Variation on Foraminiferal Composition in Cretaceous Black-Gray-Red Bed Sequence of Southern Tibet, China

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ABSTRACT: An Upper Cretaceous black-gray-red bed sequence was deposited in the Tethys-Himalayan Sea where abundant foraminifera, especially planktons, were yielded. In the shallow shelf to the upper slope on the north margin of Indian plate was recorded an extinction-recovery-radiation cycle of foraminiferal fauna highly sensitive to paleoceanographical changes. The black unit, consisting of the Late Cenomian-earliest Turonian beds, displays a major extinction with keeled planktonic and many benthic species as the principal victims at the end of the Cenomanian when existed only low diversity. Surface water-dwelling foraminifera. The gray unit spans a long-term recovery interval from the Turonian to the Early Santonian with keeled planktonic foraminifera returning stepwise to the water column. The planktonic biota in the red unit, extremely abundant, indicate a biotic radiation during the Late Santonian and the Early Campanian, implying that the high oxygen levels had returned to all the oceanic depth levels, and that water stratification disappeared, followed by the radiation of all depth-dwellers. The variation on foraminiferal faunas from the whole sequence refers to the extreme warm climate that appeared in the Middle Cretaceous and to the declined temperature toward the late epoch. Substantial deposits for this warming and cooling zones represent the black shales in the Middle Cretaceous and the red beds in the later period of the southern Tibet. The change in the foraminiferal composition corresponded to the formation of dysaerobic facies and to the development of high-oxidized circumstances.

KEY WORDS: Cretaceous, foraminifera, black shale, red bed, Tibet.

INTRODUCTION
Significant paleoceanographic changes occurred in the Late Cretaceous. In the marine geological record, extremely warm climate appeared in the Middle Cretaceous and the temperature declined toward its late epoch. Substantial deposits for this warming and cooling zones represent black shales in the Middle Cretaceous and the red beds in the later period in the southern Tibet. Their occurrences have been explained mostly by the deposition in a poorly to highly oxygenated environments. Recently, paleontological data have ignited a renewed interest in the change in the Cretaceous oceanic dissolved oxygen resulting from the paleoclimate fluctuations. The climate fluctuations due to the greenhouse warming or reverse greenhouse cooling, a feedback to excessive burial of organic carbon, were further modulated by the changes in eustatic sea level. Such a circumstance resulted in the change from anoxic to oxic sediment depostions in the Late Cretaceous world oceans. This change represents a unique Late Cretaceous event. It remains unknown what triggered such a profound oceanic change in the deposition from organic carbon-enriched sediments during the Cenomanian-Turonian to the latest Cretaceous sediments devoid of any carbons. The global change from the deposition of pelagic “black shale” to that of oxic sediments like “red bed” may indicate more fundamental changes in the long-term carbon cycle on the earth. The climatic cycle from the extreme warmth to the extreme cold in the Late Cretaceous represents one of the best examples of “greenhouse” climate conditions in the geolog-

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tical record. Our interest in the Cretaceous oceanic change stems from the current concern over modern global warming. The change from anoxic to oxic Cretaceous sedimentation may serve as an example of the global oceanic change in the geological history.

The Cretaceous deposits in the southern Tibet present a black-red cycle. The southern Tibet was a part of the Tethys-Himalayan Sea. The semi-pelagic to pelagic Upper Cretaceous on the northern margin of the Indian plate is represented by a set of sandy and calcareous sedimentary rocks with intercalations of volcanic rocks and siliciclastics. In this sequence, occurred a group of black shale to red marl and foraminiferal wackestone. These so-called “black shale” and “red beds”, widespread in this sedimentary belt, were deposited in deep marine anoxic to oxic environments. Recent reports from the sections in the southern Tibet have suggested the presence of oxygen-restricted deposition in the region, evidenced by the presence of dark shale and marl sediments (Wang et al., 2001). Turnover of fossils in this interval has also been reported, implying that the C-T mass extinction may also have occurred in the southern hemisphere (Zhong et al., 2000; Wan et al., 1997; Willems, 1993). Little has been known of the marine sedimentary and fossil record after the C/T boundary event in the southern Tibet, especially the record of foraminiferal morphotypes in the black to red sequence. Biosphere is sensitive to climate change, and how it is adapted to the global change is the interests of the present authors. The patterns of how life responds to the changing environments can provide important insights into the processes of oxygen content in the Tethys-Himalayan Sea to constrain both the timing and the nature of the anoxic to oxic sequence, and up to the associated biotic extinctions and recoveries in the southern Tibet. The turnover of the foraminiferal fauna, especially the planktonics, a particular focus of our study, provides a sensitive monitor of the Late Cretaceous events.

MATERIAL AND METHODS

Detailed fieldwork has been made in the southern Tibet in recent years. Samples about 180 g were collected for the micropaleontological study. For the foraminiferal analysis, soft samples were crushed to pea-sized pieces and dissociated by repeated soaking and drying in 10 % Na2SO4 solution. All soft samples were wet-sieved through a 0.5 mm mesh after many soaking/drying cycles. Residues were separated, dried, weighed and size-sorted using a nest of sieves of 0.5, 0.25 and 0.16 mm mesh. Residue greater than 0.5 mm was regarded as unprocessed, and its weight was recorded and deducted from the original sample weight to give an effective sample weight. Specimens of 0.5 – 0.16 mm size fraction were picked. The fossil assemblages are largely composed of planktonic foraminifera. Most of the specimens were fractions in >0.25 mm size, with some juveniles and benthic foraminifera from the <0.25 mm fractions. All of the genera and species of foraminifera in each sample were identified. Hard samples were cut into thin sections in different orientations for foraminifera's observations. The counting of total numbers was then corrected to the effective sample weight to yield a final figure of total specimens per 100 g of original sediment. The counting of thin sections only gives species diversities, as the counting of abundance from thin sections does not coincide with that from soft samples.

BIOSTRATIGRAPHY OF BLACK TO RED SEQUENCE

Complete Upper Cretaceous strata are widespread in the southern Tibet. The data of the present work are mostly collected from the Gamba, Tingri, Gyangze, Saga, Saga and Gyirong regions. Reference sections are located in Gamba and Gyangze (Fig. 1). General stratigraphic work was done by many previous researchers (Zhao and Wan, 2003; Wang et al., 2001; Zhong et al., 2000; Li et al., 1999; Wan et al., 1997; Willems, 1993; Wu, 1987; Hao and Wan, 1985; Wen, 1974). The Upper Cretaceous in Gamba was divided into the Lengqingre, Gangbacunkou and Zongshan formations; while that in Gyangze roughly named the Zongzuo Formation.

Figure 1. Sketch map showing localities of studied sections in southern Tibet. S1. Gamba Section; S2. Gyangze Section,
The Lengqinigre Formation is composed of dark shale and rhythmically bedded marl with intercalations of nodular limestone. The Gambacunkou Formation consists of alternating beds of greenish-grey shale and thin-bedded limestone. The lower part of Zongshan Formation is a group of micrite limestone with abundant planktonic foraminifera, and the upper part of the formation at the top of the sequence is mostly foraminiferal wackestone. Red beds are well exposed in the uppermost of the Zongzuo Formation characterized by semi-pelagic red shale and marl.

The Upper Cretaceous stratigraphic sequence can be recognized as three units by color: black, gray and red. This sequence is well constrained by microfossils. The biostratigraphic work undertaken during this work has shown that changes in the microfossil assemblages in the southern Tibet coincide with those observed in other major regions of the world. Foraminifera are the dominant fossil groups in the southern Tibet.

The black unit consists of the Lengqinigre Formation, where the occurrence of microfauna has led to the development of a detailed zonal succession. The late Cenomanian-earliest Turonian beds are biostratigraphically composed of 2 planktonic foraminiferal zones, in an ascending order: the Rotalipora cushmani (Morrow) and Whiteinella archaeocretacea (Pessagno) Zones. The R. cushmani Zone is defined by the total range of R. cushmani, and its top is marked by the last appearance (LA) of the zonal species. The extinction of R. cushmani marks the extinction of this genus. The age of this zone is the late Cenomanian. The Whiteinella archaeocretacea Zone is defined as the interval from the LA of Rotalipora cushmani to the first appearance (FA) of Helvetoglobotruncana helvetica. This zone spans the Cenomanian-Turonian boundary.

The gray unit is composed of a group of greenish gray to gray interbeds of marls and thin bedded limestones. This unit is biostratigraphically recognized as Turonian Helvetoglobotruncana helvetica and Marginotruncana sigali Zones; Coniacian Dicarinella primitiva Zone, Coniacian-Santonian Dicarinella concavata Zone, and Santonian Dicarinella asymetria Zone. More fossil species of Helvetoglobotruncana, Dicarinella, Marginotruncana and Globotruncanita first appeared from different levels of these zones.

The red unit is well developed in the uppermost part of the Zongzuo Formation in Gyangze. This horizon is parallel to the lower part of the Zongshan Formation in Gamba, the latter is also rich in planktonic foraminifera, but light gray in color. Planktonic biota in the red unit is extremely abundant. The reference section of 26 m thick in Gyangze has been recognized as 4 planktonic foraminiferal zones. The Dicarinella asymetria Zone marks the base of red unit. The Globotruncanita elevata Zone is in the lower part of the Campanian. The FA of Globotruncanita ventricosa defines the top of this zone, and the zonal marker ranges above this zone. The Globotruncanita ventricosa Zone defines the interval from the FA of Globotruncanita ventricosa to the FA of Globotruncanita stuarti. The Globotruncanita calcarata Zone occurs in the upper part of red unit. The base of this zone is defined as the FA of Globotruncanita stuarti, and the FA of Globotruncanella havanensis is used to define the top layer of this zone.

MICROFAUNA OCCURRENCES

The biostratigraphic work undertaken in this project has shown that changes in the microfossil assemblages in the southern Tibet coincide with those observed in other major regions of the world. In the southern Tibet, microfauna is composed mostly of foraminifera, ostracods and radiolarians. Foraminifera, the dominant fossil group, display distinct occurrences in different units (Fig. 2).

Foraminifera Occurrence in Black Unit
Abundance and diversity

In the reference section of Gamba, 43 foraminiferal species belonging to 21 genera have been identified from the upper Cenomanian and the lowermost Turonian black units, in which 27 species from 9 genera are planktonic and 16 species from 12 genera are benthic. In abundance, the planktonic foraminifera are dominant and the benthos relatively rarely occurred. The variations on diversity and abundance of the different groups are similar, indicating the presence of two evolutionary phases that coincide with the R. cushmani and W. archaeocretacea Zones. In the R. cushmani Zone, both diversity and abundance of foraminifera are greater with similar pattern of plankton and benthos variations. The values in Fig. 2 decrease upward. The variations on the diversity and abundance roughly coincide with the lithological change, higher in clays and relatively lower in black shales. Planktonic foraminifera, dominant in this zone, are dominated by Rotalipora that are distin-
guished by the trend stepwise to the top of this zone. In the W. archaeocretacea Zone, foraminifera occurred in the lowest diversity and abundance, but a significant extinction of the Rotalipora fauna with disappearance of Praeglobotruncana and Globigerinelloides occurred underneath this zone, while Whiteinella occurred at the bottom of this zone. In the lower part of the zone, below the Cenomanian/Turonian boundary, foraminifera are very rare and barren from some horizons. Specimens of foraminifera slightly increase above the Cenomanian/Turonian boundary.

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Figure 2. Composition of foraminifera in black-gray-red bed sequence of Gamba, southern Tibet. The red unit is a stratigraphic horizon represented by its red color in the reference section of Gyangze. It is in gray color in the Gamba Section.

**Ratio of planktonic and benthic foraminifera (P/(P+B))**

Planktonic foraminifera were frequent in the black unit although their abundance and diversity were decreasing towards the Cenomanian-Turonian boundary. Benthonics were generally fewer and almost absent towards the C-T boundary. The percentage of planktonics in the whole sample accounts for above 75% of the black unit and shows an increasing trend towards the C-T boundary. The planktonic/benthic foraminifera ratios vary from 75% to 98% in the R. cushmani Zone. The general tendency of the ratios appears to increase upwards. At the boundary of the K. cushmani and W. archaeocretacea zones, the P/B ratios increase sharply from 74% to 99% and maintain a higher value of above 93% in the W. archaeocretacea Zone, and decrease back to 74% close to the top of this zone.

**Ratio of keeled and nonkeeled foraminifera (K/(K+nK))**

Planktonic foraminifera, a group of pelagic fauna, are loosely stratified in the water column. Cretaceous morphotypes were distributed at their relative water depth. Compared with modern morphotypes of planktonic foraminifera, the Cretaceous fauna showed the same ecological characters. Nonkeeled planktonics, regarded as the fauna living in the upper water column less than 50 m deep, include genera Whitelella, Hedbergella, Globigerinelloides and Heterohelix. Keeled planktonics, the fauna living in the water column more than 100 m deep, are dominated by Rotalipora, Praeglobotruncana, Dicarinella, Marginotruncana, Globotruncanita, Globotruncanella, Globotruncana and Contusotruncana. Genera Helvetoglobotruncana lived in middle water column roughly in 50–100 m deep. In the Gamba Section, the keeled and nonkeeled planktonic foraminiferal ratio displays a similar pattern with the P/(P+B) ratio by its three intervals coinciding with those of fossil zonation. The K/(K+nK) ratio varies from 76% to 100% in the R. cushmani Zone, but declines rapidly from 100% to 2% close to the top of this zone. The ratio in the W. archaeocretacea Zone is relatively lower and increases upward.
Extinctions at C-T boundary interval

The occurrence of foraminifera in the black unit can be recognized at two intervals, i.e. the extinction interval in the R. cushmani and lower W. archaorectacea Zones, and the survival interval in the upper W. archaorectacea Zone.

In the extinction interval, both diversity and abundance of foraminifera from the R. cushmani Zone of the black unit are relatively high. Planktonic foraminifera are the major fossil group in the R. cushmani Zone with Rotalipora, the dominant genus. All species of this genus go extinct in a stepwise manner at the top of the R. cushmani Zone, with the zonal marker extinguished lastly at the top of this zone. Other planktonic foraminifera genera like Praeglobotruncana disappear temporarily at the top of the zone, whilst other genera (e.g. Hedbergella, Heterohelix and Whiteinella) range up to the W. archaorectacea Zone, although in a reduced abundance.

The majority of the recorded benthic foraminifera were characterized within the R. cushmani Zone by a high diversity but low abundance population (Wan et al., 1997). Both the diversity and abundance of the benthic foraminifera decrease upward. Most of the taxa are of limited range, only Ammodiscus and Lenticulina have a longer fossil record and a higher abundance, but they, too, temporarily disappeared near the C/T boundary. Dorothis and Anomalina disappeared at the stage boundary.

Beneath the C/T boundary, 12 species of foraminifera (28% of the total) disappear, among which 7 planktonic species were extinguished, accounting for 34% of the total planktonic number. Nineteen species make up the surviving taxa. Foraminiferal data from the C/T boundary in the southern Tibet clearly record the deterioration in the foraminiferal fortunes at this time. The extinction rates for planktonic foraminiferal species are 34%, and up to 50% for the benthos in the Gamba Section. The extinction levels of both planktonic and benthic foraminifera are comparable to the global average, whereas considerable variations are present between regions. For example, in the Pacific, the extinction rate of planktonic foraminifera across the C/T boundary was 28% (Sliter, 1989), whereas the global extinction rates were calculated to be around 41% (Caron, 1985). The extinction rates of benthic foraminifera increase from open oceanic setting, e.g. 37% in Japan (Kaiho and Hasegawa, 1994), to 53% recorded in epicontinental seas, such as in Poland (Peryt and Wyrwicka, 1991), to a peak of 69% in the US Western Interior seaway (Eicher and Worstell, 1970).

The survival interval that occurred immediately after the mass extinction at the Cenomanian-Turonian boundary, covers the upper part of the W. archaorectacea Zone where foraminifera are of the lowest diversity and abundance. In addition to the absence of 12 species (5 genera) of foraminifera, 8 species (6 genera) of foraminifera temporarily disappeared at this time. Only nine species of foraminifera, belonging to Hedbergella, Heterohelix and Whiteinella, are present during this interval. Planktonic elements dominate the microfauna in this phase, and in some horizons the percentage of planktonics is 100%. All planktonic foraminifera are nonkeeled surface dwellers, such as Hedbergella, Heterohelix and Whiteinella.

Foraminifera Occurrence in Gray Unit

Following the extinction in the W. archaorectacea Zone spanning the Cenomanian-Turonian boundary, the recovery began at the bottom of gray unit, which is both regarded as a long-term recovery interval from the Turonian to the early Santonian and marked by an increase of both abundance and diversity of foraminifera, especially the stepwise increase of keeled deep-water dwellers that show three clear peaks in the Turonian, and relatively a low rate in Coniasian.

The recovery interval in the southern Tibet, ranging from the H. helvetica Zone of the upper Turonian to the D. concavata Zone of the early Santonian, is marked by an increase in both abundance and diversity. The thermocline dweller, Helvetoglobotruncana helvetica, originated first from the lower level, and then from the keeled species. The origination of keeled elements that appear stepwise in this interval, are mostly the species of Dicarinella, Marginotruncana and Globotruncanita. The gray unit can be recognized as two intervals by species diversity. The lower interval is in the Turonian and the upper one spans the Coniasian and the early Santonian.

In the lower interval, occurred a total of 21 species (16 genera) of foraminifera, including 12 new and 5 Lazarus foraminifera species. The ratio of planktonic/benthic foraminifera remains high at this time, although benthic foraminifera increase in the middle part of this interval. Microfauna in this inter-
val occupied the whole water column. Mid-water dwellers, such as *Helvetoglobotruncana*, dominate the planktonic populations of the earlier stage. The deeper-dwelling planktonic foraminifera *Dicarinella* and *Marginotruncana*, originating in this interval, turn more abundant upward, resulting in the relatively less importance of surface-dwellers. On the whole, a considerably more stratified planktonic foraminifera community was present in the water column of the lower interval of gray unit.

In the upper interval, more species existed, totaling 41 species (15 genera) of foraminifera, among which there are 34 species (9 genera) of planktons and 7 species (6 genera) of benthics. Planktonic foraminifera are still dominant, but deeper-dwellers are in relatively lower diversity.

**Foraminifera Occurrence in Red Unit**

The red bed unit, of the upper Santonian and the Campanian ages in both reference sections of Gyangze and Gamba, is a stratigraphic horizon represented by its violet red color in the reference section of Gyangze, but by its gray color in the Gamba Section. This unit is characterized by its abundant foraminifera, with a high peak in the upper Santonian of Gamba (Fig. 2) and the other one in the middle Campanian of Gyangze (Fig. 3). The occurrences of foraminifera in both sections show a similar pattern. In the period of red bed deposition, both abundance and diversity of foraminifera reached its maximum. Newcomers of keeled elements, such as *Globotruncana*, and *Contusotruncana*, are dominant, which is regarded as a radiation interval with maximum abundance of planktonic foraminifera.

![Figure 3. Foraminiferal species ranges in red unit of Gyangze Section.](image-url)

In Gyangze, occurred a total of 16 species (6 genera) of foraminifera, all of which are planktons without benthos. Among them, 14 species are keeled planktonic foraminifera that account for 87% of the total. The peak species diversity is in *G. calcarata* Zone of the middle Campanian. In Gamba, the total foraminifera include 44 species (17 genera), 31 planktons and 13 benthos of them. The maximum diversity located in the *D. asymetrica* Zone of the upper Santonian shows that the majority of the species are planktonic foraminifera, with the decline of benthics. The ratio of the keeled and nonkeeled planktonic foraminifera is clearly higher than that in the recovery interval. The planktonic and benthic ratio
remains higher in this time, as benthic foraminifera were a less important group in the red unit, especially in the reference section of Gyange. In this thin section, the abundance of foraminifera accounts for 60 %—80 % of the sediments in both Gamba and Gyange.

RESPONSE OF FORAMINIFERA TO OCEANIC ANOXIC-OXIC ENVIRONMENTAL CHANGES

It is generally accepted that the largest transgression occurred in the Cretaceous but the highest sea level occurred in the Middle Cretaceous (Hart and Ball, 1986; Sliter, 1976). The southern Tibet was located in the east Tethys and on the northern margin of the Indian plate. The large Cretaceous transgression also occurred in the southern Tibet (Wan et al., 1997) and generated a group of black sediments. In the Gamba Section, the black unit reveals that the foraminiferal extinctions occurred in two pulses of the late R. cushmani Zone. Both extinctions were associated with the development of dysoaerobic strata. The development of dysoaerobic facies late in the Cenomanian coincided with the crisis in the microfaunal assemblages. The loss of benthic foraminifera (except for a few small Lenticulina and agglutinated specimens at scattered horizons) was probably directly related to the low oxygen levels at the seafloor; but the extinction of planktonic foraminifera suggests that the change in seafloor ventilation was somehow related to water column changes. The intensification of the water column stratification is a possible mechanism that would hinder the overturn, thereby reducing oxygen supply to the seafloor and increasing the amount of nutrients “lost” beneath the density interface. Such a change could also explain the total loss of keeled planktonic foraminifera (e.g., Rotalipora, Praeglobotruncanica, Dicarinella and Marginotruncanica) in the C-T boundary interval. The comparison with keeled modern taxa (Be, 1977) suggests that this group migrated over considerable vertical distances within the upper water column; a life strategy that may have been curtailed by water column stratification. The foraminiferal extinction in the latest Cenomanian of southern Tibet is closely comparable in both timing and magnitude to that observed elsewhere in the world, with keeled planktonic and many benthic species being the principal victims. High-resolution studies of other C-T boundary sections have revealed that the foraminiferal extinctions occurred in two pulses spaced roughly 100 ka apart in the late R. cushmani Zone (Kaiho and Hasegawa, 1994). Both of these extinctions are associated with the development of the dysoaerobic strata. The extinction phase in the southern Tibet coincided with this double extinction interval, which may not have been the case if the extinction is classified as two discrete pulses based on the currently available data. In this case, a higher resolution sampling is required. Jarvis et al. (1988) have suggested a similar extinction mechanism for foraminiferal populations from the southern England, although in their model the development of oxygen-poor lower water column is held directly responsible for the planktonic extinctions. There is no direct evidence for dysoxia above the seafloor in our studied sections, although more persistent anoxia is recorded throughout the black unit.

The gray unit consists of a long interval of biorecovery that spans the lower Turonian to the lower Santonian. Just above the Cenomanian/Turonian boundary, the planktonic foraminifera increase rapidly from 2 to 15 species, with the reappearance of the keeled fauna. The construction and weakening of the oxygen-minimum zone from the early Turonian allowed the recolonisation of new Turonian groups that gradually evolved to refill the niches left vacant by the end-Cenomanian extinction. Benthic foraminifera are still rare. In the Turonian, foraminifera remain a medium number ranging from 3 to 12 species. A shallow water fauna including Hedbergella, Whiteinella and Heterohelix returned first, followed by a deeper water fauna including Helvetoglobotruncanica helvetica and Marginotruncanica. It is postulated that the seawater was gradually reoxygenized from the surface to deep level during the Turonian. The Conian and lower Santonian interval displays a bigger recovery including three peaks of foraminifera indicated by species numbers of 19, 16 and 16. Benthic species are more in number in the lower part and decline upward, probably because after the dysoaerobic environment the water column was largely reoxygenated, but that persistent low oxygen waters still at depth caused benthic foraminifera to have rarely occurred until the earliest Conianian. The recolonisation of the niches vacated by benthic species was slow in contrast to the planktons, and is also a result of the slower migration rates of benthos.

The radiation of planktonic foraminifera in the period of the red unit deposition presents a general overturn of the fauna after a long-term recovery. The
composition of foraminiferal assemblages somehow reflects a complete oxidized circumstance. Two peaks of abundance and diversity occurred in the late Santonian (in Gamba) and middle Campanian (in Gyange), with planktonic foraminifera accounting for almost 100%, suggesting that the intensification of oxygen has more or less returned to its original conditions before anoxia. Clear fluctuations are shown from the high rate of keeled planktonic foraminifera (e.g. *Globotruncanca* and *Contusotruncanca*), indicating a reversed pattern from the anoxic period. Radiation of keeled fauna indicates that high-oxygen levels had returned to the ocean, and stratification disappeared followed by the recovery and radiation of faunas. This variation coincides with the study of Kaimo (1994) on change of oxygen content in seawater, who stated that the highest oxygen levels occurred in the Santonian to the Campanian. Two peaks of foraminiferal diversity in both Gamba and Gyange drop in this interval also imply a high oxic circumstance. During that time, Gamba was in a shallow shelf and Gyange in an outer shelf or upper slope environments (Zhao and Wan, 2003), indicating that the oxic deposits widespread from the shallow shelf to the upper slope coincided with two diversified peaks of foraminifera in the late Santonian and the middle Campanian in the southern Tibet. Opposite to the anoxic condition, the temperature cooling and decline of nutrient levels may have caused more persistent oxia, and the oxygen-rich environment approximately may have caused the radiation of foraminifera. The two peaks in the late Santonian and the middle Campanian might have occurred in the extra-oxidized circumstances, which is supported by the red deposition.

**CONCLUSIONS**

1. The marine upper Cretaceous can be recognized as black, gray and red units that show different foraminiferal compositions and depositional environments. The three units represent extinction, recovery and radiation intervals of foraminiferal biota, respectively.

2. The end-Cenomanian extinction in the black unit coincides with the development of dysaerobic facies, which is characterized by the absence of keeled planktonic and benthic foraminifera.

3. The gray unit consists of a long interval of bio-recovery. Rapid recovery in the early Turonian saw an appearance of new species, the reappearance of many Lazarus species and the reestablishment of a diverse community of planktonic foraminifera including a range of shallow to deep-water column dwellers. This recovery interval lasted until the early Santonian with several fluctuations of biota.

4. The deposition period of the red unit represents a radiation of foraminiferal fauna with keeled planktons that dominated in the ocean and diversification of all depth-dwellers, in which two peaks of diversity might indicate the highest oxidized conditions in the late Santonian and the middle Campanian.

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