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Shell concentrations of Early Silurian virgianid brachiopods in northern Guizhou: Temporal and spatial distribution and tempestite formation

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Shell beds in the uppermost Xiangshuyuan Formation and its coeval Upper Shihniulan Formation (Lower Silurian), northern Guizhou, SW China, are interpreted as tempestites occurring on the Upper Yangtze Platform. The shells are dominated by two endemic and transient virgianid (brachiopod) taxa, *Paraconchidium shiqianensis* and *Virgianella glabera*, which vary in relative abundance and deposited as fragments of valves with cemented micrite that differs from the surrounding sediment, demonstrating that the shells were not originally preserved in growth positions. The thicknesses of individual shell layers vary from ten centimeters to more than four meters. Shells had been strongly stirred up by high-energy currents, mainly caused by ocean storm events and probably related to the profile of the geographic shape of the coastline. Fragmentation of shells, in particular, their thinning anterior parts of ventral and dorsal valves are more intensive. The benthic assemblages are from lower BA2 to upper BA3 in depth, assigned to near shoal belt in geographic background. Breakage and stacking density are of the indexes of proximal and distal transportations. Northern Guizhou was located within the lower latitudes of the Southern Hemisphere during the Silurian time, and obviously affected the depth of the virgianid inhabitation. Most of these shells were disturbed repeatedly by surges. It is inferred that on average, several ten thousand years of growth of shells were required for development of shell layers, followed by storm disruption.

northern Guizhou, Llandovery, Xiangshuyuan Formation, Shihniulan Formation, virgianid, brachiopod, tempestite

This paper describes the nature and distribution (spatial and temporal) of the virgianid (pentamerid)-dominated beds of Aeronian, Llandovery, Lower Silurian from northern Guizhou, and assesses the storm event of shallow marine sedimentary environments on the South China Block.

Storm as a kind of catastrophic weather accompanying with gale and heavy rain is triggered by typhoon or tornado. The gale with wind velocity of more than 12 Beaufort degree is called hurricane. Bore invades landward rapidly due to the tsunami caused by individual or pooled actions of atmosphere circumfluence, astronomical tide as well as earthquake of the ocean basin,

and strongly reforms the biota and sediments within designated depth of the sea floor. Frequency of storm surges may occur several times per year from some modern coastal regimes and the powers may touch the depth of about 200 m maximally. The term “tempestite” was proposed by Ager^[1] to define special sedimentary associations reworked by storms. Aigner^[2] first presented a sedimentary mode of tempestite. Barron^[3] re-

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viewed the tempestite records in Earth history. These studies supply basic archives for our understanding of this subject.

It is hard to determine the frequency of storm events in ancient time due to dating limitations and the difficulty of palaeolatitude reconstructions (since tempestites likely formed in low latitudes associated with hurricanes). One storm deposit is easily moved elsewhere by the next storm, and in these deposits, this is likely to happen. However, tempestite beds may be viewed as a standard for high-resolution stratigraphic correlations because of their representation as instant events, and depth above the major storm base.

Silurian tempestite examples have been recorded from both carbonate and terrigenous lithofacies. Most of the literatures are based on the cases from Europe and North America (e.g., Avalonia, Laurentia and Baltica blocks)^[4], and few are documented from China. Rong et al.^[5] described the *Pentamerifera* (pentamerid) layer of the Ludlow Series from western Junggar, Xinjiang, northwest China, and interpreted a regional disaster event. Zhang et al.^[6] analyzed the Upper Llandovery Ningqiang Formation crinoidal grainstone beds from Guangyuan and Ningqiang, the border area of Shaanxi and Sichuan provinces, and suggested that coarser relicts (e.g. crinoidal debris) formed hard substrata and taphonomic feedback for reefal community growth after finer muddy sediments were washed away by storms. Baarli^[4] cited this case and pointed out that South China Block was also impacted by storm events in later Llandovery though it was situated in the leeward of the Gondwana Continent. However, the crinoidal tempestite from the Ningqiang Formation is quite different from that of the present study.

It is well-known that pentamerid brachiopods form shell beds in Silurian carbonate-dominated sediments. In many cases, the shells are well preserved, but in others, the shells are severely fragmented and developed as layers of debris, seemingly created by storm action, often referred to as tempestites^[4]. In the South China Block, pentamerid shell beds are abundant in shallow marine facies of Llandovery (Lower Silurian) limestones in northern Guizhou Province. The middle Aeronian virgianid shell concentrations occur in the horizons close to the topmost part of the Xiangshuyuan Formation and the upper part of the Shihniulan Formation in northern Guizhou (Figure 1), near Qianzhong (central Guizhou) Land (Figure 2)^[7]. Differentiation of sedimentary facies was mainly controlled by geographic patterns of Cathay-

sian Land from the east and Dianqiangui (Yunnan-Guizhou-Guangxi) Land from the south. Lithofacies analysis shows that limestones intercalated with muddy shales of the Xiangshuyuan Formation in the east are laterally equivalent to terrigenous deposits of the Upper Lungmachi Formation and limestones of the Shihniulan Formation in the west. Also, nearshore “Baisha-type” limestones in the south are laterally equivalent to deeper “Yinjiang-type” micritic limestone intercalated with shales in the north. “Baisha-type” limestones were recognized in 1979^[8,9], and are marked by three groups: 1) shelly beds of brachiopods; 2) patch reefs and biostromes of coral-stromatoporoids; 3) crinoidal grainstones together with less coral fragments. The dominated elements in the first group include virgianids (most common), pentamerids, atrypids and trimerellids.

1 Temporal and spatial distribution

Virgianid shelly beds in northern Guizhou are mainly composed of two taxa, *Paraconchidium shiqianensis*^[9,10] and *Virgianella glabera*^[9]. They may occur together (e.g. localities at Baimapo, Baisha, Shiqian and Balixi, Fenggang) or separately (e.g. Juntianba, Shiqian and Tuping, Zheng'an). They have similar inner structures of a long and thick medium septum supporting a spondylium in the ventral valve and convergent cruralium in the dorsal valve. Key difference between the two species is that *V. glabera* has smooth shell surface, whereas *P. shiqianensis* possesses radial costae. However, the two species are difficult to distinguish on a polished slab.

Virgianid valves vary in size, breakage and gregarious density, and occasionally mix with scarce corals (e.g. *Crystiphyllum*, *Favosites*). White valves are distinctive against a background of dark micrites in outcrops (Figure 3(a)–(d)), especially when they are wet by water. One to four individual layers from 0.1 m to a few meters in thickness may be present within one section, and are intercalated by other kinds of limestones.

Regarding dating of the virgianid shelly beds, the Upper Xiangshuyuan Formation plus the overlying Leijiatusun Formation in northeastern Guizhou is approximately correlated to the Shihniulan Formation in northern Guizhou^[7]. However, no sharp boundary exists between them; the two facies may interfinger spatially. Generally, lithofacies in northeastern Guizhou comprise more terrigenous components than those occurring more generally in northern Guizhou. The latter shows domi-

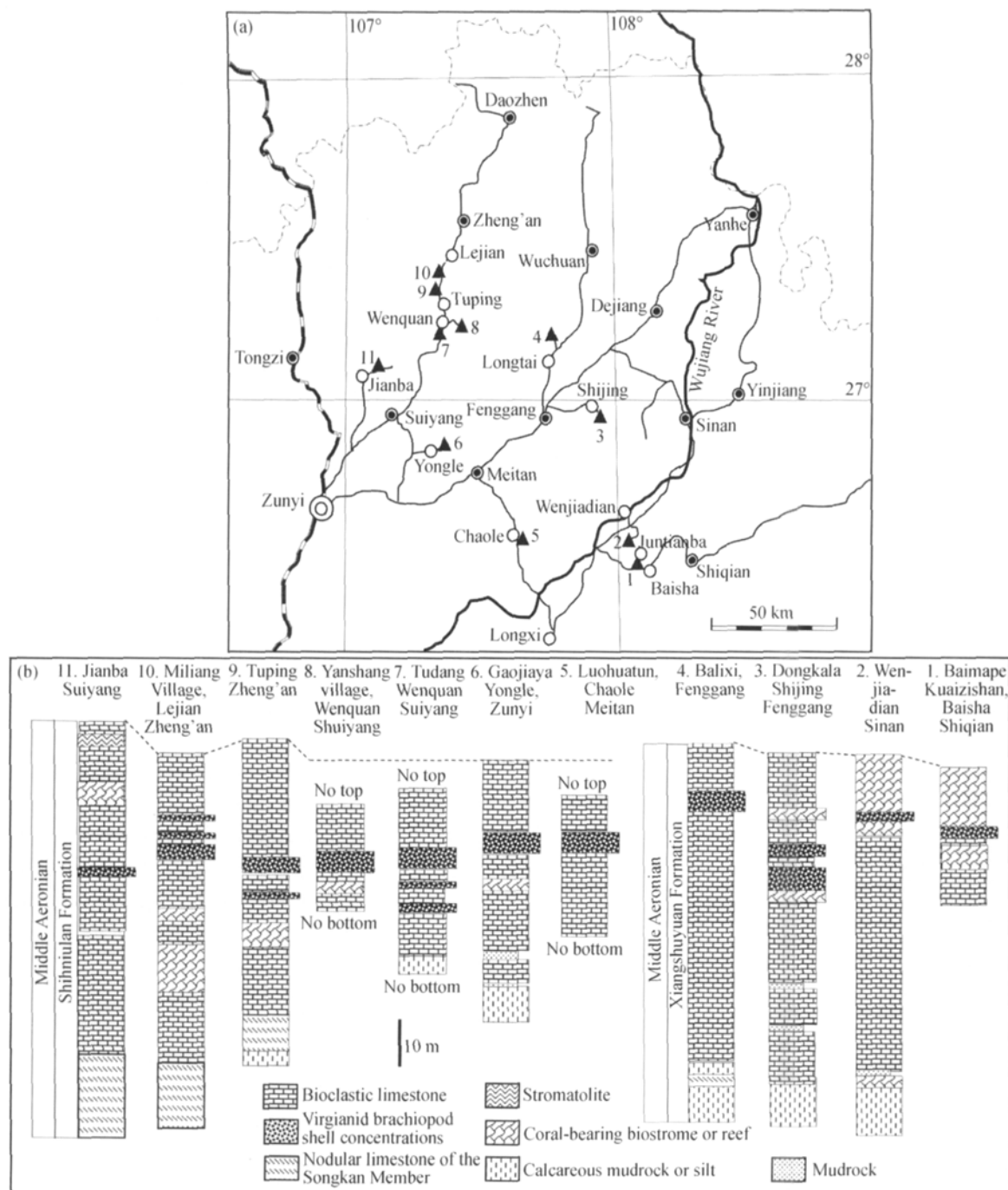


Figure 1 Temporal and spatial distribution of the Lower Silurian virgianid shelly units in northern Guizhou. (a) Localities of sections, their names coinciding with the logs of the sections (b); (b) sedimentary sequences, enlarging some very thin layers and thickness recorded in the text in detail.

nation by limestones. Due to the lack of some index fossils such as graptolites and conodonts, it is hard to date their ages precisely. We approximately assign them as mid Aeronian in age rather than their former placing in the Telychian^[8], based on the biota below and above (Figure 1). The shelly beds are widespread and correlatively stable in extension and medial in thickness. They

could be viewed as being equivalent in time and as a proxy of frequent storm occurrence in this region.

Ge et al. (Figure 5 on page 178)^[8] recorded “Baisha-type” with nine localities: Baisha and Juntianba, Shiqian; Wengxi, Sinan; Dongkala and Balixi, Fenggang; Xinlongchang and Songyan, Meitan; Wenquan, Suiyang; Tuping, Zheng’an. Rong and Yang^[9] supplemented three

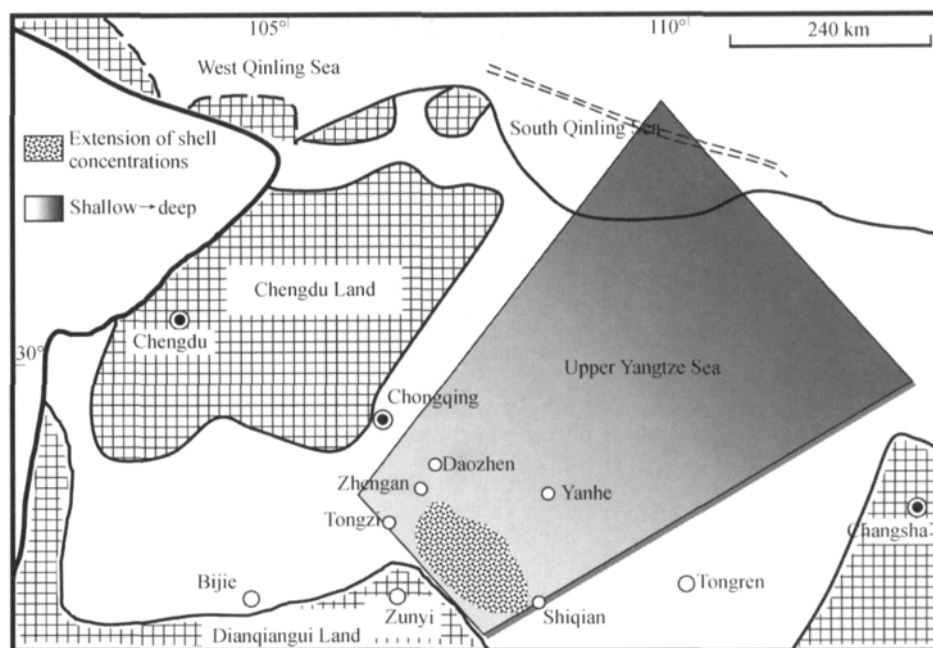


Figure 2 Middle Aeronian, Early Silurian Paleogeographic reconstruction map of southern Guizhou^[7] showing the background geography of the virgianid shelly beds. Grey trapezium interpreted intensification of storm action in the region of northern Guizhou.

localities: Shuitiangou, Baisha, Shiqian; Suiyangchang, Fenggang and Huangjiawuji, north of Zheng'an County Town. We reassess the database, exclude some localities that lack virgianid shelly beds, and add some new sites. Updated spatial distributions as well as sedimentary sequences are shown in Figure 1 with descriptions in east-westward and north-southward areas as follows.

(1) Baisha, Shiqian County (four localities). In the early 1970s, fieldwork by Rong and co-workers first discovered the virgianid shelly beds in the Upper Xiangshuyuan Formation in this area. Their thickness is 3.7 m (Juntianba, northern Baisha Town); 2.43 m (Baimapo) and 4.1 m (Shuitiangou), near Baisha Village. In fall of 1998, Li^[11] additionally found new locality, Kuaizishan, 300 m east of Baimapo with thickness of 2.5 m. Similar sedimentary sequences at dispersed localities circumbulate within several kilometers. The virgianid shelly beds are underlain by a biostrome composed of oncolites, stromatoporoids and corals, and overlain by a biostrome composed of massive corals.

(2) Wenjiadian, Sinan County. Regional Geological Survey of Guizhou recorded a 4.15 m-thick virgianid shelly sequence totally with denser shell concentration of 0.7 m. This bed is intercalated by a biostrome composed of rugose corals, which is underlain by bioclastic limestone with marls and overlain by low-relief reef or

biostrome with bitumen-bearing in cavities.

(3) Dongkala, Shijing, Fenggang County (at least two localities). About 3 km west of Shijing Town, Shihniulan Formation is well exposed between Dongkala Hydroelectric Station and Qingtan Bridge at both sides of the Liuchi River. In spring of 1998, Rong and co-workers measured the 4.21 m thick virgianid sequences of the lower layer, 0.34 m and 0.10 m thick combined upper layer from western roadside. Limestone, 6.5 m thick, is intercalated between the layers. 10 m and 25 m above the top of the virgianid bed horizons are of 0.36 m thick *Trimerella* (brachiopod) concentration and the basement of the unconformable overlying unit. In spring of 2005, Li measured the sequence of the Liuchi Riverside, 150 m east of Rong's section. The virgianid units are exposed in two layers but vary in ascending thicknesses of 3 m and 1.8 m respectively to those from western roadside section. However, shell densities are vertically variable within layers, and ten and four rhythmic layering can be further distinguished in the lower and upper layers respectively. Rare angular pebbles composed of long-stem crinoidal particles occur amongst the brachiopod shells (Figure 4(e)). Beds separating the two layers are 2 m thick silver grey micritic limestone with bird-eyes structures (Figure 4(d)). The basement of the virgianids is thin-medium bedded nodular bioclastic limestone

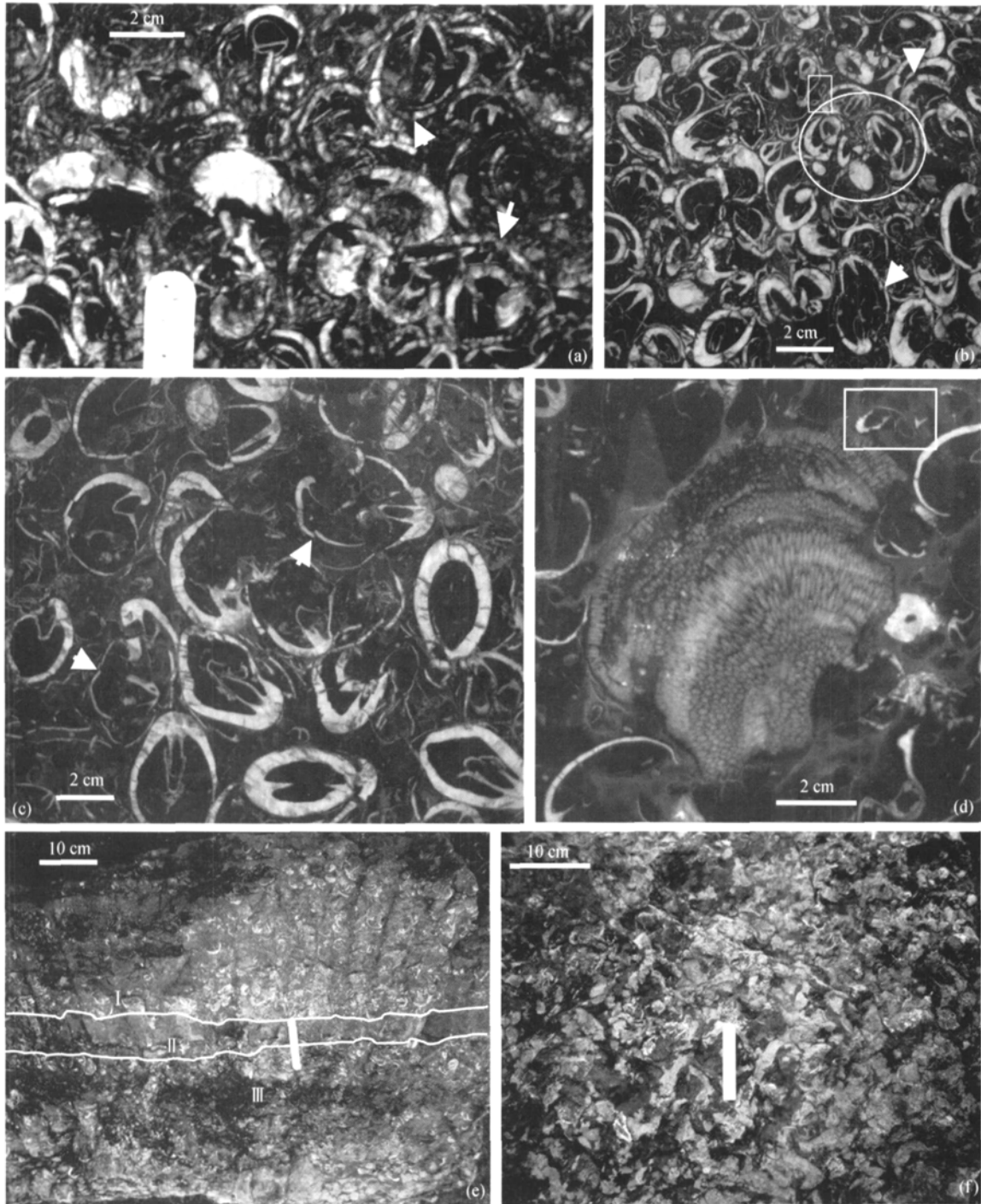


Figure 3 Lithological features of the two types of virgianid shelly beds from Gaojiaya, Yongle, Zunyi. (a)–(d) Photos taken from vertically-cut slabs. (a)–(c) Packstones, (d) wackestone. (a) Valves showing intensive breakage, dense stacking, thicker ventral crushed during compaction (arrow marks the crushed point, the same below). (b) Valve medial breakage, but gregarious occurrence, ventrals mostly preserved, smaller valves stacking into the cavities of bigger ones (circle marking), thinner dorsal valves occasionally preserved (square marking). (c) Valves lower breakage. (d) Well-preserved *Favosites* (massive tabulate coral) and lower breakage ventrals (including dorsal in square). (e) Two types of sedimentary rocks alternating in outcrop: I, III: packstones, higher density of valve; II: wackestone, lower density of valves. (f) *Thalassinoides* (trace fossil) in wackestone.

rich in corals (Figure 4(f)).

(4) Balixi, Fenggang County. According to Ge et al.^[12],

Silurian sequences are well exposed at Balixi, Longtai, along the roadside between Suiyangchang and Tuxi. 14 m

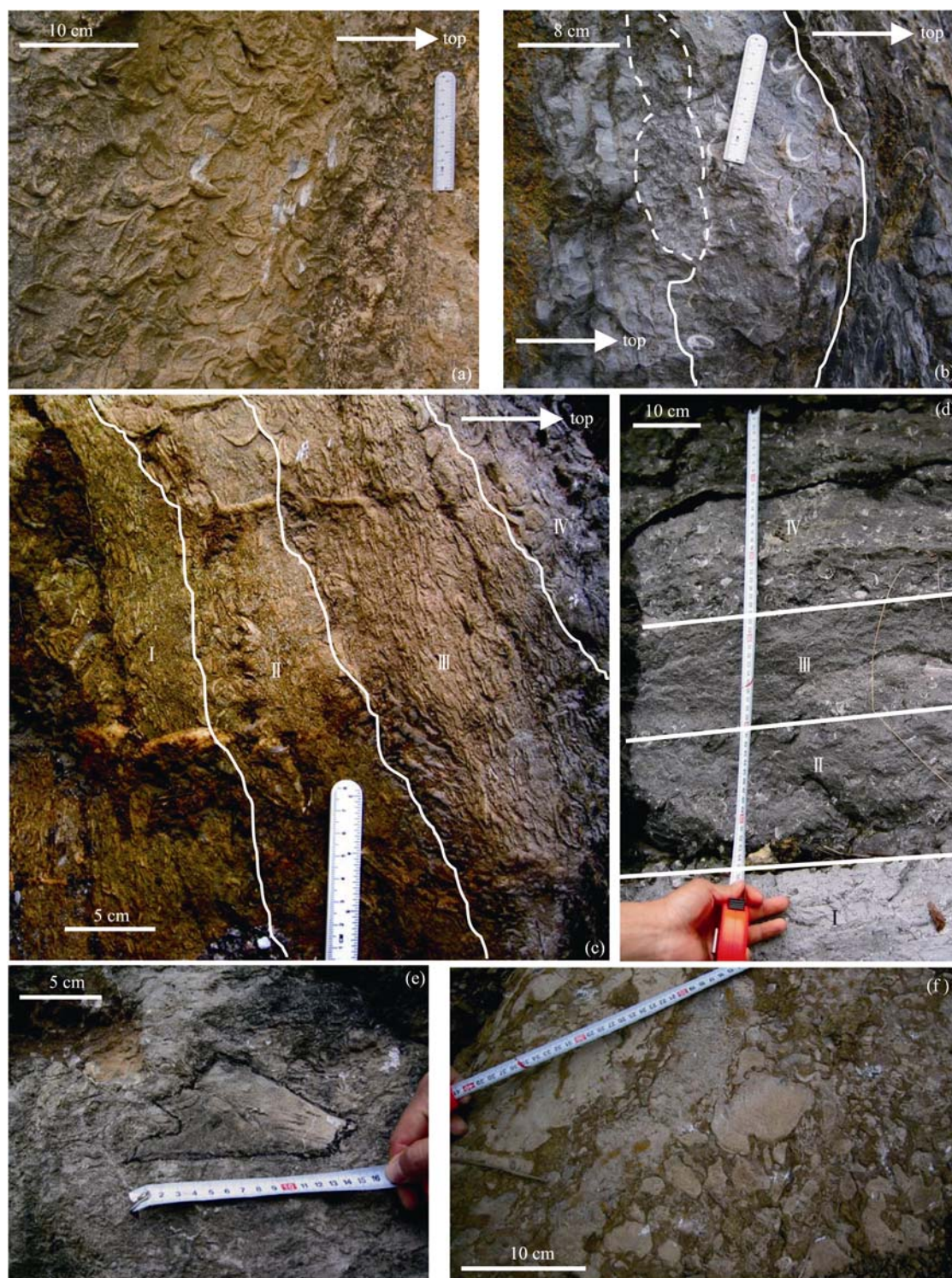


Figure 4 Sedimentary sequences of the shelly beds. (a) Ventral convexity mostly orientated downward (Guankou, Tuping, Zheng'an). (b) Shelly bed basement erosion, limestone conglomerate in grooves, marked by broken line, valves accumulation above (Guankou, Tuping, Zheng'an). (c) Breakage varying within a single packstone sequence: I, III: higher breakage; II, IV: medial breakage (Yanshang Village, Wuquan, Suiyang). (d) Shelly densities and breakages vary in the wackestones: I: limestone with bird-eyes structures in the upper shelly layer basement; II, IV: medial density and breakage of valves; III: millimeter-sized shelly particles and sparse in density (Dongkala, Shijing, Fenggang). (e) Angular pebbles composed of long-stem crinoidal particles (Dongkala, Shijing, Fenggang). (f) Biostrome composed of corals overlying a shelly bed (Dongkala, Shijing, Fenggang).

below the top of the Xiangshuyuan Formation is *Paraconchidium shiqianensis* shelly unit together with *Songkanoceras* (nautiloid), 4.2 m in thickness. Below the shelly beds, grey thin-bedded nodular micritic limestones composed of rich corals and brachiopods form biostromes. The latter is intercalated by less yellow shales and limestone lenses occasionally. Grey nodular micritic limestones with *Eospirifer* (brachiopod) overlie the shelly beds.

(5) Chaole, Xinglongchang, Meitan County. Shihniulan Formation crops out at an abandoned small quarry near Luohuatun Village, 1.5 km south of Chaole. The strata dip almost vertically. The base and top of the virgianid beds are recognized and measure 3.6 m in thickness. The shelly beds are overlain by thin-bedded micritic limestone with coral frameworks and trace fossils of *Cosmorhapha*.

(6) Yongle, Zunyi County. In spring of 1998, Rong and his colleagues paid attention to excellent slabs cut from virgianid shelly limestones in a building material manufactory at Tuanze, Zunyi, and got to know that the raw materials are from Gaojiaya, 4 km northeast of Yongle, eastern Zunyi. In fall of 2005, Li measured the shell concentration unit and found that it was 3.7 m thick totally. The unit is composed of 5–6 rhythmical units with alternations of the shelly density. Massive *Favosites* (tabulate corals) occur throughout the sequences, irrespective of the abundance of virgianid shells. However, *in situ* fasciculate rugose corals only occur in sparser shelly layers. The shelly beds are in conformable contact with the thin bedded bioclastic limestones from below and above the units.

(7) Tudang, Wenquan, Suiyang County. Two limbs of an anticline crop out on both the north and south borders of Wenquan Town. Three virgianid layers occur in the Upper Shihniulan Formation and exposed beside the milestone of 152 km of Provincial Road No. 207 in southern Wenquan Town; they are 0.35 m, 0.67 m and 1.36 m in thickness in ascending order, and intercalated by 0.7 m thick bafflestone composed of fasciculate corals from the lower and 0.13 m thick bioclastic limestone with sparse virgianid shells in the upper. Thus, total thickness of the unit is 3.39 m. Rocks underlying and overlying the shelly beds are bioclastic limestones yielding sparse crinoidal and coral fractions.

(8) Yanshang Village, Wequan, Suiyang County. Northern Wenquan Town is located on the north limb of

the anticline. An outcrop of a virgianid unit is 4 km away from Tudang section, and can be accessed along a path from the milestone of 150 km of Provincial Road No. 207. The strata dip almost vertically. The total thickness of the virgianid unit is 2.4 m. Brachiopod valves in some layers have been intensively broken and densely stacked (Figure 4(c)). Thick bedded bioclastic limestones rich in corals and stromatoporoids lie below, and medium-thick bedded nodular bioclastic limestones rich in crinoidal debris lie above, with the shelly beds being conformable.

(9) Tuping, Zheng'an County. Silurian strata have almost vertical dip at the roadside of Guankou, between milestone at 137–138 km of Provincial Road No. 207, and 3.5 km north of Tuping Town, Zheng'an County. Shelly beds in the upper Shihniulan Formation are abundant. Two layers of the shelly concentrations with individual thickness of 0.17 m and 1.3 m in ascending order are intercalated by 0.4 m thick bioclastic limestones and shales. Thickness of the coeval shelly units somewhat changes into 0.12 m and 1.53 m at the outcrop 150 m extending northward. Units below the shelly beds are thin-bedded muddy striped limestone with some breccia (Figure 4(b)). Thin bedded micritic limestones with shrinkage structures overlie the shelly beds.

(10) Miliang Village, Lejian, Zheng'an County. Shelly beds of the Upper Shihniulan Formation are well exposed on a steep slope, western side of the 127 km milestone of Provincial Road No. 207. Three shelly layers with thickness of 1.9 m, 0.22 m and 0.13 m respectively occur in ascending order, and separated by 0.6 m and 0.29 m thick dark micritic limestones. Brachiopod valves show medial breakage and high density. Medium-thin bedded dark grey or grey micritic limestones with sparse corals underlie and overlie the unit.

(11) Jianba, Suiyang County. Shelly bed of the Upper Shihniulan Formation is exposed on a cliff beside a path, 5 km north of Jianba Town, Suiyang County. One layer of the shelly concentration laterally changes to 0.13–0.2 m in thickness within meters extending. Virgianid shells are deposited as medial breakage and density. These beds are underlain by dark grey, thin bedded nodular micritic limestone and overlain by grey thin-medium bedded bioclastic limestone with sparse corals.

Database from 15 localities mentioned above indicate that the total thickness of virgianid shelly units in north-

ern Guizhou is mostly around 3–4 m. The thickest unit of 4.8 m is recognized from eastern Liuchi riverside, Shijing Town, Fenggang, Zheng'an. The spatial extension of the unit may be outlined as southeasternmost around the Baisha, Shiqian, westernmost in Jianba, Suiyang, and northernmost in Lejian. The southern margin of the distribution is approximately parallel to, or close to the northern coastline of the Qianzhong Land. Such a pattern shows that the extension of the virgianid shelly concentration unit is about 7500 km² within the shallow carbonate platform of the southern Upper Yangtze Epicontinental Sea.

2 Lithological features and index of the current energy

Almost all virgianid fossils are more or less preserved as broken and disarticulated valves^[9,10,13]. Slabs from the Upper Shihniulan Formation at Gaojiaya, Yongle, Zunyi clearly show diverse styles of the valve stacking. The limestone of shell concentration may be subdivided into two types lithologically according to the carbonate catalogues by Dunham^[14]: 1) packstone supported by fragments and filled by micrites; 2) wackestone supported by micrites and filled by fragments. Micritic components are very common in Silurian limestones possibly attributed to the micritization of cyanobacterial aragonites or long duration of the shelly degradation, but most micrites were probably deposited. Parts of micrites are possibly analogous to the peloids sourcing from the activities of worms. Recrystallized areas occurring locally within micritic matrixes may be a result of pressure solution between layers. Micrite production was presumably significant in the sequence. Two types of the shell concentrations varying in micritic components may occur individually (Figure 4(c)–(d)) or alternatively (Figure 3(e)). It indicates a variety of intensity of current energy during a process of shell accumulation.

2.1 Packstone

Packstones are composed of shelly fragments which vary in size. Thicker structures such as posterior and central parts of ventral walls as well as its attachments (e.g. spondylium) mostly remain. Thinner parts such as the anterior part of ventral walls and central to anterior parts of dorsal walls are fragile, with the latter being more intensive in fragmentation. Few fragments of brachial plates in dorsal valves remain (Figure 3(b), (d)).

Shell fragments accumulate in the cavities of ventral valves. Some valves even form dense stacks (Figure 3(b)). However, the degree of breakage varies from bed to bed even though they are consistent in grain-supported packstone (Figure 3(a)–(c)). Shelly concentrations in tempestites near Yanshang Village, Wenquan, Zheng'an are most intensively broken, and only the thickest part of ventral valve remains and even rounded (Figure 4(c)). It shows the highest current energy.

Most of the shells were impacted directly by high energy currents in a suspended condition before their final deposition on the sea floor. However, some fragmentations are possibly caused by swells on the sea floor or displaced by shear force during diagenesis as some displacements only occur between fragments of a same valve. Nevertheless, breakage of compaction is much lower in percentage (Figure 3(b)–(c)).

2.2 Wackestone

This type is characterized by a lower density of shell concentration with matrix of micrite and silty-sized shelly particles. Breakage of most valves is relatively low. Very few massive corals such as *Favosites* stayed in their *in situ* growth position on the micritic basement (Figure 3(d)). Even though the massive coral is more potential for anti-wave, higher micritic component and lower breakage of shell both indicate the decline of the current energy locally.

However, the shell density is not directly related to the degree of breakage. Shelly particles in some special wackestones are millimeters in size (Figure 4(d)). Nevertheless, packstone is an index of energy higher than that of wackestones obviously. Micrites deposited during lower current energy intervals, and some trace fossils such as *Thalassinoides* were thus formed (Figure 3(f)).

Lithological features between packstone and wackestone are gradational. It reveals stepwise alternation of current energy from layer to layer, and place to place. Moreover, shelly concentrations are poorly bedded although their densities are changeable vertically. Shells are equably dispersed.

3 Mechanism of the tempestite

Glaciations of the Gondwana Land during the latest Ordovician resulted in global sea-level drop^[15]. Warm climate triggered off sea level rise from the earliest Silurian^[16–18]. Sequences of the Xiangshuyuan and Shihniulan

lan formations mark a regional regression of the Aeronian time in northern Guizhou^[7]. The South China Block was approximately located around the lower latitude of about 15–30° of Southern Hemisphere^[19], and northern Guizhou was the southern part of the Yangtze Platform with palaeolatitude of about 20 degree, coinciding with the tropical-subtropical zones of the 20–30 degree where ocean hurricanes frequently happen in modern times. Reefs and biostromes rich in cyanobacteria, calcareous algae, corals and stromatoporoids are abundant in both formations. Thus, biotic evidence demonstrates that the northern Guizhou was formed in a tropical shallow marine regime^[19,20].

The Upper Yangtze Epicontinental Sea extended more than 1000 km east-westward and south-northward during Early Silurian^[7], and was surrounded by Chengdu Land from west, Dianqiangui Land from south and Cathaysian Land from east. Such a great bay setting reinforced the strength of water mass surging from the north open sea, therefore, water piling up strongly affected the depth where was inhabited by *P. shiqianensis* and *V. glabera* communities. The southwestern distribution margin of the fauna is only about 20 km away from the northern coastline of the Qianzhong Land. Combinative effect of cyclone and coastline profile reinforces the severity. Once gales sweep over the ocean surface, the strong power drives landward. Consequently, high energy current reconfigures sediments on shallow marine floor and transports the particles moving in a circular motion in response to waves passing overhead^[21]. Storm wave has density flow and draft flow, which move particles vertically and horizontally respectively. The sea-floor near Qianzhong Land inclined northward gently^[22], without steep slope. Hydrodynamic behavior was mainly of density flow. Tempestites in Baisha, Shiqian show that the distribution pattern of the shelly concentration is wide flat-style rather than narrow barrier-style.

Virgianid brachiopods possess relatively large shells without a pedicle. Its original dwelling style has the beak pointing downward, and umbo sinking into the micritic substrate. However, we have not found such a case in northern Guizhou. Its taphonomic catalogue is assigned to the “shelly tempestite bed” of Seilacher’s scheme^[23], a kind of necrolysis. Physical disruption completely reconfigured the primary burial style after natural death. All shells were passively suspended by surges, and crushed each other. Living shells were sud-

denly killed, and postmortem shells were winnowed and broken repeatedly. We have also found angular pebbles composed of nodular limestones from the basement of the shelly concentration at Guankou, Tuping, Zheng’an (Figure 4(b)). Some pebbles mixed with valves forming shell concentration at Dongkala, Shijing, Fenggang (Figure 4(e)). These cases indicate that the energy of some severe surges might have been big enough to erode the indurated rocks. Some surges even rounded the edges of the thick ventral shells in Yanshang Village, Wenquan, Suiyang (Figure 4(c)). Storm surges partly washed away the micrite sediments. Some thick but broken shelly remains were deposited again on the sea floor once the current action was weakened. Such a grading procession resulted in packstone forming due to a higher shelly remain.

The style of accumulation of the valves prefers the ventral convex downward in Guankou, Tuping, Zheng’an (Figure 4(a)), being quite different from the tempestite case in Carboniferous limestone from southwestern Scotland^[24]. Valves of the latter had been the convex downward to the substrates initially from suspended state. However, they were further disturbed repeatedly by currents on the sea floor and finally reformed into convex upward, which is the most stable style for stacking. The convex downward cases from northern Guizhou indicate that the shells possibly had been acted by the storms multiple times, but were not further overturned by lower energy currents of post-storm. Moreover, the depth of the virgianid shelly concentrations might range within a major storm base, deeper than the tidal belt. Repeated storms could not completely wash away all micrite and result in grainstone of spars cementation. Heavier shells were transported only for short distance. Therefore, most of the packstones with denser shelly concentration indicate that they are approximate tempestites. Their depositional sites are more compatible with the major wave base, in the centers of the storm action. The fact that no microbilitite growth and micritic envelopment can be found from valve walls suggests that storms were high in frequency and some relative quiescence durations were not long enough for the growth of cyanobacteria. Several thousand years duration was possible for several meters of shelly bed to form. It is very unlikely that such a thickness was formed by one storm event, it might have been formed by repeated storms. Several centimeters thick individual layer may represent hundreds of years,

and may have been also affected by repeated storms.

Most of the micrites and parts of shelly particles might be deposited in areas of reduced energy. Micrite might be deposited during the quiescence interval, or carried by lower energy currents from elsewhere. Reefs with anti-wave function occur approximately parallel to the coastline from the Upper Xiangshuyuan Formation. They have the potential to weaken the storm energy and promote micrite deposition and wackestone forming although the age of tempestites and reefs are not precisely correlated. Wackestones are more analogous to distal tempestite proxy. Wackestones from Dongkala, Shijing, Fenggang is somewhat special for its sandy-sized shelly particles in component (Figure 4(d)). They lack typical tidal environmental features such as cross bedding, therefore, we may exclude that they were formed in the tidal belt. Seaward resurges might transport finer shelly particles to deeper water, and deposit them together with more micrites. It is of more characteristics of distal tempestite sediment.

It is necessary to emphasize that Paleozoic rocks in northern Guizhou were considerably pinched tectonically. The shelly concentration extension on present map is obviously less than what it was in Silurian Period. When storms invaded landward, surges energy started decreasing from surf zone and the major wave base ascended. Nevertheless, surges impacted the depth of the BA3 (the depth less than 60 m), and could not reach to the base of BA4 (around 120 m). Energy of surge was further decreased from lower BA2 to upper BA3, the inhabitation depth of the virgianids. Maximum major wave base in modern oceans may be 200 m in depth, and compared to them, the Silurian reveals a much shallower surf zone. The wide and gentle slope of the Upper Yangtze Sea floor is interpreted as having gradually declined the current energy along the storm path; this procession resulted in an elevated major wave base. Two types of rocks, packstone as index of approximate tempestite and wackestone as index of distal tempestite, occur alternatively from one sequence in northern Guizhou. It suggests that the centers of the storms migrated from place to place, and were controlled by both changes of the seascape and coastline, although it is not possible at present to distinguish in detail here. Some bedding structures such as hummocky cross stratification which commonly occur in terrigenous sedimentary system in modern basin^[2] have not been found in the

carbonate facies of the present study.

Johnson^[25] estimated 2–3 years are the frequency of the storm in the shallow marine tempestite bed of the Rytteraker Formation, Llandovery in southern Norway based on the population age of the *Pentamerus* (brachiopod) and the sedimentary recycles of storm-no storm layers. It was assigned as “event concentration layer” according to the tempestite catalogue by Kidwell^[26,27]. However, the present virgianid case in northern Guizhou is more likely the “compound or multiple events concentrations” caused by repeated storm actions. The time duration of individual tempestite bed is possibly dozens of thousand years. Low diversity and virgianid-dominated associations were not transported for a long distance. Thus, dozens of thousand years for the accumulation of 3–5 m thick of the shelly productive are suggested herein.

Estimation of storm periodicity is another significant aspect of the study. If shells had not been agitated frequently by storms, they would have been maintained in their inhabitation positions and cemented with the micritic matrixes. If it was the case, it is more likely that later surges could crush rocks of the shelly beds into pebbles rather than agitated individual shells easily from sea floor. We have not found such a case in the study area. It is reasonable that the storm periodicity will be shorter than lithogenesis. Adult shells are most abundant in the rocks. Only a small number of organisms might survive the aftermath of the storm. Therefore, the virgianid community had grown in a relative quiescence interval on micritic basement before the storm attacking, and a considerable duration for the complete recovery of the community and their growth into adults and gregarious quantity was necessary. We can infer that the storm periodicity might be longer than this duration. Limited by the material, we can not provide an exact age curve leading to a precise calculation of community recovery interval. Strictly speaking, the terminology of the storm periodicity herein means the alternation of the higher storm frequency and relative calm marine condition during geological time rather than annual alternations of storm and quiescence in modern oceans.

Other brachiopod communities inhabited widely on the Upper Yangtze Epicontinental Sea during the Aeronian time. They also suffered from storms, and more kinds of shelly tempestite beds were formed. We have found shelly beds composed of high richness but mono-

species of *Pentamerus* (pentamerid) or *Trimerella* (trimerellid) from dark grey limestones of the Upper Shihniulan Formation in northern Guizhou and southern Sichuan, and of *Zygospiraella* (atrypid) from calcareous mudstones of the middle Xiangshuyuan Formation, northeastern Guizhou. Additionally, the case from the Shihniulan Formation in Tongzi, northern Guizhou illustrates that storm punctured immature stromatolites growth. It is reasonable that storm surges attacked different ecosystems spatially beside the virgianid community. Study of these subjects is beyond the present paper. Nevertheless, rigid constitution of the virgianid shells as well as other brachiopods or special building style of stromatolites are advantage to be idealized as a carrier of the event and utilizable for us to detect the storm saga in remote times. Evidence of storm events is hard to be preserved and recognized from communities to be too weak to stand a gust of wind.

4 Conclusions

(1) Virgianid shelly concentrations from the Aeronian “Baisha-type” of shallow marine limestones in northern Guizhou are significant markers of storms on the marine shelf. Near shoal belt of the southern margin of the wide Upper Yangtze Epicontinental Sea was the target of storm action. Virgianid shelly concentrations inhabited the depth of BA2-3 from 20–40 m and covered a regime of about 7500 km². Storms did frequently attack place and depth.

(2) Water piling up controlled by cyclone and profile of the coastline is the mechanism for the formation of

the virgianid shelly concentrations. Rich packstones indicate approximate tempestite which is in short-distance transportation of organic particles. By contrast, wackestones might be more favorable as indicators of distal tempestite, in which the particles were relatively moved farther away from the storm center or the energy was lower. The thickness of the two types is changeable, and shows vertically alternative in the sequences. Such facts suggest that the high frequency of the storms during Llandovery time attacked Upper Yangtze Sea especially northern seaward of the Qianzhong Land, but storm centers are changeable timely.

(3) The palaeogeographic setting of the shallow marine northward of the Qianzhong Land was very possibly close to the equator from Southern Hemisphere based on the biotic evidence of reefs composed of corals and stromatoporoids from the Xiangshuyuan Formation in northeastern Guizhou. Tropical storms rather than frigid zone hurricanes strongly influenced the region. The ecological niche of the virgianid shelly concentration indicates the maximum high-stand tract in Aeronian^[7]. The final regression accompanying essential lithological and ecosystem changes results in the disappearance of the virgianid fauna from northern Guizhou.

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