## **RESEARCH ARTICLE**

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# Increase of organic carbon burial response to mangrove expansion in the Nanliu River estuary, South China Sea



Tao Liu<sup>1,2</sup>, Shengfa Liu<sup>3,4\*</sup>, Bin Wu<sup>3</sup>, Huipeng Xu<sup>1</sup> and Hui Zhang<sup>3</sup>

### **Abstract**

Due to high productivity, periodic submersion, and rapid sedimentation rate, mangroves are important carbon sinks in tropical-subtropical coastal zones. Mangrove expansion can significantly enhance burial carbon storage in coastal zones and has been reported in many subtropical regions due to climate change in recent years. To better understand the response of carbon storage to climate change in subtropical-tropical coastal zones, it is necessary to estimate the change in burial organic carbon (OC) storage in mangroves undergoing expansion. In the Nanliu River estuary of South China, the total mangrove area has increased from 72 to 622 ha in recent decades. Based on a sedimentology study combined with historical satellite images analysis, the accumulation rate of burial OC in these mangroves is estimated to be 400-500 g·m<sup>-2</sup>·y<sup>-1</sup>, of which the part imported to the stratigraphy beneath the mangrove deposit layer is approximately  $130 \text{ g} \cdot \text{m}^{-2} \cdot \text{y}^{-1}$ . Globally, the reported OC accumulation rate is linearly correlated to the accretion rate in mangroves. The accumulation rate of mangrove burial OC estimated in this study is significantly higher than the corresponding value on this fitted curve, indicating that the OC accumulation rates may be underestimated in such mangroves because the OC imported to the lower root layer has been not been taken into account. Based on the estimated OC accumulation rate and the time-series data of the mangrove area, the increase in burial OC storage in the mangroves of the Nanliu River estuary from 1988 to 2018 is estimated at more than 35 Gq. This study provides an example of estimating soil OC storage increase in expanding mangroves, which can help us better understand the response of coastal carbon pool to climate change.

Keywords: Climate change, Mangrove, Accumulation rate, Organic carbon burial, South China Sea

### 1 Introduction

Mangrove sediment can sequester a large amount of organic carbon (OC) due to the high primary productivity, rapid accretion rate, and water-logged anaerobic soil environment of mangroves (Mcleod et al., 2011; Alongi, 2014; Jardine and Siikamäki, 2014). Although mangroves only cover 0.5% of the global coastal area, they account for 10–15% of coastal sediment OC storage (Donato et al., 2011; Ezcurra et al., 2016). The total mangrove area of the

world has decreased sharply in the past century mainly due to human-induced land-use change (Giri et al., 2011). However, in recent decades, mangroves in many subtropical regions are reported to have expanded due to climate change (Pérez et al., 2017; Saintilan et al., 2014a; Cavanaugh et al., 2014; Liu et al., 2017).

To estimate the increase in carbon storage by mangroves, the increase in burial OC storage due to mangrove expansion should be determined. In the Nanliu River estuary of South China, mangroves have replaced most of the salt marsh and have expanded into bare flat land due to increases in rainfall. This has resulted in a significant increase in the mangrove area from 73 ha in 1988 to 622 ha in 2018. The aim of this study is to determine the burial OC

<sup>&</sup>lt;sup>3</sup>Key Laboratory of Marine Geology and Metallogeny, First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China <sup>4</sup>Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China Full list of author information is available at the end of the article



<sup>\*</sup> Correspondence: liushengfa@fio.org.cn

accumulation rate and the increase in burial OC storage due to the expansion of mangroves in this area. Based on divisions of the sedimentary facies in two sediment cores, the amount of burial OC related to the presence of mangroves was calculated using the depth profile of OC density. Using the age of mangrove plants determined by historical satellite image analysis, the accumulation rate of burial OC in mangroves was calculated. Furthermore, using the OC accumulation rate and the time series of the mangrove area, the increase in burial OC storage from 1987 to 2018 was estimated. To estimate the storage of OC related to mangrove forests, it is necessary to identify the mangrove deposit layer in stratigraphy. By studying the OC content, sand content, and plant residual in sediment cores, three kinds of sedimentary facies can be identified.

## 2 Study area and methods

This study was conducted in the Nanliu River estuary along the northern coast of the South China Sea (Fig. 1). The study area is influenced by a subtropical monsoon climate. During the past 60 years, the average annual temperature was 22 °C and the average annual rainfall was approximately 1600 mm. With an average tidal range of 2.5 m, the diurnal tide dominates in this region. Large mangroves grow on the upper tidal flat of the river mouths. The vegetation mainly consists of *Aegiceras corniculatum*, with a small number of *Kandelia candel* as well as *Sonneratia apetala*. The plant height is in the range of 1–4 m. An increase in river discharge during this period is thought to have triggered the rapid expansion of mangroves, a significant expansion of mangroves in Nanliu River estuary during past decades could be found in Fig. 2.

In 2017, two sediment cores (100 cm in length and 5 cm in diameter) were collected from a mangrove forest off the mouth of the Nandongjiang River (a distributary of the Nanliu River). Core C3 was collected in a relatively older mangrove patch (~20–30 years) while core C7 was collected from a young mangrove patch of approximately 10 years (as inferred using satellite remote sensing images). The sediment cores were sectioned in 2 cm intervals. Then, once the fresh roots were removed, each subsection was analysed for dry bulk density, total organic carbon (TOC), and grain size in a laboratory.

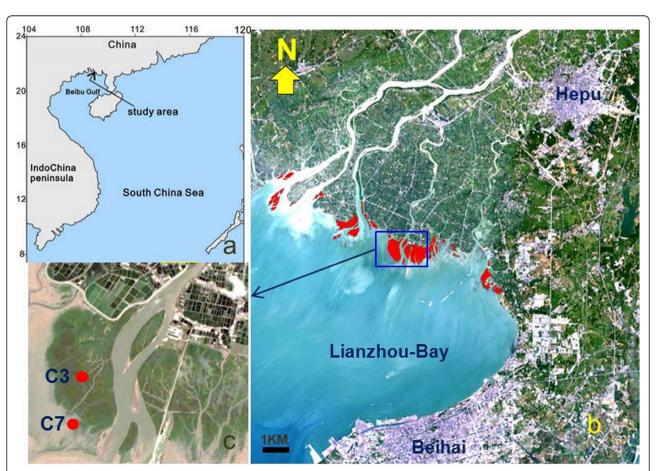


Fig. 1 Study area (a) and the spatial distribution of mangroves off Nanliu River mouth (b), mangroves are marked by the red area, the position of sediment cores is marked too (c)



Fig. 2 The significant expansion of mangroves in Nanliu River estuary during past decades

We utilised a mini ring-knife and a drying oven to determine the dry bulk densities. TOC was measured with a Shimadzu SSM-5000A organic carbon analyser. For sediment grain size analysis, we used a MasterSizer-3000 laser particle size analyser made by the Malvern Company. Firstly, calcareous clastic and organic matter were removed using 5% HCl and 10%  $\rm H_2O_2$  solution, respectively. Secondly, 6% (NaPO\_3)\_6 solution was added as a dispersing agent while the solution was stirred with a glass rod. Thirdly, the sample was added to the laser particle size meter for particle size measurement. Finally, the excess  $^{210}\rm Pb$  radioactivity of the sediment samples was detected by a  $\alpha$ -multichannel spectrometer in the State Key Lab of Lake Sciences of China.

#### 3 Results

### 3.1 Mangrove deposit layer identification in stratigraphy

In core C3, as the depth increased, deposits of mangrove, salt marsh, and bare flat sediment emerged in turn (Fig. 3). The mangrove deposit (0-22 cm layer) was characterised by high OC content (3-4%) and stable low sand content (approximately 20%). Residual mangrove litter can also be found in this layer. The salt marsh deposit (depth range 22-46 cm) was characterised by relatively high OC content (2-3%) and fluctuating sand content (15-40%). The residual of salt marsh plant petioles can also be found in this layer. The bare flat sediment deposit constitutes the layer below 46 cm and is characterised by low OC content (1-2%) and high sand content (40–60%). In core C7, collected in young mangroves which colonised bare flat sediment after 2005, the mangrove deposit layer directly overlays the bare flat deposit. Here, the bare flat deposit is only 10 cm in thickness.

## 3.2 Age of mangrove plants and accretion rate in mangroves

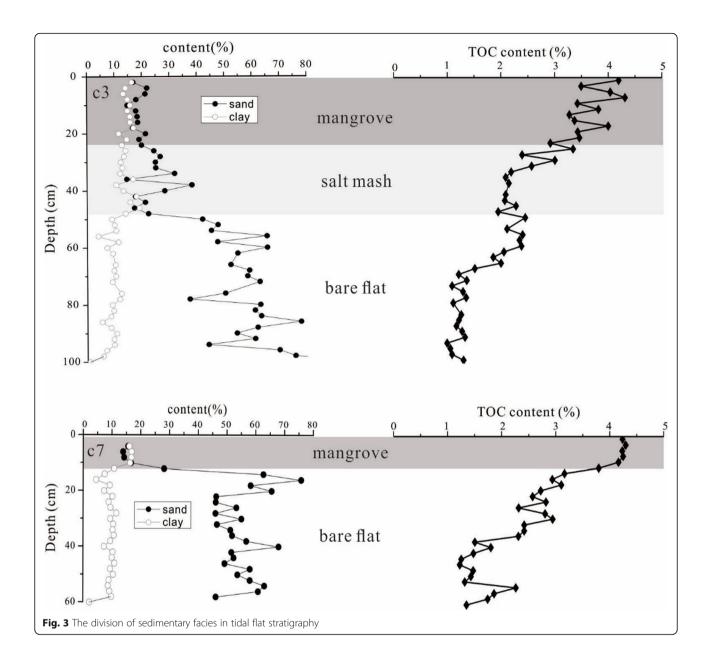
To estimate the accumulation rate of OC in mangroves, it is necessary to determine the age of the mangroves. In this study, we estimated the age of mangrove plants

based on historical satellite images (Fig. 4), according to which we can judge that the mangrove colonising the site where core C3 was taken ('C3 site') in 1992 or 1993. The mangrove plants at this site were approximately 24 years old in 2017. Given that the thickness of the mangrove deposit layer was 22 cm (Fig. 3), the accretion rate in the mangroves of this site is thus around 9 mm/a. Historical satellite images show that the C7 site was located just at the margin of the mangrove in 2005. At the end of 2009, the mangrove patch of this site was very clear, indicating the adjacent canopies have been in full touch. This needs more than 3 years in this area. The mangrove colonised there most likely during 2005-2007. The age of the mangrove plants at the C7 site was no more than 12 years in 2017. Given the thickness of the mangrove deposit layer at this site was 12 cm (Fig. 3), the accretion rate in the mangrove is therefore estimated at more than 10 mm/a.

In addition to the analysis based on historical satellite images, we also calculated the accretion rate using the excess Pb<sup>210</sup> radioactivity in core C3. As shown in Fig. 5, except for some abnormal data, excess Pb<sup>210</sup> radioactivity in the sediment declined exponentially with depth. Using the CS-CF modal, the accretion rate was calculated at 9.1 mm/a in the mangrove deposit layer and 11 mm/y in the salt marsh deposit layer. The mangrove is thus estimated to be 22 years old. The accretion rate of the mangrove deposit layer calculated by the Pb<sup>210</sup> method is almost the same as that determined using historical satellite images analysis, indicating the validity of historical satellite images analysis in estimating the age of young mangroves.

#### 3.3 Accumulation rate of burial OC in mangroves

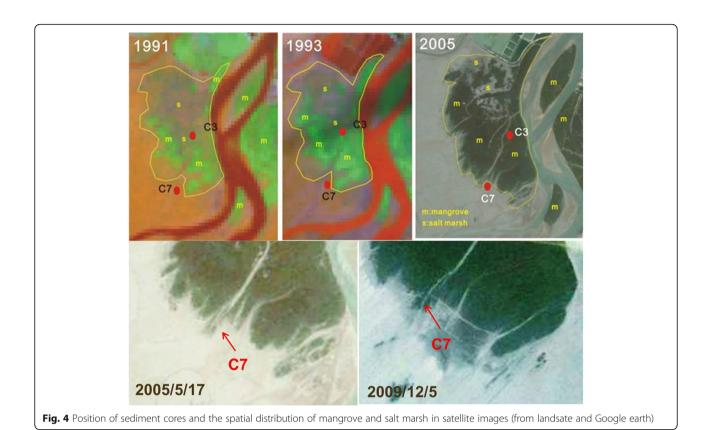
Based on the division of sedimentary facies, the amount of OC buried in the mangrove deposit layer and the OC imported to the lower layer can be respectively calculated. At the position of core C7, the burial OC stored in the mangrove deposit layer was calculated to be 4436 g

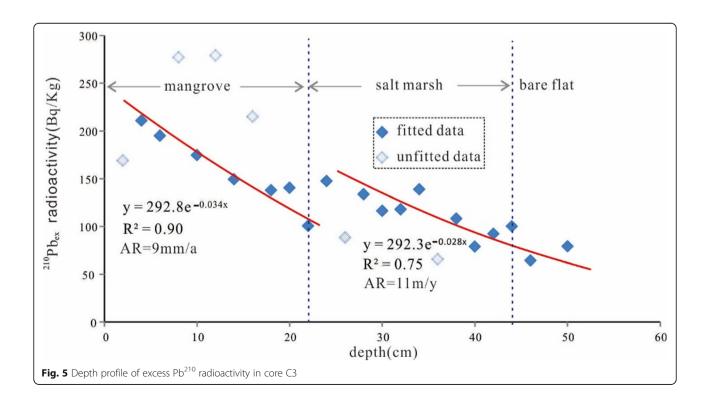


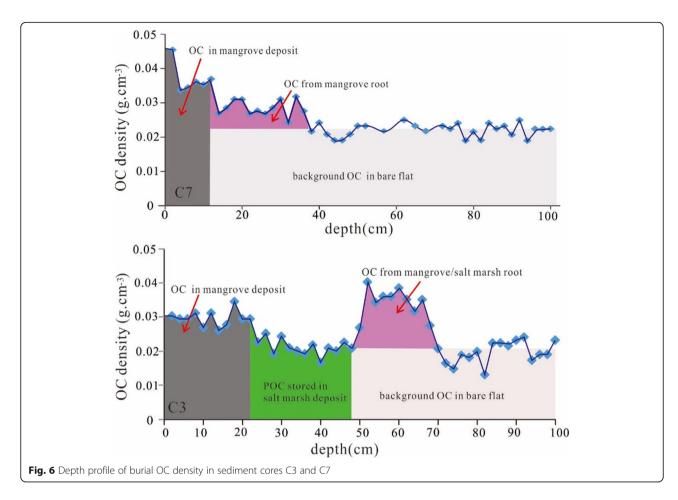
per square meter (Fig. 6a, Table 1). In the bare flat deposit layer below 40 cm, OC density is stable and was approximately  $0.022\,\mathrm{g\cdot cm^{-3}}$  on average. In the upper part of the bare flat deposit layer (12–40 cm), the OC imported by mangrove roots resulted in an abrupt increase in OC density. The amount of OC per square meter sourced from mangrove roots in this layer is thus determined by subtracting the background OC (5520 g) from the total OC (7074 g) and is approximately 1554 g. At this site, the total burial OC related to mangroves is thus 5990 g. Given that the mangrove age at this site was around 12 years at the time of core extraction, the total accumulation rate of burial OC related to mangroves is around  $500\,\mathrm{g\cdot m^{-2}\cdot y^{-1}}$ , in which the accumulation

rate of OC imported to the lower layer is estimated at  $130\,\mathrm{g}\cdot\mathrm{m}^{-2}\cdot\mathrm{y}^{-1}$ .

At the position of core C3, the amount of burial OC per square meter in the mangrove deposit layer is calculated to be 6498 g. The amount of OC storage by mangrove roots cannot be determined because of its mixing with the OC from the salt marsh (Fig. 6b). However, we can estimate the OC imported to the lower layer using the data of core C7. Given that the age of the mangrove at this site is around 24 years, the OC imported to the lower layer is estimated to be 3120 g·m². Using this data, the total OC related to mangroves and the total OC related to the salt marsh are determined as 9618 g·m² and 5655 g·m², respectively.







The accumulation rate of burial OC related to mangroves is thus estimated at  $400 \text{ g} \cdot \text{m}^{-2} \cdot \text{y}^{-1}$  (Fig. 7).

#### 3.4 Increase in burial OC storage in expanding mangroves

Using the estimated accumulation rate of burial OC in the mangrove and the time series of the mangroves of the Nanliu River estuary from 1988 to 2018, we estimated the variations of OC storage in the Nanliu River estuary during this period. As shown in Fig. 8, the increase in burial OC storage in each year was calculated by multiplying the burial OC accumulation rate with the mangrove area for that year. The time series of burial OC storage increment were then summed to determine the total increase in burial OC storage during this period. In this study, we used the accumulation rate of burial OC in core C3 (400 g·m<sup>-2</sup>·y<sup>-1</sup>) as a conservative estimate. Using this, the increase in burial OC storage in

the mangroves of the Nanliu River estuary over the past 30 years is estimated at approximately 35 Gg.

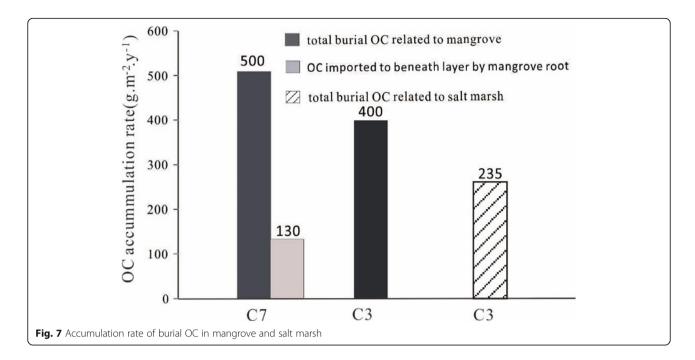
#### 4 Discussion

In the Nanliu River estuary, the accumulation rate of burial OC in mangroves ranged from  $400-500\,\mathrm{g\cdot m^{-2}\cdot y^{-1}}$ . The highest value was observed in a young mangrove with low substrate elevation, where the OC content in sediment was higher than in the older mangrove. This can be attributed to the lower decomposition rate of organic debris in the sediment combined with a higher sediment rate and longer inundation time (Alongi et al., 2005; Nguyen et al., 2004).

The accumulation rate of burial OC in mangroves is generally estimated by multiplying the OC content with the sediment accumulation rate in the mangrove deposit layer. The OC imported to the stratigraphy beneath the

**Table 1** Amount of burial OC (per square meter)related to mangrove and salt marsh

Position	OC stored in mangrove deposit layer	OC imported to beneath layer by mangrove root	Total OC related to mangrove	Total OC related to salt marsh
C7	4436 g	1554 g	5990 g	=
C3	6498 g	3120 g	9618 g	5655 g

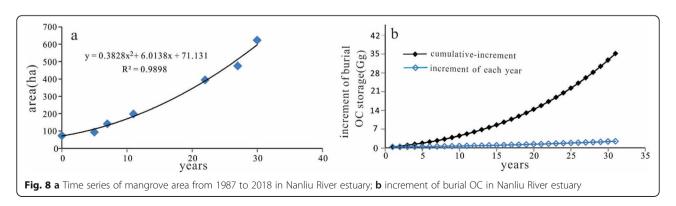


mangrove deposit layer may be neglected, especially when the sediment core is not long enough to cover the whole depth range of the mangrove root network. The results of this study suggest that in a young Aegiceras corniculatum forest, the accumulation rate of OC imported to the lower layer is around  $130\,\mathrm{g\cdot m^{-2}\cdot y^{-1}}$ , which was 26–32% of the total estimated OC accumulation rate. This evidence suggests that the burial OC accumulation rate in mangroves may be significantly underestimated if we neglect the OC imported to the lower layer.

According to published data gathered around the world, the relationships between the OC accumulation rate and the sediment accretion rate in mangroves can be well described by a linear law. This linear law is also valid for the data of this study if we neglect the OC imported to the stratigraphy beneath the mangrove deposit layer (Fig. 9). However, the total OC accumulation rate estimated in this study is significantly higher than this fitted curve, indicating that the OC accumulation

rate is likely to be undervalued in many mangroves around the world. On the other hand, in the regions where mangroves have replaced salt marsh, the lower salt marsh deposit layer can be mistaken for mangrove deposit. Given that the OC accumulation rate in the salt marsh is usually lower than that in the mangrove forest, the mangrove burial OC accumulation rate may be undervalued.

Due to climate change, mangroves have been expanding into salt marsh areas in many regions in recent years (Comeaux et al., 2012; Saintilan et al., 2014b; Liu et al., 2017). The increase of OC burial in such mangroves is considerable. Estimating the increase in burial carbon storage in mangroves undergoing expansion is an important scientific task that will allow for a better understanding of changes in coastal carbon storage. Traditionally, changes in burial OC storage in mangroves during a certain period may be estimated using the burial OC accumulation rate, mangrove patch area, and time span. This method may be valid for stable mangroves with a



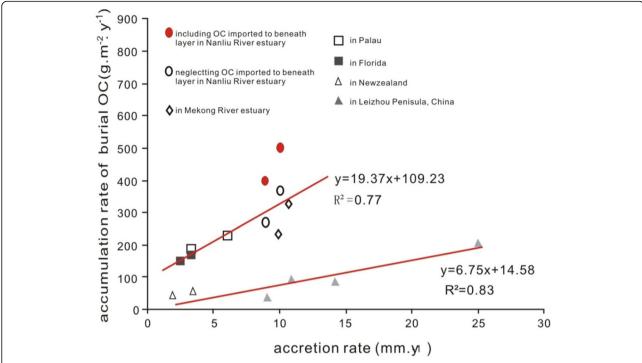


Fig. 9 The relation between accretion rate and OC accumulation rate in mangroves around the world (the data used here are revised from MacKenzie et al., 2016; Smoak et al., 2013; Pérez et al., 2017; Yang et al., 2014)

fixed area, but may not be valid for expanding mangroves. A new method must therefore be developed to solve this problem. In this study, we show an effective method for estimating the increase in the burial OC storage of mangroves undergoing expansion. Besides the accumulation rate of burial OC, this method requires the burial OC accumulation rate and the time series of the mangrove area. The increment of burial OC storage in the mangrove for each year is calculated by multiplying the OC accumulation rate with the mangrove area of that year. Then, the total increase in burial OC during this period is estimated by summing the time series of burial OC increment. Since plenty of satellite images have been taken during past decades, we can accurately establish the time series of mangrove area in a certain region. The regional increase of OC burial in mangroves thus can be obtained easily by this method. With global warming, mangrove expansion may take place in the regions of higher latitude. According to the process and rate of mangrove expanding in a similar environment, the future change of OC burial in coastal wetlands of a certain area also can be predicted by this method. This can help us in evaluating the response of coastal carbon pool to climate change.

#### **5 Conclusions**

(1) Based on the division of sedimentary facies from two sediment cores and estimates of mangrove age determined by historical satellite image analysis, the burial OC accumulation rates of mangroves in the Nanliu River estuary were estimated. The results show that the OC accumulation rate in these mangroves is approximately  $400-500\,\mathrm{g\cdot m^{-2}\cdot y^{-1}}$ , of which the OC imported to the lower layer of the mangrove roots is approximately  $130\,\mathrm{g\cdot m^{-2}\cdot y^{-1}}$ .

(2) Globally, reported burial OC accumulation rates in mangroves are well linearly correlated to the accretion rate. In this study, however, the total OC accumulation rates are significantly higher than the corresponding value on the fitted curve, indicating that the burial OC accumulation rates may be undervalued in these mangroves because the OC imported to the lower layer by mangrove roots has been neglected.

(3) Using an integrated method, we utilised the burial OC accumulation rate and the time series of the mangrove area from 1988 to 2018 to estimate the increase in burial OC storage in mangroves. By our estimate, burial OC storage by mangroves amounts to more than 35 Gg over this 30 year period.

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#### Authors' contributions

TL participated in the data analysis and research idea design and completed the main work of the paper. SFL conceived of the study and participated in its design and coordination. BW participated in the data analysis and drafted the manuscript. HPX participated in the sample analysis and drafted the

manuscript. HZ participated in the sample analysis and drafted the manuscript. All authors read and approved the final manuscript.

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#### Availability of data and materials

The dataset supporting the conclusions of this article can be found in the supplementary files.

#### Competing interests

The authors declare that they have no competing interests.

#### **Author details**

<sup>1</sup>School of Marine Sciences, Guangxi University, Nanning 530004, China. <sup>2</sup>Key Laboratory of Environment Change and Resources Use in Beibu Gulf, Ministry of Education, Guangxi Teachers Education University, Nanning 530004, China. <sup>3</sup>Key Laboratory of Marine Geology and Metallogeny, First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China. <sup>4</sup>Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China.

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