Cambrian-Ordovician sequence stratigraphy on the northern Tarim Platform and its correlation with Yangtze Platform and North China Platform

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Abstract The Cambrian and Ordovician on the northern Tarim Platform are mainly composed of carbonates. On the basis of detailed outcrop analysis, the sequence stratigraphic system of the Cambrian-Ordovician in the northern Tarim Platform is outlined in this paper. Altogether 35 third-order sequences, 12 supersequences, 4 supersequence sets and 2 megasequences are recognized. The characteristics of the major sequence boundaries have been documented with an integrated examination of outcrop, seismic and borehole data, and the ages of these sequence boundaries have been calibrated through the combination of sequence stratigraphy with biostratigraphy. It is discovered that there is good correlation of the sequence stratigraphy of the Cambrian-Ordovician among Tarim, Yangtze and North China platforms. This may illustrate that the development of the Cambrian-Ordovician carbonate sequences in these three platforms is mainly controlled by regional or global sea level changes. This forms the theoretical basis for the construction of high-resolution chronostratigraphic system of the Cambrian-Ordovician in the three platforms in China.

Keywords: sequence stratigraphy, Cambrian-Ordovician, Tarim Platform, Yangtze Platform, North China Platform.

Sequence stratigraphy is a new subdiscipline of stratigraphy[1—7]. There are still different opinions as to the driving mechanism of global sea level changes that control sequence development. Studies have indicated that the sequence architectures developed under varied tectonic settings may be quite different because of the different controlling factors. The Tarim Basin in northwestern China is one of the largest hydrocarbon-bearing intracontinental basins in the world, and its position in Chinese petroleum industry is well known. Sequence stratigraphic research in Tarim Basin began in 1991 and in the last 10 years many achievements have been acquired in the Cambrian-Ordovician. These include sequence boundaries and system tracts of carbonate sequences, architecture models of different kinds of sequences, sea level changes, computer simulation of carbonate sequences, the biostratigraphy of the sequences, and the relation of sequence stratigraphy to oil and gas reservoirs [8—25]. In this paper, we will focus our attention on construction of the carbonate sequence stratigraphic system of the Cambrian-Ordovician on the northern Tarim Platform and its correlation with those in Yangtze and North China platforms, and also a discussion of the major controlling factors on the development of the cratonic carbonate sequences within the relatively strict chronostratigraphic framework established through detailed correlation between chronostratigraphy and sequence stratigraphy.

1 Stratigraphy and depositional setting of the Cambrian-Ordovician on the northern Tarim Platform

The study area is located in the Keping area, northern Tarim Platform (fig.1). The major measurement sections include the Xiaoerbulak (Cambrian) and the Dawangou (Ordovician). Detailed study on biostratigraphy and chronostratigraphy in these two sections has been carried out in the past several years[8, 10, 11, 24], which provides a good condition for further study of sequence stratigraphy of the Cambrian and Ordovician in the area.

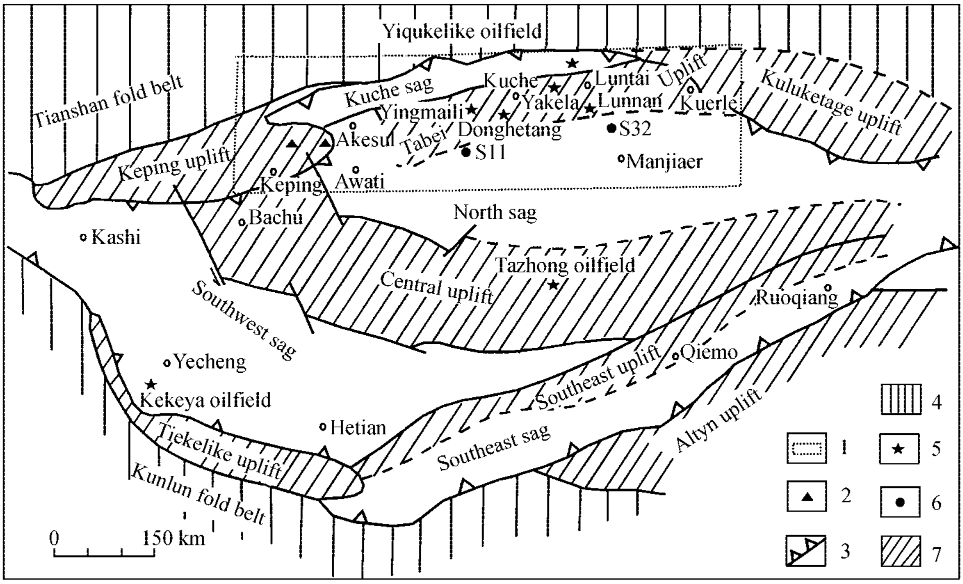


Fig. 1. Position of the study sections and their tectonic setting. 1, Study area; 2, location of outcrop sections; 3, present basin boundary; 4, fold belt; 5, oil/gas field; 6, bore well; 7, uplift.

The Cambrian and Ordovician are mainly composed of carbonates (fig. 2). The Cambrian consists in descending order of the Yuertusi, Xiaoerbulak, Wusonggeer, Shayilike, Awatage, and Xiaqiulitage formations (fig. 2). At the bottom of the Yuertusi Formation is a thin dolomite bed deposited in the shallow sea, which passes upwards into black shale interbedded with silicalite and phosphorite. From the Xiaoerbulak Formation to the Xiaqiulitage Formation, the strata are mainly composed of different kinds of dolomites, including micritic dolomite, muddy dolomite, algal stromatolite dolomite, dolarenite, dolomite breccia, etc. The Penglaiba, Yingshan, and Dawangou formations belong to the Lower Ordovician, and are composed of sparry grainstone, micritic grainstone, wakestone and micrite. The Saergan Formation consists of black shale interbedded with micrite layers or lenticule, which merges from the Lower to Middle Ordovician. The Kanling and Qilang formations in the Middle Ordovician are mainly composed of black shale and micrite with some interbedded bioclastic layers. The Yingan Formation belongs to Upper Ordovician and consists of black shale.

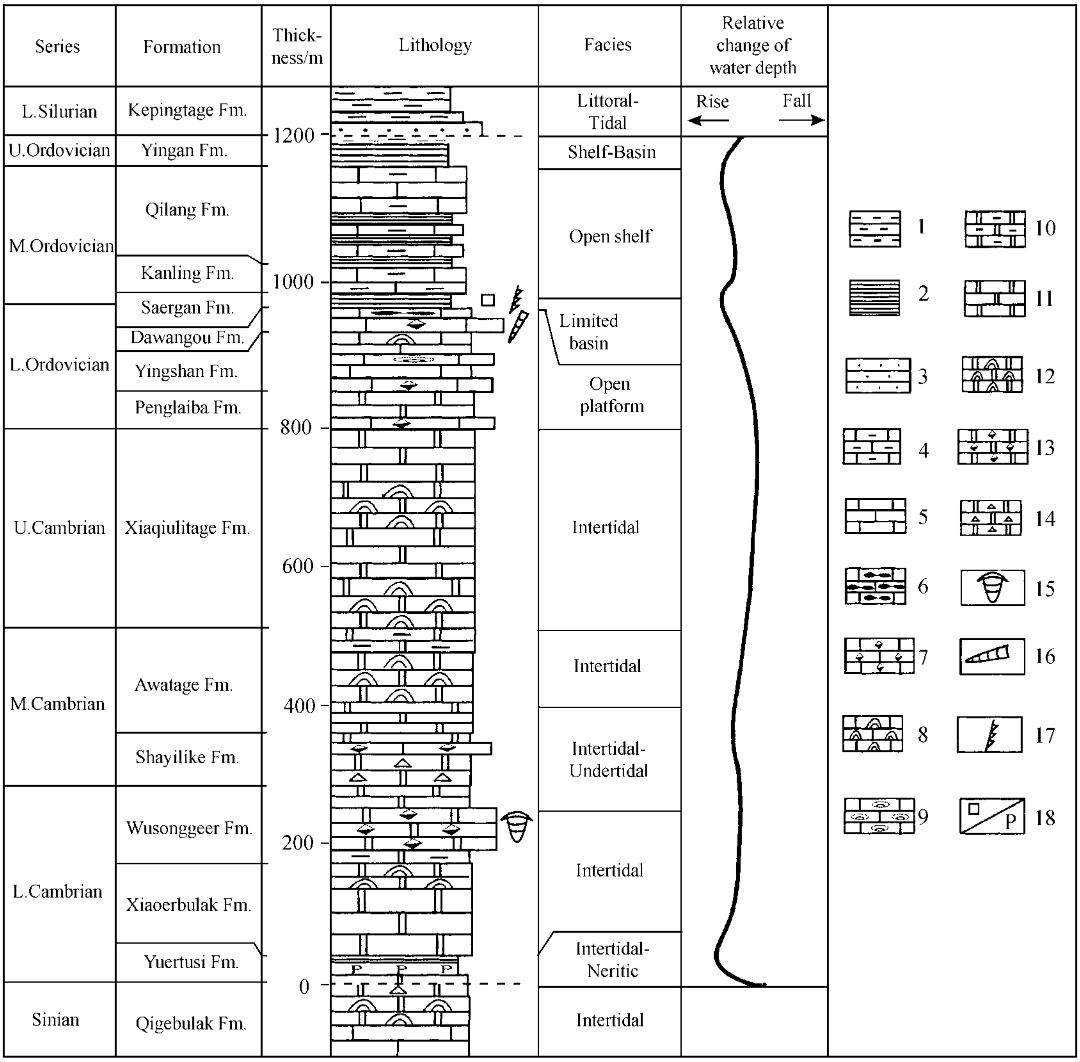


Fig. 2. The stratigraphic column and depositional characteristics of the Cambrian-Ordovician in Keping area. 1, Mudstone; 2, shale; 3, sandstone; 4, muddy micrite; 5, micrite; 6, nodular limestone; 7, calcarenite; 8, stromatolite limestone; 9, limestone with algal fragments; 10, muddy dolomite; 11, micritic dolomite; 12, stromatolite dolomite; 13, dolarenite; 14, dolomite breccia; 15, trilobita; 16, cephalopoda; 17, graptolithina; 18, pyrite/phosphorite.

2 The Cambrian-Ordovician sequence stratigraphic system on the northern Tarim Platform

The sequence stratigraphic system as understood here is composed of different orders of sequences, including sequences, supersequences, supersequence sets and megasequences. The sequence(third-order) is the basic unit. As the sedimentary characteristics of sequences have been discussed in the previous papers[8—25], we will focus in the following discussion on the composite architecture and superposed patterns of the sequences.

2.1 Sequence (the 3rd-order sequence)

The recognition of a sequence is mainly based on the integrated analysis of the stratigraphic contact relation, superposed pattern of parasequences, evolution of depositional facies, fossil contents and geochemistry of the strata. An example of sequence analysis of the Cambrian-Ordovician is shown in fig. 3. There are 35 sequences recognized in the Cambrian-Ordovician in the northern Tarim Platform (fig. 3). The ages of some sequence boundaries were estimated through

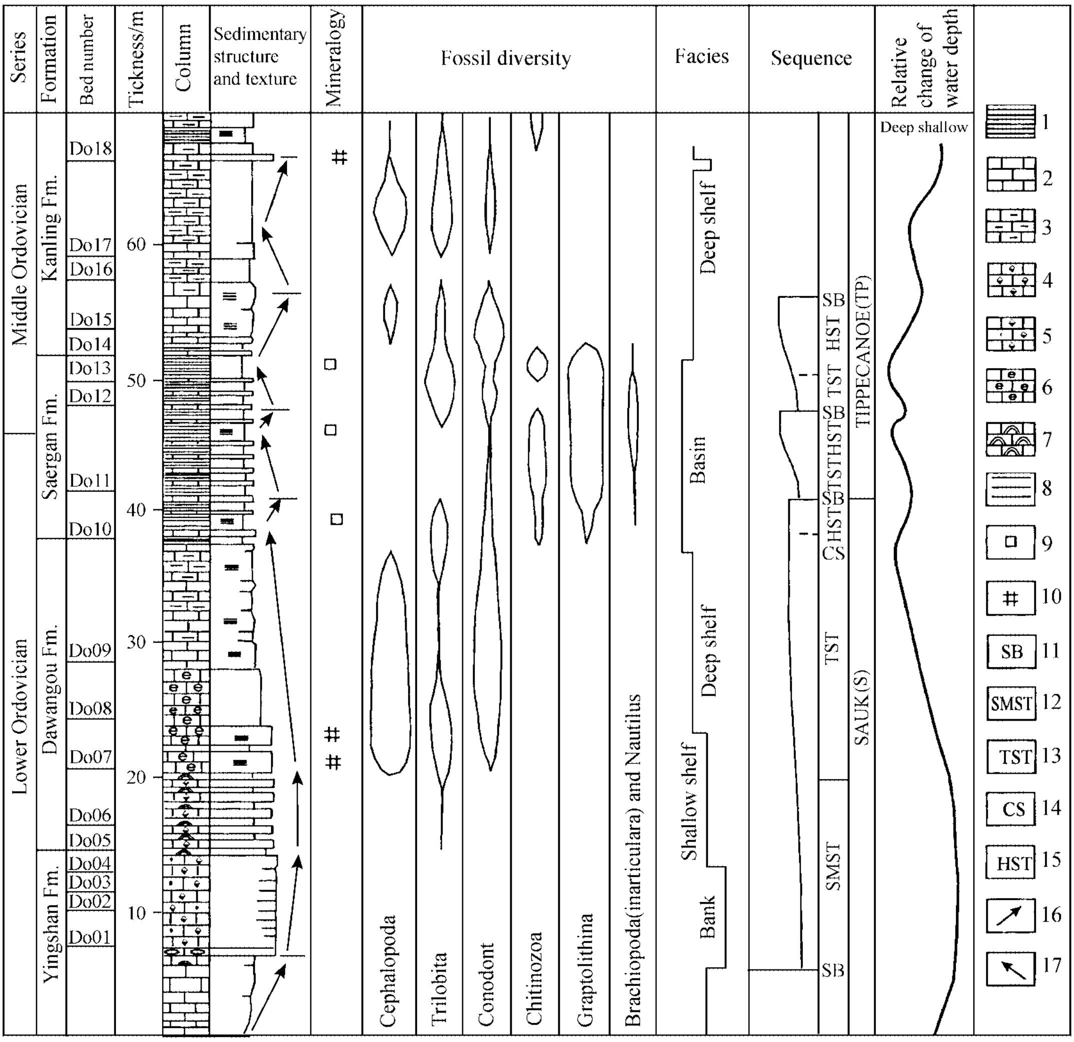


Fig. 3. Stratigraphic column showing the continuous deposition through the boundary between the Sauk and Tippecanoe megasequences. 1, Shale; 2, micrite; 3, muddy micrite; 4, micrite calcarenite; 5, sparry calcarenite; 6, bioclastic limestone; 7, algal boundstone; 8, horizontal bedding; 9, pyrite; 10, glauconite; 11, sequence boundary; 12, shelf margin systems tract; 13, transgressive systems tract; 14, condensed section; 15, highstand systems tract; 16, progradational parasequence set; 17, retrogradational parasequence set.

the combination analysis of biostratigraphy and sequence stratigraphy (fig. 5). The comprehensive results of biostratigraphy, lithostratigraphy, sequence stratigraphy and chronostratigraphy are shown in fig. 4. This is, in fact, a chronostratigraphic frame with the third order sequences as its basic stratigraphic units.

2.2 Supersequence and supersequence set

Supersequences and supersequence sets are the stratigraphic units higher than the sequences in sequence stratigraphy. Supersequences are recognized in terms of the prograding or retrograding stacking patterns of the sequences. For example, the seven sequences from the ∈Sq1 to the ∈Sq7 comprise 3 cycles from retrogradation to progradation and represent 3 supersequences. Altogether twelve supersequences are recognized within the 35 sequences of the Cambrian Ordovician in the northern Tarim Platform. The relative change of coastal onlap relations observed in seismic profiles has been taken as a criterion to identify the supersequence sets which represent the superposed patterns of supersequences. It can be shown that the seismic sequences recognized in seismic profiles are corresponding to the supersequences identified in outcrops[17,19]. As the relative degree of coastal onlap reflects the relative amount of sea level change, the falling inflection points in the curve of coastal onlap will indicate a marked change of sea level, and therefore will correspond to sequence boundaries of a higher order (the supersequence sets)[4,5,26—28]. There are 4 supersequence sets recognized in the 12 supersequences in the Cambrian-Ordovician.

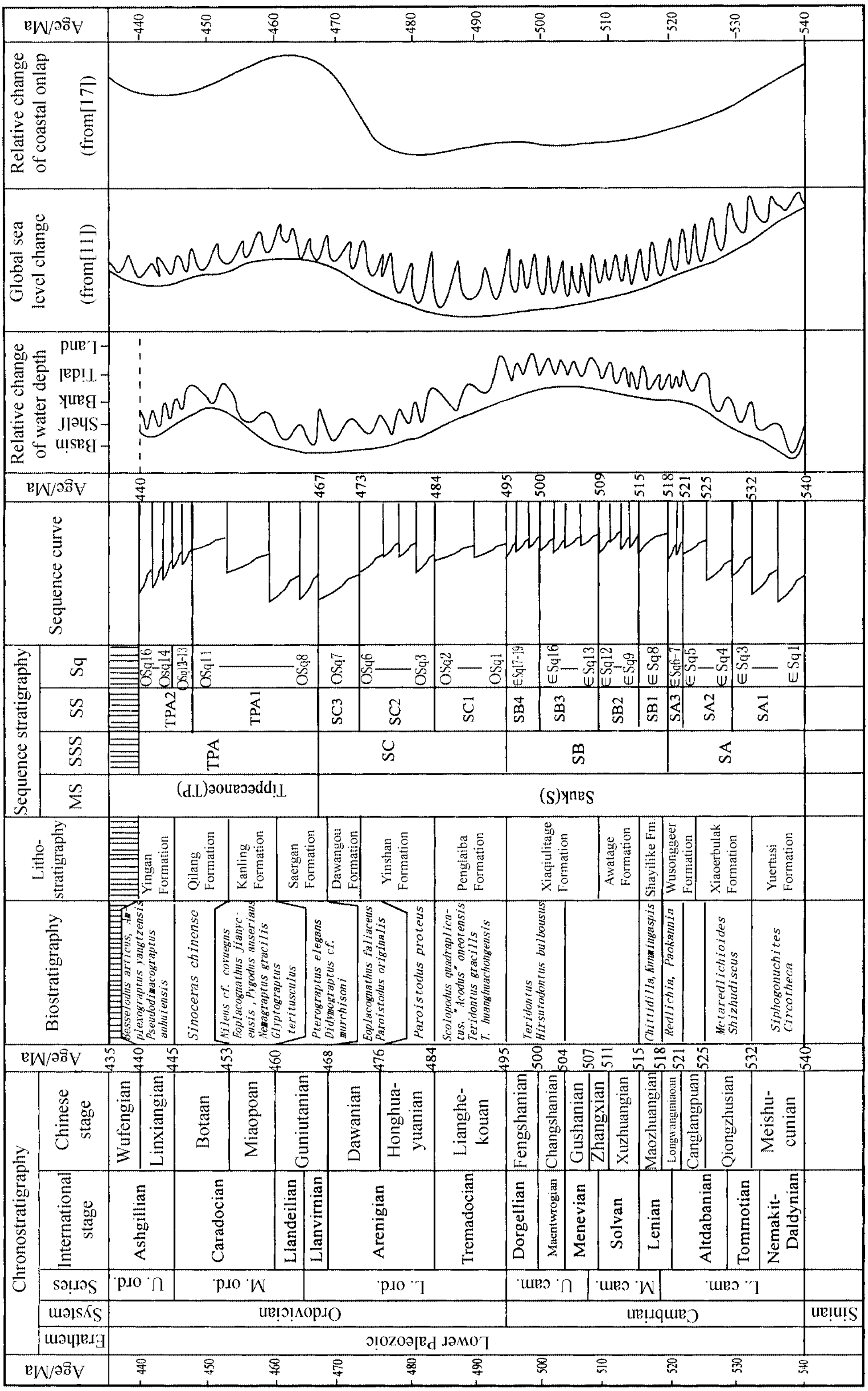
2.3 Megasequence

We may see that the 4 supersequence sets in the Cambrian-Ordovician comprise 2 megasequences corresponding to the 2 first order cycles in the diagram of coastal onlap and global sea level change. Because of the lack of the Upper Ordovician Wufengian, the upper megasequence is not complete. The megasequence boundaries are very clear in the outcrop, seismic , as well as the boring well sections.

The bottom boundary of the lower megasequence (SAUK) is an unconformity surface between the Sinian and the Cambrian in the outcrop section of Keping area. The boundary between the lower and the upper megasequence (SAUK and TIPPECANOE) separates the Lower and the Middle Ordovician. This boundary is an unconformity surface in the Manjiaer area in the central and northern part of the present Tarim Basin (seismic profile E59 and Well S11)[17]. However, this boundary in the Keping area is situated at the middle of a bed of black shale with graptolites, which should have been deposited near the center of the marine basin of the time. Evidently, no hiatus is present in this black shale (figs.3 and 4)[34], and it is clear that when unconformity was formed elsewhere, the Keping area received deep marine continuous deposits because of the rapid subsidence of basement. It can be seen that local tectonic activity can play an important role in the sequence development.

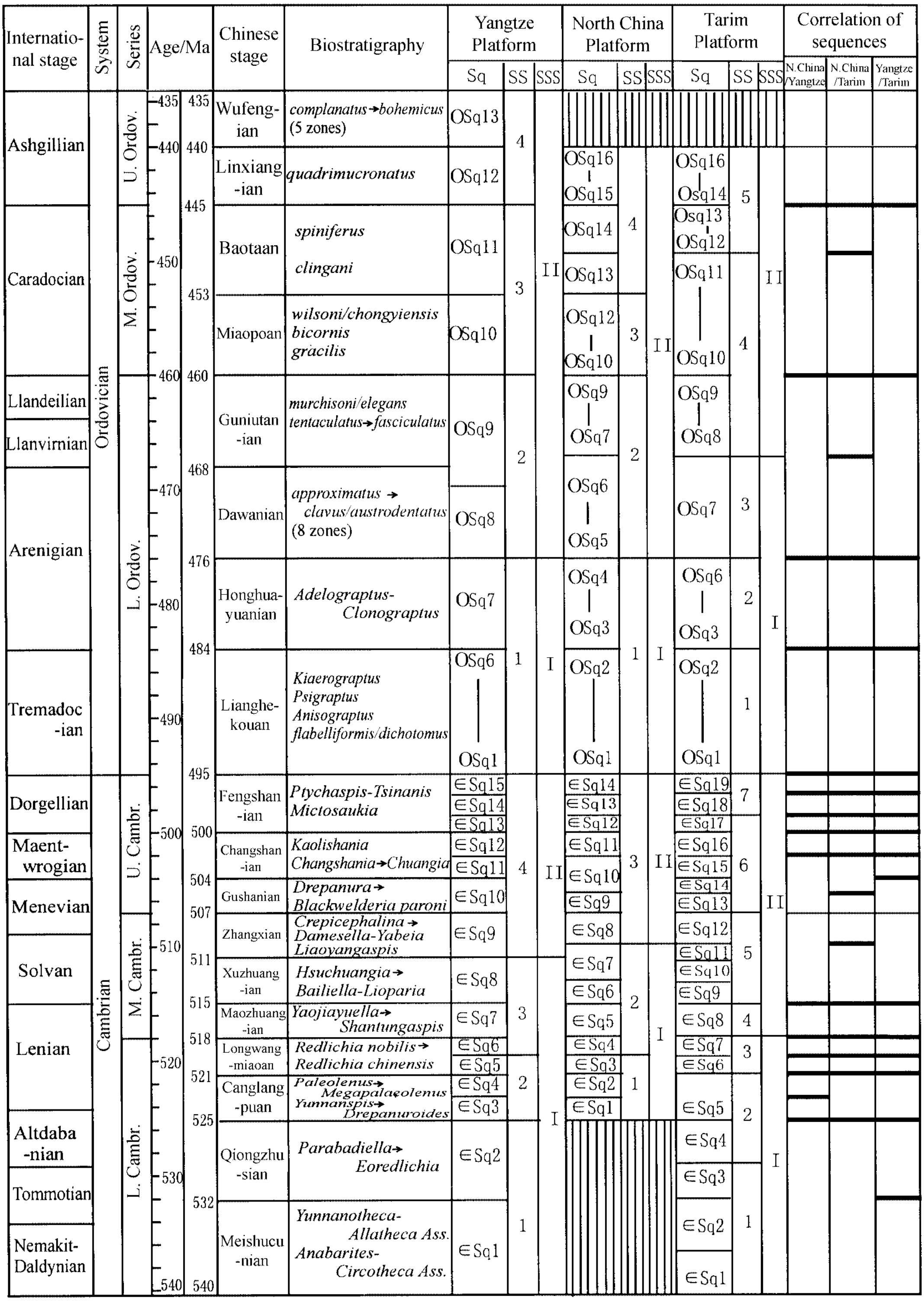
3 Correlation of sequence stratigraphy of the Cambrian-Ordovician on the northern Tarim Platform with those on the Yangtze and North China platforms

Studies in recent years indicate that sequence stratigraphy and sea level changes among the relative stable interior continents are possessed of fairly good relation comparability. Sea level



Sq. sequence(3rd-order); SS,supersequence; SSS,supersequence set; MS,megasequence

Fig. 4. Sequence stratigraphic system and sea level changes of the Cambrian-Ordovician in the northern Tarim Platform.



Sq,sequence (3rd-order); SS,supersequence; SSS,supersequence set

Fig. 5. Correlation of sequence stratigraphy of the Cambrian-Ordovician among the three platforms of China.

changes are usually the main factors controlling the sequence architecture and patterns in the carbonate platform area with little terrigenious input. Previous studies in Yangtze , North China and Tarim have formed a good basis for the correlation of sequence stratigraphy and sea level changes among the three platforms of China[11,29—34]. It is inferred that the Yangtze Platform was not very far away from the Tarim Platform in the Cambrian-Ordovician period according to the correlation of fossil zones, and both were located in the area of low latitudes.

The Cambrian-Ordovician in China is relatively well preserved in the Yangtze Platform. Most strata of the Cambrian-Ordovician in the Tarim Platform are similar to those in the Yangtze except lacking of the upper part of the Ordovician System. The lower part of the Lower Cambrian and the upper part of the Upper Ordovician are lacking in the most parts of the North China Platform and this is different from those on the Yangtze and Tarim platforms.

The Cambrian sequence stratigraphic system in the Yangtze Platform is mainly established from studies in western Hunan, which contains 15 sequences[29]. On the North China Platform the Cambrian sequence framework is mainly established on outcrop studies in Shandong, Tangshan and Baoding of Hebei Province, and Beijing areas[32]. The comparison of the Cambrian sequences among the three platforms in China is shown in table 1 and fig. 5.

Table 1 Comparison of the Cambrian sequences among the three platforms in China

Chronostratigraphic units	Yangtze Platform	North China Platform	Tarim Platform
Upper Cambrian	6	6	7
Middle Cambrian	3	4	5
Lower Cambrian (Canglangpuan—Longwangmiaoan)	4	4	3
Total number	13	14	15

In regard to the number of sequences, from the Lower Cambrian Canglangpuan to Upper Cambrian Fengshanian (528—495 Ma), there are 13 on the Yangtze Platform with an average duration of about 2.54 Ma, 14 on the North China Platform with an average time span of about 2.36 Ma, and 15 on the Tarim Platform with an average duration of about 2.20 Ma.

It is worthy of attention that there is an equal number of sequences in the Longwangmiaoan and Fengshanian on the three platforms. The former consists of 2 and the latter of 3 sequences. This may illustrate that the 3rd-order sea level change cycles are synchronous in the two epochs on the three platforms of China.

Out of the 13, 14 and 15 sequence boundaries existing from the Lower Cambrian Canglangpuan to the Upper Cambrian Fengshanian in the three platforms respectively, there are 10 sequence boundaries, which are comparable with each other in all the three platforms of China. The series boundaries of the Cambrian-Ordovician are also coincident with the sequence boundaries and they are all comparable among the three platforms.

The comparability of 3rd-order sequences of the Ordovician on the three platforms in China is less than that of the Cambrian (table 2 and fig. 5). This may mean that the paleoclimatic and paleotectonic controls on the sequence development in the Ordovician are stronger than in the

Cambrian.

Table 2 Comparison of sequence number from the Ordovician on the three platforms of China

Chronostratigraphic units	Yangtze Platform	North China Platform	Tarim Platform
Upper Ordovician(up to Linxiangian)	1	2	3
Middle Ordovician	2	5	5
Lower Ordovician	9	9	8
Total number	12	16	16

In regard to the number in sequences of the Ordovician, there are 12 on the Yangtze , 16 on the North China and 16 on the Tarim platforms (fig. 5). There are eight to nine sequences in the Lower Ordovician on the three platforms [33]. The number of sequences of the Cambrian on the three platforms are similar and suggests that their development is synchronous to some extent, but there are differences in the same series on the three platforms. For example, there are 6 sequences in the Tremadocian on the Yangtze Platform, but 2 in the same series on the North China Platform and the Tarim Platform. In regard to the conditions of sequence boundaries, only those corresponding to the bottom and top boundaries of Honghuayuanian, and the bottom boundary of Miaopoan are correlatable on the three platforms in China (fig. 5).

The result of comparison from the Caradocian to the lower Ashgillian on the platforms is similar to that of the Lower Ordovician. The total number of the sequences is approximately equal on the three platforms, but the correlation of sequences and sequence boundaries is not clear. The reason might be the low sensitive response of the depositional sequences to sea level changes because of the global anoxic and glacier events during the Late Ordovician. The only sequence boundary, which is correlatable during this stage on the platforms, is the bottom boundary of the Caradocian. This boundary can also be identified in the other main continents of the world based on the organic evolution, depositional characteristics and anoxic events, which denotes a global transgressive event. It is sure that the regional and global correlation of the Ordovician sequence stratigraphy needs further study.

In brief, the architecture, number and boundary characteristics of the sequence developed on platform contain a rich information of regional and even global sea level changes. Through sequence stratigraphic correlation we may infer that the correlatable sequences on the platforms of China are mainly developed in the stage of rapid or during the highstand of sea level. The regional relation comparability of the sequences formed during highstand of the global sea level is better than that formed during lowstand of sea level probably because of the stronger local tectonics and climatic influence in lowstand regions.

4 Controlling factors on sequence development

It is widely accepted that the development of sequences is controlled by the interplay of sea level change, basement subsidence, supply of sediments and climate conditions. In recent years, many cyclic records in carbonates corresponding to different orders of sea level changes have been documented[35—44]. The relative change of coastal onlap conditions in the Tarim Basin is to a large extent consistent with the idea of global or eustatic sea level changes (fig. 4). Although the trend of the relative change of water depth of the Cambrian in the Keping area is rather different from the global sea level change, the general trend of sea level change obtained from the outcrop section after correction of basement subsidence and sediment productivity in this area is nearly identical to that of the global sea level change. This illustrates that sea level change is the main factor controlling the development of sequences in the carbonate platforms with low basement subsidence[20]. Nevertheless, local tectonics may play an important part in the development of sequences in the tectonic active area, for instance, the Keping area with rapid basement subsidence from the late Lower Ordovician to the Middle-Upper Ordovician.

5 Conclusions

The Cambrian-Ordovician on the northern Tarim Platform is composed of 35 3rd-order sequences. They comprise 12 supersequences, 4 supersequence sets and 2 megasequences. The superimposed different orders of sequences in the chronostratigraphic framework construct a complicated sequence stratigraphic system of the Cambrian-Ordovician on the northern Tarim Platform.

The correlation of sequence stratigraphy of the Cambrian-Ordovician on the northern Tarim Platform with those in the Yangtze and the North China platforms indicates that many sequences and their boundaries are comparable on the three platforms of China, especially in the Longwangmiaoan and Fengshanian stages. The relation of sequences formed during the highstand of sea level is usually better than that formed during the lowstand of sea level. It is suggested that the Cambrian-Ordovician carbonate sequences on the three platforms were mainly controlled by regional or global sea level changes.

The relative change of coastal onlap in the Tarim Basin is consistent with the global sea level change. The sea level change obtained from the outcrop investigation after correction of basement subsidence and sediments productivity is more similar to the global sea level change. Global sea level changes seem to be the main factor controlling the development of the carbonate sequences of the Cambrian-Ordovician in the three platforms of China. Tectonism may be locally important in some areas with strong tectonic activity.

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