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Cycle–Sequences, Carbon Isotope Features and Glacio–Eustasy of the *Triticites* Zone in Southern Guizhou

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Abstract In light of the principle of sequence stratigraphy, detailed analysis of depositional sequences and systematical carbon isotope measurements were done for the *Triticites* zone of the typical Late Carboniferous section in the Dushan area of southern Guizhou. Two sequences and seventeen parasequences, which can be correlated with the two sequences and seventeen subsequences in the North American Midcontinent, are distinguished in the Gzhelian, which provides convincing evidence of the global synchroneity of the depositional records. The internal relations between carbon isotope evolution and eustasy were studied and the evolutionary characteristics of carbon isotopes in depositional sequences have been summarized.

Key words: Upper Carboniferous, carbonate sequence stratigraphy, eustasy, *Triticites* zone, carbon isotope

1 Geological Setting

It is well known that in geological history the Carboniferous Serpukhovian–Gzhelian Age became a critical transition period when Pangaea began to form. The study on the global synchroneity of sedimentary records and relationships of the compositional variation of stable isotopes in sea water with the palaeoclimate and sedimentary records in this period is considered to be one of the most interesting topics among geoscientists at present (Beauchamp, 1992). The Dushan area is located in southern Guizhou where lies China' s typical Carboniferous section reflecting the sedimentary evolution history of the Carboniferous Yangtze plate. Due to weakening of intraplate rifting, the Yangtze Plate entered a stable tectonic stage in the Late Carboniferous (Chen Wenyi, 1991).

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According to the internationally accepted division scheme, the Gzhelian stage accommodates the *Triticites* zone (sensu lato), i. e. the *Montiparus* and *Triticites* zones, underlain by the *Fusulinella–Fusulina* zone and overlain by the *Pseudoschwagerina–Sphaeroschwagerina* zone. In the study area, the Gzhelian strata are equivalent to the lower part of the Maping Formation (*Triticites* zone and *Pseudoschwagerina* zone), namely the *Triticites* zone, with a time range 295 Ma to 290 Ma (Wang and Li, 1990) (Fig. 1). Elements of the *Montiparus* zone are not well developed in this area.

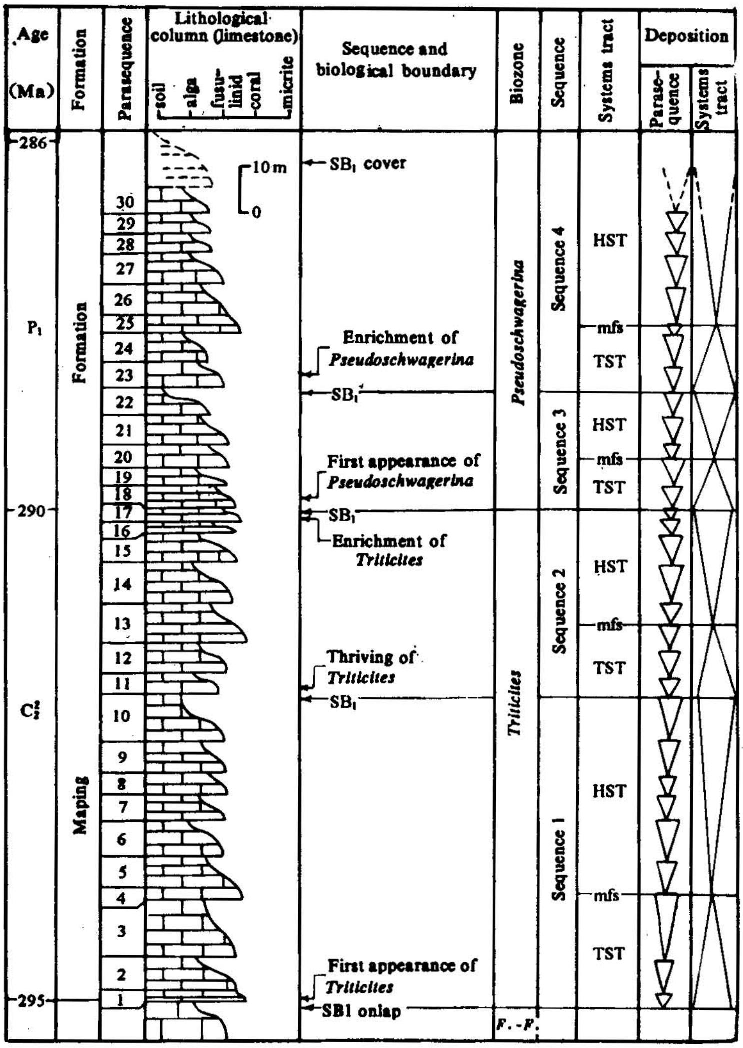

Fig. 1. Sequence stratigraphic column of the Maping Formation in the Dushan area.
TST = Transgressive systems tract; HST = highstand systems tract;SB1 = I–type sequence boundary; mfs = maximum flooding surface; F.–F. = *Fusulinella–Fusulina* zone.

The Maping Formation is characterized by monotonous lithology, without marked unclear physical indicators for the key surfaces between some sedimentary sequences. Hence in the sequence stratigraphical analysis we started with the investigation of microfacies and cyclicity of carbonates, defined parasequences bounded by flooding surfaces, recognized depositional systems tracts in light of the stacking patterns of parasequences, and determined sequence boundaries with integrated methods①.

Accordingly, four third–order sequences and more than thirty parasequences have been recognized (Fig. 1). This paper is directed towards the depositional sequence, glacio–eustasy and carbon isotope compositions as well as the hierarchy of sequences in the *Triticites* zone (Gzhelian).

2 Cyclic Sequences and Glacio–Eustasy in the *Triticites* Zone

2.1 Fossil associations and microfacies of a primary sequence

The *Triticites* zone in the study area is composed, in ascending order, of biodetritus–bearing micrites, solitary coral–bearing biosparites, fusulinid–bearing biosparites and algal–laminated micrites with bird–eye structure, representing the evolution from the subtidal zone to tidal flat in an open carbonate platform (Fig. 2).

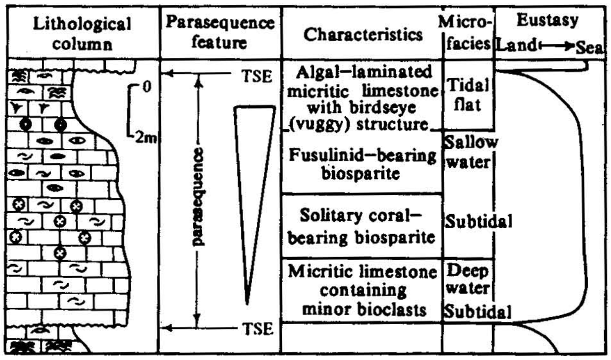

Fig. 2. Primary sequence of the *Triticites* zone in the Dushan area.
TSE = Transgressive surface of erosion.

2.2 Punctuated aggradational cycle and parasequences

All cyclic primary sequences in the *Triticites* zone possess the characteristics of punctuated aggradational cycle (PAC), indicated by rapid deepening at the base marked by a flooding surface, then gradual shallowing upwards and finally appearance of supratidal exposure (Fig. 2). Such a shallowing–upward primary sequence (cycle) that is bounded by a flooding surface is represented by a parasequence in the study area.

2.3 Parasequence components and transgressive erosion surface

Vertical comparison among the boundaries of parasequences demonstrates that the components of the parasequences are variable (Fig. 1). Most of them possess a complete succession shown in Fig. 2, while some have no upper or lower component. For example, the

① Li Rufeng, Sea level change, carbon isotope features and forming mechanism of Carboniferous sequence stratigraphy in Southern Guizhou and Northern Guangxi, PhD. Dissertation of China University of Geosciences, 1995.

algal–laminated micrites with a bird–eye structure of tidal flat in parasequence 17 and the deep–water subtidal bioclastic micrites in parasequence 7 are absent. The former resulted from succeeding transgressive erosion, and the latter was due to a relatively small amplitude in sea–level rise with no subtidal bioclastic micrites formed.

Transgression induced by sea–level rise might produce a distinct transgressive erosion surface (TES) in areas from littoral zone to shallow shelf and the erosion might reach the strata as deep as 10 m (Weimer, 1993). The sea–level oscillation of rapid rise and slow fall exhibited by the parasequences in the *Triticites* zone of the Dushan area agrees well with the pattern of rapid thawing and slow growing of the terrestrial glaciation. Therefore, the study of transgressive erosion surface at the bottom of parasequence will help to recognize sequence (parasequence) boundaries.

2.4 Depositional systems tract and sequence boundary

Parasequence sets, representing the trend of the third–order sea–level changes, have been established based on the preservation of microfacies succession, thickness variation and the fossil features of every parasequence in the *Triticites* zone; then stacking patterns of the parasequences were used to determine the boundaries of third–order depositional sequence and its depositional systems tracts (Fig. 1).

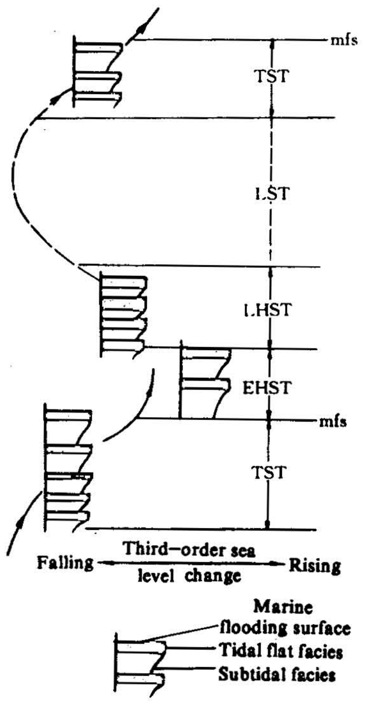

Fig. 3. Relations of stacking patterns for parasequences and depositional systems tracts in carbonate platform (ramp) (after Tucker, 1993).

Stacking patterns of the parasequences and their relationships with depositional systems tracts in the two third–order sequences are demonstrated in the following aspects (Fig. 3). (1) Parasequences in the TST are upward–thickening and characterized by a larger proportion of subtidal micrites to tidal flat algal–laminated micrites, indicating a retrogradation pattern and an increase of accommodation with sea–level rise (parasequences 1–3 and 11–13). (2) Highstand systems tracts (HST) are well developed on carbonate platforms (or ramps) and can be subdivided into two phases, i.e. the early highstand systems tracts (EHST) and the late highstand systems tracts (LHST), based on the stacking patterns. EHST is dominated by thick subtidal micrites without increase of accommodation (parasequences 5 and 6), while LHST is upward–thinning and characterized by a smaller proportion of tidal flat algal–laminated micrites to subtidal micrites (parasequences 7–10 and 14–17), commonly associated with transgressive erosion (parasequence 17). (3) Lowstand systems tracts (LST) on the inner carbonate platform and ramp are not well developed and the third–order depositional sequence includes merely TST and HST. (4)

Since the water depth of the carbonate platform (ramp) is rather small and the glacial sea-level fall is relatively large (60–100 m ±), the sequence boundaries are predominantly of type I (SB_1) (Tucker, 1993).

The lower sequence in the *Triticites* zone belongs to type I, indicated by an eastward onlapping of the midium- to thick-bedded limestones (TST) onto the massive dolomitic limestone (HST) of the *Fusulinella–Fusulina* zone of the uppermost Dala Formation. This onlapping surface is attributed to the fall and succeeded rise of sea level driven by the Gondwana glacial events. The upper boundary of the lower sequence lies at the top of parasequence 10, marked by algal-laminated micrites with a birdseye structure. The lower boundary of sequence 2 is marked by ill-rounded rudstones, which were deposited in the subtidal zone as lags during the rapid transgression of the lower part of parasequence 11. Sequence 2 is capped by incomplete parasequence 17. The absence of tidal deposits in the parasequence resulted from the combination of regressive and succeeded transgressive erosions.

3 Evolution of Carbon Isotopes in the Depositional Sequence of the *Triticites* Zone

3.1 Sampling and results

Fifty eight carbonate bulk-rock samples were systematically collected from the 2 sequences and 17 parasequences in the Late Carboniferous *Triticites* zone (112 m thick in total). The analysis was conducted by means of the orthophosphoric acid method (concentration 100%) with equilibrium temperature 25℃ and time 4 h. $\delta^{13}C$ and $\delta^{18}O$ were determined on a MAT-251 mass spectrograph after transforming carbonate rocks into CO_2. The Ordovician Zhoukoudian limestone was taken as the laboratory working standard with $\delta^{13}C$ 0.6‰ against PDB and $\delta^{18}O$ −8.5‰ against PDB. The analytic precision is higher than ±0.1‰. The results are listed in Table 1.

Table 1 Data of carbon and oxygen isotopes of the *Triticites* zone in the Dushan area

Parasequence	$\delta^{13}C$‰ (PDB)	Parasequence	$\delta^{13}C$‰ (PDB)	Parasequence	$\delta^{13}C$‰ (PDB)	Parasequence	$\delta^{13}C$‰ (PDB)	Parasequence	$\delta^{13}C$‰ (PDB)	Parasequence	$\delta^{13}C$‰ (PDB)
18	−0.3 −1.1 −0.4	15	−1.3 −1.4 −0.3 0.3	12	−1.9 −1.6 −1.3	9	−1.7 −1.4	6	−1.3 −1.1 −0.5 −0.7	3	−0.8 −0.7 −0.5 −0.3 −0.3
17	−0.7 −0.8 −0.8 −0.4 −0.3	14	−1.4 −0.8 −1.7 −1.7	11	−0.9 −1.0	8	−1.1 −0.7	5	−2.3 −0.6	2	−0.5 −0.3 −0.2 −0.1 0.1
16	−1.3 −1.7 −1.0 −1.2	13	−2.7 −2.2 −1.7	10	−3.6 −2.6 −1.6 −0.3	7	−1.1 −0.9 −1.1	4	−1.0 −0.5 −0.6	1	−0.3 0.1 0.3

Analyzed by the Isotope Lab of China University of Geosciences (Beijing).

3.2 Features of $\delta^{13}C$ in parasequence

$\delta^{13}C$ values of the whole rocks in the *Triticites* zone vary regularly on the scale of a parasequence. Each parasequence begins with relatively high $\delta^{13}C$ PDB, decreases gradually upwards and reaches minimum at the top of a parasequence (Fig. 4; Table 1). Some parasequences (14, 15 16 and 17) have higher $\delta^{13}C$ values at their top parts, which might be related to large burial rate of organic carbon and incompleteness of parasequences.

Researches demonstrate that $\delta^{13}C$ values of marine carbonates could reflect the sedimentary environments where they were deposited (Schidlowski et al., 1975). They are primarily related to the redox condition, burial rate of organic carbon (bioclasts) and water depth. The first two factors are mainly controlled by water depth in clean–water carbonate environment. $\delta^{13}C$ values can reflect the change of sea level. This can be seen from the fact that every parasequence experienced a process from rapid rise to gradual fall in sea level change, so that the deeper water, higher burial rate of organic carbon and redox condition at the forming stage of the lower parasequence brought about higher $\delta^{13}C$ values; while the sea level fall and lower burial rate of organic carbon and higher likelihood of oxidation resulted in smaller $\delta^{13}C$ values due to carbon isotopic exchanges between sedimentary carbonates and CO_2.

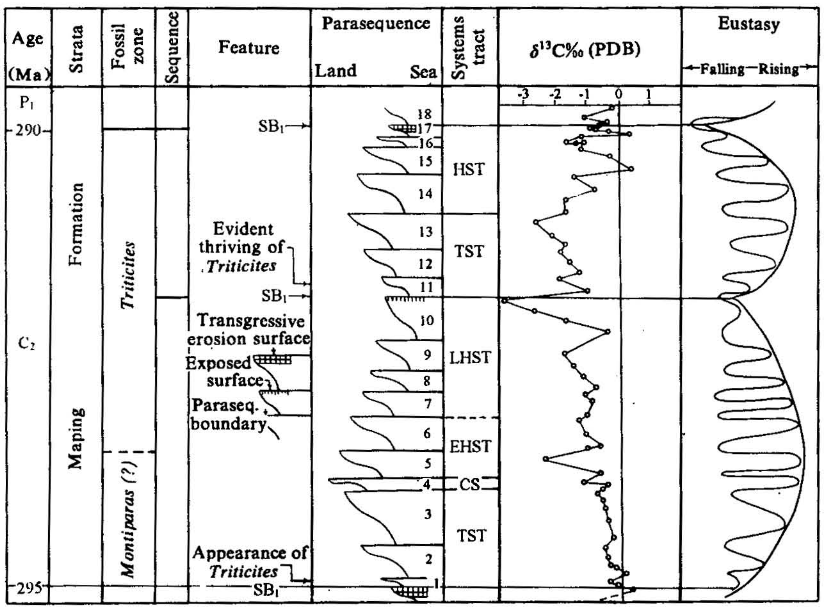

Fig. 4. Relations of sequence stratigraphy and carbon isotope evolution in the *Triticites* zone of the Dushan area.

3.3 Features of $\delta^{13}C$ in depositional systems tracts

Two transgressive systems tracts in the *Triticites* zone are represented respectively by parasequences 1–3 and 11–13 and two highstand systems tracts by parasequences 5–10 and 14–17 (Fig. 5). A line is drawn connecting each intersection point of the evolutional trend line of $\delta^{13}C$ values in the parasequences with the parasequence boundaries (flooding surfaces), which delineates the variation of $\delta^{13}C$ values in depositional systems tracts. In TST, the slope of the line is larger than 90° , indicating that $\delta^{13}C$ values are getting enriched upwards. In the HST, the trend line has its slope smaller than 90° , indicating that $\delta^{13}C$ values tend to be depleted upwards (Fig. 5).

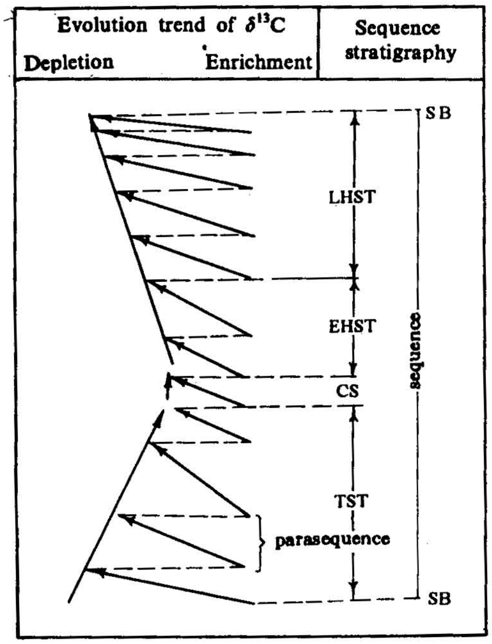

Fig. 5. Model of $\delta^{13}C$ evolution in the carbonate sequence stratigraphy of the Dushan area.
SB = Sequence boundary; CS = condensed section.

3.4 $\delta^{13}C$ features of sequence boundary

Tops of the two sequences are made up of parasequences 10 and 17 respectively. The former consists of algal–laminated micrites with birdseye and vuggy structures of upper intertidal to supratidal environments. Negative $\delta^{13}C$ anomaly is seen around the sequence boundary (−3.6‰). The latter is characterized by the absence of algal–laminated micrites, with a negative $\delta^{13}C$ anomaly (−0.7‰). This negative anomaly is not as large as in parasequence 10 but is still significant compared with the overlying parasequence 18 (−0.4‰). The authors hold that the stratigraphic hiatus caused by transgressive erosion is the major reason for the decrease of the negative $\delta^{13}C$ anomaly in sequence 2 (Fig. 5).

3.5 Distribution of carbon isotopes and palaeoclimate

Carbon exists in nature in two states: carbonate rocks and organic carbon. Carbon cycling takes various forms at the earth' s surface, but the carbon total remains constant and so do its stable isotopes ^{12}C and ^{13}C. Therefore, increase of organic carbon will lead to increase of ^{12}C absorbed by photosynthesis, which results in increase of marine carbonate ^{13}C, otherwise marine carbonate ^{13}C will decrease.

The Late Carboniferous is a glacial stage of the Gondwana land and glacial ablation inevitably caused the rise of the global sea level, reduction of oxidation area, increase of burial rate of organic carbon and $\delta^{13}C$; while glacial growth caused the fall of sea level, increase of oxidation area, decrease of burial rate of organic carbon and $\delta^{13}C$. Therefore, variation of $\delta^{13}C$ values in marine carbonates provides significant information regarding to palaeoclimate.

4 Hierarchy, Mechanism and Correlation of Depositional Sequences

4.1 Hierarchy and terminology

Controlled by different factors, corresponding sea–level changes would differ in cyclic period, which is represented by different hierarchies of depositional sequences. Accordingly, various subdivisions concerning periodicity of sea–level changes and terms of sequence hierarchy have been proposed (Table 2).

Table 2 Classification of depositional sequence orders

Cycle order	Vail et al. (1977, 1991)			C. E. Brett (1990)		Wang Hongzhen		This paper		
	Name	(Ma)	(Ma)	Name	(Ma)	Name	(Ma)	Name		(Ma)
I	Megaseq.	200–400		L.seq.	50–60	L.seq.	60–120	L.seq.		50–100
II	Superseq.	10–100	27–30 36–40	Holoseq.	1–10	M.seq.	M.seq.	30–40 9–12		10–50
III	Seq.	1–10	0.5–5	Seq.	2–3	Positive seq.	2–5	Seq.		1–10
IV	Paraseq.set	0.2–0.5	0.2–1	Subseq.	1.0–1.5	Subseq.	0.1–0.4			0.2–1
V	Paraseq.		0.01–0.5	S.seq.bed	0.45	S.Seq.	0.02–0.04	Paraseq.set Paraseq.	Sub-seq.	0.01–0.2
VI				S.seq.	0.10					
VII				Rhythmic layer	0.02			Rhythmic layer		

Paraseq. = parasequence; Seq. = sequence; S. = small; M. = medium; L. = large.

In consideration of different evolutionary rates of the earth' s spheres and the variable completeness of geological records in different geology stages, it is reasonable to propose a time range of 1–10 Ma for the third–order depositional sequence of the Palaeozoic (Table 2). In the study area, for example, the average duration of the two third–order sequences in the *Triticites* zone is 2.5 Ma, whereas it is 6.5–10 Ma for the five sequences in the Lower Carboniferous①.

For some sedimentary cycles which have time durations far less than 1 Ma but display typical physical evident for a third–order depositional sequence, we propose to use the term "subsequence" in this study. It should be noted that the duration and the relative sea–level change of a subsequence can be equal with those of a parasequence set or parasequence.

4.2 Mechanism and correlation scope

Diversified conclusions have been drawn among geologists throughout the world concerning whether third–order sequences can be correlated regionally or even globally. A comparison of depositional sequences in the *Triticites* zone was made by the authors among the Yangtze plate, North China Plate and North American Midcontinent①. It has been demonstrated that: (1) two traceable third–order depositional sequences are developed in all these three areas; (2) seventeen fourth–order transgressive–regressive (T–R) cycles were recorded in southern Guizhou of China and over the North American Midcontinent and all the seventeen T–R cycles are PACs featuring rapid transgressive and slow regressive characteristics and absence of regressive deposits in the uppermost part of the *Triticites* zone (Boardmen et al., 1993). Such comparison confirms that the 17 T–R cycles can be correlated between the southern Guizhou area and the North American Midcontinent.

① Li Rufeng, Characteristics and mechanism of sequence stratigraphy, eustasy and carbon–oxygen isotope of Carboniferous in Southern Guizhou and Northern Guangxi, China. Ph.D. Dissertation of China University of Geosciences, 1995.

The consistency of depositional cycles discussed above may be explained by the following facts. Relatively stable Pangaea already had its embryonic form in the Late Carboniferous (Gzhelian) and all the above–mentioned plates had similar palaeolatitudes, i.e. in tropical to subtropical zones, and were subjected to the same influence of glacio–eustasy related to the waxing and waning of Gondwana ice sheets. Controlled by this glacio–eustasy, two third–order sequences and seventeen fourth– to fifth–order T–R cycles have been formed in the *Triticites* zone in both southern Guizhou and North American Midcontinent. Nevertheless, differences in tectonics, palaeogeography and sedimentary rate between the southern Guizhou area and North American Midcontinent have resulted in different contents of the depositional sequences though they were under the same order of eustatic cycles. For example, the Dushan area in southern Guizhou was located in a stable clean–water carbonate platform in the Late Carboniferous (Gzhelian), characterized by monotonous lithology and small thickness, where one fourth–order eustatic cycle produced merely depositional records of a parasequence; whereas the North American Midcontinent was in a deep–water shelf environment characterized by notable subsidence of the basement and abundant terrigenous influx, thus one fourth–order eustatic cycle (>60m) would produce depositional records of a subsequence.

5 Conclusions

(1) The two third–order sequences and seventeen parasequences recorded in the *Triticites* zone in the Dushan area of southern Guizhou in China can be fully correlated with 2 third–order sequences (Busch and Rollins, 1984) and 17 subsequences (Ross C.A. and Ross J.R., 1987) recognized in the North American Midcontinent in the strata of the same age. This was caused by the global glacio–eustatic changes and has provided evidence for the synchroneity of global sedimentary records in the Late Carboniferous Gzhelian Age.

(2) Systematic measurement of carbon isotopes reveals the internal relationship between carbon isotopic evolution and global sea–level change, on the basis of which the authors proposed the evolutionary pattern of carbon isotopes in depositional sequences: $\delta^{13}C$ values in parasequences decrease upwards from the bottom; they tend to become larger and smaller respectively in TST and HST, and show negative anomalies around the boundaries between sequences (parasequence) in general.

(3) Third–order sequence or even some higher–frequency depositional sequences like the fourth–order ones, can be traced globally if they were formed in a stable tectonic setting influenced mainly by glacio–eustasy, only the contents of depositional records being varied due to multiple factors. Thus, in the study of sequence stratigraphy attention should be paid to the analysis of sequence hierarchy and the forming mechanism. Only on such a basis, a synchronous stratigraphic framework and a correct correlation relationship of the strata can be established.

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