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SPECIAL

Palaeokarst and its implication for the extinction event at the Frasnian–Famennian boundary (Guilin, South China)

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A prominent palaeokarst within cyclic peritidal strata reported here at the Frasnian–Famennian boundary in Guilin, southern China, displays karren (scalloped surfaces), dissolution pits and pipes. The last contain residual soil (terra rossa), and are then filled with marine sediment of the overlying strata. The features of the palaeokarst, depth of pipes and amount of missing strata indicate a significant and long-lasting (> *c.* 50 ka) fall of sea level at the end of the Frasnian. The coincidence of the significant sea-level fall with the first stage of the Frasnian–Famennian mass extinction (which mostly affected shallow-marine and reef-dwelling fauna), and of the subsequent rapid sea-level rise with the second stage of the extinction (which mostly affected deeper-water organisms), reinforces the importance of sea-level change in this mass extinction.

Keywords: China, Upper Devonian, palaeokarst, sea-level changes, mass extinction.

The sea-level variations across the Frasnian–Famennian boundary during the Late Devonian are of great importance to understanding and constraining the biotic crisis at this level, which is regarded as one of the ‘big five’ mass extinctions of the Phanerozoic (McGhee 1996). However, there is still much uncertainty and debate over the eustatic pattern of sea-level change at this time (for a review, see Hallam & Wignall 1999). Although there is one case of no apparent sea-level fall during this interval (Morocco, Wendt & Belka 1991), most studies have documented a prominent sea-level fall near the end of the Frasnian (late *linguiformis* conodont zone), which caused emergence and karstification of carbonate platforms, and progradation and collapse of platform margins (Johnson *et al*. 1985; Geldsetzer *et al*. 1993; Muchez *et al*. 1996; House *et al*. 2000; Mountjoy & Becker 2000; Whalen *et al*. 2000; George & Chow 2002). This regression coincided with, and thus has been linked to, the major phase of the Frasnian–Famennian biotic crisis (Sandberg *et al*. 1988; Becker & House 1994; George & Chow 2002; Chen & Tucker 2003). In most cases, a rapid sea-level rise then followed in the very latest Frasnian, leading to deposition of organic-rich sediment, particularly apparent in intra-shelf basin successions. This is the well-known Upper Kellwasser horizon of northern Germany and its equivalent elsewhere (e.g. Schindler 1993; Over 2002). Thus, some workers have proposed, further, that these events were the major cause of the Frasnian–Famennian biotic crisis (e.g. Buggisch 1991; Joachimski & Buggisch 1993; Schindler 1993).

It might seem, therefore, that both the fall and then the rise of sea level played an important role in the Frasnian–Famennian biotic crisis. However, in their review, Hallam & Wignall (1999) disputed the significance of regression in the Frasnian–Famennian transition, and suggested that sea-level change happened well before and well after the extinction event; they concluded that cooling and anoxia were more salient factors in the biotic crisis. Cooling has also been invoked recently as a trigger by Joachimski & Buggisch (2002).

This paper describes a well-developed palaeokarst that occurs at the Frasnian–Famennian boundary in China. This discovery not only provides definitive evidence of a significant fall of sea level at the end of the Frasnian, and subsequent rapid rise of sea level in the earliest Famennian, with associated climatic changes, but also reaffirms the coincidence of sea-level change with this mass extinction event.

Geological setting. The Frasnian–Famennian palaeokarst described here is located at the foot of Elephant Hill on the Li River, a feature that is a scenic symbol of Guilin City. Geologically, this area was part of the Guilin Platform during the Late Devonian, and was surrounded by interplatform basins (Fig. 1). Progressive transtensional rifting was responsible for the formation of the platform–basin configuration (see Chen *et al*. 2001*b*, 2002). The palaeokarst, which was revealed only because the river level was exceptionally low, occurs within the Dongcun Formation, dominated by pale grey to white fenestral limestones. This formation extends from the upper Frasnian through the Famennian (Chen *et al*. 2001*a*).

Correlation of the Elephant Hill section with the platform succession at Tangjiawan 3 km to the south (see Fig. 1 and Chen *et al*. 2001*b*; Chen & Tucker 2003), which includes the Frasnian–Famennian boundary, indicates that the palaeokarst is within the boundary interval. A less prominent exposure horizon occurs at Tangjiawan, with a thin intraformational breccia in a reddened matrix.

Sedimentological context. At Elephant Hill, the depositional facies below and above the palaeokarst include two major types: fenestral limestones and dark grey limestones.

Dark grey limestones have a distinctive dark grey colour (commonly lightening upwards) and range from 0.1 to 1.5 m thick. Only two beds occur at this locality, so they are of minor importance volumetrically. The basal one covers the palaeokarstic surface and fills the dissolution pits and pipes (Fig. 2a–d). The beds mainly comprise lime mudstone with subordinate peloidal wackestone–packstone. Biota is extremely rare, and consists mostly of ostracod shells. These features suggest deposition in a very shallow to intermediate subtidal environment.

Fenestral limestones are the dominant lithology. They are mostly pale grey to white, to light pink in colour (Fig. 2a and b). Two subtypes are present based on the morphology of the fenestrae, whether they are irregular or laminoid (as at Tangjiawan and elsewhere (Chen *et al*. 2001*a*)). Beds with irregular fenestrae commonly grade upwards into ones with laminoid cavities, defining upward-shallowing, decimetre- to metre-scale cycles (Chen & Tucker 2003). These beds mainly consist of

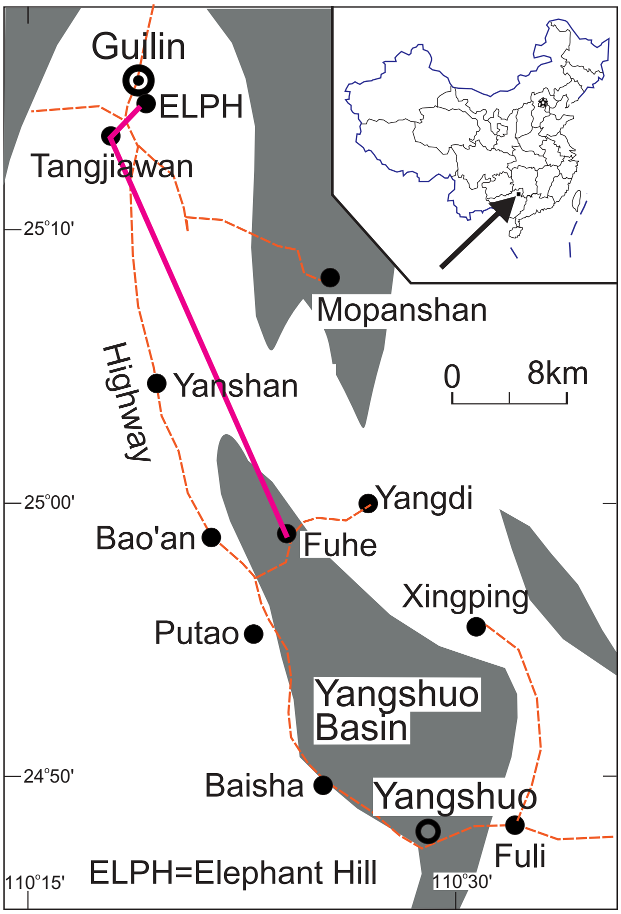

Fig. 1. Lithofacies distribution of Upper Devonian strata in the Guilin area. The shaded and non-ornamented areas indicate basinal and platform facies, respectively. Continuous line from Elephant Hill (ELPH) to Fuhe is the location of the cross-section illustrated in Fig. 3.

wackestone–packstone dominated by peloids, microbial lumps, radial ooids and calcispheres. The fenestral cavities are commonly rimmed with bladed to equant calcite cements, rarely with internal sediments or pendant micritic cements. Macrofossils are extremely rare. These features suggest deposition in a restricted, very shallow subtidal to intertidal environment, with abnormal salinity and/or nutrient levels (see Chen & Tucker 2003).

Palaeokarst features. The palaeokarst is present under the 'nose' of the 'Elephant' near the Li River (Fig. 2a). Dissolution features include karren (scalloped surfaces), pits and pipes. Leached residual soil and sediment of overlying strata occur within the dissolution pipes and pits (Fig. 2a–d).

Scalloped surfaces in cross-section are rough to smooth depressions with curved to irregular bottoms, generally ranging from a few centimetres to metres in width and depth (maximum 1.5 m) (Fig. 2a–d). These decimetre- to metre-scale features are dissolution pits or kamenitzas. There is no microbial encrustation of the surface, as reported, for example, in Devonian palaeokarsts of the Canning Basin (e.g. George & Chow 1999). Dissolution vugs are rare in the host fenestral limestones beneath the exposure surface.

The scalloped surface sharply demarcates the underlying fenestral limestones from the overlying dark grey lime mudstones (Fig. 2a–d). However, the dark grey beds thin and pinch out westwards (Fig. 2a and b), implying an increased relief in that direction. Thus there, fenestral limestones occur above and below the scalloped surface. The scalloped surface is morphologically similar to the modern karren that develop on subaerially exposed limestones with or without a soil cover (e.g. Esteban & Klappa 1983), although erosion may have modified the surface during the subsequent transgression.

Dissolution pipes are common below the exposure surface, and are vertical to subvertical in cross-section. They are generally 10–50 cm wide at the top, tapering and locally curving to become subhorizontal at depth; they extend down from tens of centimetres to 2 m (Fig. 2c and d). The walls are irregular to smooth.

Sediment-fills in the dissolution pits and pipes include dark grey lime mudstone and terra rossa soil. The dark grey facies that overlies the dissolution depressions generally lightens upwards into pale grey to white fenestral limestone (Fig. 2b). Terra rossa occurs only at the bottom of a few pipes. It is pink to reddish in colour (Fig. 2d), and mainly consists of kaolinite and calcite. It represents the leaching residue formed under abundant rainfall, good drainage and acidic water, characteristic of subtropical to tropical weathering (e.g. Potter *et al*. 1980).

Sequence stratigraphic interpretation. The presence of a prominent palaeokarst upon fenestral limestone with the features described above suggests a long-lasting subaerial exposure event as a result of a long-term, high-amplitude sea-level fall. Thus, this palaeokarstic surface is interpreted as a third-order sequence boundary (see Sarg 1988). The stratal pattern above the surface, of 2 m scale, upward-shallowing cycles of dark grey lime mudstone to pale fenestral limestone (Fig. 3), is similar to that straddling the Frasnian–Famennian boundary in the platform carbonates at Tangjiawan, 3 km to the south (see Fig. 1 for location), except that there is one cycle more with dark grey facies at Tangjiawan. This could be the result of erosion at Elephant Hill owing to the subaerial exposure or, more likely, non-deposition as a result of relief on the unconformity. The metre-scale cycles with dark grey facies were the result of high-frequency sea-level changes superimposed on a longer-term (third-order) eustatic rise (Chen & Tucker 2003).

It is worth noting that there are no similar subaerial exposure surfaces within the succeeding Dongcun Formation, which comprises almost all the Famennian and is nearly exclusively composed of cyclic fenestral limestones.

As a result of a high-resolution cyclostratigraphic and sequence stratigraphic correlation of the platform carbonates at Tangjiawan with cyclic basinal deposits, well dated by conodonts, at Fuhe (Fig. 3; Chen & Tucker 2003), the shallowing event (sequence boundary) recorded within the Frasnian–Famennian strata at Tangjiawan is constrained to the latest Frasnian. This was followed by a major rise of sea level (third-order) with the three superimposed fifth-order sea-level oscillations that are equivalent to the Upper Kellwasser horizon (e.g. Schindler 1993). From conodonts again, the Frasnian–Famennian boundary itself is then placed at the top of the first metre-scale dark grey facies-bearing cycle. Thus, the base of the cyclic carbonates immediately above the palaeokarstic surface at Elephant Hill is equivalent to the Frasnian–Famennian boundary, as the first 'dark grey facies'-bearing cycle, as described above, is missing.

A stromatoporoid-bearing bed and two distinctive metre-scale cycles occur above the sequence boundary at Tangjiawan, but they too are missing at the Elephant Hill locality. It is most likely that they were not deposited here either. Accordingly, the duration of the exposure at Elephant Hill was at least three cycles of 1 m scale, and as these are likely to have been of precession origin (Chen & Tucker 2003), the exposure event here lasted more than

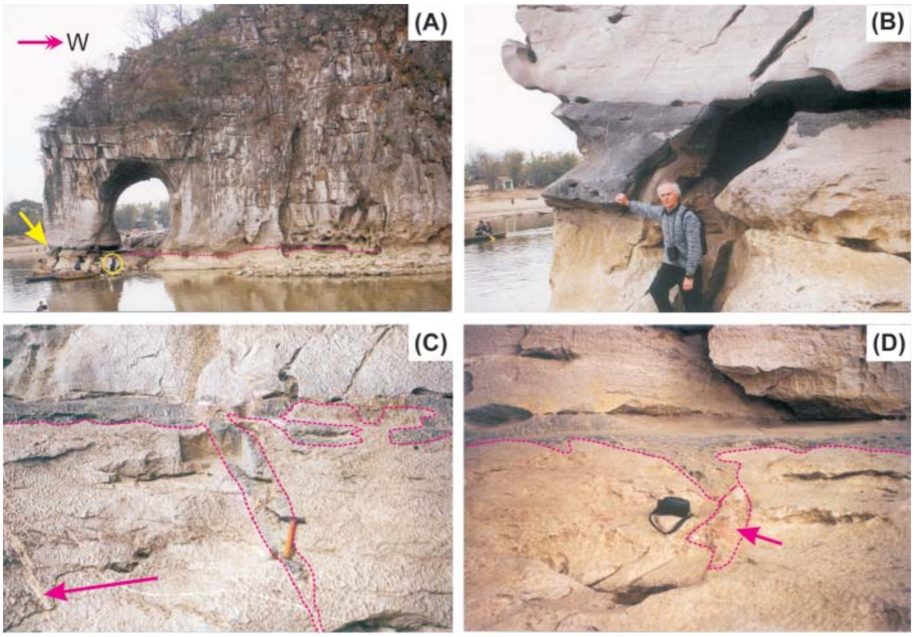

Fig. 2. Features of the palaeokarst and host rocks. (**a**) Panoramic view of the palaeokarst (arrow; see details in (**b**)) under the Elephant Hill. The mild scalloped surface of the karst should be noted (dashed line). People on boat (within circle) for scale. (**b**) Close-up of the palaeokarst in (**a**) with prominent dissolution depression cut into pale grey fenestral limestone and filled by dark grey lime mudstone. Person standing (M.E.T) for scale. (**c**) Dissolution pits (upper right) and pipe (location of hammer) beneath palaeokarstic surface. Light pink calcite-filled vein is tectonic (arrow). Dashed line marks the palaeokarstic surface. Hammer 35 cm long. (**d**) Dissolution pipe filled by dark grey lime mudstone, with reddish terra rossa soil at the bottom (arrow). Camera bag is 15 cm wide.

50 ka. Finally, there is one more very thin, decimetre-scale cycle between the two dark grey facies-bearing cycles, which is absent between their equivalents at Tangjiawan and Fuhe (Fig. 3). This is probably due to the ‘missed-beat effect’ in deeper-water environments (e.g. Goldhammer *et al*. 1990) or an autocyclic effect.

Discussion. In the discussion by Hallam & Wignall (1999) of the Frasnian–Famennian boundary, they disputed the notion of a significant sea-level fall near the end of the Frasnian, on the basis of a review of studies in Morocco and southern Poland, and accepted only high-frequency eustatic oscillations during this time interval. They further contended that regression played no role in the Frasnian–Famennian biotic crisis. In Morocco, a persistent deepening occurred from the late *rhenana* until the middle *crepida* conodont zones with no apparent sea-level fall within this interval (Wendt & Belka 1991). It could be argued that high subsidence rates of the rift basin there meant that a regressive signal was not recorded.

More recent studies in Poland and a refinement of the biostratigraphy (Racki *et al*. 2002) have now identified evidence for regression near the end of the Frasnian, producing a prominent karstic unconformity on carbonate platforms and deposition of calciturbidites on slopes.

The presence of a major palaeokarst at the Frasnian–Famennian boundary at Elephant Hill, Guilin, unequivocally indicates a significant drop in sea level near the end of the Frasnian. The immediately overlying two subtidal metre-scale cycles that grade upwards into cycles exclusively composed of fenestral limestones (see above) suggest a rapid rise of sea level with several superimposed higher-frequency eustatic oscillations. This pattern of sea-level change fits well with the eustatic pattern proposed by Johnson *et al*. (1985), shown in Figure 3.

There is now a growing body of independent evidence from different depositional contexts and localities around the world that increasingly supports a significant (third-order) sea-level fall near the end of the Frasnian (Johnson *et al*. 1985; Sandberg *et al*. 1988; Muchez *et al*. 1996; House *et al*. 2000; George & Chow 2002; Racki *et al*. 2002; Chen & Tucker 2003). An exceptional magnitude for this fall of 130–150 m was deduced in Western Canada (Mountjoy & Becker 2000).

The latest Frasnian sea-level fall was followed by a rapid sea-level rise responsible for the deposition of the Upper Kellwasser horizon and equivalents (Buggisch 1991; Schindler 1993; Over 2002). This Upper Kellwasser horizon, however, may not have been deposited or preserved everywhere (e.g. on shallow-water platforms or marginal slopes), such that the base of the Famennian may locally overlie the exposure horizon or sequence boundary directly (e.g. House *et al*. 2000; Racki *et al*. 2002), as at Elephant Hill. It should be noted that the onset and termination of the Upper Kellwasser interval may also have not been exactly contemporaneous, in view of depositional location, topography and sediment supply (e.g. Over 2002).

Astrochronological dating through a detailed cyclostratigraphic approach (see Chen & Tucker 2003) indicates that the third-order regression, which culminated in the palaeokarst and spanned about 400 ka (four cycle-sets = four short eccentricity cycles; Fig. 3), was much longer than the subsequent rapid transgression (*c*. 50 ka). Our study also suggests that the IId transgressive–regressive cycle of Johnson *et al*. (1985) is composed of two third-order sequences, each spanning 1.0–1.2 Ma in duration (see Fig. 3 and Chen & Tucker 2003). Thus, the sea-level changes across the Frasnian–Famennian boundary are third-order (according to definitions of Vail *et al*. 1977), rather than only high-frequency (fourth- to fifth-order) eustatic oscillations as suggested by Hallam & Wignall (1999).

Although there are numerous hypotheses for the cause of the Frasnian–Famennian biotic crisis (see McGhee 1996), the fact that the major demise of the marine fauna, especially those of shallow-water and reef-dwelling habitats, occurred in parallel with the major fall of sea level in the latest Frasnian (e.g. Sandberg *et al*. 1988; Becker & House 1994; Racki 1998; George & Chow 2002; Chen & Tucker 2003) does strongly suggest some role of this regression in the biotic crisis, a view challenged by Hallam & Wignall (1999). The role may well have been indirect, rather than direct of course. Also, the coincidence of the subsequent, further biotic decline (of deep-water species mostly) with the subsequent sea-level rise and associated anoxia (e.g. Schindler 1993) supports a role of the subsequent transgression in the biotic turnover as well. These data, and especially the evidence from China presented here, show that both regression

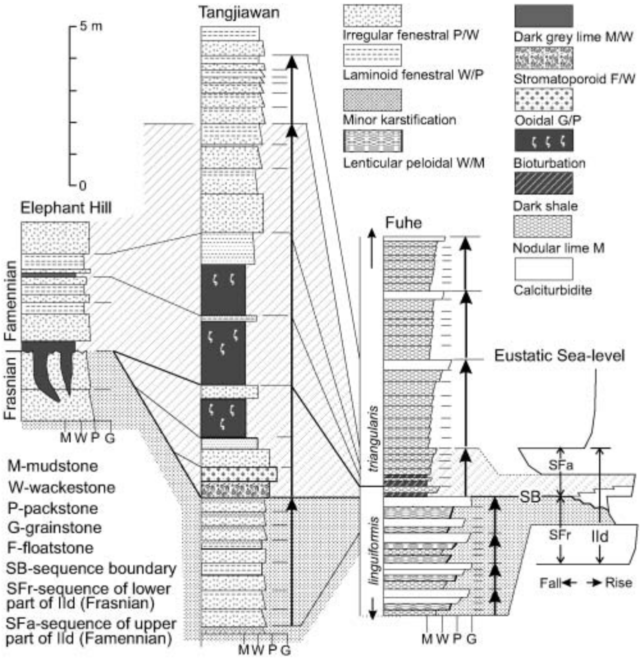

Fig. 3. Lithological succession and upward-shallowing cycles across the palaeokarstic surface at Elephant Hill in Guilin and their correlation with those at Tangjiawan (platform) and Fuhe (basin). (See Fig. 1 for location.) Short lines on the right of logs mark the boundaries of upward-shallowing cycles on the platform and bed-bundling cycles in basin; arrows mark the range of cycle-sets that are interpreted as the result of eccentricity-forcing (*c.* 100 ka) (see Chen & Tucker 2003). Sequences SFr and SFa respectively represent the lower and upper part of the IId transgressive–regressive cycle of Johnson *et al.* (1985). Zones of dots and oblique lines represent the regressive (late highstand) and transgressive deposits of SFr and SFa, respectively.

and subsequent transgression coincided with the Frasnian–Famennian faunal crisis, and probably had direct and indirect influences on this mass extinction.

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