and Furongian series, are typical examples of drowning type unconformities (Xiao et al., 2017a,b).

3.2b. Fengshan Formation

Fengshan Formation is exposed beside G-109 Highway running to Eerduosi (Ordos) city of Inner Mangolia. The formation is believed to have deposited in two third-order depositional sequences DS_5-DS_6 (Figs. 2,6,8), which are described as under:

i. ***First third-order sequence (DS_5)***

Shelf facies: Dark green calcareous mudstone and shale having edgewise conglomerate, 2m thickness (forming CS).

Deep to middle ramp facies: Thinning upward gray to green marl with lenticular lenses of edgewise conglomerate interbedded with medium bedded mud-intercalated micrite, forming L-M type meter-scale cycle, 4m thickness (forming HST).

Shallow ramp facies: Bioherm bearing massive micrite having interbeds of thin bedded mud-intercalated micrite, forming subtidal type meter-scale cycle, 21m thickness (forming FRST).

ii. ***Second third-order sequence (DS_6)***

Deep ramp facies: Calcareous mudstone having lenses of micrite, 13m thickness (forming CS).

Middle to shallow ramp facies: Thin bedded mud-intercalated micrite and burrowed massive micrite, forming subtidal type meter-scale cycle, 25m thickness (forming HST).

Shallow ramp to tidal flat facies:

Gray to dark gray, medium bedded dolomitic micrite and massive tidal flat muddy dolomite, forming peritidal type meter-scale cycle, 30m thickness (forming FRST).

The shallow ramp facies of micritic limestone in the top part of Changshan Formation is overlain by the calcareous mudstone at the bottom of the first third-order depositional sequence within Fengshan Formation, representing the typical drowning unconformity type sequence boundary. Whereas, the boundary between Fengshan Formation and overlying Ordovician sediments is a typical exposure discontinuity, which represents the Type 1 sequence boundary of Exxon model.

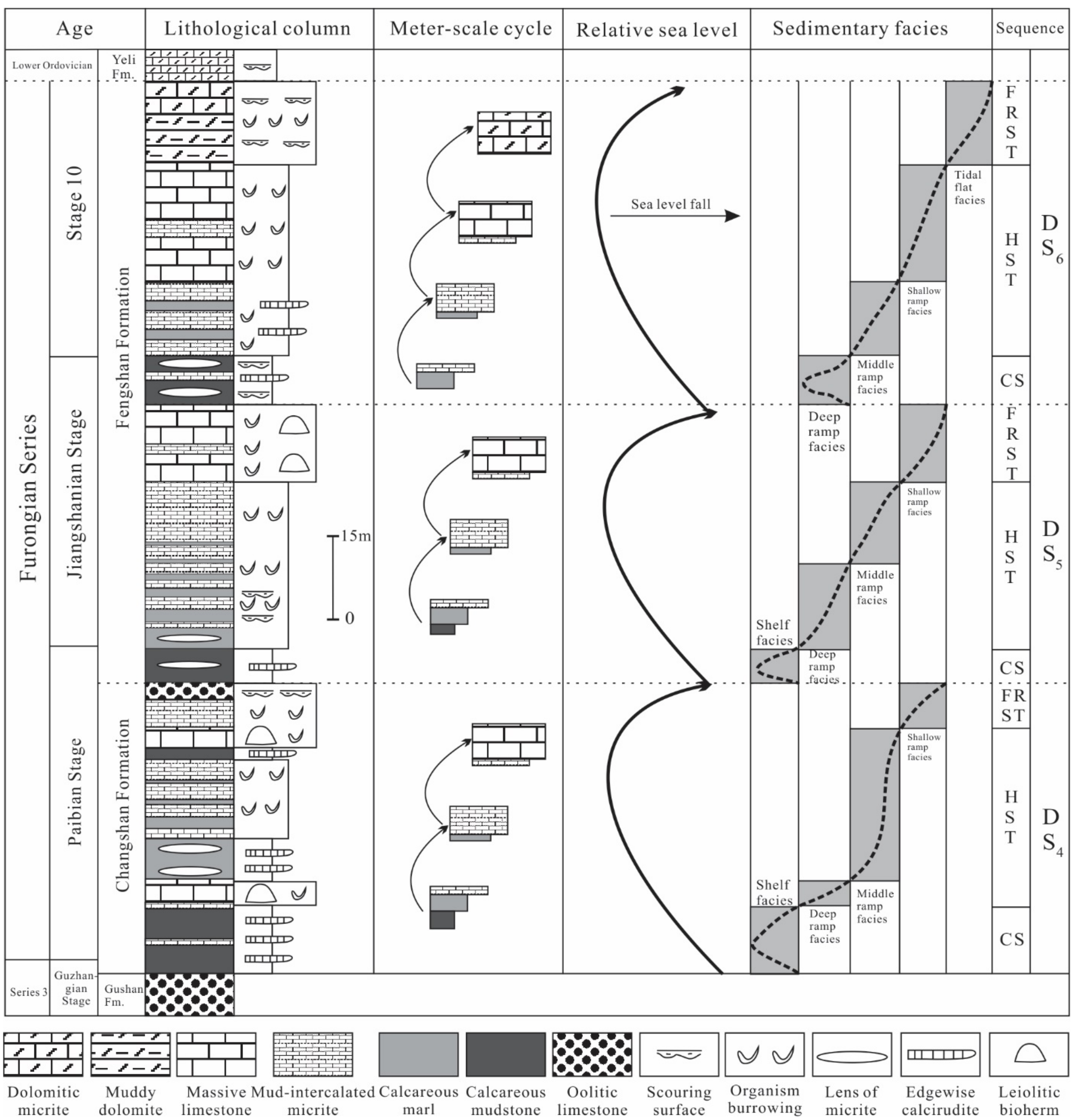

Fig. 6. Sequence stratigraphy of Furongian series strata at Kouquan section (following Xiao et al., 2017a,b).

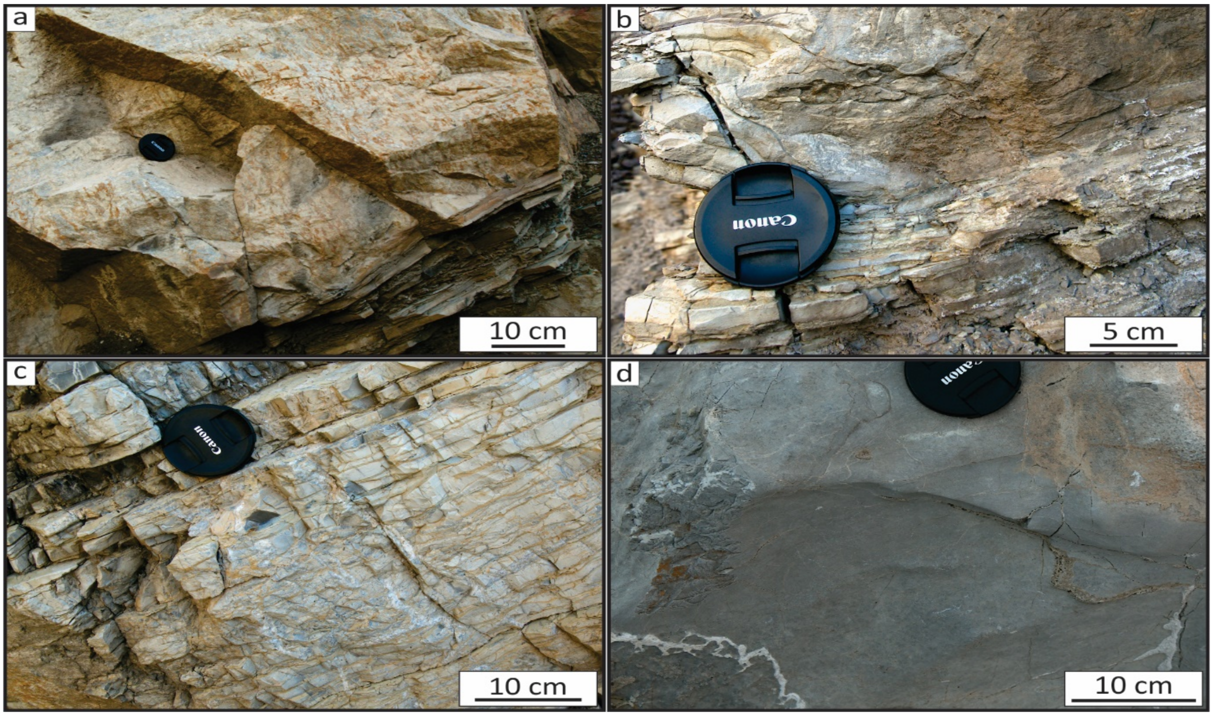

Fig. 7. Field photographs showing a-massive micritic limestone in Changshan Formation; b-intercalated marl and shale with calcirudite lens in Changshan Formation; c- thin bedded mud-intercalated micritic limestone in Changshan Formation; d- thick bedded oolitic grainstone in Changshan Formation.

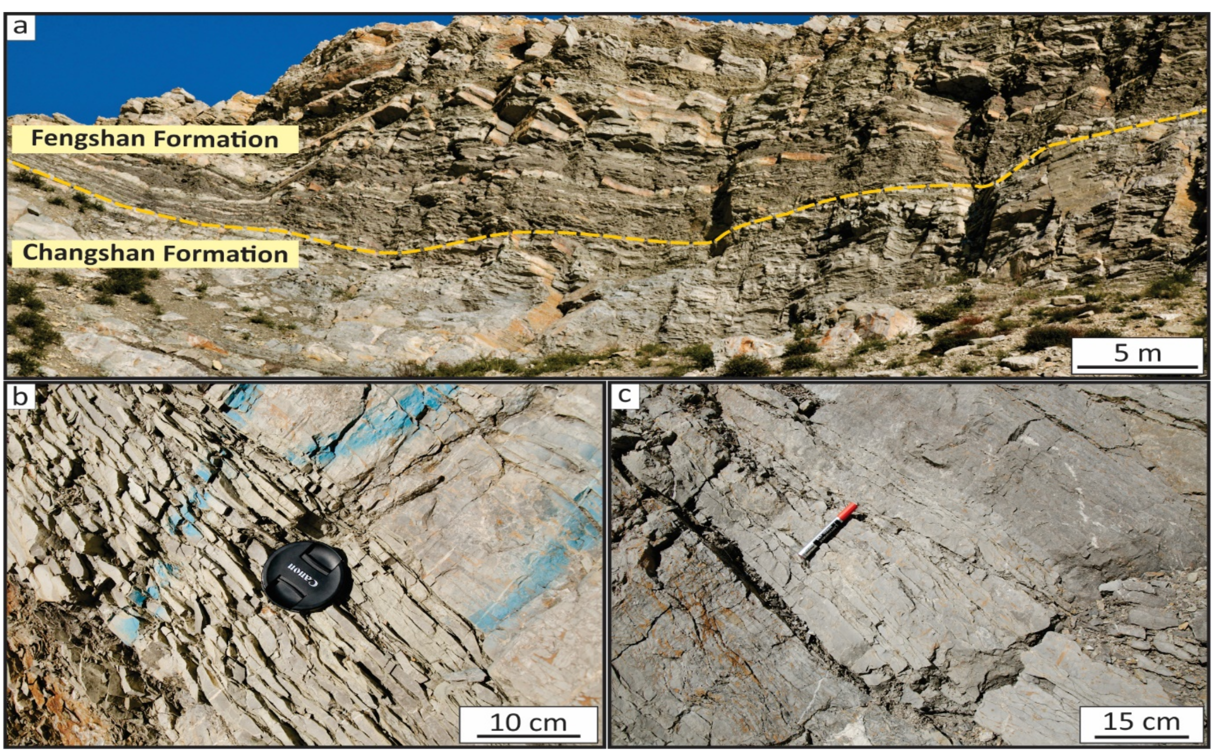

Fig. 8. Field photographs showing a-contact between Changshan and Fengshan formations; b-thin bedded mud-intercalated micrite and massive biohermal micrite in DS_5 of Fengshan Formation; c-massive tidal flat muddy dolomite in DS_6 of Fengshan Formation.

4. Conclusions

1. The second-order transgression in Kouquan section shows a facies change from the mixed tidal flat to ramp carbonate deposits. During Cambrian Series 3, the evolution of mixed clastic-carbonate rocks forming deep ramp condensed section in Xuzhuang Formation to the shallow water carbonate deposits represent a relative sea-level rise during its development to mature stage of carbonate platform. In the sedimentary records of the mature stage of carbonate platform, the platform drowning events are controlled by multiple stages of submergence. A sum of five sequence boundaries of drowning unconformity type are recognized within the Cambrian Series 3 and Furongian series, whereas the whole Cambrian succession is bounded at the top and bottom by Type 1 sequence boundaries of Exxon Model.

2. The overall Cambrian strata can be divided into six third-order depositional sequences on the basis of facies changes and cyclicity in sediments, one each recognized for Xuzhuang, Zhangxia, Gushan and Changshan formations, while Fengshan Formation was deposited in two third-order sequences. Zhangxia Formation can be subdivided into three fourth-order sequences bounded by flooding surfaces, whereas the whole sequence is bounded by drowning unconformities at top and bottom.

3. In comparison to the development of thick bedded grain bank facies of oolitic grainstone in Cambrian Series 3, the Furongian succession mainly developed massive biohermal limestones. Along with the development and abundance of oolitic grain banks during Series 3 and their subsequent declination during Furongian series, the deposition of storm deposited edgewise conglomerates and uniform bioherm development in the increased microbial carbonate deposits in Late Cambrian constitute the skeleton-poor style stormy sea sedimentation in Furongian of North China Platform.

4. The sequence stratigraphic division of Cambrian strata in Kouquan section of Shanxi province provides a reference data for the style of sedimentation in the North China Platform, as well as a reliable example for the comparative study of the Cambrian system on wider scale in future. Furthermore, the development of multiple bioherms in Late Series 3 and Furongian strata offers new dimensions of research endeavors being a complex problem in sedimentology.

Recommendations

The carbonate rocks in the Cambrian strata of the North China Platform possess large number of pore types and subsequent significant porosity and permeability, and may therefore be evaluated for hydrocarbon resource potential. The micritic limestones and bioherms may possess good source rock characteristics due to their enriched organic content, as well as serve as hydrocarbon reservoirs because of certain microbial textures and fabrics. The overlying oolitic grainstone deposited in higher energy grainstone banks may reserve oil and gas, while the marl, shale and mudstones may serve as high-quality seals.

Authors' Contribution

Khalid Latif, proposed the main concept and involved in write up. Enzhao Xiao, assisted in establishing sequence stratigraphy of the section. Muhammad Riaz, collected field data. Long Wang, did provision of relevant literature, and review and proof read of the manuscript. Muhammad Younis Khan, did technical review before submission and proof read of the manuscript. Abdullah Ali Hussein, did collection of field data. Muhib Ullah Khan, was involved in *assistance in preparation of illustration and plates of figures.*

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