Dear editor:

We highly appreciate the opportunity for submitting a revised version of our manuscript. We are thankful for all the valuable comments and suggestions. Here, we submit a thoroughly revised version and marked-up version of our manuscript, which has been modified according to the reviewers' suggestions.

- *Efforts are made to check for English language and to correct typos. Co-author Dr. Dasgupta proofreads the manuscript.*
- *CT analysis and image analytical approaches, including contrast resetting (revised Fig. 3c), pixel values extraction (revised Fig. 3d), 3D reconstruction (revised Fig. 4), are used to play with the contrast of density change around the burrow. Comparison of integrated density around 113 burrows and undisturbed area are statistical analyzed with the function "polyfit" in MATLAB following reviewer's suggestion (revised Fig. 5). The functions of bioturbated zones and control zones are discrete with a statistical significance (with 95% confidence bounds).*
- *Micro-structure of nanofossils, elemental and isotopic evidences are discussed to explore the mechanism of carbonate lithification enhanced by bioturbation. Stable carbon isotope data of different portions of carbonate samples (revised table 1) are valuable to interpret the dissolution and recrystallization of carbonates. Schematic model for carbonate lithification influenced by bioturbation on the SWIR (revised Fig. 10) is highlighted and discussed to interpret the significance for their case.*

Below we have pasted in the entire review, and we have inserted our responses to the suggestions (blue font).

Sincerely,

Xiaotong Peng, on behalf of the co-authors.

Response to the comments by referee#1

RC1: This manuscript evaluates the impact of macrofaunal activity on the lithification of deepsea carbonates. This appears to be an interesting and previously not very thoroughly explored topic, and has the potential to advance our understanding of both the impact of bioturbation, as well as the controls on carbonate lithification. I especially appreciate the fact that this paper is very to the point, and not overly extended (although it does require some in depth discussion on some points, see below).

Reply: Thank you very much for your appreciation on the overall performance of the research work.

RC1: One immediate problem with the manuscript in its current form is the sometimes confusing writing style.

Reply: We take the utmost care to refine our English. In revised version, co-author Dr. Dasgupta proofread the manuscript.

RC1: Additionally, most of the discussion rests on speculation, rather than data, which undermines the value of this manuscript. I believe the authors should expand their observations, and especially include a thorough, quantitative assessment to elucidate the relative importance of bioturbation for carbon lithification.

Reply: Thank you for your comments on the discussion part. We have made efforts to improve the discussion basing on your suggestions. In revised manuscript, we first demonstrate the localized changes around burrow in several aspect in section 5.1. This part is based on the close inspection of hand specimens and CT images. Then, how these changes can enhance the carbonate lithification in deep-sea is discussed in section 5.2. Geochemical evidence indicating the diagenetic differences around the burrows are discussed thoroughly. Stable carbon isotope data are used as tracers to discuss the pathways of lithification influenced by bioturbation. It is assumed that faecal pellets may strongly depleted in ^{13}C in isotopic mass balance with the ^{13}C enrichment of the organism (Damste et al., 2002). Isotopic composition in gray excrements is lighter compared to the chalks. That means bioturbated organic particles like mucus will inherit enriched ^{13}C, which is the major carbon source for microbial metabolic reaction. Thus, the local elevated concentration of dissolved CO_2 in pore water trigger the dissolution of the original $CaCO_3$ phases and lead to the repreciptation of calcites as cements with higher ^{13}C in carbonate rocks.

Major specific comments:

RC1: Language: While this is not the case for the manuscript as a whole, there are a lot of parts which suffer from bad spelling and grammar (see the technical corrections for specific examples, that list is not exhaustive). Before this manuscript can be accepted, it should be thoroughly revised for language.

Reply: Thank you very much for your reminding in English language and specific corrections. We have deeply checked for English language.

RC1: Interpretation of the figures: I have some difficulties with following the interpretation of the images presented in Fig. 2 and 3. On P7L6-7 you state that it is difficult to know the real depth of each burrow. How exactly do you then go from the pictures in Fig.2a-d to the burrow shapes in Fig. 2e? How do you know they are J-shaped, and not just U-shaped, but broken off? Did you do this by eye, or did you use a cast, or scanning techniques?

Reply: We have included detailed interpretations and comparisons of burrow shape in the revised paper version.

The depth and shape of burrow are summarized form close inspection of CT images. With the help of CT analysis, we can classify burrows in straight branched or J- and U-shaped (Fig S1). If the J-shaped burrow is mistaken by broken U-shaped, it can be showed by the symmetrical difference of density distribution. The evidence that no density change symmetrically (Fig S1c and d, Yellow arrow), make it classified as J-shaped burrow. Based on the CT images, we give the sketch for different burrow structures in Fig. 2e.

CT images are helpful to peer inside the carbonates. For one burrow in different CT slides, the slides with longest burrow size is taken to estimate the burrow length.

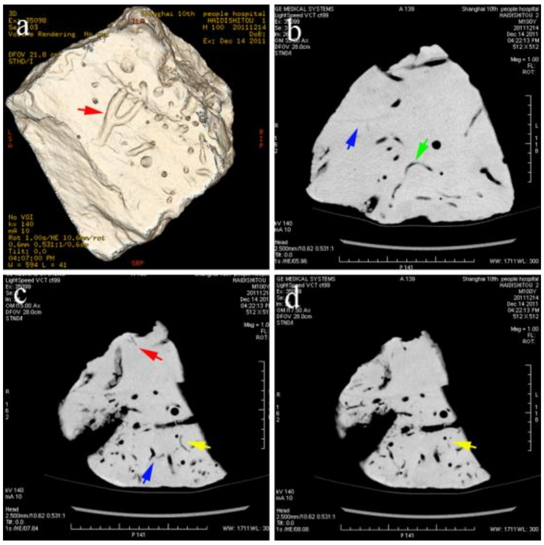

Figure S1 CT images of carbonate samples. b, c and d are different CT scanning slides of same carbonate rock. The slice thickness between c and d is 2.5 mm

Arrows in different colors represent different shape of burrows. Red -- Y-shaped, blue -- branched, yellow -- J-shaped and Green -- U-shaped.

RC1: Please expand the same remark for Fig. 3, you state (P5L22-23) that 'the most readily observable feature is the localized enhancement of density around the boring'. I have looked at the images, and even with the arrows, I have a lot of difficulties finding these enhancements. Since most of your discussion rests on these observations, I think you should expand and more clearly explain on what this statement is based. You might want to consider playing with the contrast, or other visual techniques, to make these features more clear (cause now I cannot see them).

Reply: Thanks for your advice. We agree that other visual techniques are required to make *the contrast more clear. In the revised manuscript version, we have used multiple image analytical approaches to make these features more clear. In Fig.3, we pick the pixel values of the CT image to contrast the changes of density around burrows. It is showed by the line scan profile that pixel values around the bioturbated area are higher than the matrix (Fig 3d). This evidence supports the localized enhancement of density around burrows. In Fig. 4, 3D reconstruction of the sample by CT analysis shows more visible density contrast (Fig 4c).*

RC1: Additionally, you need to expand on the statistics used to generate the linear correlations in Fig. 5.

Reply: Data used for comparison come from the gray values of CT images. In the revised manuscript, function of "polyfit" in MATLAB, which is suggested by anonymous Referee #2, is used to estimate the difference between bioturbated area and the control with 95% confidence intervals. (Fig. 5). Function "polyfit" returns a polynomial p(area) that is best fit for the data of integrated density. With 95% confidence bounds, the functions of bioturbated area and control are discrete with a statistical significance.

RC1: Discussion: I believe the biggest problem with this manuscript is the lack of data, and a quantitative discussion. I am supportive of the authors efforts, and I do believe that bioturbation could play a role in carbonate lithification. However, to make this case based on a few images, without any quantitative discussion, seems a bit of a short- cut. The authors should expand on these observations, and give a better mechanistic explanation on how bioturbation would enhance lithification, and include a thorough quantitative assessment of the relative importance of this process.

Reply: Thank you very much for your comments. In revised manuscript, we take the comparison of density change from CT images by line scanning of pixel values. Area near the burrow always show higher pixel value than area away far from the burrow (Fig 3d). The evidence that enhanced density near the burrow supports our deduction that carbonate lithification is enhanced by bioturbation. What's more, enhanced lithification is also supported by micro-structure of nanofossil. In addition, geochemical records including elemental and stable isotopic results indicate the lithification influenced by bioturbation. Organic matter re-distribution by bioturbation acceleration the microbial oxidation around the burrow.

Minor specific comments:

RC1: The authors use 'boring' throughout the manuscript when they discuss the burrowing of macrofaunal organisms. This is rather confusing, as in my experience, it is more common to use 'burrowing' and 'burrow(s)'. I would suggest to change this throughout the manuscript to improve readability

Reply: We highly appreciate the term names clarification, and understand that is preferable avoid any confusing terminology. In revised manuscript, "boring" are replaced by "burrow".

RC1: Additionally, I had to google the word 'endolith'. While it is correctly used, I again would suggest to avoid the use of this word, and use the more common 'macrofaunal', 'benthic fauna' or others, to improve readability

Reply: It has been changed. The revised title is "Macrofauna bioturbation Enhance the Deep-sea Carbonate Lithification on the Southwest Indian Ridge". "Endolith" used in the manuscript are also changed.

RC1: Results: at the start of the results (P5L3) it is immediately stated that the macrofaunal burrows were lined with ferromanganese crusts. While this assumption is used aplenty throughout the manuscript (see for example Fig. 7), you do not provide evidence that these are indeed ferromanganese crusts. Please justify this assumption (or say it is just an assumption, but then explain why).

Reply: They are named basing on the elemental composition. In revised manuscript, "Mn- and Fe-oxide precipitates" are used instead of "Ferromanganese crusts" because that "Mn- and Fe-oxide precipitates" is a better term to describe our samples.

Elemental composition of Mn- and Fe-oxide precipitates by SEM-EDS

Element	C	O	Na	Mg	Al	Si	Cl	Ca	Mn	Fe	Total
Wt %	3.9	19.44	0.93	3.19	1.95	2.63	2.13	42.64	18.89	4.31	100

Elemental composition of chalk by SEM-EDS

Element	C	O	Mg	Al	Si	Ca	Total
Wt %	3.81	19.5	1.49	1.47	2.14	71.59	100

RC1: P6L21-25: a lot of discussion about Sr, but it is not shown? Table 1 is too long to be readable. I would suggest to make this a supplementary table, and take out the most important trends and plot those in a figure.

Reply: The change was done accordingly. It is visible to plot the important trend (e.g. Sr/Ca) in a figure and show elemental data in a supplementary table.

RC1: P6L33: how exactly does bioleaching deplete the isotopic value?

Reply: Stable isotope values of carbonate rock reflect a mixture of calcareous biogenic debris which is equilibrium with sea water during the growth of organisms and the alteration of diagenetic fluid. One of mechanism that bioturbation can enhance the carbonate lithification is the microbial oxidation of organic matter increasing the pore-water CO_2 concentration. Microbial metabolic reaction usually leads to enrichment of biospheric carbon in ^{12}C. Thus, the dissolution and reprecipitation of carbonate influenced by bioturbation could enrich in heavy carbon in the interior of carbonate. Meanwhile, light carbon enriched in newly burrowing portion like the gray excrements. This has been further discussed in revised manuscript.

RC1: P7L15-16: why do these carbonate deposits form a favourable environment? What is special about them?

Reply: Sorry for misleading. This sentence has been deleted.

RC1: P7L5-11: I cannot follow the reasoning behind this estimation. You cannot find the real depth of the burrows, but assume 6 cm, with is the median value. How do you get a median value if you cannot determine the real burrow depth? How do you get to 12 holes per 1dm2 surface? Should you not compare volume to volume? Please be more explicit.

Reply: Sorry for the confusion. We want to estimate the volume of burrows occupied in carbonate samples. So a comparison of volume to volume is used. Although real depth of burrow is hardly to measure, we can make the estimation from the CT image. CT images are helpful to peer inside the carbonates. For one burrow in different CT slides, the slides with longest size is taken to estimate the burrow depth. At the same time, the density of burrow is also enumerable from the CT images.

Technical corrections:

RC1: - P1L11: 'macrofaunal inhabitants' -> not correct, better: 'benthic macrofauna'

Reply: Thanks for your correction. We have checked through the manuscript.

RC1: - P1L15-16: 'Our study reports an unfamiliar phenomenon : : : and interested by the : : :' -> this sentence is very vague, and also wrong (what is interested?), please rephrase

Reply: Thanks for your reminding. It has been rephrased.
"Here, we report the lithification of deep-sea carbonate associated with macrofaunal burrowing."

RC1: - P1L16-17: 'These carbonate rocks may : : :' -> it is not the carbonate rocks that provide a mechanism, please rephrase: : :

Reply: It has been rephrased.
"Macrofaunal burrowing provides a novel driving force for deep-sea carbonate lithification at the seafloor, illuminating the geological and biological importance of deep-sea carbonate rocks on global mid-ocean ridges."

RC1: - P1L29: 'remains' -> remain

Reply: Thanks for your correction.

RC1: - P2L10: 'Burrowing and boring' -> I believe these are synonyms 'because it enhances'-> because they enhance

Reply: The sentence has been rephrased.
"Benthic fauna drilling into the substrate play a critical role in sediment evolution."

RC1: - P2L13: 'organismic burrowing and boring' -> same remark as above, and organismic can be removed

Reply: Thanks for your correction.

RC1: - P21L21: 'between the bioturbation' -> 'between bioturbation'

Reply: Thanks for your correction.

RC1: - P2L30: 'it has been well proved' -> it has been well proven 'bursting' -> what does this sentence mean? Biogenic bloom was bursting?

Reply: The sentence has been rephrased.
"It has been widely reported that primary productivity increased substantially at the Indian Ocean during the Latest Miocene–Early Pliocene."

RC1: - P2L32-P3L2: I understand the sentence, but he is not constructed correctly : : :

Reply: The sentence has been rephrased.
"This phenomenon known as "biogenic bloom" promoted significantly high quantities of carbonates deposit at the seafloor between 9 to 3.5Ma."

RC1: - P5L9: 'herald' -> indicate

Reply: Thanks for your correction.

RC1: - P5L10-11. What does this sentence mean?

Reply: We have rephrased in a comprehensible way.
"Burrows can be classified in three categories."

RC1: - P5L14-16: the message you are trying to convey is unclear, please rephrase

Reply: The sentence has been rephrased.
"It has been suggested that Mn- and Fe-oxide precipitates grow at very slow rate of 1-10mm/Ma. Coating of black Mn- and Fe-oxide precipitates on the surface of the latter two burrows indicate that they may form much earlier than other burrows."

RC1: - P5L31 'quart' -> quartz?

Reply: Thanks for your correction.

RC1: - P6L13-15: sentence does not make much sense

Reply: The sentence has been rephrased.
"It is common to observe the accretionary overgrowth of calcite around the foraminifera test form SEM image (Fig. 6c). Dissolution of the coccolith plates is evident both on the surface of the thin black Mn- and Fe-oxide precipitates and in the interior of carbonate rocks (Fig 6e)."

RC1: - P6L17: ‘dipartite evolutionary of diagenesis’ -> what does this mean?

Reply: This sentence has been rephrased.
“Smooth surfaces of the coccoliths in gray excrements reveal that dissolution commonly occurs influenced by bioleaching of benthic fauna (Fig 6f).”

RC1: - P6L21-25: ‘character’ -> characteristic, ‘is highly variable of Sr’ -> is the highly variable Sr, ‘different portion of’ -> different portions of, ‘mainly accounted for the substitution’ -> mainly caused by substitution ‘recrystallization, resulting in’ -> recrystallization results in ‘The loss of’ -> the decrease of ‘could also a response’ -> could also be a response

Reply: Thanks for your correction. This paragraph has been carefully revised.
“Three types of samples (chalk, gray excrements and thin black Mn- and Fe-oxide precipitates) exhibit similar elemental concentration patterns for high CaO content, reflecting the strong dilution effect of biogenic calcium. One of the main characteristics of major and rare elements is the highly variable Sr concentrations in different portions of the carbonate. The storage of Sr on seafloor is mainly caused by substitution of Ca in calcium carbonate while the diagenetic recrystallization results in the decrease of Sr from the sediment (Plank and Langmuir, 1998; Qing and Veizer, 1994). The lower of Sr/Ca in chalk compared to the gray excrements could also be a response to the lithification of carbonate (Fig 7). Although biogenic calcium diluted the detrital REE fraction, it made little direct contribution to bulk REE concentrations (Xiong et al., 2012). REE patterns of the three types of sample do not exhibit any hydrothermal anomalies, e.g. positive Eu anomaly, but inherit the characteristics of sea water by enrichment of HREE compared with LREE and negative Ce anomaly (except the Mn- and Fe-oxide) (Fig. 8). The influence of nearby hydrothermal system and other detrital input to the studied carbonate area should be negligible during the lithification history.”

RC1: - P6L31: statement needs a reference (‘typical values for biogenic carbonates’)

Reply: A classical references was added.

RC1: - P7L12 ‘several boring purposes are served for the benthic animals’ -> does not make any sense, benthic fauna form burrows for certain purposes.

Reply: Thanks for your reminding. It has been rephrased.
“Benthic fauna form burrows for certain purposes of gaseous exchange, food transport, gamete transport, transport of environmental stimuli, and removal of metabolites.”

RC1: - P8L1-2: ‘Alternatively, bacteria and organic detritus are considered to the major source of benthic fauna in deep-sea’ -> this sentence means that benthic fauna originates from bacteria and organic detritus. While this is possibly true from an evolutionary perspective, I do not think this is what you want to say here : :

Reply: Sorry for misleading. It has been corrected.
“Alternatively, bacterial metabolites and organic detritus are considered to the major source of food for benthic fanua in deep-sea environment which is limited by availability of organic

matter."

. Response to the comments by referee#2

RC2: The manuscript titled "Endolithic Boring Enhance the Deep-sea Carbonate Lithification on the Southwest Indian Ridge" details observations and analyses of deep-sea carbonate samples that appear to be experiencing enhanced lithification associated with benthic faunal burrowing. The study employs computed X-ray tomography, visual and microscope observation, and geochemistry to evaluate the relationships between burrowing and the degree of carbonate lithification. The main conclusion is that burrowing is likely an important process accelerating carbonate lithification in the deep-sea. The findings are intriguing and certainly of interest to a wide readership.

Reply: We are very thankful to the anonymous reviewer for constructive feedbacks and insightful comments on our manuscript.

RC2: My main reservations about this manuscript are twofold: (1) it is not immediately clear in some CT-scan images that there are density contrasts (enhanced lithification) surrounding the burrows (Figure 4).

Reply: We agree that the CT images in earlier version of this manuscript need improvement. In order to make the density contrasts clearly, we pick the pixel values of the CT image to contrast the change of density around burrow. It is showed by the line scan profiles that pixel values around the bioturbated area is higher than matrix indicating the localized enhancement of density around burrows (Fig 3d). 3D reconstruction of the sample by CT analysis also has been added in revised manuscript (Fig 4b). It can conclude that the enhancement of density around the burrows is consistent with the halo defined by the sediment being lighter in color (Fig 4a, c).

RC2: (2) it is not clear based on the data treatment that there is true statistical significance in the difference in density between bioturbated zones and control zones (Figure 5). See specific comments on these below. If the authors can address the above major points then I can see this manuscript being of interest to a wide readership. I agree with the authors that burrowing-enhanced lithification would appear to be an important process if it can extrapolated to deep-sea carbonates world-wide.

Reply: Thanks very much for your advisable suggestions to promote the quality of data treatment. In revised paper, function "polyfit" in MATLAB as you advised is used to generate the polynomial p(area) that is a best fit for the data for integrated density (with 95% confidence bounds). The functions of bioturbated zones and control zones are discrete with a statistical significance (Fig 5).
Data used for comparison come from the gray values of CT images. In Fig. 3d, an example of the density change around the burrow is showed by line scanning. When comes to the Fig 5, whose data are generated from 113 burrows, the statistical results support our conclusion that macrofaunal burrowing enhance the deep-sea carbonate lithification on the Southwest Indian

Ridge.

RC2: While the English is already commendable for authors for whom English might be a second language, and it is possible to follow what the authors are saying throughout the manuscript, there remain minor issues with English throughout the manuscript. This should be easily fixed with a careful proofread by a native speaker.I would consider the revisions required to address the general comments above and specific comments below to be major - significant blocks of text should be revised and additional statistical treatment should be applied to the dataset.

Reply: Thank you very much for your reminding in English language. In revised version, co-author Dr. Dasgupta proofread the manuscript.

Specific Comments

RC2: Abstract, line 9: I'm not sure that one can say that lithification of deep-sea carbonates is a "mystery"; there is a respectable body of literature on lithification mechanisms and rates dating back over three decades. Perhaps better would be something like "the role of deep-sea macrofauna in their lithification remain poorly understood".

Reply: The sentence has been revised.
"The role of deep-sea macrofauna in carbonate lithification remains poorly understood."

RC2: Abstract, line 12: "in the sample" makes it read as if there was only a single hand sample, when it appears that grab buckets provided multiple samples. This occurs elsewhere in the manuscript as well.

Reply: Thanks for reminding. It has been modified and we have checked the whole manuscript to avoid this mistake.

RC2: Abstract line 16: "interested by" doesn't make much sense - please re-phrase.

Reply: The sentence has been deleted.

RC2: Abstract, last sentence: these results don't really speak to the importance of deep-sea carbonate sediments, simply the mechanisms of their formation. Please re-phrase.

Reply: The sentence has been revised.
"Macrofaunal burrowing provides a novel driving force for deep-sea carbonate lithification at the seafloor, illuminating the geological and biological importance of deep-sea carbonate rocks on global mid-ocean ridges."

RC2: Main text in general: while I find that the text is written in a clear and straightforwards manner, there remain minor grammatical errors throughout. If english is the authors' second language, then they should be commended - this manuscript already reads decently well. Nonetheless, further editing by a native english speaker is necessary to wrap up the grammatical loose ends that are apparent throughout the manuscript.

Reply: whole manuscript has been deeply checked for English language.

RC2: Page 2, line 24: it might offend researchers in diverse fields to say that the entire Indian Ocean is "poorly understood".

Reply: Thanks for the comment. This sentence has been deleted.

RC2: Page 2, line 30-34: grammatical issues, please re-phrase.

Reply: It has been modified.
"This phenomenon known as "biogenic bloom" promoted significantly high quantities of carbonates deposit at the seafloor between 9 to 3.5Ma (Gupta et al., 2004; Dickens and Owen, 1999)."

RC2: Materials and Methods: certain phrases in the methods have been reproduced wordfor-word from previous work. For example, page 4, lines 12 through 14 - these identical lines are also found in Li et al. (2014). Even if the same methodology was used for both studies, it would be prudent to re-word the text in the methods.

Reply: The text has been re-phrased.
"Small fragments of the dried samples were fixed onto aluminum stubs with two-way adherent tabs, and allowed to dry overnight. They were sputter coated with gold for 2-3 minutes before being examined on a Philips XL-30 scanning electron microscope equipped with an accelerating voltage of 15kV at the State Key Laboratory of Marine Geology, Tongji University." The elemental composition of selected spots was determined by energy dispersive X-ray (EDX) analysis on the SEM with an accelerating voltage of 20 kV.

RC2: Page 4, line 21: there should be no "elution" step in this technique. Also line 22, how was precision evaluated? Repeat measurements of standards? Finally, how were these measurements standardized - using multi-element solutions or by measurement of geostandards? The methods are not sufficiently detailed here.

Reply: Sorry for my mistake. There is no "elution" step.
Analytical precision was monitored using the Chinese national carbonate standard, GBW04405. Conversion of measurements to the Vienna Peedee Belemnite (PDB) scale was performed using NBS-19 and NBS-18.

RC2: From page 5 onwards: these are not ferromangense crusts in the strict sense of the word. Perhaps "Mn- and Fe-oxide precipitates" is a better term.

Reply: thanks for your advice. It has been changed.

RC2: Page 5, line 10: I suggest re-phrasing this sentence.

Reply: This sentence has been re-phrased.

"Burrows can be classified in three categories."

RC2: Page 6, line 16-17: I suggest re-phrasing.

Reply: This sentence has been re-phrased.
"Smooth surfaces of the coccoliths in gray excrements reveal that dissolution commonly occurs influenced by bioleaching of benthic fauna (Fig 6f)."

RC2: Page 6, line 24–25: you can't lose a ratio (but you can lower it).

Reply: Thanks for reminding. It has been corrected.

RC2: Page 7 line 1: I suggest re-phrasing.

Reply: This sentence has been re-phrased.
"Positive correlation of δ^{13}CPDB andδ^{18}OPDB values of chalk and gray excrements (r = 0.91) reveals minor environmental influence on early lithification (Fig. 8) and bioturbation should be a critical factor during the lithification."

RC2: Discussion in general: it would be nice if the authors could elaborate on why a decrease in carbonate saturation state (leading to dissolution) promotes lithification (as opposed to an increase in carbonate saturation state leading to precipitation).

Reply: Thanks for your comments. Cementation after dissolution of biogenic debris is of the important process of carbonate lithification. We have made efforts to explain the dissolution and reprecipitation of calcite to cement in revised manuscript. The dissolution of carbonate in the ocean is primarily controlled by the degree of pore water undersaturation with respect to the biogenic carbonate phase. Bioturbation can redistribute the organic matter around the burrow. Thus, oxidation of organic matter will accelerate the concentration of pore water CO_2 leading to the undersaturation of calcites.
Furthermore, thin Mn- and Fe oxide precipitates prevent the rapid ion exchange between bottom water and pore water within carbonate rocks because larger grain surfaces and porosity of fine-grained poorly sorted carbonate oozes compared to Mn- and Fe oxide precipitates. The products of $CaCO_3$ dissolution may trend to diffuse toward to the interior of carbonate rocks, and lead to an enhanced CO_3^{2-} ion gradient in pore water profile and ultimately promoting the reprecipitation of calcites as cements around the burrows in carbonate rocks.

RC2: Also, while aerobic respiration decreases the local carbonate saturation state, sulfate reduction will increase it. Can the authors include a statement about oxygen penetration and the depth of sulfate reduction (even if it is simply based on the findings of others in similar settings)?

Reply: Thanks for your valuable comment.
We cannot exclude the potential that sulfate reduction have happened in studied samples. This can be illustrated for the present study by examining the observed variations in ion

content of the pore water.
However, carbonate samples here were collected by TV-grabs bucket. It is too difficult to take the measurement of pore water chemistry. Several literatures support our discussion that pore-water CO_2 by oxidation of organic matter is responsible for the carbonate dissolution. (Broecker and Peng 1982; Jahnke et al. 1994; Noé et al. 2006; Croizé et al. 2013). Metabolic activity may disintegration of organic material causing dissolution of carbonate and increasing the degree of supersaturation. In the condition that bioturbation processes succeed in redistribution of organic matter around the burrow, concentration of CO_2 in pore water could increase. Although we could not elaborate the influence of sulfate reduction, aerobic respiration is reasonable to the decrease of carbonate saturation state.

RC2: Figure 1 Legend: The legend indicates that the red triangle is an inactive hydrothermal field while the caption indicates that it is active - this contradiction needs to be resolved. Also at the end it should read "red circle".

Reply: It has been corrected. The red circle is active hydrothermal field and the red triangle indicates inactive fields.

RC2: Figure 2e should have a scale bar.

Reply: The scale bar has been added.

RC2: Figure 4b: Contrary to the caption, it is difficult to see any enhanced of density in this image. Figure 4c and d: what do the different arrows represent? In a related vein, for Figures 4 b, c, and d in general - the areas of higher density are not obvious at all. Perhaps circle them or find some better way of highlighting these areas? Also could another presentation method be employed (e.g., an additional panel with contrast adjustments to better show the differences, perhaps shown alongside an un-modified version of the same figure for traceability)?

Reply: Thanks for your advice.
Both Fig. 3 and Fig. 4 have been changed. We pick the pixel values of the CT image to contrast the changes of density around burrows. It is showed by the line scan profiles that pixel values around the bioturbated area is higher than matrix indicating the localized enhancement of density around burrows.

Figure 5: This is not a statistical analysis in the sense that it does not provide any measure of confidence in the comparison between the two slopes (e.g. whether they can be considered different with 95% confidence). For this you would need to use something like the function "polyfit" in MATLAB (for example). No statistical evidence is presented that these slopes are indeed different... this is a major point as the paper hinges on the importance of burrowing effects.

Reply: Thanks very much for your valuable suggestions. The figure has been revised. Difference can be showed with the function "polyfit" with 95% confidence intervals.

RC2: Figure 8: As a Kiel carbonate device was used, these are not "bulk" C isotope measurements, but C_carb measurements (same for oxygen isotopes). That is to say, organic matter in the sample is not measured during the analyses when a Kiel carbonate device is used, only carbonate - this should be clarified.

Reply: Sorry for the mistake. It has been corrected.

Macrofaunal burrowing~~Endolithic Boring~~ Enhance~~ the~~ Deep-sea Carbonate Lithification on the Southwest Indian Ridge

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Abstract. Deep-sea carbonates represent an important type of sedimentary rock due to their effect on the composition of upper oceanic crust and their contribution to deep-sea geochemical cycles. However, roles of deep-sea macrofauna in carbonate lithification remain poorly understood~~the lithification of deep-sea carbonates at the seafloor has remained a mystery for many years~~. A large lithified carbonate area, characterized by thriving benthic faunas and tremendous amounts of ~~endolithic borings~~burrows, was discovered in 2008, blanketed on the seafloor of ultraslow spreading Southwest Indian Ridge (SWIR). ~~Macrofaunal~~ Benthic inhabitants including echinoids, polychaetes, gastropods, as well as crustaceans, are abundant in carbonates~~the sample~~. The ~~most readily apparent feature of the sample is the localized enhancement of density around the borings.~~burrowing features within these carbonate rocks, and factors that may influence deep-sea carbonate lithification, were reported. ~~The bBoring~~We suggest that burrowing~~ features of~~ in these carbonate rocks~~ and factors that may~~ enhance deep-sea carbonate lithification~~ are reported~~. We ~~suggest~~ propose that active ~~boring~~ bioturbation may trigger the dissolution of the original calcite and thus accelerate deep-sea carbonate lithification on mid-ocean ridges.~~ Our study reports an uncommon unfamiliar phenomenon of that bioturbation enhance non-burial carbonate lithification and interested by the observation that it is often associated with boring featureon in deep-sea. These carbonate rocks~~~~Endolithic boring~~ Macrofaunal burrowing ~~may~~ provides a novel ~~mechanism~~ driving force for deep-sea carbonate lithification at the ~~deep-sea~~ seafloor~~, which and also~~ illuminates the geological and biological importance of deep-sea carbonate rocks on global mid-ocean ridges.

1 Introduction

Carbonate rocks and sediments~~ formed~~ of various types have been discovered on~~ various~~ mid-ocean ridges through dredging or drilling (Thompson et al., 1968; De et al., 1985; Cooke et al., 2004). These carbonates, which are important elements of the upper oceanic crust, cover approximately half of the area of the entire ocean floor. As such, they may influence the composition of oceanic crust and alter the geochemical balance between the total amounts of calcium, magnesium, and carbon in oceanic waters (Holligan and Robertson, 1996; Rae et al., 2011; Yu et al., 2014; Anderson et al., 1976).

Most carbonates in ~~the~~ the deep sea ~~is~~ are biogenic in origin and may involve diagenetic products that originate~~s~~ from calcareous biogenic debris. ~~Porosity l~~Loss of porosity with increasing age and burial depth is associated with the transformation of deep-sea calcareous ooze to chalk, and subsequently to limestone~~s~~ (Flügel, 2004). Nevertheless, ~~the~~ processes involved in the formation of deep-sea carbonate rocks remains controversial. It has commonly been assumed that deep-sea carbonate lithification is driven by various processes, including gravitational compaction ~~and~~, pressure dissolution, and reprecipitation that takes place during burial (Croizé et al., 2013). Local dissolution and reprecipitation of biogenic calcite or aragonite from foraminifera, nanofossils, and pteropod oozes may serve to transform the original sediments to chalk or limestone (Schlanger and Douglas, 1974). These explanations, however, cannot completely explain the facts that (i) the degree of burial is commonly inconsistent with the known burial depth and paleontological age (Schmoker and Halley, 1982), and (ii) lithified carbonate rocks found on the seafloor commonly show no evidence of ~~ever being buried~~burial (Thompson et al., 1968). Lithification of deep-sea carbonate~~s~~s has also been associated with the ~~submarine~~ breakdown of oceanic basalts or prolonged exposure to the chemical gradients at the sediment-water interface (Pimm et al., 1971; Bernoulli et al., 1978). ~~Nevertheless~~However, the processes responsible for such seafloor lithification remain ~~open to debate~~debatable.

~~Burrowing and boring organisms~~Benthic fauna drilling into the substrate play a critical role in sediment evolution, because of ~~it~~ enhanced~~s~~ interactions between sediments, ~~the~~ interstitial water~~s~~ and overlying water, by changing the geochemical gradients in the sediment, restructuring bacterial communities, and influencing the physical characteristics of the sediments (Lohrer et al., 2004; Meysman et al., 2006; Barsanti et al., 2011; Lalonde et al., 2010). Although ~~organismic~~ burrowing ~~and boring~~ has already been recognized as a factor that may influence $CaCO_3$ sediment profiles (Emerson and Bender, 1981; Aller, 1982; Emerson et al., 1985; Green et al., 1992), and may promote carbonate dissolution in coastal sediments (Gerino et al., 1998), little is known about the ~~relationship between boring and bioturbation~~lithification effects ~~in~~ of semi-lithified and lithified carbonate rocks in deep sea settings.

~~This study is based on n~~Non-burial ~~chalk~~ carbonate samples ~~that~~ were collected in 2008 near a newly discovered hydrothermal vent on Southwest Indian Ridge (SWIR) during the DY115-20 cruise of R/V Dayang Yihao, which was conducted by the China Ocean Mineral Resource R&D Association (COMRA) (Fig. 1). These carbonate ~~deposits~~rocks, which ~~are~~ were associated with a thriving benthic biota, are characterized by numerous macrofaunal burrows~~endolithic borings~~. ~~This~~ In this research, we attempted to explore the ~~mystery of the~~unique non-burial carbonate lithification in the deep-sea and to highlight the interactions that take place between ~~the~~ bioturbation and lithification on the mid-ocean ridge.

2. Geological Setting

~~The Indian Ocean includes an important but poorly understood part of the global meridional ocean.~~ The Southwest Indian Ridge (SWIR), which is the major boundary between the Antarctic Plate and the African Plate, and characterized by its ultraslow and oblique expansion, is one of the slowest-spreading ridges (1.4-1.6 cm/yr) in the global ocean ridge system (Dick et al., 2003). Three main ridge sections of eastern part of the SWIR are divided by the Gallieni Transform Fault (GTF) and the Melville Transform Fault (MTF) (Cannat et al., 1999). In 2008, a large lithified carbonate area, approximately 15 km long and 150 km wide ~~in~~ at ~~water~~ 2000 to 2500 m water de~~e~~pths, was found on segment 26 of the SWIR, near a newly discovered hydrothermal field (Fig. 1). It has been ~~well proved~~ widely reported that primary productivity increased substantially at ~~thriving biogenic bloom through the~~the Indian Ocean ~~were bursting~~ during the Latest Miocene–Early Pliocene ~~by ODP sediment sequences~~ (Arumugm et al., 2014; Gupta et al., 2004; Rai and Singh, 2001; Singh et al., 2012). This phenomenon ~~coined~~known as ~~“~~“biogenic bloom~~’’~~” ~~The bloom lead to~~promoted significantly ~~higher carbonate mass accumulation rates than present day between 9.0 to 3.5 Ma and promote the~~ high quantities of carbonate~~s~~ deposits at the seafloor between 9 to 3.5Ma (Gupta et al., 2004; Dickens and Owen, 1999).

3. Material and Methods

3.1 Sampling

The deep-sea carbonate samples were collected in 2008 by TV-grabs bucket operated from the R/V Da Yang Yi Hao. The survey sites covered an area of approximately 15 km long and 150 km wide. When carbonate samples were spread on the deck, benthic organisms were usually evident among the fractured rocks. Samples were subsampled after recovery, and then stored at -20°C in plastic bags for mineralogical and geochemical analysis. Subsamples for molecular phylogenetic analysis ~~, that~~ were kept in dry ice frozen and transported to the laboratory.~~, were described by Li et al. (2014).~~

3.2 Computerized X-ray tomography (CT)

Quantitative measurement of the significance of biological influence is difficult because the physico-chemical properties around ~~boring~~burrow walls are dynamic. Computerized X-ray tomography is a non-destructive method that has been used ~~in~~ to measure various rock properties (e.g., bulk density, porosity, macropore size), by determining the numerical value of the X-ray attenuation coefficient. For relatively homogeneous marine sediments, this coefficient is expressed as Hounsfield units (HU), which is correlated with sample density (Michaud et al., 2003). In this study, computerized X-ray tomography measurements were performed using a GE Light Speed VCT instrument ~~that is~~ located in the Shanghai 10th People Hospital, Tongji University. CT images were computerized by reconstruction of the distribution function of the linear attenuation coefficient, each with a 64-slice system with 64 × 0.625 mm detector banks and a z-axis coverage of 40 mm. The slice thickness was~~is~~ 2.5 mm and the accuracy of distance measurements in the x and y-planes ~~is~~ was 0.2 mm. The instrument ~~operates~~ operated at 140 kV, with a 10 mA current, and 1.5 s exposure.

CT images were further characterized by *Image J*, which ~~is~~ was a public domain Java-based image processing program. Gray values, which correlated with the attenuation values and HU, were extracted to make a comparing description of the density changes of the carbonate sample~~s~~. 40 CT images were selected, and each gray value inverted using min = 0 and max = 255, regardless of the data values; that ~~i~~was, the theoretical integrated density value without the carbonate sample will be close to zero. The calibration function was used to calibrate whole images to a set of density standards before extracting. After all images selected were calibrated, the integrated density of the rock around the ~~boring~~burrows ~~can~~ could be calculated from the gray values. For this study, the gray values of the 10 pixels (approximately 0.3 cm, compared to the diameters of ~~boring~~burrows are approximately 0.9 cm) around the ~~boring~~burrow holes were measured. Additionally, randomly selected areas away from~~around~~ the ~~boring~~burrows were selected as ~~control~~ controls. Function of “polyfit" in MATLAB was used to interpret the difference between two data sets with 95% confidence bounds.

3. 3 X-ray diffraction (XRD)

Small pieces of the samples, which were freeze-dried under vacuum conditions to avoid oxidation during drying, were thoroughly ground using a pestle and mortar to produce a fine-grained, uniform powder. These powders were analysed using a D/max2550VB3+/PC X-ray diffractometer (Rigaku Corporation) at 40 kV and 30 mA, which is housed at the State Key Laboratory of Marine Geology at Tongji University.

3. 4 Scanning electron microscope (SEM)

~~Small fragments of the dried samples were fixed onto aluminum stubs with two-way adherent tabs, and allowed to dry overnight. They were then sputter coated with gold for 2-3 minutes. All samples were examined with a Philips XL-30 scanning electron microscope that is equipped with an EDAX energy dispersive X-ray spectrometer and analytical software at the State Key Laboratory of Marine Geology, Tongji University and Department of Earth and Atmospheric Sciences, University of Alberta. Energy dispersive X-ray spectroscopy (EDS) was mainly qualitative because of the irregular surface topography of the samples. The SEM was operated at 15 kV with a working distance of 10 mm to provide optimum imaging and minimize charging and sample damage. For the X-ray analysis, an accelerating voltage of 20 kV was used in order to obtain sufficient X-ray counts.~~Small fragments of the dried samples were fixed onto aluminum stubs with two-way adherent tabs, and allowed to dry overnight. They were sputter coated with gold for 2-3 minutes before being examined on a Philips XL-30 scanning electron microscope equipped with an accelerating voltage of 15kV at the State Key Laboratory of Marine Geology, Tongji University. The elemental composition of selected spots was determined by energy dispersive X-ray (EDX) analysis on the SEM with an accelerating voltage of 20 kV.

3.5 Element and isotope analysis

After fusion of 0.1 g of sample material with 3.6 g of dilithium tetraborate at 1050 °C for ca. 16 min, major elements were measured using X-ray fluorescence Shimadzu XRF-1800 spectrometer at 40 kV and 95 mA that is located at Shanghai University. The trace element and rare earth element (REE) compositions of the samples were determined by inductively coupled plasma-mass spectrometry (ICP-MS) using a Thermo VG-X7 mass spectrometer at the State Key Laboratory of Marine Geology, Tongji University. ~~The s~~Samples for these analyses were dissolved using a solution of HNO_3 + HF on a hot plate. The eluted sample was then diluted with 2% HNO_3. The analytical precision and accuracy, monitored by geostandard

GSD9 and sample duplicates, ~~The precision of the sample duplicates, as well as of the repeated analyses, was~~were better than 5%.

Stable oxygen and carbon isotope ratios of bulk samples were measured using a Finnigan MAT252 isotope ratio mass spectrometer equipped with a Kiel III carbonate device at the State Key Laboratory of Marine Geology, Tongji University. Bulk samples were oven-dried at 60°C. Analytical precision was monitored using the Chinese national carbonate standard, GBW04405. Conversion of measurements to the Vienna Peedee Belemnite (PDB) scale was performed using NBS-19 and NBS-18.

4. Results

4.1 Macroscopic observations

The carbonate rocks retrieved from the SWIR we~~a~~re characterized by complex honeycombed structures~~ and the~~, with Mn- and Fe-oxides ~~ferromanganese crusts~~ commonly encrusting the surface and inner surface of carbonate rocks (Fig. 2). Benthic~~Macrofaunal~~ inhabitants, including echinoids, polychaetes, gastropods, and crustaceans, which are usually recognized as successful ~~boring~~burrowing classes in marine sediments (Kristensen and Kostka, 2013), wer~~ar~~e abundant in ~~the~~ hand specimens (Fig. 2c, d).~~carbonate sample with~~ Burrows drilled by benthic fauna showed from CT scanning images are in straight, branched, or J- and U-shaped, with density up to 12 per dm^2 (Fig. S1). ~~its density up to 12 per dm^2 (Fig. 2).~~ ~~Boring holes drilled by benthic fanua~~fauna~~, in straight, branched, or J- and U-shaped (Fig. 2e)~~ Burrows commonly penetrate 6 to 10 cm into the rock with several ~~millimeters~~millimetres to 2 cm in diameter~~, commonly penetrate 6 to 10 cm into the samples~~. The area that surrounds the hole is usually brighter than that away from the ~~boring~~burrow, which may ~~herald~~ indicate a different degree of lithification (Fig. 3a, 4a).

Burrows can be classified in three categories.~~Independent of location and shape, endolithic borings present three basic categories.~~ ~~The most prominent feature of the carbonate is that thriving benthic biota are intimately related with the carbonate ever since the biogenic debris had deposited on the sea floor because three types of boring are easily identified.~~ ~~Boring~~Burrows with living organisms can be categorized explicitly as fresh ~~boring~~burrows (Fig. 2c, d). The second type is considered to be the vacant ~~boring~~burrows which ~~is~~ are filled by gray excrements (Fig. 2b). Thin black ~~ferromanganese~~Mn- and Fe-oxide precipitates ~~crusts~~ commonly encrust the surface of carbonate and the inner surface of empty ~~boring~~burrows (Fig. 2a, c, d) and ~~this can be~~thus are classified as the third type of ~~boring~~burrow. It has been suggested that Mn- and Fe-oxide precipitates grow at a very slow rate of 1-10mm/Ma. Coating of black Mn- and Fe-oxide precipitates on the surface of the burrows indicate that they may form much earlier than other burrows.~~The latter two borings should be old generations because gray excrements and (or) encrusted black ferromanganese crusts should be~~were ~~subsequently deposited after the boring formation, with the fact of which the latter two borings can be classified as old generations.~~ ~~It has been suggested that ferromanganese crusts grow at very slow rate of 1-10mm/Ma.~~ Thus, the influence of bioturbation in this area is most likely a continuous process during the early lithification and could play a significant role in both geological and biological processes.

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4. 2 Enhanced lithification around ~~boring~~burrow

Computerized X-ray tomography (CT) was used for better characterization of local changes of density in the carbonate rocks, which would reflect their degree of lithification. A darker ~~color~~colour in the tomographic cross-section image of the sample represents lower attenuation and thus lower density and higher porosity. The most ~~readily~~ apparent feature of the CT image is ~~the~~ localized enhancement of density around the ~~boring~~burrow (Fig. 3, 4~~c, d~~). The shapes of the area with ~~a~~ higher density around the holes ~~is~~are triangular, quadrangular, hexagonal, round or irregular (Fig. 3b, c~~4~~). ~~The i~~Integrated density profiles extracted from the tomographic cross-section images ~~intuitively reveals the relative~~make the contrast of density change around the ~~boring~~burrow more clear (Fig. 3d). 3D reconstruction of the sample by CT exhibits that the enhancement of density is visible around the burrow, which is consistent with the enhancement of brightness around the burrow as shown in hand specimen (Fig. 4). ~~The density enhancement can increase by 120% relative to the surrounding sediment~~Statistical analysis of density of 113 burrows (Fig. 5)~~, which~~ provides robust evidence for density enhancement around the burrows, illuminating the significant influence of bioturbation in ~~deep-sea carbonate~~ lithification. In addition, the results of CT also show that ~~the~~ density is generally higher at the bottom than at the top of the carbonate rocks (Fig. ~~3a,~~ 4c~~b~~).

4. 3 Mineralogy

Based on XRD and elemental analyses, ~~the sediment and~~ rock samples consisted almost entirely of calcite and detectable quartz, halite which ~~is~~ are typical for deep-sea chalk defined as ~~"~~soft, pure, earthy, fine-textured, usually white to light gray or buff limestone of marine origin, consisting almost wholly (90-99%) of calcite, formed mainly by accumulation of calcareous tests of floating micro-organisms (chiefly foraminifers) and of ~~comminuted~~comminute remains of calcareous algae (such as coccoliths and rhabdoliths) set in a structureless matrix of very finely crystalline calcite (Wolfe, 1968; Flügel, 2004)~~"~~. Thin section and scanning electron photomicrographs show that biogenic components, mainly planktonic foraminifera (*Globigerina bulloides*) and cocolithophorid (*Coccolithus pelagicus*) dominate (Fig. 6). The presence of *Globigerina bulloides* indicates that the lithification history of carbonate rocks ~~are~~is less than 5 Ma (Pliocene-Recent) old. Therefore, carbonate deposit on the SWIR ~~should~~ could be ~~the~~ bioclastic deposition from the productivity related events 'biogenic bloom' to large part of Indian Ocean during middle Miocene to the early Pliocene (Singh et al., 2012; Rai and Singh, 2001; Gupta et al., 2004; Arumugm et al., 2014).

Although it ~~is~~ was difficult to separate and quantify the small tests from the very fine matrix, the carbonates exhibited a relatively high test to matrix ratio ~~which~~ that is representative of deep-sea chalk (Fig. 6a). Original skeletal grains were~~are~~ held together by cement. Body chambers in the foraminiferal tests, for instance, ~~are~~ were partially filled by calcite cements (Fig. 6b, c). It wa~~i~~s common to observe the ~~A~~accretionary overgrowth of calcite around the foraminifera test form SEM images ~~also is common which are observed coating by coccoliths~~ (Fig. 6c). Dissolution of the coccolith plates is evident both on the surface of the thin black ~~ferromanganese~~Mn- and Fe-oxide precipitates ~~crust~~ and in the interior of carbonate

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rocks (Fig. 6e). The gray excrements filling in the ~~boring~~burrow primarily consisted ~~primarily~~ of plates of coccolithophorids (*Calcidiscus leptoporus, Emiliania huxleyi* and *Gephurocapsa oceanica*). Smooth surfaces of the coccoliths in gray excrements revealed that dissolution commonly occurs influenced by bioleaching of benthic fauna (Fig. 6f). ~~The smooth surfaces of plates in gray excrements reveal that dissolution of the original plates has already occurred (Fig 6f), which also presented dipartite evolutionary of diagenesis compared to the chalk.~~

4.4 Geochemistry and isotope analysis

Three ~~portions~~ types of samples (chalk, gray excrements and thin black ~~ferromanganese crust)~~ Mn- and Fe-oxide precipitates) exhibited similar elemental concentration patterns for high CaO content, reflecting the strong dilution effect of biogenic calcium (Table S1)~~m in bulk samples~~. One of the main characteristics of major and rare elements is the highly variable ~~of~~ Sr concentrations in different ~~portions~~ types of the ~~carbonate~~sample. The storage of Sr on ~~the~~ seafloor is mainly ~~account for~~caused by ~~the~~ substitution ~~for~~ of Ca in calcium carbonate while ~~the~~ diagenetic recrystallization~~, resulting~~ results in the decrease of Sr ~~loss~~ from the sediment (Plank and Langmuir, 1998; Qing and Veizer, 1994). The ~~loss~~ lower ~~of~~ Sr/Ca ratio in chalk compared to the gray excrements could also be a response to the lithification of carbonate (Fig. **7). Although biogenic calcium diluted the detrital REE fraction, it made little direct contribution to bulk REE concentrations (Xiong et al., 2012). REE patterns of the three ~~portions~~ types of sample ~~do~~ did not exhibit any hydrothermal anomalies, e.g. positive Eu anomaly, but inherit the characteristics of sea water by enrichment of HREE compared with LREE and negative Ce anomaly (except the Mn- and Fe-oxide~~ferromanganese crust~~) (Fig. ~~7~~8). The influence of nearby hydrothermal system and other detrital input to the ~~study~~ studied carbonate area should be negligible during the lithification history.

The $\delta^{13}C_{PDB}$ values of 46 bulk samples we~~a~~re -0.37 to 1.86‰ which are typical for biogenic carbonates (e.g. Cook and Egbert 1979). These samples have a relatively narrow $\delta^{18}O_{PDB}$ range of 1.35 to 3.79‰. ~~There is an evident depletion of carbon and oxygen isotopic values of gray excrements compared to chalk which reflects the bioleaching effect by benthic fauna.~~ ~~The bulk~~ Positive correlation of $\delta^{13}C_{PDB}$ and $\delta^{18}O_{PDB}$ values of chalk and gray excrements ~~are positively correlated with bulk~~ ~~$\delta^{18}O_{PDB}$ values~~ (r = 0.91) ~~(Fig. 8), which~~ reveals minor environmental influence on early lithification (Fig. 9) and ~~endolithic boring~~bioturbation should be a critical factor ~~influence~~ during the lithification. There is an evident depletion of carbon and oxygen isotopic values of gray excrements compared to chalks (Fig. 9). Carbon isotope signatures of carbonates near burrow with higher density were relatively high compared to undisturbed areas (Table 1).

5. Discussion

5.1 ~~Endolithic boring~~Bioturbation in carbonate rock on SWIR

~~Boring holes generally with several millimeters to 2 cm in diameter, commonly penetrate 6 to 10 cm into the chalks and ultimately reach a density up to 12 per dm~~~~^{2}~~ ~~(Fig. 2a)~~. ~~Although the real depth of each boring hole is difficult to determine~~

~~accurately because the full lengths of boring usually are not apparent, –~~The dimensions of ~~boring~~burrow~~ hole~~s can be estimated~~assessed by~~ from~~ CT analysis~~ tomographic cross-section of the samples. ~~to estimate the extent of substratum reconstruction. Boring~~Burrow~~ hole~~s were generally ~~with several~~few ~~millimeters~~millimetres to 2 cm in diameter, commonly penetrating 6 to 10 cm into the ~~chalk~~rocks and ultimately reaching a density of up to 12 per dm^2. If ~~boring hole~~burrows in straight, branched, or J- and U-shaped (Fig. 2e) are simplified to a cylinder with the diameter of 1 cm and height of 6 cm, which are the median value of the ~~boring hole~~burrows, estimated ~~the~~ volume ~~occupied by the boring can be estimated in a~~this ~~simplified~~e ~~model~~of the simplified cylinder would be helpful to reckon the extent of substratum reconstruction by bioturbation. ~~The boring in straight, branched, or J- and U-shaped (Fig 2e) are simplified to a cylinder with the diameter of 1 cm and height of 6 cm, which are the median value of the boring holes.~~ In this model, 1 dm^2 surface area which can harbor 12 ~~boring hole~~burrows on the surface may reach to 0.226 dm^3 ~~boring~~burrow space. Eventually, ~~Although it is hard to determine the dimension of each boring hole accurately, A~~an ~~important conclusion can be~~ we can deduce~~d from this~~e ~~simplified model~~ that ~~the~~ carbonate substratum is ~~were~~ reconstructed by ~~the boring~~ bioturbation to a great extent.

~~Several b~~B~~oring purposes~~enthic fauna maintain~~form~~ ~~boring~~burrows for certain purposes of ~~are served for the benthic animals such as~~ gaseous exchange, food transport, gamete transport, transport of environmental stimuli, and removal of metabolites (Kristensen and Kostka, 2013). Polychaetes, the most successful burrow class for example (Díaz-Castañeda and Reish, 2009), were abundant and conventionally produced J- or U- shaped burrow extended as long as several decimetres in hand specimens (Fig. 2 c, e). Relic burrows allow sea water to directly penetrate into carbonate rocks, which is beneficial to the precipitation of black Mn- and Fe-oxide precipitates on the inner surface of burrow (Fig. 2a, c). The genetic models for Mn- and Fe-oxide precipitates has been attributed to the minerals precipitated out of the cold ambient seawater onto the rock surface with the aid of biogenic activity (Hein and Koschinsky, 2014). Burrowing benthic fauna excrete mucus to garden their burrow holes by incorporating organic matter into the walls (Dworschak et al., 2006; Koller et al., 2006). The mucus layer may act as favourable site for the accumulation of metallic ions through organo-metallic complexation or chelation at suitable Eh, pH and redox conditions (Lalonde et al., 2010; Banerjee, 2000). Thus, along with ~~Carbonate mass accumulation during the Latest Miocene–Early Pliocene at Indo-Pacific provided the bioclastic deposition to the sea floor (Singh et al., 2012; Rai and Singh, 2001; Gupta et al., 2004; Arumugm et al., 2014). These carbonate sediments deposit on the seafloor thus form a favorable environment for benthic fauna (fig 2). Polychaetes, taking the most successful boring class for example (Díaz-Castañeda and Reish, 2009), are abundant and conventionally produce J- or U- shaped boring extended as long as several decimeters in carbonate sample (Fig. 2 c, e). During the frequent construction and maintenance of boring, not only the~~ carbonate reworking and bio-mixing~~ occurs by boring~~ during frequent construction and maintenance of burrow, ~~the redox~~mineralogical and geochemical parameters~~, including pH~~, ~~were~~ are also assumed to oscillate around the ~~bioturbate structure~~burrow~~–~~. ~~Relic borings allow sea water to directly penetrate into carbonate rocks, which is benefit to the precipitation of black ferromanganese crusts on the inner surface of boring (Fig. 2a, c). Moreover, boring organisms excrete mucus to garden their boring holes by incorporating organic matter into the walls (Dworschak et al., 2006; Koller et al., 2006), the mucus layers lined on the inner side of boring walls usually are as thick as 5 μm and are composed of protein-rich~~

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~~mucopolysaccharide (Petrash et al., 2011). The mucus layer may friendly help constructing a favorable site for the accumulation of metallic ions through organo-metallic complexation or chelation at suitable Eh, pH and redox conditions (Lalonde et al., 2010; Banerjee, 2000).~~

In addition to the ~~boring~~ burrowing activity, benthic fauna ingest and excrete the substrate which usually serve the ~~boring holes~~burrows as traps for fecal pellets (Fig. 2b) (Hydes, 1982; Aller and Aller, 1986). Although benthic fauna ingest organically enriched particles, thus removing the organic matter, ~~the~~ bulk sample is often still enriched in residual fecal material (Dauwe et al., 1998). Regardless, organic matter influenced by bioturbation and delivered as biodeposits in surface sediments, and vice versa, may therefore create a dynamic and heterogeneous chemical, physical, and biological micro-environment in the deep-sea carbonate ~~area~~zones. Eventually, a microenvironment friendly for heterotrophic microorganism may be formed in the carbonate due to ~~the~~ redistribution of organic particles. The biodiversity of the prokaryotic communities within the samples examined by Li et al. (2014) inferred that the distribution of Acidobacteria and Bacteroidetes noted in this study might indicate the greater organic carbon availability in the interior carbonates. ~~.~~ Alternatively, bacterial metabolites and organic detritus are considered to be the major sources of food for benthic ~~fanua~~fauna in deep-sea environment, ~~where are~~which is limited by availability of organic matter (Raghukumar et al., 2001). Thus, a balanced ecological sustainability ~~are~~ is established by the carbonate deposits and ~~the~~ continuous biological processes, which may ~~be~~ largely influence~~d~~ the lithification history of the carbonates.

5. 2 ~~The r~~Roles of ~~endolithic borings~~bioturbation in lithification of carbonate rocks on the SWIR

Abundant macrofaunal burrows~~endolithic borings~~, as well as ~~a~~ benthic fauna (e.g. polychaete worm, Fig. 2c) present on a cross section of ~~a~~ carbonate rocks ~~(e.g. polychaete worm, Fig. 2c), the dissolution of coccolith plates observed by SEM (Fig 6),~~ and enhancement of density around ~~boring hole~~burrows commonly observed from CT images (Fig. 3, 4), ~~as well as elemental composition change between different portion of carbonate (Table 1)~~ provided robust evidence for the significant role of bioturbation in present lithified deep-sea carbonates. The lithification of carbonate is confirmed by the dissolution of coccolith plates observed by SEM (Fig. 6) and elemental composition change between different portions of the carbonate (Fig.*** 7). Water depth of ~~the~~ studied carbonate ~~rock~~ area on SWIR varies approximately from 2000 to 2500 meters (Fig. 1), which is above the calcite saturation horizon (Broecker et al., 1982). In this range of water depth, the key point of carbonate lithification is how ~~the~~ original tests or plates are dissolved under saturation condition. Although less stable $CaCO_3$ phase (e.g., biogenic, high-Mg calcites) may dissolve above the calcite saturation horizon (Jahnke and Jahnke, 2004), they are not likely to happen here, since our samples are low-Mg calcites. As a general rule, compaction takes place with ~~the~~ gradual~~ly~~ increas~~ing~~e of overburden pressure, ~~and~~ resulting in loss~~sing~~ of porosity through mechanical and chemical compaction in moderate-deep burial stage. However, present carbonate samples show~~s~~ they have never been buried. ~~The its~~Their lithification ~~of carbonate~~therefore may be different from ~~carbonate from~~ other deep sea carbonates. Elements and isotope results reveal ~~that~~ minor external impact on the early lithification. ~~Thus, the simultaneously activities of both thrive benthic fanua and lithification of carbonate should unavoidable have some connections~~ The construction and ventilation of

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burrows can fundamentally alter biogeochemical processes and produce lateral heterogeneity intensifying the redistribution of pore water fluids. Moreover, the ecological niches for microbial life are also formed by bioturbation~~ with the fact that the construction and ventilation of boring by benthic fauna could fundamentally alter biogeochemical processes and produce lateral heterogeneity intensify the redistribution of pore water fluids and could create ecological niches for microbial life~~ (Ghirardelli, 2002; Koretsky et al., 2013). Thus, the simultaneous activities of both thriving benthic fauna and lithification of carbonate, are potentially connected.

~~Providing that biogenically-produced $CaCO_3$ particles typically have very large surface areas due to the presence of pores in foraminiferal tests and coccolithophorid plates which may be increasingly exposed to pore waters as the primary particles are broken and dissolution proceeds (Jahnke and Jahnke, 2004).~~ The organic matter~~ should have been~~ is possibly significantly low in the deep-sea sediment. However, the distribution and diversity of the prokaryotic communities inhabiting carbonate samples imply the greater organic carbon availability in the interior carbonates compared to the exterior (Li et al., 2014). It is known~~assumed~~ that polychaetes' mixing sediment~~s~~ particles is an important driving force behind chemical reaction and transport of organic matter in marine sediments (Levinton et al., 1995). ~~Endolithic borings~~~~Boring~~Benthic fauna~~ in carbonate~~, including polychaetes~~ included~~~~as discussed above~~, reconstruct~~ed~~ the carbonate substratum to a great extent and result~~ed~~ in a fundamental~~ly~~ alteration of sedimentary environment. ~~The a~~Aerobic respiration of bioturbated organic particles like mucus ~~and fecal pellets~~ would positively contribute to the aerobic respiration of bioturbated organic particles by heterotrophic (micro)organisms (Lohrer et al., 2004), whose reaction product CO_2 may be responsible for~~ the~~ lowering the pH of porewater around the ~~boring hole~~burrow relative to the inner carbonate sediment, which may drive the dissolution of original calcite in microenvironment (Fig. 10) (Emerson and Bender, 1981; Aller, 1982; Kristensen, 2000). Isotopic composition in gray excrements is lighter compared to the chalks (Fig. 9; table 1). It is assumed that faecal pellets may strongly depleted in ^{13}C in isotopic mass balance with the ^{13}C enrichment of the organism (Damste et al., 2002). That means bioturbated organic particles like mucus will inherit enriched ^{13}C, which is the major carbon source for microbial metabolic reaction. ~~Thus, active bioturbation in carbonate rocks may provide a feasible pathway for the dissolution of tests or plates at such depth.~~ The local elevated concentration of dissolved CO_2 in pore water would trigger the dissolution of the original $CaCO_3$ phases, which is consistent with the results of SEM observation. For instance, ~~B~~body chambers in the foraminiferal tests are partially filled by calcite cements (Fig. 6c~~, Fig. 7c~~), which is believed to be derived internally through solution transfer (Durney, 1972).

In addition, relic ~~borings~~ burrows make sea water directly penetrate into carbonate rocks and lead to the precipitation of black Mn- and Fe-oxide precipitates in ~~ferromanganese crusts on~~ the inner surface of the ~~boring hole~~burrow. ~~The m~~Microbial oxidation of Fe^{2+} and Mn^{2+} in these sites would also greatly accelerate the dissolution of $CaCO_3$ fossils (Emerson and Bender, 1981; Aller and Rude, 1988). Furthermore, thin Mn- and Fe-oxide precipitates ~~ferromanganese crust and grey sediments~~may prevent the rapid ion exchange between bottom water and ~~pore~~ porewater within carbonate rocks.~~,~~ ~~which may cause Ca^{2+} and CO_3^{2-}, the production of $CaCO_3$ dissolution,~~ Ca^{2+} and CO_3^{2-}, the products of $CaCO_3$ dissolution~~-~~,

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prefer to diffuse ~~toward~~ to the interior of carbonate rocks, and lead to the repreciptation of calcites as cements with higher $\delta^{13}C_{PDB}$ in carbonate rocks (Fig. 10).

6. Conclusions

A lithified carbonate area characterized by active ~~endolithic boring~~ bioturbation was ~~investigated and discussed regarding~~studied to explore the area's biological and geological interactions. Although the effect of different parameters influenced by ~~boring~~bioturbation cannot easily be differentiated in study of natural samples, available evidences show that active ~~endolithic boring~~bioturbations may trigger the dissolution of ~~the~~ original calcite above the saturation horizon ~~and~~, thus ~~enhance~~ enhancing deep-sea carbonate lithification on mid-ocean ridges. The novel mechanism proposed here for non-burial carbonate lithification at the deep-sea seafloor sheds light on the potential interactions between deep-sea biota and sedimentary rocks, and also illuminate the geological and biological importance of deep-sea carbonate rocks on mid-ocean ridges.

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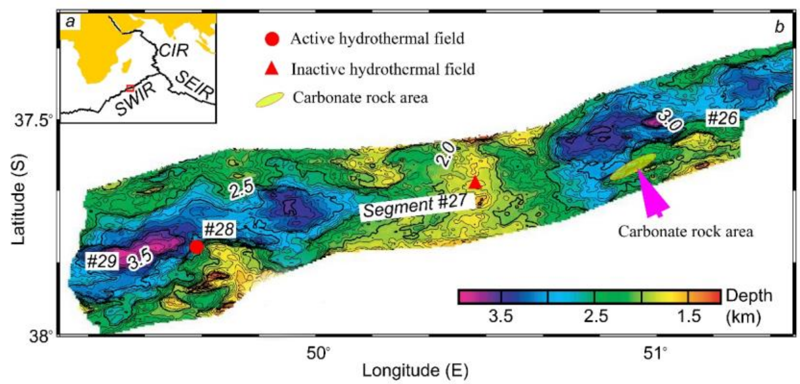

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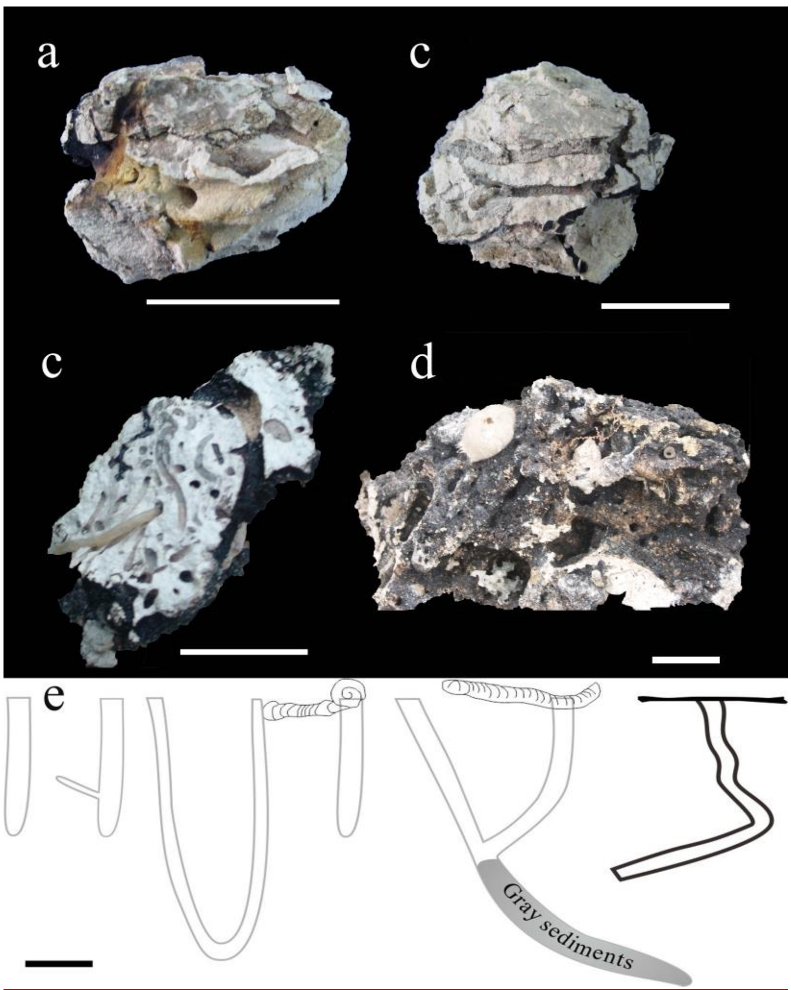
Figure 1: (a) Location of study area on the Southwest Indian Ridge. (b) Bathymetric map of area which show the location of the carbonate rock area (green ellipse), the active hydrothermal field (red cycle~~triangle~~), and the inactive hydrothermal field (red triangle~~cycle~~).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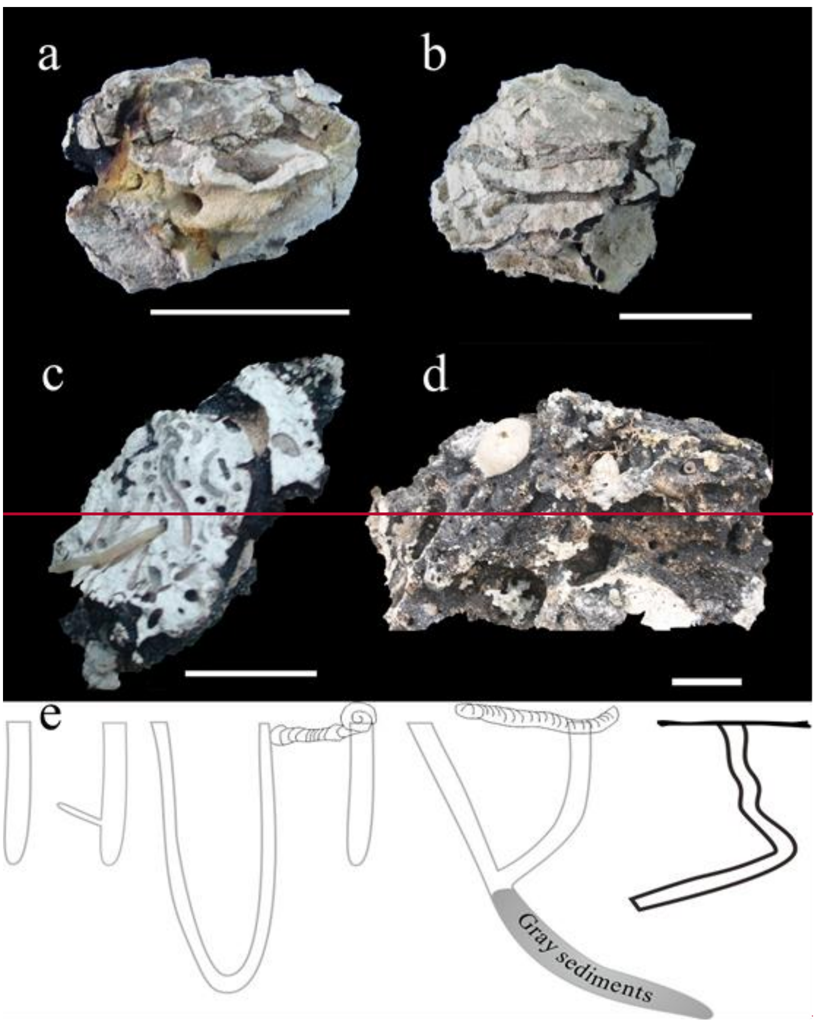
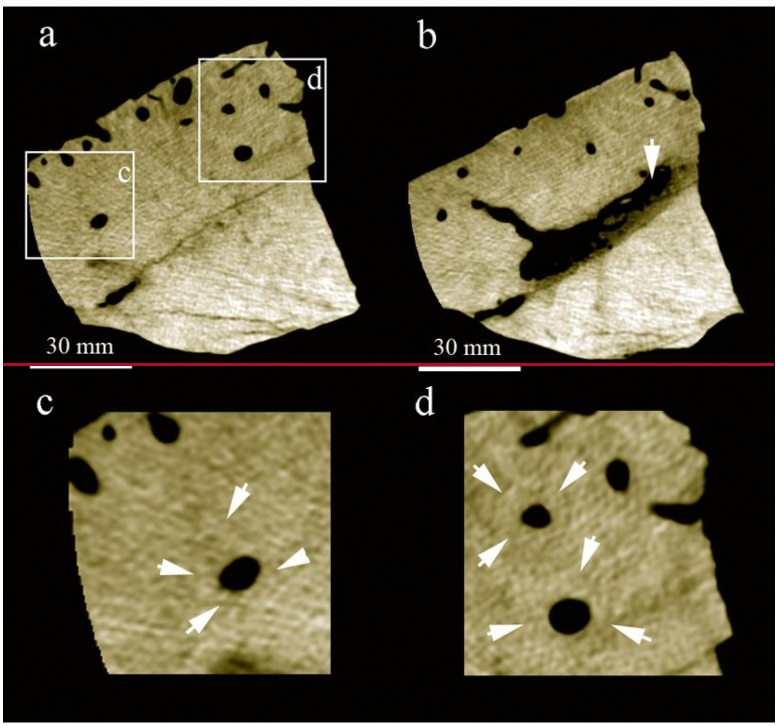
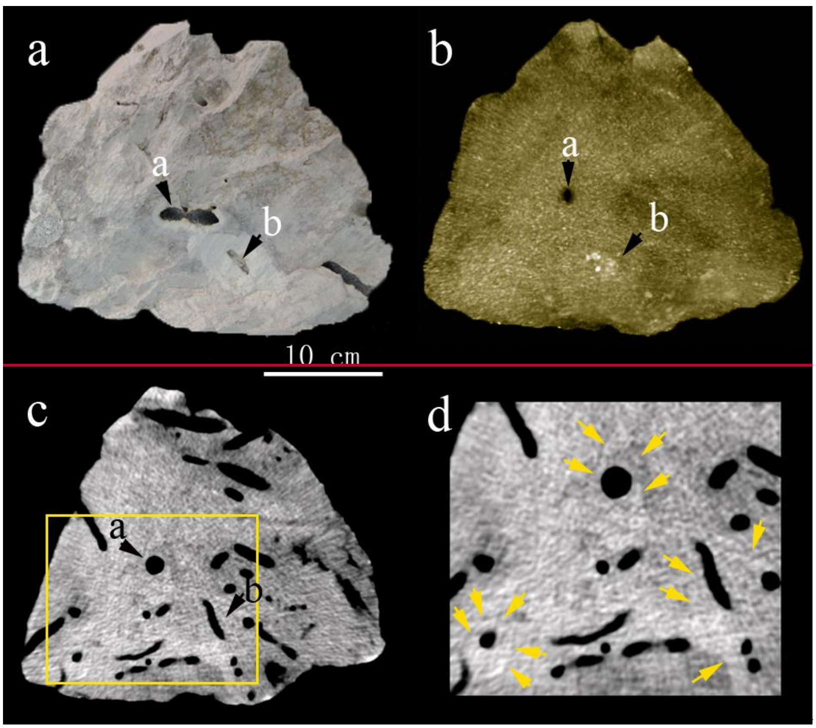


Figure 2: Deep-sea carbonate rocks collected from the SWIR. (a) A carbonate rock sample shows empty ~~boring hole~~burrows are partly covered by ferromanganese crusts. (b) Straight and branched ~~boring~~burrows are infilled by grey sediments. (c) Abundant ~~boring~~burrows, as well as a benthic fauna (polychaete worm), are present on a cross section of a carbonate rock. (d) An echinoid, together with other benthic faunas, ~~boring~~burrows on a carbonate rock with the honeycombed structures and encrusted by thin

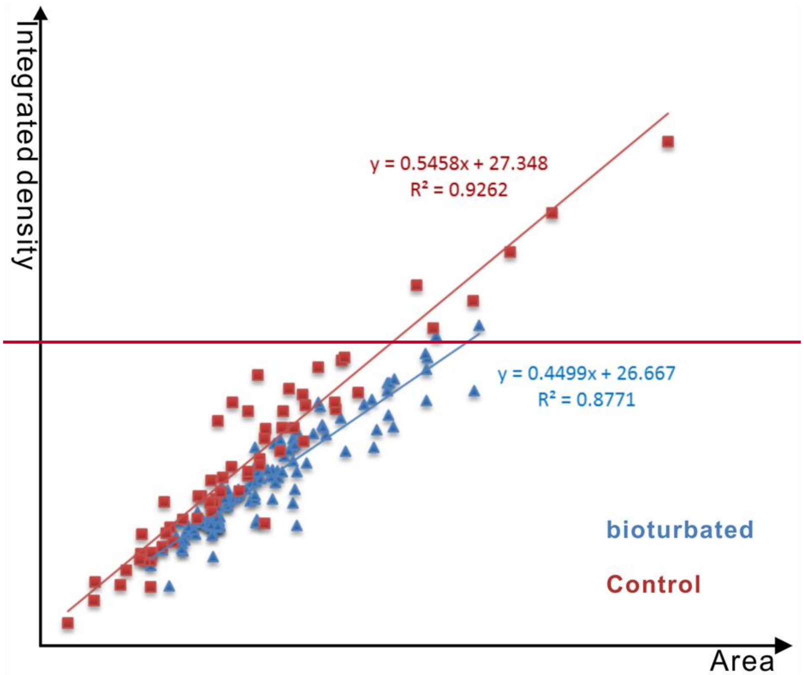
ferromanganese crusts. (e) Sketch for different ~~endolithic boring~~burrow structures in deep-sea carbonate rocks collected from the SWIR. Scale bar of a, c are 5cm, and the b, d e is 3 cm.



~~**Figure 3: (a, b) Tomographic cross-sections of a sample show the density is higher at the bottom than at the top. Darker colors represent lower attenuation and thus lower density and higher porosity. Boring holes are black in the figure. (c, d) The enlargement of Fig.6A shows the elevated density around the boring holes.**~~



~~Figure 4: (a) A hand specimen shows the enhancement of brightness associated with burrow structures. (b) 3D reconstruction of the sample shows enhancement of density around the burrows. Arrows point out the location of burrows. Darker colors represent lower attenuation and thus lower density and higher porosity. Burrows are black in the figure. (c) Tomographic cross-section of the sample reveals that abundant burrows are clearly present in the interior of the samples. Higher density areas with triangular, hexagonal and irregular shapes are visible around the burrows. (d) The enlargement of Fig. 4c.~~



~~**Figure 5: Statistical analysis of integrated density extracted from selected area around boring holes and paralleled undisturbed area clearly shows enhancement of density around the holes. Both images were inverted so that bigger slope means a darker color in original CT image. The total number of analyzed holes=113.**~~

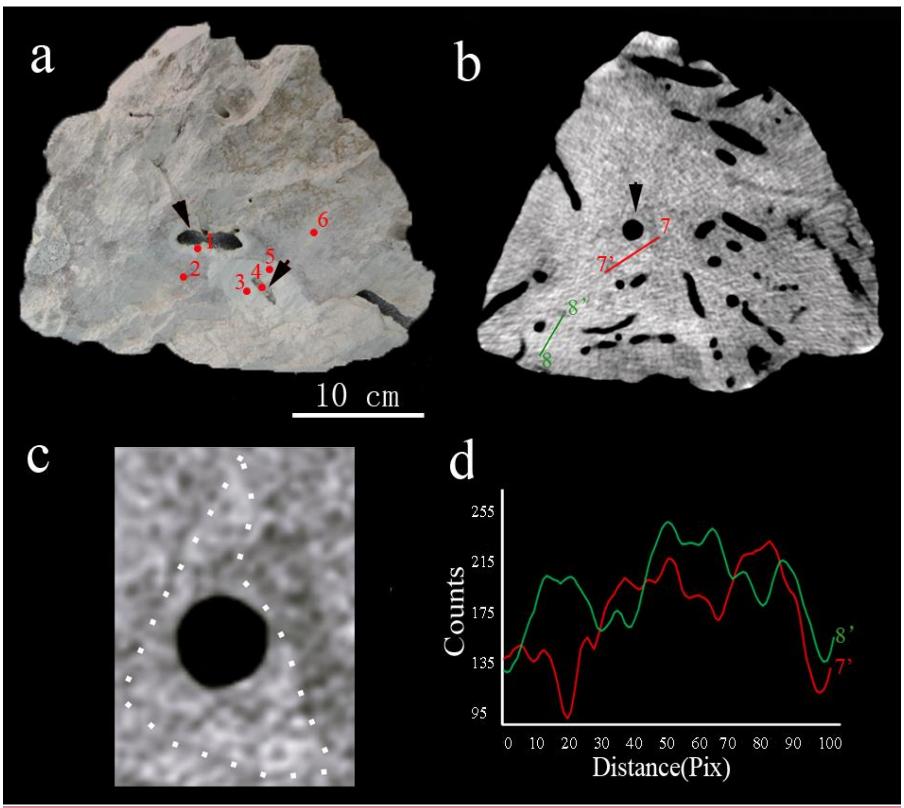


Figure 3: (a) A hand specimen shows the enhancement of brightness associated with burrow structures. Numbers of red dots indicate the subsamples for carbon and oxygen isotope analysis in table 1. (b) Tomographic cross-section of the sample reveals that abundant burrows are clearly present in the interior of the samples. Higher density areas with triangular, hexagonal and irregular shapes. (c) The enlargement of Figure 3b shows the triangular shape of higher density (white dash line). (d) Line scan profiles of gray values along solid line (7-7' and 8-8') in Figure 3b.

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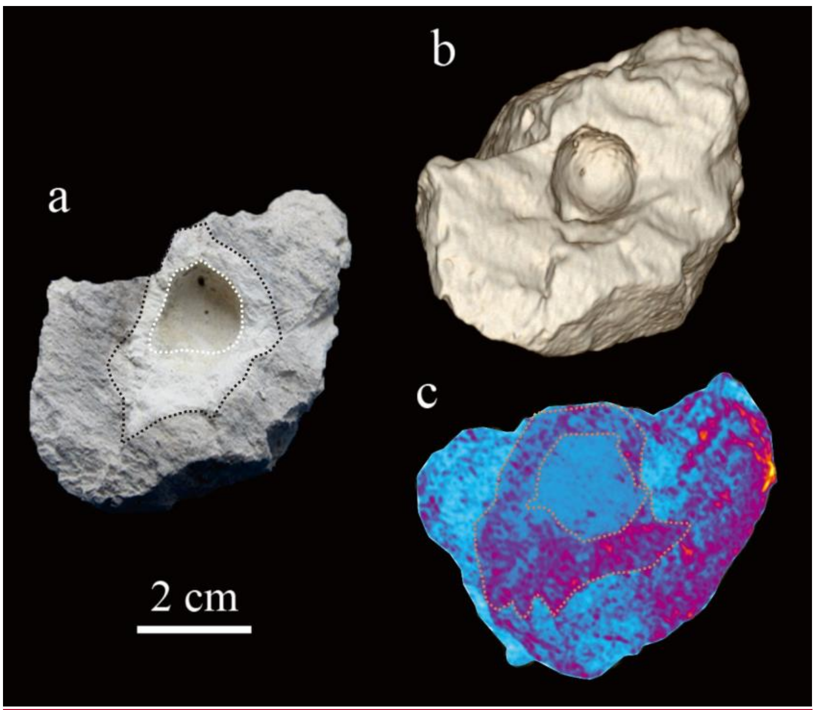

Figure 4 (a) A carbonate rock sample shows the enhancement of brightness associated with a burrow structure. (b) 3D reconstruction of the sample by CT shows the morphology of the sample. (c) 3D reconstruction of the sample by CT exhibits that the enhancement of density is visible around the burrow, which is consistent with the enhancement of brightness around the burrow as shown in Fig.4 a.

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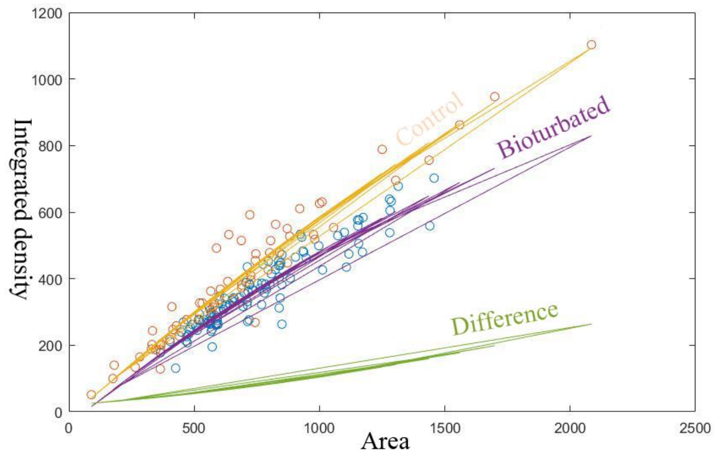

Figure 5 Statistical analysis of integrated density extracted from selected area around burrow and paralleled undisturbed area clearly shows different density around the burrows. Both images were inverted so that bigger integrated density means a darker colour in original CT image. The total number of analyzed burrows are 113. With 95% confidence bounds, the goodness of fit is showed by $R^2_{bioturbate}$=0.9312 and $R^2_{control}$=0.8802.

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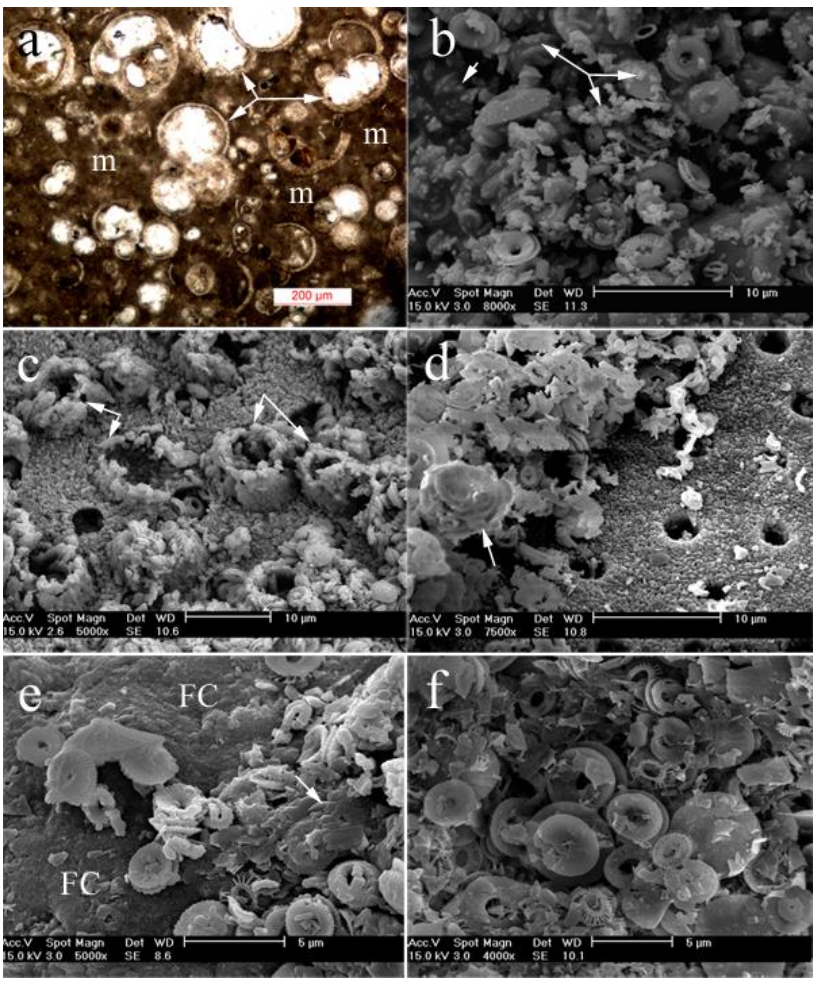
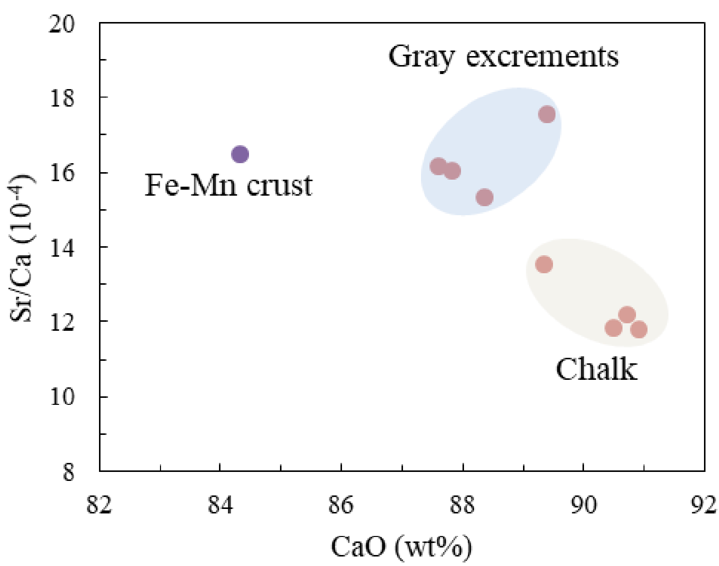


Figure 6: (a) photomicrograph of thin sections of carbonate rocks shows a relatively high test (arrows) to matrix (m) ratio. (b) Scanning electron micrograph reveals abundant micritic carbonate particles (arrows) with many plates of coccoliths in the interior of carbonate rocks. (c) Scanning electron micrograph shows overgrowths of calcites on the foraminiferal in the interior of carbonate rocks. (d) Scanning electron micrograph shows dissolution of coccoliths in the interior of carbonate rocks. (e) Scanning electron micrograph shows the surface of carbonate rock covered by thin Mn- and Fe-oxide precipitates~~ferromanganese crusts~~

(~~c~~FC). Arrow points out the dissolution of the coccoliths. (f) Scanning electron micrograph shows grey sediments which infill the ~~boring~~burrow. Smooth surfaces of the coccoliths indicate that the dissolution commonly occurs.



5 Figure 7: The lower of Sr/Ca in chalk compared to the gray excrements represents the lithification of different portions of carbonate.

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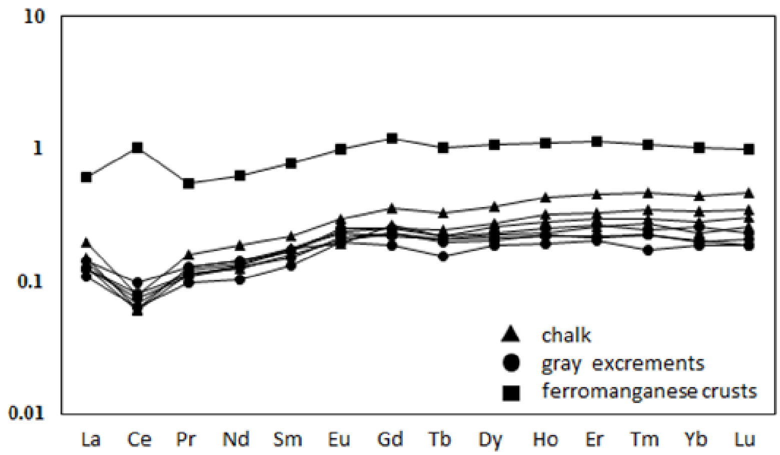

Figure ~~7~~8: PAAS-normalized REE distribution patterns of selected samples from the SWIR.

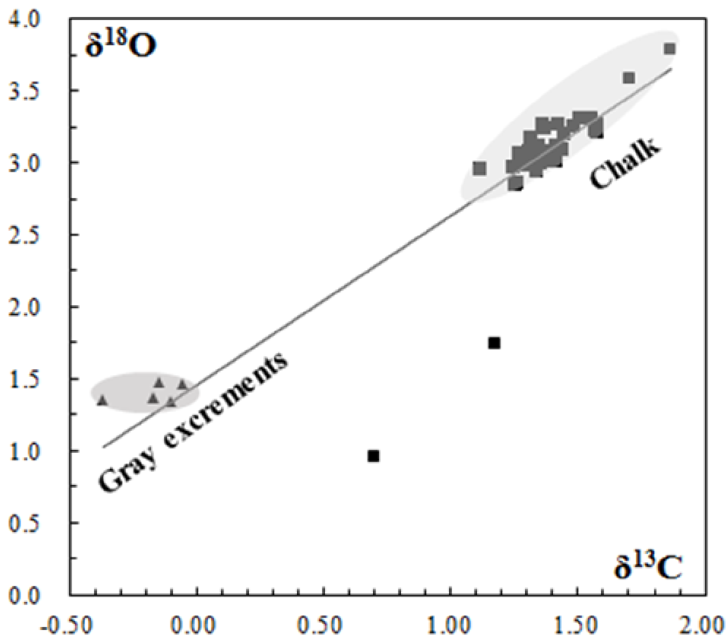

Figure ~~8~~ 9 Oxygen and carbon isotopic composition of carbonate samples from the SWIR. ~~The g~~Gray excrements contain the light carbon and oxygen isotopic values compared to the chalk. The ~~bulk~~ δ^{13}CPDB values of chalk and gray excrements are positively correlated with ~~bulk~~ δ^{18}OPDB values (r=0.91).

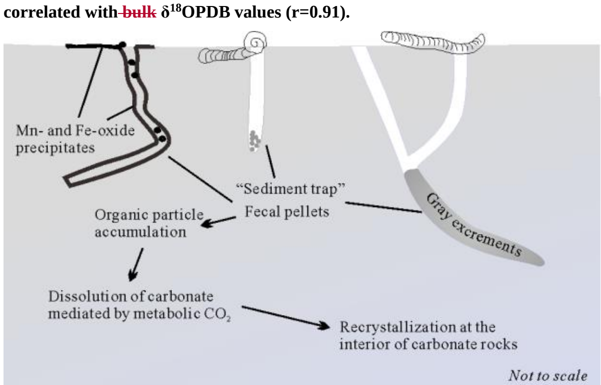

Figure 10 Schematic model for carbonate lithification influenced by bioturbation on the SWIR.

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Sample NO.	δ^{13}C PDB	δ^{13}O PDB
1	1.36	3.04
2	1.28	2.99
3	1.30	3.09
4	-0.37	1.56
5	1.28	3.00
6	1.11	2.97

Table 1

Isotope data for samples collected from the Figure 3a. 1, 3 and 5 represent the higher density influenced by bioturbation compared to 2 and 6. 4 represents gray excrements infilled in the burrows.

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supplementary table

Sample NO.	CaO	SiO_2	Al_2O_3	Na_2O	SO_3	Fe_2O_3	MnO	K_2O	P_2O_5	Cr_2O_3	L.O.I	Total
C1	87.60	5.01	1.60	1.26	1.01	0.99	0.08	0.14	0.12	0.07	2.10	100.00
C2	89.39	4.73	1.54	0.49	1.10	0.91	0.07	0.09	0.12	0.06	1.50	100.00
C3	87.81	5.02	1.64	1.01	0.91	1.08	0.09	0.13	0.14	0.07	2.10	100.00
C4	88.35	4.46	1.53	1.25	1.06	0.88	0.06	0.15	0.11	0.07	2.07	100.00
C5	90.70	4.09	1.04	0.45	0.84	1.09	N.D.	0.12	0.08	0.09	1.50	100.00
C6	90.91	4.42	1.12	0.44	0.61	1.11	0.05	0.16	0.11	0.09	0.99	100.00
C7	90.49	4.37	1.14	0.32	1.21	1.18	0.08	N.D.	0.10	0.07	1.04	100.00
C8	89.33	4.88	1.18	0.40	1.37	1.24	0.06	0.15	0.09	0.06	1.23	100.00
M1	84.31	4.64	1.22	0.50	2.18	3.12	1.57	0.14	0.20	N.D.	1.96	99.83

Sample NO.	Li	Be	Sc	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb
C1	12.394	0.151	1.327	9.067	6.101	7.499	16.927	16.284	8.453	2.272	1415.280	7.398	5.971	0.774
C2	14.326	0.030	1.541	9.584	6.823	8.314	14.787	22.730	12.296	1.971	1570.712	7.794	6.433	0.710
C3	9.924	0.060	1.452	10.544	7.200	16.402	13.308	14.540	6.429	2.073	1408.932	8.692	6.449	0.841
C4	5.187	0.070	1.229	8.446	5.837	5.697	10.295	13.203	8.925	3.008	1355.301	6.697	4.917	0.650
C5	9.269	0.050	1.427	6.355	4.520	3.033	9.568	27.786	10.845	2.794	1105.468	12.841	6.884	0.549
C6	7.282	0.150	1.307	6.643	4.289	3.621	8.299	15.830	9.795	3.092	1071.291	9.646	6.613	0.579
C7	6.185	0.150	1.556	7.123	4.938	6.265	23.184	12.959	15.942	2.823	1071.415	11.043	6.335	0.579

C8	8.970	0.160	1.804	8.559	5.833	8.389	22.501	16.538	11.005	3.067	1210.755	17.159	8.369	0.842
M1	17.389	0.270	2.805	76.871	7.806	432.418	111.399	29.926	38.920	4.272	1389.487	32.831	21.581	3.863

Sample NO.	Mo	In	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er
C1	0.342	0.010	0.101	161.531	4.724	5.981	0.965	4.342	0.824	0.231	1.076	0.151	0.955	0.221	0.613
C2	0.340	0.000	0.110	157.972	4.802	6.363	0.990	4.482	0.950	0.250	1.020	0.160	1.010	0.220	0.620
C3	0.391	0.010	0.100	171.936	5.397	7.801	1.122	4.867	0.921	0.270	1.182	0.170	1.081	0.250	0.751
C4	0.220	0.010	0.180	131.332	4.188	4.987	0.870	3.528	0.730	0.210	0.880	0.120	0.880	0.190	0.570
C5	0.150	0.010	0.180	14.327	5.757	4.879	1.137	4.879	0.978	0.259	1.167	0.190	1.267	0.319	0.938
C6	0.160	0.010	0.180	13.665	4.818	4.768	1.017	4.269	0.888	0.219	1.077	0.160	1.057	0.229	0.728
C7	0.319	0.010	0.140	19.573	5.357	5.367	1.067	4.599	0.978	0.209	1.227	0.170	1.197	0.279	0.838
C8	0.261	0.010	0.110	18.141	7.497	6.344	1.413	6.254	1.213	0.321	1.674	0.251	1.724	0.421	1.293
M1	6.498	0.020	0.150	69.355	23.288	82.052	4.831	21.082	4.342	1.058	5.500	0.789	4.991	1.098	3.204

Sample NO.	Tm	Yb	Lu	Hf	Ta	Tl	Pb	Th	U	ΣREE	LREE	HREE	LREE/HREE	δEu	δCe	Ce_{anom}
C1	0.090	0.573	0.080	0.181	0.161	0.020	3.699	0.684	0.251	20.83	17.07	3.76	4.54	0.75	0.63	-0.20
C2	0.090	0.560	0.090	0.220	0.180	0.050	4.142	0.730	0.260	21.61	17.84	3.77	4.73	0.77	0.65	-0.18
C3	0.100	0.721	0.100	0.230	0.140	0.020	2.283	0.801	0.240	24.73	20.38	4.36	4.68	0.79	0.71	-0.15
C4	0.070	0.530	0.080	0.170	0.130	0.020	0.300	0.590	0.210	17.83	14.51	3.32	4.37	0.80	0.59	-0.23
C5	0.140	0.948	0.150	0.210	0.110	0.010	0.708	0.529	0.249	23.01	17.89	5.12	3.50	0.74	0.43	-0.37
C6	0.110	0.648	0.110	0.190	0.140	0.010	0.608	0.549	0.269	20.10	15.98	4.12	3.88	0.69	0.48	-0.31

C7	0.120	0.778	0.130	0.209	0.100	0.010	1.905	0.549	0.259	22.32	17.58	4.74	3.71	0.58	0.50	-0.30
C8	0.190	1.243	0.200	0.281	0.120	0.020	2.486	0.712	0.271	30.04	23.04	7.00	3.29	0.69	0.43	-0.37
M1	0.429	2.865	0.429	0.669	0.180	0.200	60.850	4.003	0.858	155.96	136.65	19.31	7.08	0.66	1.74	0.24

$\delta Eu=(Eu)_N/0.5(Sm+Nd)_N$

$\delta Ce=(Ce)_N/0.5(La+Pr)_N$

$Ce_{anom}= \log(Ce/Ce^*)_{SN}= \log[2Ce_{SN}/(La_{SN}+Pr_{SN})]$

Table 1 Geochemical character parameters of Carbonate rocks. C1-C4 represent the gray sediment infilled in the burrows, C5-C8 represent the white carbonate and M1 represent the thin black Mn- and Fe-oxide precipitates~~ferromanganese crusts~~, some white part may be mix unavoidable.

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