SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

May 2012 Vol.55 No.5: 699–713
doi: 10.1007/s11430-012-4376-5

Tracking shallow marine red beds through geological time as exemplified by the lower Telychian (Silurian) in the Upper Yangtze Region, South China

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Received August 3, 2011; accepted February 8, 2012; published online March 23, 2012

Marine red beds occur frequently in China through geological time. Despite their complex environments, the red beds are found in three depositional settings: 1) oceanic, deep water, as in the Upper Cretaceous of southern Tibet; 2) outer shelf, deeper water, as in the Lower-Middle Ordovician of South China; and 3) inner shelf, shallow water, as in the Silurian and Triassic in South China. The Silurian marine red beds are recurrent in the lower Telychian, upper Telychian, and upper Ludlow. This paper is to document the marine nature of the lower Telychian red beds (LRBs) in the Upper Yangtze Region and to discuss the spatial and temporal distribution of the LRBs and their depositional environments. The LRBs are best developed on the north side of the Cathaysian Oldland, which can be interpreted as the source area. It is inferred that they were deposited during a marine regression, characterized by the lack of upwelling, low nutrition and organic productivity with a decrease of biodiversity and a high rate of sedimentation. The iron-rich sediments may have been transported by rivers on the oldland into the Upper Yangtze Sea, as rates of deposition were rapid enough to counteract normal reducing effect around sediment-water interface. The LRBs are different from the off-shore, deeper water red beds of lower Telychian in Avalonia and Baltica and further from the oceanic, deep water red beds of Upper Cretaceous in southern Tibet chiefly in palaeogeographic settings, biotic assemblages and marine environments.

shallow marine red beds, lower Telychian of Lower Silurian, South China, distribution, environments

Citation: Rong J Y, Wang Y, Zhang X L. Tracking shallow marine red beds through geological time as exemplified by the lower Telychian (Silurian) in the Upper Yangtze Region, South China. Sci China Earth Sci, 2012, 55: 699–713, doi: 10.1007/s11430-012-4376-5

Phanerozoic marine red beds are known in various parts of China through geological time. The complex depositional environments of the red beds can be divided broadly into three groups on the basis of palaeogeographical positions and other contributing factors: 1) oceanic, deep water, typically represented by Upper Cretaceous red limestones in southern Tibet [1–9]; 2) outer shelf, deeper water, exemplified by the Zitai Formation [10–14] (Floian-Darriwilian, Lower to Middle Ordovician) of the Yangtze Region; and 3) inner shelf, shallow water, usually with thick clastic sedimentary sequences, such as the Hongshiya Formation (Floian, Lower Ordovician) in eastern Yunnan, the Rongxi and Huixingshao formations [15–23] (Telychian, Llandovery, Silurian) in the Upper Yangtze Region, and the Feixianguan and Badong formations (Lower Triassic) in South China. In general, the red beds, especially those in the latter two depositional settings, have not received as much study as black shales in China [24].

The Silurian marine red beds are known to occur widely from China. They are of shallow water origin with the ex-

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ception of deep water red beds of Wenlock age in the Qinfang Region of western Guangxi Province [25]. In South China, the Silurian red beds occur mainly in the following three horizons: the lower Telychian, the upper Telychian, and the upper Ludlow [10, 26] (Figure 1). Additionally the Telychian shallow marine red beds are commonly developed in western Tarim of Xinjiang [27] (the Yimugantaw and Keziltag formations), the Qilian Mountains of Gansu (the Quannaogou and Hanxia formations), Ningxia (the Tongxin Formation), and elsewhere. Among them, the lower Telychian red beds are known to have the widest palaeogeographical distribution.

The Aeronian-Telychian strata are widespread and well exposed in the Upper Yangtze Region, and are composed of, in ascending order: 1) the middle-upper Xiangshuyuan, Leijiatun, Majiaochong, Rongxi, Xiushan and Huixingshao formations in northeastern Guizhou, southeastern Chongqing, and northwest Hunan [15]; 2) the middle-upper Lungmachi, Hsiaohopa or Shihniulan, and Hanchiatien formations in northern Guizhou and southern Chongqing [28]; 3) the Lojoping and Shamao formations in western Hubei; and 4) the Wengxiang and Kaochaitien formations in southeastern and central Guizhou respectively [16–23].

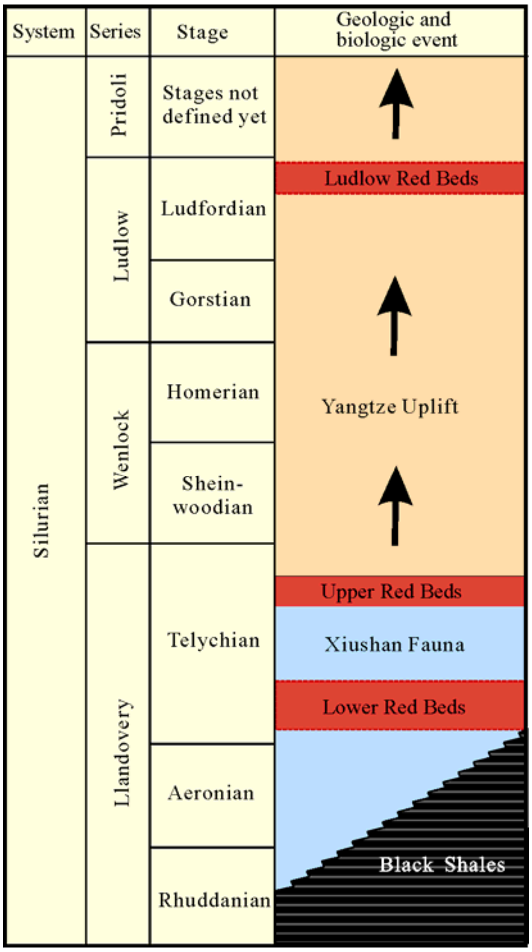

Figure 1 A sketch showing stratigraphical positions of Silurian shallow marine red beds of the Upper Yangtze Region, including the lower and upper Telychian red beds, and Ludlow red beds. The first two are separated by the Xiushan Fauna and the latter two by the Yangtze Uplift.

The Telychian red beds occur in two horizons, informally called the Lower Red Beds (LRBs: such as the Rongxi Formation) and the Upper Red Beds (URBs: such as the Huixingshao Formation) which have been widely used by regional geologists [15, 29][1)]. Stratigraphically, these two units of red beds are located between the underlying Majiaochong Formation and the overlying Xiushan Formation and their coeval strata. The upper part of the Xiushan Formation yields a well-known, short-ranged, widely distributed, mixed fauna, i.e., *Coronocephalus* (trilobite)-*Sichuanoceras* (nautiloid)-*Salopinella* (brachiopod)-*Stomatograptus sinensis* (graptolite) Fauna of middle-late Telychian age [15, 23]. Lithologically, the LRBs are marked by the appearance and disappearance of purple-red, fine clastic deposits as basal and top boundaries, interbedded by yellow-green or blue-gray mudstone and siltstone intercalated with fine-grained sandstone (Figure 2).

The LRBs are characterized by a striking colour, rare macro-fossils, and relatively stable stratigraphical position, which make them easily recognizable for regional correlation, despite a certain degree of diachroneity. Originally, its value for stratigraphic correlation was recognized by teachers and students from Beijing College of Geology in the 1950s when they worked for geological mapping in Xianfeng, Enshi, and Wufeng counties of southwestern Hubei Province. The LRBs were also used as marker beds by regional geologists of Guizhou, Sichuan (including Chongqing at that time), and Hunan for the mapping and other investigations [30–33][2)]. The Shamao Formation in western Hubei consists of yellow-green, fine-grained clastic sediments intercalated with relatively thinner red beds which can be included into the LRBs. Fauna within the LRBs is typically of low diversity and high abundance of a single species of bivalves, ostracods, or gastropods (mainly BA 1) in a few horizons at some localities indicating rather shallow marine environments [34–37].

Ge et al. [15] and Rong et al. [23] produced lower Telychian palaeogeographical maps of the Upper Yangtze Region based on data of 44 and nearly 60 sections respectively. In terms of the past investigations of the LRBs [15, 17, 23, 38] along with geological reports of relative provinces, we have gathered considerable data with new observations during the last ten years. Information of the LRBs is

1) Wang L T. Silurian of Guizhou (in Chinese). Guiyang: Geological Bureau of Guizhou Province, 1976. 68

2) Survey Team of Bureau of Geology and Mineral Resources of Sichuan. Summary Report of Stratigraphy of Sichuan Province (in Chinese). Chengdu: Bureau of Geology and Mineral Resources of Sichuan, 1978. 331

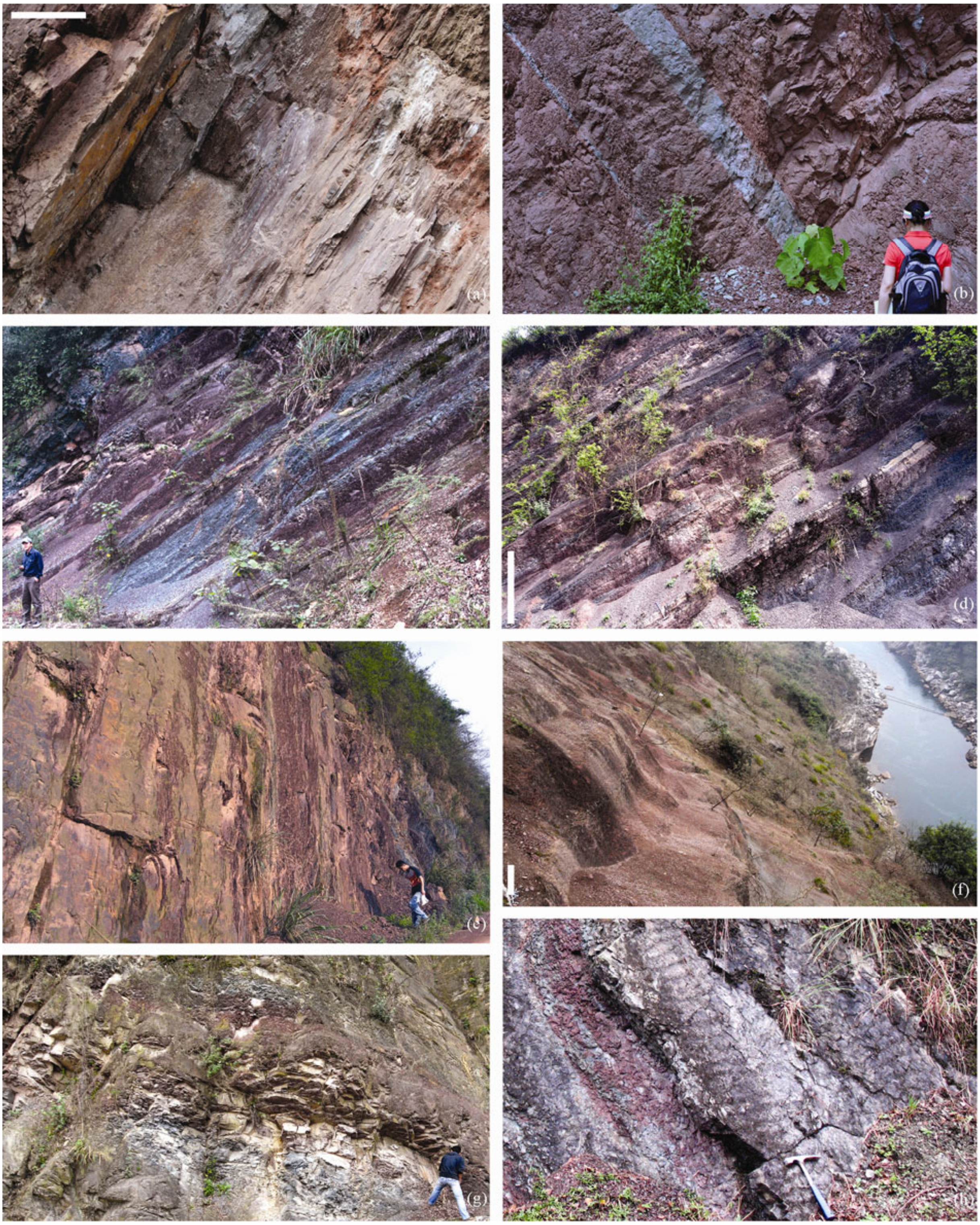

Figure 2 Outcrops of the Rongxi Formation and its corresponding strata of lower Telychian (= the Lower Red beds, LRBs) in Sichuan, Guizhou, Chongqing, Hunan, and Hubei provinces. (a) and (b) The type section of the Rongxi Formation at Rongxi, Xiushan, southeastern Chongqing: (a) Yellow-green siltstone intercalated with purple-red and blue-gray mudstone, scale bar 1 m; (b) purple-red mudstone intercalated with blue-gray mudstone. (c) Wentang section, Zhangjiajie, northwestern Hunan. (d) Shimaxi section, Yanbodu of Cili, northwestern Hunan, scale bar 2 m. (e) Kuangchang section, Shimen, northwestern Hunan. (f) Shatan section, Renhuai, northwestern Guizhou, purple-red mudstone within the Hanchiatien Formation, scale bar 2 m. (g) Pingluo section, Changyang, western Hubei, yellow-green siltstone intercalated with purple-red mudstone in the Shamao Formation. (h) Leijiatun section, 8 km north of Shiqian, northeastern Guizhou, shallow water ripple marks seen on a bedding plane.

derived from 213 sections (176 and 37 with and without the LRBs, respectively) in Yunnan, Guizhou, Sichuan, Chongqing, Hunan, and Hubei provinces. This paper is to document the temporal and spatial distributions of the LRBs in the Upper Yangtze Region, as a case study of the Silurian shallow marine red beds, and to explore preliminarily their depositional environments.

1 Palaeogeographical distribution

New investigation shows that the sediments of the LRBs of the Upper Yangtze Region were derived from oldland regions. The Cathaysian Oldland was united with the Dianqian (Yunnan-Guizhou) Oldland, as the largest one in South China during the Silurian. The LRBs are best developed on the northern side of the coalesced oldland (Figure 3A and B). There existed the Chuanzhong (=Central Sichuan) Oldland, around which four isolated areas known occurred as peripheral sites for the LRBs (Figure 3C). Moreover, the LRBs are also traced in northern Hubei, which was located in the southern side are of the Eyu (Hubei-Henan) Oldland (Figure 3D).

1.1 Northern side area of the Cathaysian-Dianqian Oldland

The LRBs are represented mostly by the Rongxi Formation

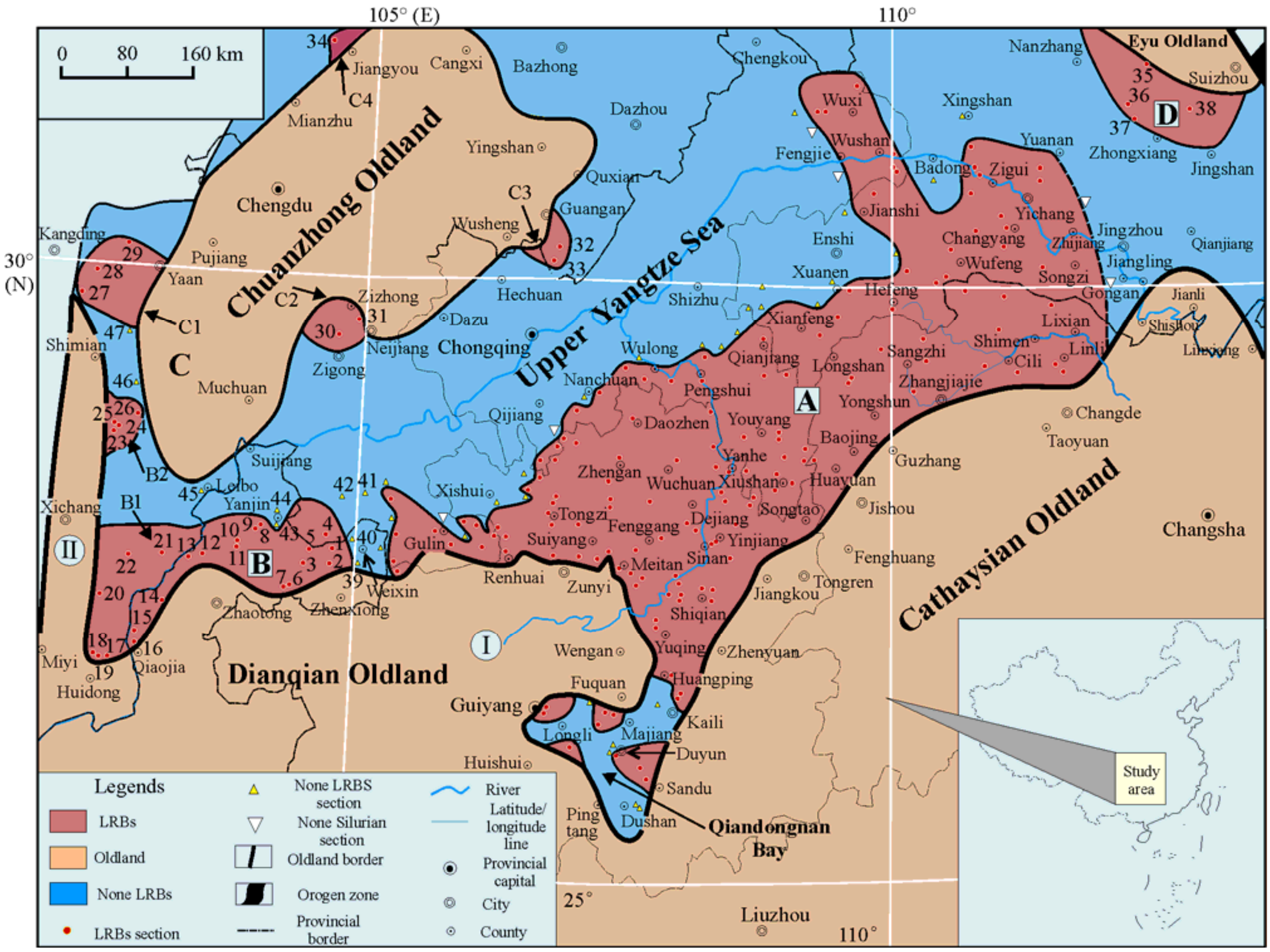

Figure 3 Palaeogeographical distribution of the lower Telychian shallow marine red beds (LRBs) in the Upper Yangtze Region. A, Northern side area of the Cathaysian Oldland and Qianzhong Oldland (I, belonging to the Dianqian Oldland), relative information will be provided in Figure 5; B, northern side area (B1) of the Dianqian Oldland and eastern side area (B2) of the Kangdian Oldland (II); C, four sites (C1–C4) around the Chuanzhong Oldland; D, southern side area of the Eyu Oldland. LRBs sections (some with thickness): 1. Sumaping (104 m), Weixin; 2, 3. Lianghekou and Shashu, Zhenxiong; 4. Luomurou (50 m), Junlian; 5–7. Bajiawo, Lutanggou and Yinchanggou (128 m), Yiliang; 8–11. Huangjingba, Laomucheng, Chahe and Huanggexi, Daguan; 12, 13. Lianfeng and Daxing, Yongshan; 14. Gengdi, Ludian; 15, 16. Anxi and Lantianba, Qiaojia; 17–19. Xinjie, Fangmaping (67 m) and Huangbai, Huidong; 20. Gantian (121.8 m), Puge; 21. Xinzhaizi, Jinyang; 22. near county town (about 100 m), Butuo; 23, 24. Xiapuxiong (48 m) and Bijishan (42 m), Yuexi; 25, 26. Minziluomu and Boboxiang, Ganluo; 27, 28. Xinglong and Erlangshan (48.2 m), Luding; 29. Longmen, Tianquan; 30. Weiyuan well (8.5 m), Weiyuan; 31. Yinshan, Zizhong; 32, 33. Hongyan coal mine (30.4 m) and Liziya (50.3 m), Huaying; 34. Gongjia, Jiangyou; 35. Banqiaodian, Yicheng; 36–38. Hujie, Zhubaobu and Kedian, Zhongxiang. *None* LRBs sections: 39, 40. Huashiban and Shizigou, Weixin; 41, 42. Xinjie and Yuhe, Xingwen; 43, 44. Huangjuecao and Wenchanggong, Yanjin; 45. Paha, Leibo; 46. Yandai, Ganluo; 47. Baishagou, Hanyuan.

and occur partly in the Hanchiatien, Shamao, Wengxiang, and Kaochaitien formations in various areas. Palaeogeographically, the occurrences of the LRBs are linked to oldlands, not as isolated lithofacies areas, and enclosed by contemporaneous rocks of non-red beds. Faunas of the LRBs suggest an inner shelf, shallow water origin, being apparently different from deeper water marine red beds [5, 39–41]. Both lithology and biodiversity of the LRBs are quite similar to those of the Telychian shallow marine red beds of the western margin belts of the Tarim Basin, western Xinjiang.

Generally, the LRBs are thicker (usually 200–500 m) and have more single red beds (each usually 2–10 m thick) in localities that were closer to the oldlands than in far away areas where the LRBs become thinner and rarer and eventually disappear [15, 16, 18–20] (Figure 4). The thickest successions of LRBs, some exceeding 500 m, are known from Wentang, Zhangjiajie City, northwestern Hunan, and those

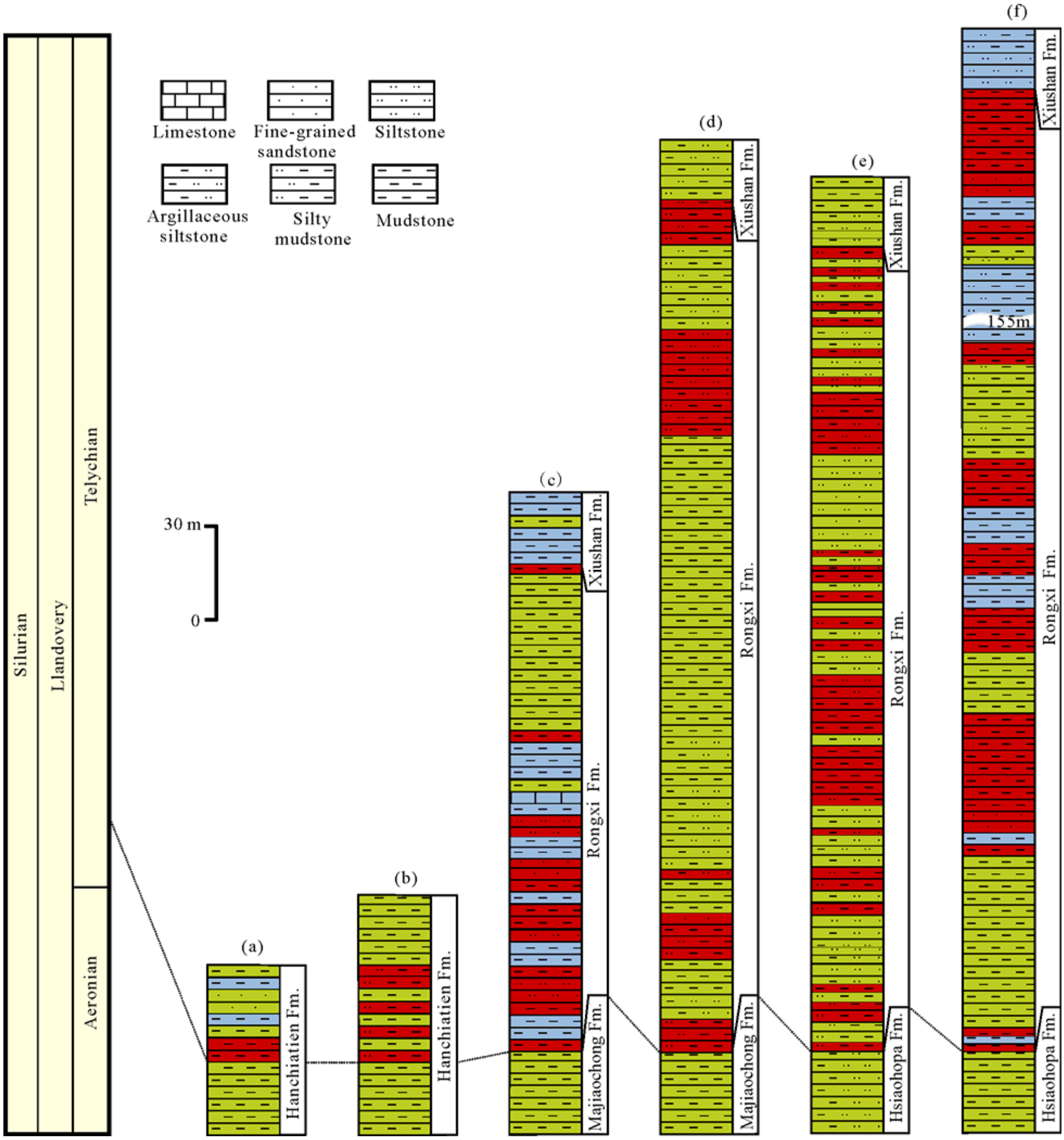

Figure 4 Correlation of the lower Telychian shallow marine red beds (LRBs) of six sections in the Upper Yangtze Region. The red beds occur in the Hanchiatien Formation at Hanjiadian, Tongzi (a) and Houba, Suiyang (b), and in the Rongxi Formation at Longjingpo, Wuchuan (c), Heshui, Yinjiang (d), Rongxi, Xiushan (e), and Bidong, Longshan (f). (a)–(d) are from northern Guizhou, (e) from southeastern Chongqing, and (f) from northwestern Hunan.

between 400 and 100 m have been observed in Hongyanxi of Longshan County, northwestern Hunan and Xiaoxian of Youyang County, southeastern Chongqing. Northwestwards, the thickness of the LRBs decreases to less than 100 m at many sites in northeastern Guizhou and southwestern Hubei where the successions of LRBs become thin (usually tens of meters) and are included in the middle part of the Hanchiatien Formation in northern Guizhou, southern Chongqing and southern Sichuan, and the Shamao Formation in western Hubei. Near the marginal areas of the LRBs (such as Shatan of Renhuai County, Maoba and Hanjiadian of Tongzi County, and north of Xiaheba, Xishui County, northern Guizhou, Guanyinqiao of Qijiang County and Sanquan of Nanchuan County, southern Chongqing, and Dazhongba of Yichang County and Daxiakou of Xingshan County, western Hubei), the LRBs became progressively thinner, only about 20 m in thickness. The LRBs are only 1.3 m thick in the Hanchiatien Formation at Goutou of Bijie City, northwestern Guizhou and down to 0.2 m at Gaojiayan, Yongle of Zunyi City, northern Guizhou. Furthermore, the LRBs disappeared and are replaced by yellow-green fine clastic rocks at some localities of Xishui County, northwestern Guizhou, Pengshui, Shizhu and Qianjiang counties, southeastern Chongqing, Xuanen, Enshi, Hefeng, Badong, and Xingshan counties, western Hubei, and Tianba, Wuxi County, northern Chongqing. The LRBs are also known from the Kaochaitien and Wengxiang formations which were deposited in the Qiandongnan (Southeastern Guizhou) Bay.

1.2 Northern side of the Dianqian Oldland

The LRBs of this area are exposed in Daguan, Yiliang, Yanjin, Yongshan, Ludian, Qiaojia, and Weixin counties, northeastern Yunnan, as well as Junlian County, southwestern Sichuan [42]. The type locality for the Sifengya Member (the LRBs) of the Daguan Formation is located at Huanggexi, Daguan, where it consists of gray, argillaceous, stripped limestone and mudstone intercalated with limestone yielding corals in the lower-middle part [43], and purple-red mudstone intercalated with fine grained sandstone in the upper part [44–46] which can be correlated partly with the Rongxi Formation [18]. No red beds are developed at Shizigou, Dashiban and Shuanghe of Weixin County. It is possible that the LRBs in this area were sourced from the Kangdian and Dianqian oldlands (Figure 3B). The LRBs are replaced by yellow-green mudstone and siltstone at 2 km north of Yanjin [47], together with some parts of Xingwen, Junlian, Leibo, and Ganluo counties. Near Tuanjie of Yongshan County, the Shimenkan Formation contains thin red beds and is overlain by so-called "Ludlow-Pridoli" marine red beds by local geologists, but is now correlated with the LRBs of lower Telychian age in this paper. The highest horizon of the Silurian rocks at Daxing of Yongshan County is the Huanggexi Member of the Daguan Formation (Aeronian) with no LRBs developed. The LRBs occur also in some areas of Buto, Puge, Ningnan, Huidong, and Jinyang counties, southwestern Sichuan[1)]. For example, the LRBs, 10–15 m thick at Bijishan, east of Yuexi County, are supposed to be constrained by the Kangdian Oldland, rather than the Chuanzhong Oldland.

1.3 Vicinity of the Chuanzhong Oldland

Four sites of the LRBs are known in the vicinities of the Chuanzhong (Central Sichuan) Oldland [48] (or Chengdu Oldland [49][3)] (Figure 3 C_1–C_4). The Baiyun'an Formation (the LRBs) is composed of interbedded purple-red mudstone and limestone, 30–50 m thick [50, 51], bearing abundant corals at its type locality of the Huayingshan area. A succession of shallow marine red beds, 8.5 m thick, occurs in the top part of the Lungmachi Formation in a drill core from Weiyuan County, southern Sichuan [52]. The Changyanzi Formation contains purple–red clastic sediments (the LRBs) with a thickness of 48.2 m in the Erlangshan area, western Sichuan [53][1,3)]. The Hongyanzi Formation at Luoquanwan, southwestern slope of the same mountains can be grouped into the LRBs with a thickness of 34.4 m [46][3)]. These LRBs may have been constrained by the Chuanzhong Oldland.

1.4 Southern side of the Eyu Oldland

Lower Telychian purple-red rocks, interbedded with gray-yellow and yellowish green siltstone/sandy shale and mudstone, are found in the Shamao Formation in Banqiaodian of Yicheng County, Kedianpo, Hujiaji and Zhubaobu of Zhongxiang County, north of Jingshan County, and west of Xiangyang City, northern Hubei Province. Southwards, the red beds are replaced by non-red sediments at Shimenchong of Jingshan County [52]. In the light of regional stratigraphical sequence and correlation, the red beds mentioned above can be correlated approximately to the Rongxi Formation in northwestern Hunan. In northern Hubei, they are also thicker in the north and thinner in the south, indicating that their distribution may have been controlled by the Eyu (Hubei-Henan) Oldland, rather than by the Cathaysian Oldland. It is interesting to note that upper Lungmachi Formation exposed there also contains purple-red beds [52], which are distinctly of Aeronian in age, stragraphically, lower than the LRBs.

Figure 5 shows the palaeogeographical distribution and isopach patterns of the LRBs in the Upper Yangtze Region.

3) Jin C T. Silurian of Southwest China (in Chinese). Chengdu: Chengdu Institute of Geology and Mineral Resources, 1982. 135

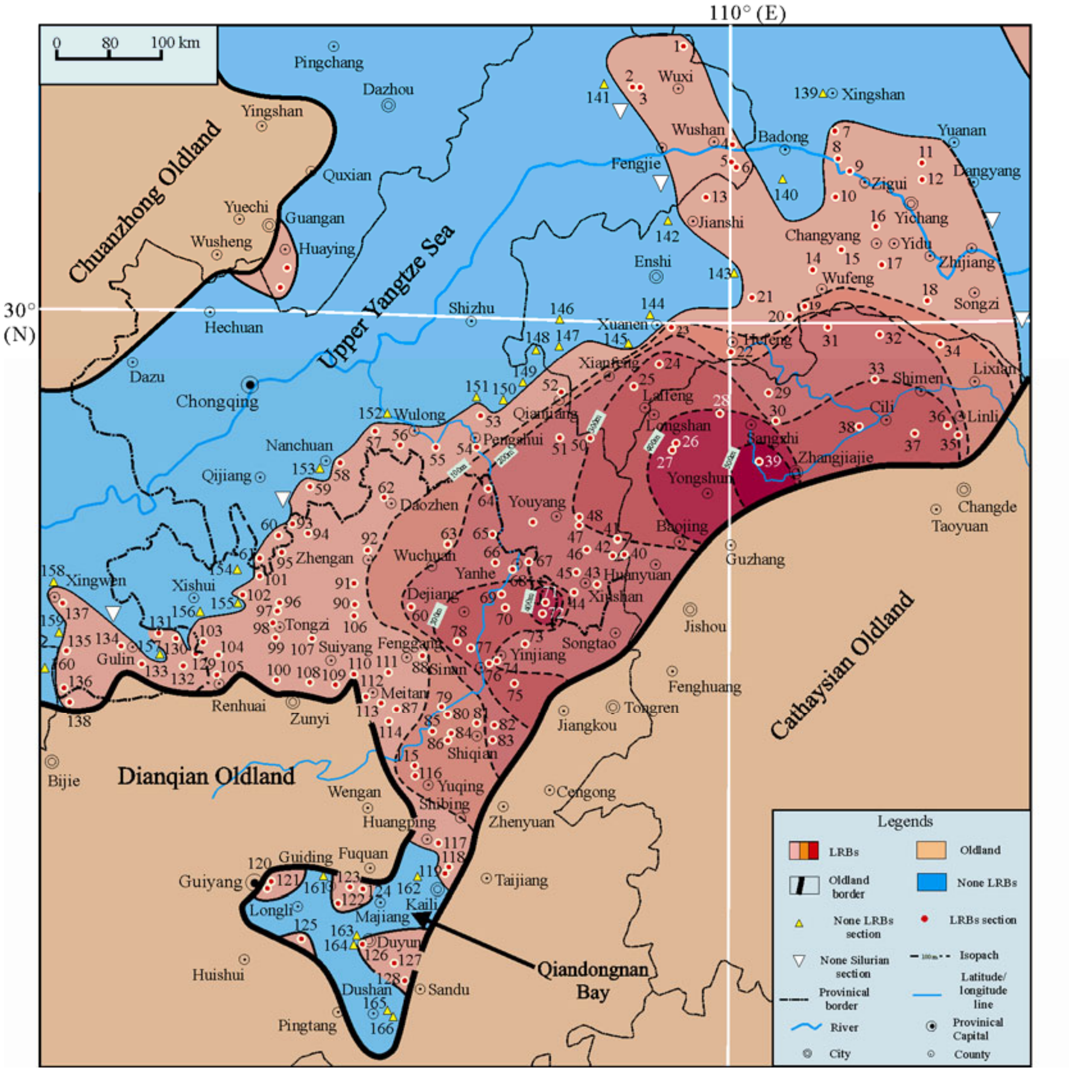

Figure 5 Palaeogeography and thickness distribution of the lower Telychian shallow marine red beds (LRBs) in the A area of Figure 3. LRBs sections (some with thickness): 1–3. Xujiaba (67 m), Xindian and Baiguo, Wuxi; 4–6. Hengshixi, Baolonghe and Taohua, Wushan; 7. Daxiakou, Xingshan; 8–10. Xintan, Miaohe and Yanglin, Zigui; 11. 12. Dazhongba (25 m) and Juntianba, Yichang; 13. Sandaoyan (65 m), Jianshi; 14–17. Xiejiaping (16 m), Bashanao, Liujiaping and Dayan (36 m), Changyang; 18. Tudiling (54 m), Yidu; 19, 20. Xiangzhangping (140 m) and Wantan (27m), Wufeng; 21, 22. Gongjiaya (8 m) and Guanwu (138 m), Hefeng; 23, 24. Lianghekou and Gaoluo (343 m), Xuanen; 25. Sanbao, Laifeng; 26, 27. Hongyanxi and Bidong (467 m), Longshan; 28–30. Chenjiahe (414 m), Linxihe (201 m) and Hongjiayu (283 m), Sangzhi; 31–33. Longchihe (270 m), Gengzishan (283 m) and Longwangdong (297 m), Shimen; 34. Huolianpo (181 m), Lixian; 35, 36. Taifushan and Wenjia (>313 m), Linli; 37. Maocaopu, Taoyuan; 38 Shimaxi (375 m), Cili; 39. Wentang (529 m), Zhangjiajie; 40. Kapeng (246 m), Huayuan; 41–46. Shidi, Xiaoyakou, Hujiadong, Changgang (280 m), Rongxi (240 m) and Miaoquan (265 m), Xiushan; 47–50. Longtan (>235 m), Buhai (260–330 m), Dingshi (250 m) and Xiaoxian (250–330 m), Youyang; 51, 52. Zhuoshui (250 m) and north of county town (40 m), Qianjiang; 53, 54. Longshe (40 m) and Wanzu (15m), Pengshui; 55–57. Jiangkou (17 m), Longdongya and Changba, Wulong; 58. Sanquan, Nanchuan; 59. Shaiguping (13 m), Wensheng; 60, 61. Guanyinqiao (8 m) and Longmenxia, Qijiang; 62. Bayu (64 m), Daozhen; 63. Longjingpo (152 m), Wuchuan; 64–70. Hongdu (297 m), Siqu, Guanzhou, Lixi, near county town, Ganxi (>300 m) and Qiaojiazhen (381 m), Yanhe; 71, 72. Ganlong and Dongjiaping (455 m), Songtao; 73–75. Heshui (268 m), Zhoujiaba (270 m) and Chanxi (348 m), Yinjiang; 76–80. Liangshuijing (348 m), Yingwuxi, Donghuaxi (310 m), Banbian (136 m) and Wengxi, Sinan; 81–86. Leijiatun (180 m), Kaiyue (245 m), Fengxiangping (about 200 m), Juntianba (160m), Benzhuang (130 m) and Baisha, Shiqian; 87–89. Yachuan (36 m), Dongkala (73m) and Balixi (240 m), Fenggang; 90–92. Tuping (53 m), Lejian (50–60 m) and Huangjiawuji (95 m), Zhengan; 93–100. Podu (3 m), Baisanxi (15 m), Hangjiadian (8 m), Xinchang, Liangfengya, Heishixi (86 m), Daijiagou (59 m) and Sancha (42 m), Tongzi; 101–102. Xiaheba (5 m) and Shuanglongchang (10 m), Xishui; 103–105. Shatan (19 m), Yangcun (40 m) and Zhongshu (40 m), Renhuai; 106–109. Wenquan (55 m), Zhanba (45 m), Simianshan and Houba (30 m), Suiyang; 110. Gaojiaya (0.2m), Zunyi; 111–113. Yongxing, Niuchang and Xinglongchang (18 m), Meitan; 114–116. Songyan (20 m), Suyang (127 m) and Xiaosai (127 m), Yuqing; 117. east of county town, Huangping; 118, 119. Wengxiang (<10 m) and Shuizhu (14 m), Kaili; 120, 121. Wudang (9 m) and Dayu, Guiyang; 122–124. Shibanzhai (29 m), Majiatun and Dalishu (122 m), Guiding; 125. Yangchang, Longli; 126, 127. west of county town and Wangsi, Duyun; 128. Sishizhai (19 m), Sandu; 129–134. Mayantan (5 m), Tiesuoqiao (9 m), Taiping (9 m), Shibao (33 m), Daping and Deyao, Gulin; 135, 136. Huangnixiang and Shuiliao (4 m), Xuyong; 137. Gusong (1 m), Xingwen; 138. Goutou (1.3 m), Bijie. None LRBs sections: 139. Gufu, Xingshan; 140. Siyangqiao, Badong; 141. Tianba, Wuxi; 142. Taiyanghe, Enshi; 143. Guandiankou, Jianshi; 144, 145. Jiaoyuan and Xiaoguan, Xuanen; 146. Zhonglu, Lichuan; 147. Huolongping, Xianfeng; 148, 149. Lishui and Heixi, Qianjiang; 150, 151. Yushan and Longshe, Pengshui; 152. Baima, Wulong; 153. Yanjiaba, Nanchuan; 154–156. Wenshui, Tuhe and Sangmuchang, Xishui; 157. Yuhua, Gulin; 158. north of county town, Xingwen; 159. Shatiantou, Xuyong; 160. Shuanghe, Weixin; 161. Yangbaoshan, Guiding; 162. Luomian, Kaili; 163, 164. Machang and Qianjiapu, Duyun; 165, 166. Wana and Lizhai, Dushan.

2 Age of the LRBs

The age of the LRBs of the Upper Yangtze Region was initially assigned to the Wenlock [29], and later commonly to lower Telychian [15–20, 22, 28, 29, 31, 32, 54–58]. Most recently, two different age interpretations have been proposed: one being a late Aeronian age based on conodonts [55, 56], and the other an early Telychian age based on chitinozoans [57]. Below is a discussion on these interpretations, with additional notes on the graptolite data.

(1) Graptolites. By using acid digestion techniques, three-dimensional graptolite specimens were recovered from a mudstone bed just below the purple-red beds at the top part of the Hanchiatien Formation at Bayu, Daozhen County, northern Guizhou, which can be correlated with the LRBs [30]. The discovery of the graptolites is important for graptolites are extremely rare in the LRBs. They were identified by Chen Xu as *Streptograptus nodifer* [59, 60], being a significant member of the *Spirograptus turriculatus* Biozone [18], and may extend up to the *Monograptus crispus* Biozone within lower Telychian [61, 62]. Additionally, graptolites of the *S. turriculatus* Biozone were discovered from gray-green and purple-red mudstone at the top of the Lungmachi Formation in a drilling well at Weiyuan, Sichuan[2)] and the graptolites–bearing horizon can be correlated with the LRBs. In the border area of Shaanxi and Sichuan provinces, the Wangjiawan Formation (the LRBs) containing purple-red beds is underlain by the Cuijiagou Formation which yields graptolites of the *S. turriculatus* Biozone [18], and the purple-red beds can be correlated with upper *S. turriculatus* and lower *M. crispus* biozones [18], supporting an early Telychian age for the LRBs.

(2) Conodonts. There are no key, age-sensitive taxa of conodonts in the Rongxi Formation [58]. The overlying lower Xiushan Formation yields the *Ozarkodina guizhouensis-Distomodus* sp. nov. fauna, which was assigned to the latest Aeronian-early Telychian or early Telychian [18, 19]. As the base of the *Pterospathodus eopennatus* Biozone from the upper Xiushan Formation is correlated with middle part of the *S. turriculatus* Biozone, the *O. guizhouensis* Biozone may correspond to the lower *Distomodus staurognathoides* Biozone straddling the Aeronian and Telychian boundary. Owing to a morphological similarity of *D.* sp. nov. to *D. staurognathoides,* the *O. guizhouensis* Biozone was considered correlative to the uppermost Aeronian and lowest Telychian [57]. Most recently, the lower Xiushan Formation and the Rongxi Formation (the LRBs) have been assigned to the basal Telychian and the upper Aeronian respectively based on the conodonts [55, 56].

(3) Chitinozoans. The *Ancyrochitina brevicollis* Biozone was recognized in the top part of the Hanchiatien Formation at Bayu of Daozhen, northern Guizhou which can be correlated with the Rongxi Formation. *A. brevicollis* is commonly associated with *Eisenachitina daozhenensis* in Qiaoting of Nanjiang, northern Sichuan, Lengji of Erlangshan, western Sichuan, Huanggexi of Daguan, northeastern Yunnan, and the eastern suburb of Ningqiang, southwestern Shaanxi [22, 63, 64]. As the first appearance of *E. daozhenensis* (FAD) is stratigraphically lower than that of *A. brevicollis* at Leijiatun of Shiqian, Hanjiadian of Tongzi, Wengxiang of Kaili, and the eastern suburb of Ningqiang, the *E. daozhenensis* Biozone has been recently established and placed in the lower Telychian [57] partly based on its occurrence from the Cuijiagou Formation corresponding to the *S. turriculatus* Biozone in Ningqiang [63]. Whereas the *A. brevicollis* Biozone can be correlative to the graptolite biozones of *S. turriculatus, M. crispus* and lower *Monoclimacis griestoniensis* [65].

At the present, it is not conclusive to assign the Rongxi Formation (the LRBs) to the Aeronian based on conodonts as the range of each biozone of the Llandovery conodonts and chitinozoans and their correlation with graptolite biozones need to be defined more precisely [55, 56, 58, 66]. Moreover, below the *S. turriculatus* Biozone and within the Telychian Stage, there is a biostratigraphical space for the *S. guerichi* Biozone which is regarded as the longest one (2.4 Ma) of the Silurian graptolite biozones [61]. Thus a possibility that the LRBs fit into an interval within the lower Telychian cannot be excluded.

In the Daguan area, northeastern Yunnan, the Daluzhai Formation contains the Xiushan Fauna [18] and the chitinozoan *Ancyrochitina longicollis* [63] and can be correlated with the upper Xiushan Formation, northeastern Guizhou and southeastern Chongqing. The Sifengya Member (the LRBs) is assignable to the *A. brevicollis* and *E. daozhenensis* biozones [63]. In the north of Yichang western Hubei, the middle Shamao Formation bears purple–red beds (the LRBs) [64] yielding the index chitinozoan taxon *A. brevicollis* [63]. In Yanglin, Zigui, again western Hubei, there occurs a thin marine red bed in the Shamao Formation and the top of the formation yields the conodont *P. eopennatus* [55, 56]. The middle–upper part of the Shamao Formation mentioned above can be assigned to lower Telychian.

To discuss the geological age of LRBs, it is necessary to refer the geological ages of overlying and underlying strata in South China. (1) The overlying Xiushan Formation consists of the lower and upper parts and its upper member yields the graptolites *Stomatograptus sinensis* and others which were correlated with upper *M. griestoniensis* Biozone to *Oktavites spiralis-Stomatograptus grandis* Biozone, middle-late Telychian [18]. (2) In the Shiqian-Yinjiang-Xiushan-Longshan depression, the upper Lungmachi Formation yields graptolites of the *Lituigraptus convolutes* Biozone of middle Aeronian. In northern Guizhou and southern Chongqing, the strata between the LRBs and Lungmachi Formation (*Campograptus communis* Biozone, middle Aeronian) were considered as late Aeronian-early Telychian [18][3)]. In light of the data analyzed above, the LRBs, although being diachronous, are better correlative within the lower Telychian (Figure 6).

The lower Telychian marine red beds are also well developed in North America and Europe [39–41]. Based on the investigation of Aeronian black shales and Telychian red-green intervening strata in Estonian and Latvia, Kiipli [40] concluded that there occur upwelling currents and bottom reduced environments (black shales and scattered iron pyrites) in the Aeronian and oxidation at sea bottoms (hematites and rare goethites) in the Telychian. A similar major change across the Aeronian and Telychian boundary in the marine system appears to be present in the Upper Yangtze Region.

3 Preliminary analysis of depositional environments

The occurrences of the inner shelf, shallower marine red beds in the lower Telychian constrained by oldlands and oxygenate conditions suggest certain palaeogeographical settings and depositional environments [18, 22, 23]. In the previous studies, the Silurian LRBs of the Yangtze Region have been interpreted variously as inner shelf, littoral facies [15, 17, 18], delta deposits [68], or lacustrine/estuary facies [69]. The chondrichthyan fossils from the LRBs proved their marine origin, which have been further confirmed by the fossil fishes [69–75] associated with other marine fossils, such as *Sinacanthus* and *Dayongaspis* from the Rongxi Formation in Zhangjiajie, northwestern Hunan Province. Similar fossil fish assemblages were recorded in the coeval LRBs of the Lower Yangtze Region, such as in southeastern Hubei [73, 76–78], northern Jiangxi [79] and southern Anhui provinces [80, 81]. There the LRBs also contain typical marine animal fossils with a low diversity, including the dendroid graptolite (e.g., *Hunanodendrum typicum*), brachiopods (*Nalivkinia, Nucleospira*, and *Striispirifer*), trilobites (*Luojiashania* and *Encrinuroides*), and echinoderm (*Pisocrinus*) mainly from yellowish green mudstone of the Rongxi Formation in some sections [15, 16, 18, 23, 29, 82][1)]. The Sifengya Member (the LRBs) in Daguan and Qiaojia counties, northeastern Yunnan Province yields marine fossils, containing rugose corals [43] and brachiopods (pers. comm. with Zhan Renbin and Li Guipeng).

It was emphasized that the Lower Silurian red beds in many regions of Europe and USA were formed during a transgressive period [39, 40]. However, the latter may not be a necessary condition to form marine red beds, since the LRBs dealt with in this study are interpreted to have been formed in a regressive state [22, 34]. Johnson [83, 84], Haq and Schutter [85] suggested that the global sea level in early Telychian contains a complex process, but rose at the beginning of the *S. guerichi* Biozone and fell in the *M. crispus* Biozone. On a regional scale, local tectonics such as in South China may also have influenced sea level fluctuations. It is likely that a relationship between the LRBs and a regressive condition may have existed in the Upper Yangtze Region in early Telychian.

During the pioneer stage of plant colonization on land, such as in the Silurian, the surface of oldlands was covered with very limited vegetation and exposures of rocks were easy to be weathered and to provide a great amount of clastic sediments. During transportation by rivers or in shallow depositional settings, the sediments were kept in an oxidized state. The tectonic activities in South China were intensive, particularly when a collision of the Cathaysian and Yangtze blocks took place in later Late Ordovician and early Early Silurian [86, 87]. Subsequently, continuous expansions of the Cathaysian Oldland [15, 17, 23] probably facilitated the accumulation of the LRBs in the study region in early Telychian. Wang [68] initially advocated that the Rongxi Formation (LRBs) in the area of Yongshun, Longshan, Zhangjiajie, Cili, and Shimen counties in northwestern Hunan Province was deposited as a deltaic plain based on evidences of many aspects. Several layers of purple-red siltstone and fine-grained sandstone with a lenticular shape in upper mudstone beds in Zigui, Hubei Province were interpreted as possible channel deposits [55]. The fine-grained clastic sediments and very few laminated or lenticular limestone were deposited on the sea bottom. Accordingly, it can be inferred that high iron-rich rocks of volcanic sources may have been widespread over the Cathaysian Oldland as a suitably oxidized source area, and their abundant ferric Fe-rich clasts were transported by rivers into inner shelf, littoral and shallow marine environments of the Upper Yangtze Sea. The clastic deposits were likely oxidized at the source or during transportation, forming the LRBs. This would have been especially true prior to the evolution of land plants and the concomitant reducing effect of organic material. This is different from the idea that the lack of physical, and possibly biological, reworking of the inshore sediments of the Appalachian Basin resulted in the unreduced state of the iron minerals in the relatively shallow, but fully marine environment [39].

Sedimentary rates of the LRBs were probably rapid enough to counteract a normal reducing effect around sediment-water interface. Those oxidized, fine-grained sediments with ferric iron sank to sea bottoms, which were rapidly buried to avoid being reduced [18]. If the basin subsidence rate was equaled by the sediment accumulation rate, water depth could have been maintained within several meters up to about 20 m depth. Moreover, sedimentary structures and faunal characteristics can also serve as indicators of a generally shallow water depositional environment, such as mudcracks in the north of Diaojingyan of Yongshun County, symmetrical/asymmetrical ripple marks at Leijiatun of Shiqian County, small to large scaled cross-beddings at Rongxi of Xiushan County, and a few beds with abundant, monotonous species assemblage of bivalves at Leijiatun of Shiqian County and of ostracods at Juntianba of Yichang

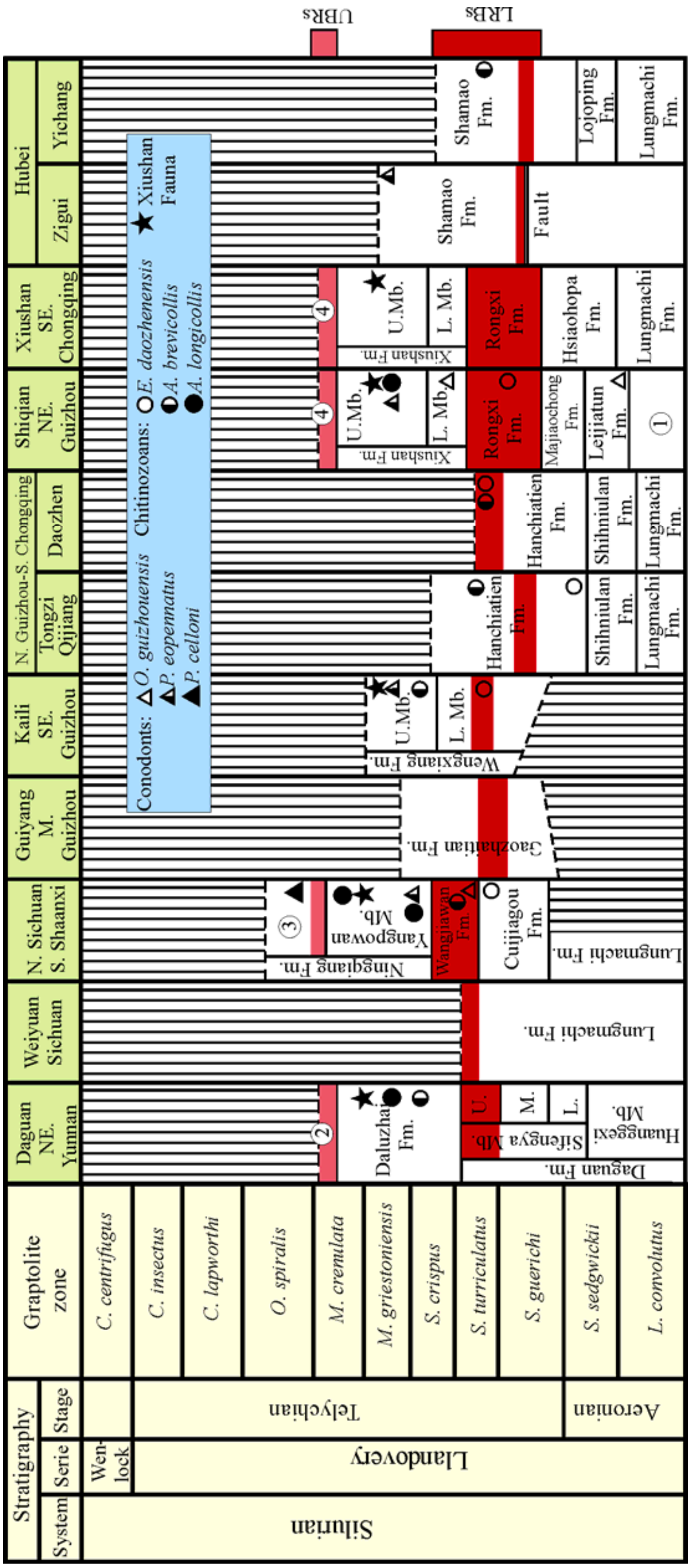

Figure 6 Stratigraphical positions and correlations of the lower Telychian shallow marine red beds (LRBs) and the upper Telychian shallow marine red Beds (URBs) in various areas of the Upper Yangtze Region. ① Xiangshuyuan Fm.; ② Caidiwan Fm.; ③ Shenxuanyi Mb.; ④ Huixingshao Fm.

City [88]. These lines of evidence all point to nearshore, very shallow water environments (BA1, similar to the "*Lingula*" Community) on the north side of the Cathaysian Oldland [15, 68, 89][1)].

As noted above, the entire sequence of the LRBs is composed of purple-red beds, interbedded with or intercalated with yellowish green or bluish gray mudstones/ siltstones. The purple-red strata have a high Fe^{3+} content and very low organic matter content, whereas the non-red rocks were deposited under relatively weak reducing conditions. The rhythmic occurrences of the red and greenish gray intercalations suggest that the sea bottoms and water interfaces were not always kept under a strong state of oxidation, but in strong and weak alternative reduction-oxidation processes.

It is reasonable to assume palaeoclimatic influences on the shallow marine red beds. It was generally inferred that the Silurian red beds were deposited under arid and warm climatic conditions. The Yangtze Sea was located at low latitudes of the Southern Hemisphere in early Telychian [89]. Geng et al. [22] suggested that glacial activities were a major cause for the marine red beds in addition to a widespread regression. The abundant rugose and tabulate corals and the shelly tempestites (e.g., the *Paraconchidium* beds) [90] in the upper Shihniulan Formation (mid-upper Aeronian) are considered to indicate a warmer condition, whereas the LRBs were accumulated possibly in relatively cooler sea water.

The Upper Yangtze Sea was a foreland basin during the Llandovery, located on the north side of the Cathaysian Oldland [91, 92], which served as a possible source area of oxidized sediments [68] (Figure 7). It can be postulated that during early Telychian, the sea was characterized by a regional regression, the lack of upwelling, a low nutrient level and low organic productivity, a possibly cooler climate, a decrease of biodiversity with a total number of the invertebrate species being less than half of the earlier period, and high rates of sedimentation.

4 Comparison

A brief comparison shows many similarities and differences between the LRBs of the Upper Yangtze Region and the marine red beds of different geological periods and regions. The similarities include a high concentration of ferric iron, a low nutrient level, low organic productivity and a strong oxidized environment, and the differences are discussed below.

4.1 Comparison with the lower Telychian marine red beds of Europe and North America

The Telychian red beds well developed in England, Wales, Scotland, Ireland, Norway, Estonia, and Latvia differ from the LRBs of the Yangtze Region in their off-shore, deeper water, outer shelf or slope depositional settings [35] with a graptolite facies containing, for example, *S. turriculatus* and the brachiopods, *Costistricklandia* or *Clorinda* communities of BA4-5 [93]. For example, the Telychian red beds of Estonia, ranging from the Rumba to Velise formations, were accumulated in a depositional environment associated with changes of upwelling and downwelling currents, where productivity and oxygen level underwent a transformation on sea floor and sedimentation rate was low [94]. The upwelling current established an anoxic shelf environment with a high productivity by providing the nutrient-rich anoxic water to shelf in the late Aeronian, while the downwelling current dropped the high oxygen surface water into deeper sea, resulting in a low productivity and the oxidized process across the sea water-deposit surface on deep continental shelf in early Telychian. The distribution of the LRBs in the Upper Yangtze Region has a close relationship with oldlands. All groups of the faunas discovered from the

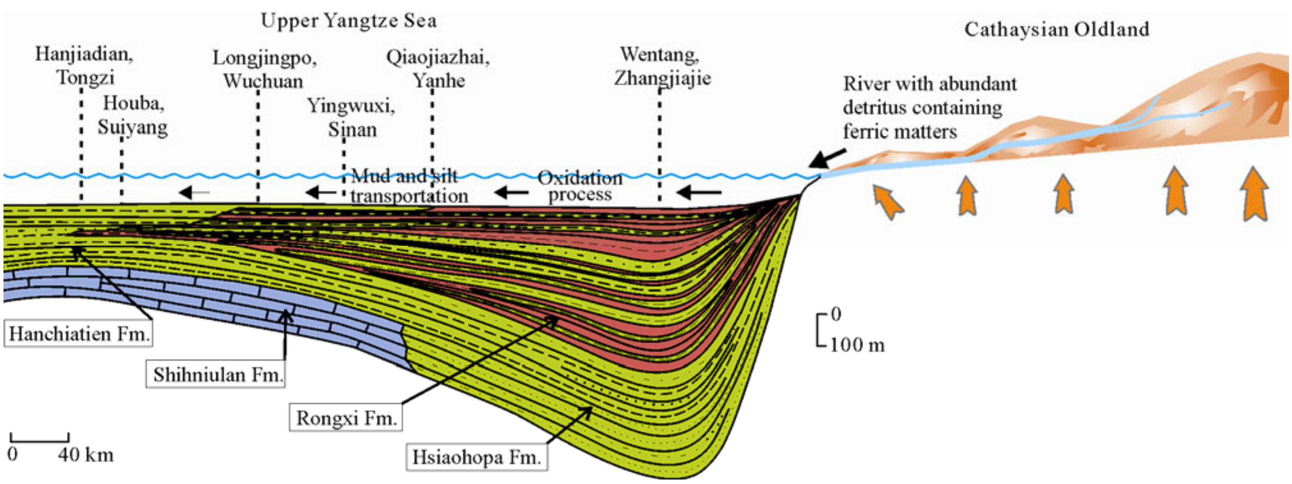

Figure 7 Overview of inferred environmental conditions of the LRBs of lower Telychian in the Upper Yangtze Region and their relationship with the then Cathaysian Oldland.

LRBs are composed of inner shelf, benthic sessile invertebrates and/or estuarine nekton vertebrates, assuming that they were generally deposited in a depth range of shallower than 20 m (BA1-2) [23, 34].

The Telychian red beds of the Appalachian Basin, USA different from the European examples, are characterized by inner shelf, shallow water deposits and contained the shallow *Eocoelia* community (BA2) [39]. The fine-grained sediments formed under oxygenated conditions and a rapid sedimentation rate within a relatively shorter time interval, rich in iron and rare in organic material, along with the lack of reducing effect. This situation is rather similar to that of the LRBs of South China. But, the Telychian red beds in the Appalachian Basin, USA were produced by erosion of the thoroughly oxidized and presumably loosely consolidated terrestrial Queenston and Juniata sediments of Upper Ordovician under a transgression, whereas the sediments of the LRBs may have been transported by rivers together with results of a local regression in the Yangtze Region in early Telychian.

4.2 Comparison with the Upper Cretaceous oceanic red beds

The Upper Cretaceous red beds are oceanic sediments, accumulated along continental shelf margins, slopes and ocean basins where water depth was over 200 m up to 1000 m [4, 6, 9]. The deposition took place through a total of 20 Ma, with about 3–8 Ma [95] at each locality, and the rate of depositions was much lower with an average of 13–14 m/Ma [8]. The oceanic red beds are composed largely of limestone, often containing chert nodules and bands of siliceous deposits [96], with a low argillaceous concentration and without shallow water sedimentary structures [4]. They yield pelagic fossils, such as foraminifers and radiolarians. In contrast, the LRBs of this study were sourced from oldlands, and the deposition lasted for a rather short time interval (less than 3 Ma), and the rate of depositions is apparently much higher (100–200 m/Ma) than that of the Upper Cretaceous oceanic red beds. Moreover, the LRBs consist of fine-grained siliciclastic deposits, such as mudstones and siltstones, rarely sandstones, accumulated in a depth range of shallower than 20 m (BA1-2) [23, 34], and contained faunal assemblages (inner shelf, benthic invertebrates: bivalves, gastropods, brachiopods, and early fish) of low diversity.

5 Concluding remarks

Marine red beds contain ferric Fe from oxidation process and black shales possess organic carbons accumulated under reducing conditions. Both may have existed simultaneously in different regions or in the same regions at different times, but show tremendous differences of the environments. Specific conditions of palaeogeography, sedimentation, environments, palaeoclimate, and tectonics led to the deposition of the LRBs in the Upper Yangtze Region. The existence, uplifting, and expansion of the Cathaysian Oldland formed embayment of the Upper Yangtze Sea and the essential palaeogeographical framework in the early Telychian; the oxidation of inner shelf sediments was crucial for the formation of the LRBs. The then Yangtze Sea probably underwent a regressive episode, characterized by the lack of upwelling, a low level of nutrient supply and organic productivity, a decrease in biodiversity, and a high sedimentation rate. The iron-rich sediments may have been transported by rivers into the sea, as rates of deposition were rapid enough to counteract the normal reducing effect around the sediment-water interface. These characters differ from the Telychian deeper water, offshore red beds of Europe [39–41] and the Lower-Middle Ordovician marine red beds (such as the Zitai Formation) of South China, and from the Upper Cretaceous oceanic red beds in much deeper, quieter and more stable environments with a much lower rate of sedimentation [1–9].

The long time interval of global greenhouse in Palaeozoic was interrupted by two ice ages, with the shorter but intense glaciations mostly in the latest Ordovician and the longer one mostly in the Carboniferous. Widespread black shales have been usually interpreted as the result of oceanic primary organic production, burial of organic carbon, leading to a sharp drop of the atmosphere carbon dioxide [61, 97–100]. Were the widespread oxidizing conditions and marine red beds related to the dramatic increase in atmospheric carbon dioxide? Were the red beds related to a cooler climate in the early Telychian than in the Aeronian with black graptolite shales and thick limestone sequences containing abundant graptolites and corals? If this is true, should the atmospheric carbon dioxide have been reduced? The Silurian and Triassic marine red beds in South China are well developed in shallow water settings. The surface of the source areas in the Silurian was almost without vegetation, whereas the terrestrial vegetations in the Triassic were severely suffered during the end-Permian mass extinction. Is there a possible relationship between near shore marine red beds and the situation of the land vegetation? Are these resulted by physical process as transported by rivers or factors of geochemistry at the sea bottom, or both with biotical participation, since marine red beds consist of abundant fine-grained ferric Fe-rich sediments?

There are many unanswered questions in the study of marine red beds, as part of the integrated problems of the earth systems and large-scale regional systems. To understand the Silurian shallow marine red beds in South China, it would be necessary to make a thorough and careful investigation of biostratigraphy (regional correlation), lithology and mineralogy (including comparison of red and non-red clastic rocks), sedimentology (such as sedimentary structure and rate), palaeogeography (such as uplift and expansion of oldlands, and tracing river system on oldlands), palaeoceanography (such as upwelling or downwelling), palaeoclimatology (such as warmer-moist or cooler-arid climate), tectonics (such as tectonic background of South China), geochemistry (such as oxiding or reducing process), and others. This paper provides merely a recognition of marine nature of the Silurian LRBs in the Upper Yangtze Region and a preliminary summary of their spatial and temporal distribution. A new project on some of these fields mentioned above has been carried out by the junior colleagues of this paper in order to offer new evidence and knowledge to improve our understanding of the Silurian shallow marine red beds.

Data used in this paper are derived partly from various reports of geological maps (1∶200000) of Guizhou, Yunnan, Hunan, Hubei, and Sichuan (including Chongqing) provinces. We are grateful to local geologists for their contributions in carrying out the reconnaissance during 1958–1978. We acknowledge valuable information and suggestion from Chen Xu, Jin Jisuo, Wu Haoruo, Wang Chengshan, Jiao Huiliang, Wang Chengyuan and Shi Xiaoying, and great help from Zhan Renbin, Zhang Yuandong, Liu Jianbo, Tang Peng, Huang Bing, Wu Rongchang, Wang Guangxu, Jiang Qing and Liang Yan in the field. This work was financially supported by Chinese Academy of Sciences (Grant No. KZCX2-YW-Q05-01), National Basic Research Program of China (Grant No. 2012CB821901), and China Geological Survey (Grant No. 1212011120116). Constructive reviews of the manuscript from Gong Yiming and an anonymous referee are greatly appreciated . This paper is a contribution to IGCP Project 591.

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