Editor: Thank you for submitting a revised manuscript. Two reviewers have now provided comments on this revised version. While both reviewers find the manuscript greatly improved, there are still a number of smaller and larger issues to address prior to publication.
The first larger issue is the English grammar, which should be improved further. While all BG-manuscripts are edited for English in the final stage before publication, a higher initial level is required. Both reviewers provide useful suggestions. If possible, please involve a native English speaker in checking the manuscript. Please note that the title also contains an error: "Enhance" should be replaced by "Enhances". The second larger issue refers to the statistics and presentation of the regression lines in Fig. 5, as pointed out by one the reviewers.

We appreciate the work of the editor and two anonymous reviewers. We are thankful for all the valuable comments and suggestions. English languages are edited with the help from a commercial language service. Fig.5 is revised following the valuable suggestions from the reviewers. Below we have pasted in the entire review, and we have inserted our responses to the suggestions (blue font).

RC1: The authors have greatly improved the manuscript and representation of the figures, I just have a few more minor comments, and some technical corrections. The only thing that bothers me a bit is the amount of grammar mistakes and spelling errors in the manuscript. I would strongly advice to proofread the MS to remove as much of these as possible (I have highlighted a few in the technical comments section.

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

Sorry for our poor English writing. We have called for Language service for help with English language editing.

Minor specific comments:

P1L16: you are more highlighting the importance of bioturbation, not really the importance of deep-sea carbonate rocks

The sentence 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 bioturbation on global deep-sea carbonate rocks."

P3L5: did you take any pictures or determined what animals were exactly present in the rocks? I see now you did this in Figure 2, please add it in the method description

It was unfortunately that we did not take pictures of burrowing animals on the sea specifically. When carbonate samples were spread on the deck, benthic organisms were usually evident among the fractured rocks. Fig. 2c, d were taken from the fractured rocks on the deck.

P8L14: How exactly does your element and isotope results reveal minor external impact on the lithification?

REE patterns of the three types of sample 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) (Fig. 8). Positive correlation of $\delta^{13}C_{PDB}$ and $\delta^{18}O_{PDB}$ values of chalk and gray excrements (r = 0.91) reveals minor environmental influence on early lithification (Fig. 9). Thus, we deduced that the influence of nearby hydrothermal systems and other detrital input to the studied carbonate area should be negligible during the lithification history.

"We deduced from elements and isotope results that the influence of nearby hydrothermal systems and other detrital input to the studied carbonate area should be negligible during the lithification history"

P9L13: same remark as above, you did not illuminate the geological and biological importance of carbonate rocks. You illuminated the importance of burrowing animals on the lithification of carbonate rocks

The sentence has been rephrased:

"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 bioturbation on global deep-sea carbonate rocks."

Technical corrections:

P1L10: a tremendous amount of burrows

Thanks for your correction.

P1L10: the ultraslow spreading Southwest

Thanks for your correction.

P1L13: enhances deep-sea carbonate lithification

Thanks for your correction.

P1L24: may include diagenetic products

Thanks for your correction.

P2L8: Benthic fauna burrowing into the substrate plays a critical role

Thanks for your correction.

P2L10: you could also cite more recent papers here, e.g., (doi:10.1007/s10498-016-9301-7)

Thanks for your reminding.

P2L29-30: promoted deposition of high quantities of carbonate deposits

Thanks for your correction.

P3L7: were kept frozen in dry ice

Thanks for your correction.

P5L29-30: this sentence is not very correct, pleas rephrase

It has been rephrased

"Therefore, the carbonate deposits on the SWIR could represent bioclastic deposition from "biogenic bloom", which was the productivity related event in a large part of Indian Ocean during the middle Miocene to the early Pliocene (Singh et al., 2012; Rai and Singh, 2001; Gupta et al., 2004; Arumugm et al., 2014").

P8L9 stable $CaCO_3$ phases

Thanks for your correction.

P8L10 that is not likely to happen

Thanks for your correction.

P8L21: Berner and Westrich, 1985, American Journal of Science is more appropriate here

Thanks for your reminding.

RC2:

Second review of BG-2018-46

I have now completed a second review of the manuscript now re-titled "Macrofaunal burrowing Enhance Deep-sea Carbonate Lithification on the Southwest Indian Ridge".

The authors have taken the previous round of reviewer comments seriously and the manuscript is much improved. That said, there are still two outstanding issues that were raised in the original review that prevent acceptance in its current form.

First, many minor grammatical errors remain – I have made suggestions for correcting some of the most glaring errors below in the specific comments. I appreciate that special attention has been made to the English in this current revision, and it is indeed improved. However, it still requires further proof-reading for English before it can be considered ready for print. I implore the authors to consider an external proofreading service or other solution that will ensure that the grammer is up to par.

Sorry for our poor English. We have called for Language service for help with English language editing.

The second and more important issue relates to the statistical analyses of the change in density surrounding the burrows. While the authors provide R-squared values for their fits, they do not plot the fits, nor their confidence bounds. Instead the current figure simply has lines connecting the points, however the points are not in increasing order, so the lines bounce all around in a zigzag manner. What I am hoping to see is the regression line drawn through the data along with the confidence bounds. See https://www.mathworks.com/help/stats/polyconf.html for an example where both the fit line and confidence bounds are shown overlaid upon the data. The basic statistical question is not "does each slope have a robust fit", which is what the authors currently provide. Instead, the basic statistical question at hand is "are the two slopes significantly different"? This is at the heart of the manuscript – whether bioturbation has a statistically significant influence on density (and thus carbonate lithification). I don't think these should be prohibitively difficult for the authors to address, and I continue to hold the opinion that this work should be eventually suitable for publication in Biogeosciences. In my opinion we aren't there yet – but definitely getting closer.

We are thankful for the valuable comments and suggestions for promoting the quality of data treatment. In the revised version of manuscript, confidence bounds are shown in the figure. With 95% confidence bonds, bioturbated area > 1000 (pixels unit) shows significantly *difference with unbioturbated area>1000. Integrated density extracted from the area <1000 seems not significant.*

Integrated density obtained by ImageJ is the summation of calibrated gray values. No matter how large the diameter of each burrow is, we measured the gray values of the 10 pixels (~0.3 cm) around the burrows. Thus, compared to the burrows with small diameter, areas around burrows with bigger diameters are more representative. Nevertheless, the difference of the integrated density can be shown from Fig. 5.

In order to make the comparison more clear, an independent t-test was run on the data (Integrated density/Area ratios in Fig. 5) with a 95% confidence interval (CI) for the mean difference. The mean difference is 0.488-0.588=0.100. The p-value of Levene's test is 0.003 < 0.005, so we reject the null of levene's test and conclude that the variance is significantly different. The negative t value in the test indicates that the mean values for the first group, bioturbated, is significantly lower than the second group, control. The 95% CI is [-0.0124, -0.0753], which does not contain zero, this agree with the small p-value (0.000) of the significance test.

	Data numbers	Mean	Std.Deviation	Std. Erro Mean
Bioturbated	113	**0.488**	0.054	0.005
Control	59	**0.588**	0.087	0.011

	Levene's test for equality of variance		t-test for Equality of means						
								95% confidence interval of the Difference	
	F	Sig.	t	df	Sig.(2-tailed)	Mean difference	Std. Error Difference	Lower	Upper
Equal variances assumed	9.110	**0.003**	-9.285	170	0.000	-0.100	0.0108	-0.1213	-0.0788
Equal variances not assumed			**-8.048**	**81.633**	**0.000**	**-0.100**	**0.0124**	**-0.1248**	**-0.0753**

Specific comments

Pg. 1, Line 10: "blanketing the seafloor of the"

Thanks for your correction.

Pg. 1, Line 12: "in this carbonate lithified area"

Thanks for your correction.

Pg. 1, Line 13: "were examined" … also "enhances".

Thanks for your correction.

Pg. 2, Line 18: This is a bit awkward, I recommend "We examined this intriguing occurrence of non-burial carbonate… and highlight the interactions…"

"In this research, we examined this intriguing occurrence of non-burial carbonate lithification in the deep-sea and highlight the interactions that take place between bioturbation and lithification on the mid-ocean ridge."

Pg. 2, Line 28: "substantially in"

Thanks for your correction.

Pg. 3, Line 19: "which is a public"

Thanks for your correction.

Pg. 3, Line 27: "The MATAB function polyfit was used"

Thanks for your correction.

Title of section 5.2: "around burrows"

YES, Maybe you refer to the section 4.2 and it has been changed.

Pg. 5, lines 29–31: There are multiple grammatical problems in this sentence.

It has been rephrased

"Therefore, the carbonate deposits on the SWIR could represent bioclastic deposition from "biogenic bloom", which was the productivity related event in a large part of Indian Ocean during the middle Miocene to the early Pliocene (Singh et al., 2012; Rai and Singh, 2001; Gupta et al., 2004; Arumugm et al., 2014). "

Pg. 6, Line 4: "from SEM images"

Thanks for your correction.

Pg. 6, Line 20: "hydrothermal systems and detrital input"

Thanks for your correction.

Pg. 7, Line 24: "bulk samples are"

Thanks for your correction.

Pg. 7, Line 31: "deep-sea environments"

Thanks for your correction.

Pg. 8, Line 7: "of the studied carbonate area"

Thanks for your correction.

Pg. 8, Line 9: "phases", then line 10: "this is not likely to occur here"

Thanks for your correction.

Pg. 8, Line 12: "However, the carbonate samples studied here have never been buried"

Thanks for your correction.

Pg. 8, Line 15: "Moreover, ecological niches"

Thanks for your correction.

Pg. 8, Line 18: The beginning of this paragraph has grammatical problems.

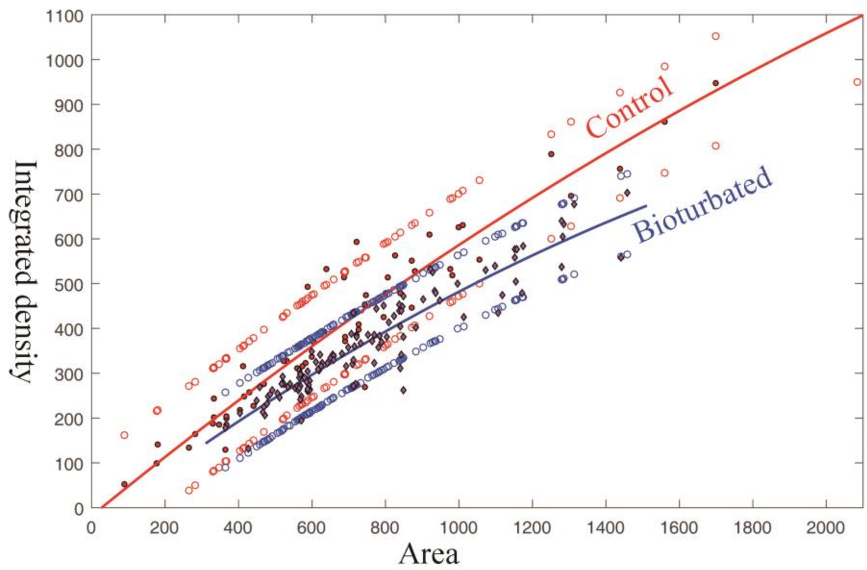
Thanks for your correction.

Conclusion: Multiple grammatical issues.

Thanks for your correction.

Figure 5: There are lines connecting the points that show a zig-zag pattern as they trace the order of the points without any sorting. In other words, they are simply connecting the points in a random order. These lines should be removed and the actual fits presented (the trendlines that go through these point clouds, which are not currently shown).

Thanks for reminding. Fig.5 has been edited following your suggestion.



Macrofaunal burrowing Enhances 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 the upper oceanic crust and their contribution to deep-sea geochemical cycles. However, the role~~s~~ of deep-sea macrofauna in carbonate lithification remains poorly understood. A large lithified carbonate area, characterized by thriving benthic faunas and a tremendous amount~~s~~ of burrows, was discovered in 2008, blanket~~ed on~~ing the seafloor of the ultraslow spreading Southwest Indian Ridge (SWIR). Benthic inhabitants, including echinoids, polychaetes, gastropods, a~~s well as~~nd crustaceans, are abundant in this carbonate lithified area~~s~~. The burrowing features within these carbonate rocks, and the factors that may influence deep-sea carbonate lithification, were ~~reported~~examined. We suggest that burrowing in these carbonate rocks enhances deep-sea carbonate lithification. We propose that active bioturbation may trigger the dissolution of the original calcite and thus accelerate deep-sea carbonate lithification on mid-ocean ridges. Macrofaunal burrowing provides a novel driving force for deep-sea carbonate lithification at the seafloor, illuminating the geological and biological importance of bioturbation in global deep-sea carbonate rocks ~~on global mid-ocean ridges~~.

1 Introduction

Carbonate rocks and various types of sediments ~~of various types~~ have been discovered on 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 the 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 deep sea are biogenic in origin and may ~~involve~~ include diagenetic products that originate from calcareous biogenic debris. The l~~L~~oss of porosity with increasing age and burial depth is associated with the transformation of deep-sea calcareous ooze to chalk~~,~~ and, subsequently, to limestone (Flügel, 2004). Nevertheless, the processes involved in the formation of deep-sea carbonate rocks remain controversial. It has commonly been assumed that deep-sea carbonate lithification is driven by various processes, including gravitational compaction, pressure dissolution, and reprecipitation, that take~~s~~ place during burial (Croizé et al., 2013). The ~~L~~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 fact~~s~~ that: (i) the degree of burial is commonly inconsistent with the known burial depth and paleontological age ~~(Schmoker and Halley, 1982),~~ (Schmoker and Halley, 1982); and (ii) lithified carbonate rocks found on the seafloor commonly show no evidence of burial (Thompson et al., 1968). The ~~L~~lithification of deep-sea carbonates has also been associated with the breakdown of oceanic basalts or prolonged exposure to the chemical gradients at the sediment-water interface (Pimm et al., 1971; Bernoulli et al., 1978). However, the processes responsible for such seafloor lithification remain debatable.

Benthic fauna ~~drilling~~ burrowing into the substrate plays a critical role in sediment evolution, because ~~of~~ they enhanced the interactions between sediments, interstitial water and overlying water~~,~~ by changing the geochemical gradients in the sediment, restructuring bacterial communities, and influencing the physical characteristics of the sediments (Furukawa, 2001; Lohrer et al., 2004; Meysman et al., 2006; Barsanti et al., 2011; Lalonde et al., 2010~~)~~ van de Velde and Meysman, 2016). Although burrowing 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 lithification effects ~~of~~ on semi-lithified and lithified carbonate rocks in deep sea settings.

Non-burial carbonate samples were collected in 2008 near a newly discovered hydrothermal vent on the 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 rocks, which were associated with ~~a~~ thriving benthic biota, are characterized by numerous macrofaunal burrows. In this research, we ~~attempted to explore the~~examined this intriguing occurrence of ~~unique~~ non-burial carbonate lithification in the deep-sea and ~~to~~ highlight the interactions that take place between bioturbation and lithification on the mid-ocean ridge.

2. Geological Setting

The Southwest Indian Ridge (SWIR), which is the major boundary between the Antarctic Plate and the African Plate, and is 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 the 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~~ at 2000 to 2500 m water depths~~, was found at water depths of 2000 to 2500 m on segment 26 of the SWIR, near a newly discovered hydrothermal field (Fig. 1). It has been widely reported that primary productivity increased substantially ~~at~~in the Indian Ocean during the Late~~st~~ Miocene–Early Pliocene (Arumugm et al., 2014; Gupta et al., 2004; Rai and Singh, 2001; Singh et al., 2012). This phenomenon known as the "biogenic bloom" promoted the deposition of~~significantly~~ high quantities of carbonate ~~deposits~~ at the seafloor between 9 to 3.5 Ma (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 a TV-grab~~s~~ bucket operated from the R/V Da Yang Yi Hao. The survey sites covered an area ~~of~~that was 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. These organisms were identified in classes of echinoids, polychaetes, gastropods, and crustaceans in hand specimens.~~-~~ Samples were subsampled after recovery, and then stored at -20 ℃ in plastic bags for mineralogical and geochemical analysis. Subsamples used for molecular phylogenetic analysis were kept frozen in dry ice ~~frozen~~ and transported to the laboratory.

3.2 Computerized X-ray tomography (CT)

The ~~Q~~quantitative measurement of the significance of biological influence is difficult because the physico-chemical properties around burrow walls are dynamic. Computerized X-ray tomography is a non-destructive method that has been used 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 located in the Shanghai 10th People Hospital, Tongji University. CT images were computerized by reconstruct~~io~~ng ~~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 2.5 mm, and the accuracy of distance measurements in the x and y-planes was 0.2 mm. The instrument operated at 140 kV, with a current of 10 mA ~~current~~, and an exposure of 1.5 s ~~exposure~~.

CT images were further characterized by *Image~~-~~J*, which ~~wa~~is a public domain Java-based image processing program. Gray values, which were correlated with the attenuation values and HU, were extracted to make a ~~comparing~~ comparative description of the density changes of the carbonate sample. A total of 40 CT images were selected, and each gray value inverted using min = 0 and max = 255~~,~~ regardless of the data values; that ~~was~~is, 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 burrows 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 burrows, which are approximately 0.9 cm) around the burrow holes were measured.

Additionally, randomly selected areas away from the burrows were selected as controls. The MATLAB ~~F~~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 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 the fusion of 0.1 g of sample material with 3.6 g of dilithium tetraborate at 1050 ℃ 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. Samples used 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 the geostandard GSD9 and sample duplicates, were better than 5%.

The ~~S~~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 ℃. Analytical precision was monitored using the Chinese national carbonate standard, GBW04405. The ~~C~~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 were characterized by complex honeycombed structures, with Mn- and Fe-oxides commonly encrusting the surface and inner surface of the carbonate rocks (Fig. 2). Benthic inhabitants, including echinoids, polychaetes, gastropods, and crustaceans, which are usually recognized as successful burrowing classes in marine sediments (Kristensen and Kostka, 2013), were abundant in hand specimens (Fig. 2c, d). the ~~B~~burrows drilled by benthic fauna ~~showed from~~revealed by CT scanning images are in straight, branched, or J- and U-shaped, with a density of up to 12 per dm^2 (Fig. S1). ~~-~~Burrows commonly penetrate 6 to 10 cm into the rock ~~with~~ and are several millimeter~~re~~s to 2 cm in diameter. The area that surrounds the hole is usually brighter than that away from the burrow, which may indicate a different degree of lithification (Fig. 3a, 4a). Burrows can be classified in three categories. Burrows with living organisms can be categorized explicitly as fresh burrows (Fig. 2c, d). The second type is considered to be~~ the~~ vacant burrows, which are filled by gray excrements (Fig. 2b). Thin black Mn- and Fe-oxide precipitates commonly encrust the surface of carbonate and the inner surface of empty burrows (Fig. 2a, c, d) and are thus~~ are~~ classified as the third type of burrow. It has been suggested that Mn- and Fe-oxide precipitates grow at a very slow rate of 1-10mm/Ma. Coatings of black Mn- and Fe-oxide precipitates on the surface of the burrows indicate that they may have formed much earlier than the other burrows. Thus, the influence of bioturbation in this area ~~is~~ was most likely a continuous process during~~ the~~ early lithification and could play a significant role in both geological and biological processes.

4.2 Enhanced lithification around burrows

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

4. 3 Mineralogy

Based on XRD and elemental analyses, these rock samples consisted almost entirely of calcite and detectable quartz and~~,~~ halite, which 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 the accumulation of calcareous tests of floating micro~~-~~organisms (chiefly foraminifers) and ~~of~~ 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*), are dominant~~dominate~~ (Fig. 6). The presence of *Globigerina bulloides* indicates that the lithification history of carbonate rocks is less than 5 Ma (Pliocene-Recent) old. Therefore, the carbonate deposits on the SWIR could ~~be~~ represent bioclastic deposition from ‘biogenic bloom’, which was the productivity related event~~s~~ ~~‘biogenic bloom’~~ ~~to~~in a large part of Indian Ocean ~~during~~ during the middle Miocene to the early Pliocene (Singh et al., 2012; Rai and Singh, 2001; Gupta et al., 2004; Arumugm et al., 2014).

Although it was difficult to separate and quantify ~~the~~ small tests from the very fine matrix, the carbonates exhibited a relatively high test to matrix ratio that is representative of deep-sea chalk (Fig. 6a). Original skeletal grains were held together by cement. Body chambers in the foraminiferal tests, for instance, were partially filled by calcite cements (Fig. 6b, c). It was common to observe the accretionary overgrowth of calcite around the foraminifera test f~~o~~rom SEM images (Fig. 6c). ~~Dissolution~~ The 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. 6d, e). The gray excrements filling in the burrow primarily consisted of plates of coccolithophorids (*Calcidiscus leptoporus, Emiliania huxleyi* and *Gephurocapsa oceanica*). ~~Smooth~~ The smooth surfaces of the coccoliths in gray excrements revealed that dissolution commonly occurs influenced by the bioleaching of benthic fauna (Fig. 6f).

4.4 Geochemistry and isotope analysis

Three types of samples (chalk, gray excrements and thin black Mn- and Fe-oxide precipitates) exhibited similar elemental concentration patterns ~~for~~ with a high CaO content, reflecting the strong dilution effect of biogenic calcium (Table S1). One of the main characteristics of major and rare elements is the highly variable Sr concentration~~s~~ in different types of ~~the~~ samples. The storage of Sr on the seafloor is mainly caused by its substitution ~~of~~for Ca in calcium carbonate, while diagenetic recrystallization results in the decrease of Sr from the sediment (Plank and Langmuir, 1998; Qing and Veizer, 1994). The lower Sr/Ca ratio in chalk compared to those in 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 the bulk REE concentrations (Xiong et al., 2012). The REE patterns ~~of~~ in the three types of samples did not exhibit any hydrothermal anomalies, e.g., positive Eu ~~anomaly~~anomalies, but they inherit the characteristics of sea water, ~~by~~ exhibiting the enrichment of HREE ~~compared with~~over LREE and a negative Ce anomaly (except the Mn- and Fe-oxides) (Fig. 8). The influence of nearby hydrothermal systems and ~~other~~ detrital input to the studied carbonate area ~~should be~~was negligible during the lithification history.

The $\delta^{13}C_{PDB}$ values of 46 bulk samples ~~were~~ ranged from -0.37 to 1.86‰, which are typical values 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‰. The ~~P~~positive correlation of $\delta^{13}C_{PDB}$ and $\delta^{18}O_{PDB}$ values ~~of~~ in chalk and gray excrements (r = 0.91) reveals the minor environmental influence on early lithification (Fig. 9), and bioturbation should be a critical factor during the lithification. There is an evident depletion of carbon and oxygen isotopic values ~~of~~in gray excrements compared to those in chalks (Fig. 9). The c~~C~~arbon isotope signatures of carbonates near burrows ~~with higher density~~ were ~~relatively high compared to~~higher than those in undisturbed areas (Table 1).

5. Discussion

5.1 Bioturbation in carbonate rock on the SWIR

The dimensions of burrows can be estimated from tomographic cross-section of the samples. Burrows were generally a few ~~millimetres~~ millimeters to 2 cm in diameter, commonly penetrating 6 to 10 cm into the rocks and ultimately reaching a density of up to 12 per dm^2. If the burrows in straight, branched, or J~~-~~ and U~~-~~ ~~shaped~~ shapes (Fig. 2e) are simplified to a cylinder with the diameter of 1 cm and height of 6 cm, which are the median values of the burrows, then the estimated volume of the simplified cylinder ~~would be helpful to reckon~~can be used to determine the extent of substratum reconstruction by bioturbation. In this model, a 1 dm^2 surface area which can harbor 12 burrows on the surface, may reach up to 0.226 dm^3 of burrow space. Eventually, we can deduce that the carbonate substratum ~~is~~ has been reconstructed by bioturbation to a great extent.

Benthic fauna maintain burrows for certain purposes, such as ~~of~~ 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 they conventionally produced J- or U- shaped burrows that extended as long as several decimet~~re~~ers in hand specimens (Fig. 2c, e). Relic burrows allow sea water to directly penetrate into the carbonate rocks, which is beneficial ~~to~~ for the precipitation of black Mn- and Fe-oxide precipitates on the inner surface of the burrow (Fig. 2a, c). The genetic models for Mn- and Fe-oxide precipitates ~~has been~~ attribute~~d to~~ the precipitation of minerals ~~precipitated~~ out of the cold ambient seawater onto the rock surface ~~with~~ to 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; Petrash et al., 2011). The mucus layer may act as a favo~~u~~rable 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 reworking and bio~~-~~mixing during the frequent construction and maintenance of a burrow, mineralogical and geochemical parameters~~,~~ are also assumed to oscillate around the burrow.

In addition to ~~the~~ burrowing activity, benthic fauna ingest and excrete the substrate which usually serves the 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, bulk samples ~~is~~are 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 zones. Eventually, a microenvironment friendly for heterotrophic microorganisms 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) indicated~~ferred~~ 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 fauna in deep-sea environments, which ~~is~~ are limited by the availability of organic matter (Raghukumar et al., 2001). Thus, a balanced ecological sustainability is established by ~~the~~ carbonate deposits and continuous biological processes, which may largely influence the lithification history of ~~the~~ carbonates.

5. 2 Roles of bioturbation in lithification of carbonate rocks on the SWIR

The ~~A~~abundant macrofaunal burrows~~, as well~~ ands~~s~~ benthic fauna (e.g., polychaete worm, Fig. 2c) present on a cross section of carbonate rocks, as well as~~nd~~ enhanced~~ment of~~ density around burrows commonly observed from CT images (Fig. 3, 4), 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 the change in elemental composition ~~change~~ between different portions of the carbonate (Fig. 7). The ~~W~~water depth of the studied carbonate area on the 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 original tests or plates are dissolved under saturation conditions. Although less stable $CaCO_3$ phases (e.g., biogenic, high-Mg calcites) may dissolve above the calcite saturation horizon (Jahnke and Jahnke, 2004), ~~they are not likely~~that is not likely to ~~happen~~ occur here~~,~~ since our samples are low-Mg calcites. As a general rule, compaction takes place with the gradual increase in~~of~~ overburden pressure, resulting in the loss of porosity through mechanical and chemical compaction in the moderatelt ~~-~~deep burial stage. However, ~~present carbonate samples show they have never been buried~~the carbonate samples studied here have never been buried. Their lithification, therefore, may be different from those of other deep sea carbonates. We deduced from elemental and isotopic results that the influence of nearby hydrothermal systems and other detrital input to the studied carbonate area should be negligible during the lithification history ~~Elements and isotope results reveal minor external impact on the early lithification~~. The construction and ventilation of burrows can fundamentally alter biogeochemical processes and produce lateral heterogeneity, thus intensifying the redistribution of pore water fluids. Moreover, ~~the~~ ecological niches for microbial life are also formed by bioturbation (Ghirardelli, 2002; Koretsky et al., 2013). Thus, the simultaneous activity~~ies~~ of both thriving benthic fauna and the lithification of carbonate~~,~~ are potentially connected.

The organic matter content is ~~possibly~~ significantly low in the deep-sea sediments. 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 that polychaetes' mixing sediment particles is an important driving force behind the chemical reaction and transport of organic matter in marine sediments (~~Levinton et al., 1995~~Berner and Westrich, 1985). Benthic fauna, including polychaetes, reconstruct the carbonate substratum to a great extent, which ~~and~~ results in ~~a~~the fundamental alteration of their sedimentary environment. The ~~A~~aerobic respiration of bioturbated organic particles, such as ~~like~~ mucus, 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 lowering the pH of porewater around the burrow relative to the inner carbonate sediment, which may drive the dissolution of original calcite in the microenvironment (Fig. 10) (Emerson and Bender, 1981; Aller, 1982; Kristensen, 2000). The ~~I~~isotopic composition in gray excrements is lighter when compared to the chalks (Fig. 9; ~~table~~ Table 1). It is assumed that fecal~~faecal~~ pellets may be 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, such as ~~like~~ mucus, will inherit enriched ^{13}C, which is the major carbon source for microbial metabolic reaction. 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 observations. For instance, the body chambers in the foraminiferal tests are partially filled by calcite cements (Fig. 6c), which is believed to be derived internally through solution transfer (Durney, 1972).

In addition, relic burrows ~~make~~allow sea water to directly penetrate into carbonate rocks and lead to the precipitation of black Mn- and Fe-oxide precipitates in the inner surface of the 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 may prevent ~~the~~ rapid ion exchange between bottom water and porewater within carbonate rocks. Ca^{2+} and CO_3^{2-}, the products of $CaCO_3$ dissolution, prefer to diffuse to the interior of carbonate rocks, and lead to the reprecipitation of calcites as cements with higher ~~-~~$\delta^{13}C_{PDB}$ values in carbonate rocks (Fig. 10).

6. Conclusions

A lithified carbonate area characterized by active bioturbation was studied to explore the ~~area's~~ biological and geological interactions in this area. Although ~~the effect of~~ different parameters influenced by bioturbation cannot be easily ~~be~~ differentiated in a study of natural samples, available evidence~~s~~ shows that active bioturbations may trigger the dissolution of original calcite above the saturation horizon, thus enhancing the 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 illuminates~~-~~ the geological and biological importance of bioturbation on global deep-sea carbonate rocks~~the geological and biological importance of deep-sea carbonate rocks on mid-ocean ridges~~.

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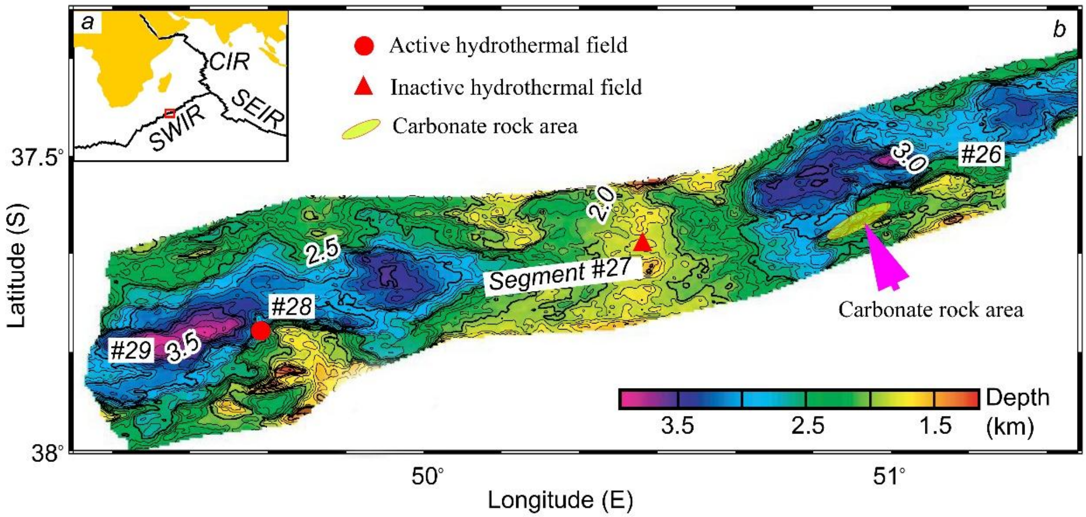

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Figure 1: (a) Location of study area on the Southwest Indian Ridge. (b) Bathymetric map of area which show the location of the carbonate rock area (green ellipse), the active hydrothermal field (red cycle), and the inactive hydrothermal field (red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

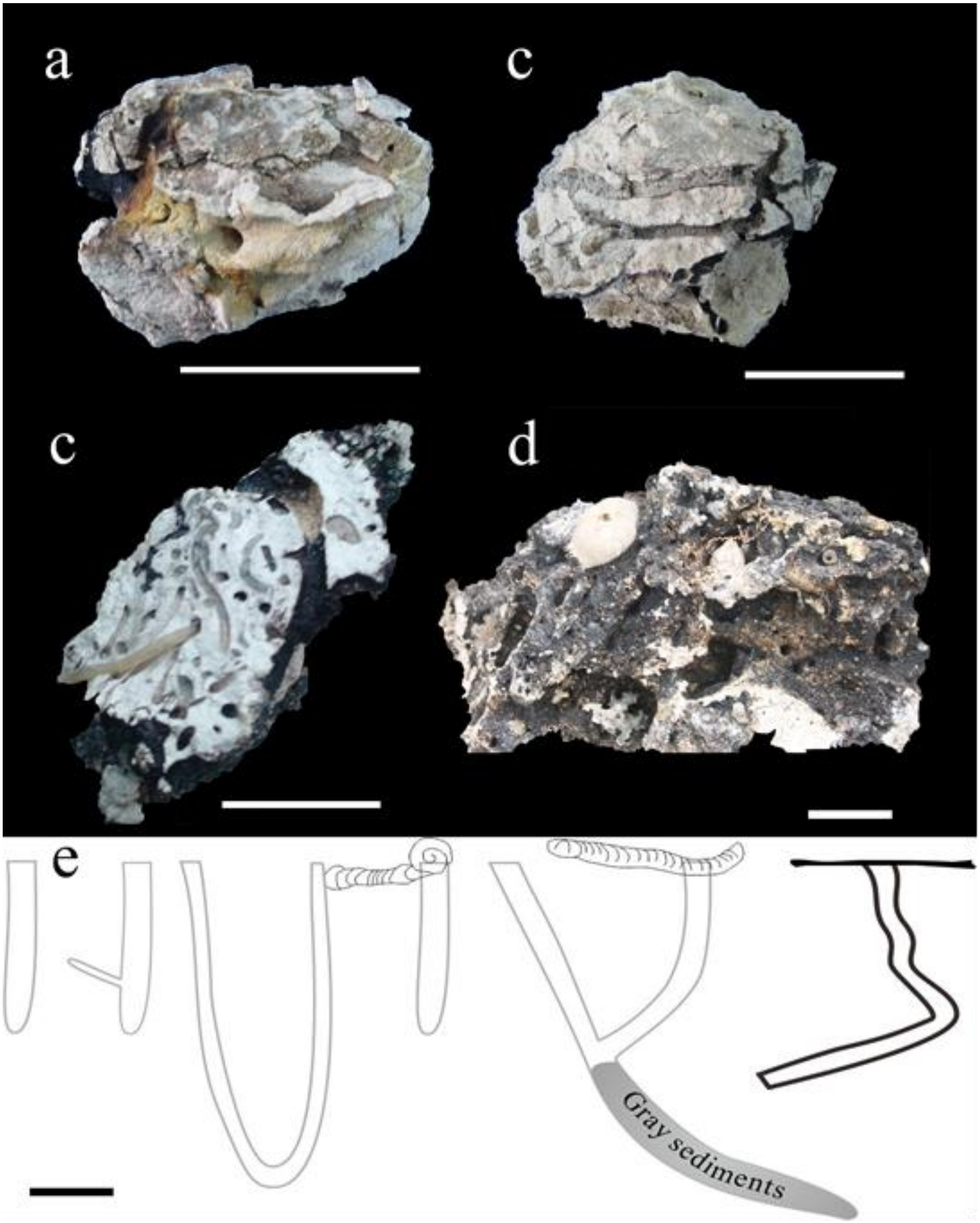

Figure 2: Deep-sea carbonate rocks collected from the SWIR. (a) A carbonate rock sample shows empty burrows are partly covered by ferromanganese crusts. (b) Straight and branched burrows are infilled by ~~grey~~ gray sediments. (c) Abundant burrows, as well as a benthic fauna (polychaete worm), are present on a cross section of a carbonate rock. (d) An echinoid, together with other benthic faunas, burrows ~~on~~ in a carbonate rock with ~~the~~ honeycombed structures and encrusted by thin ferromanganese crusts. (e) Sketch for different burrow structures in deep-sea carbonate rocks collected from the SWIR. Scale bar of a, c ~~are~~ is 5 cm, and the b, d e is 3 cm.

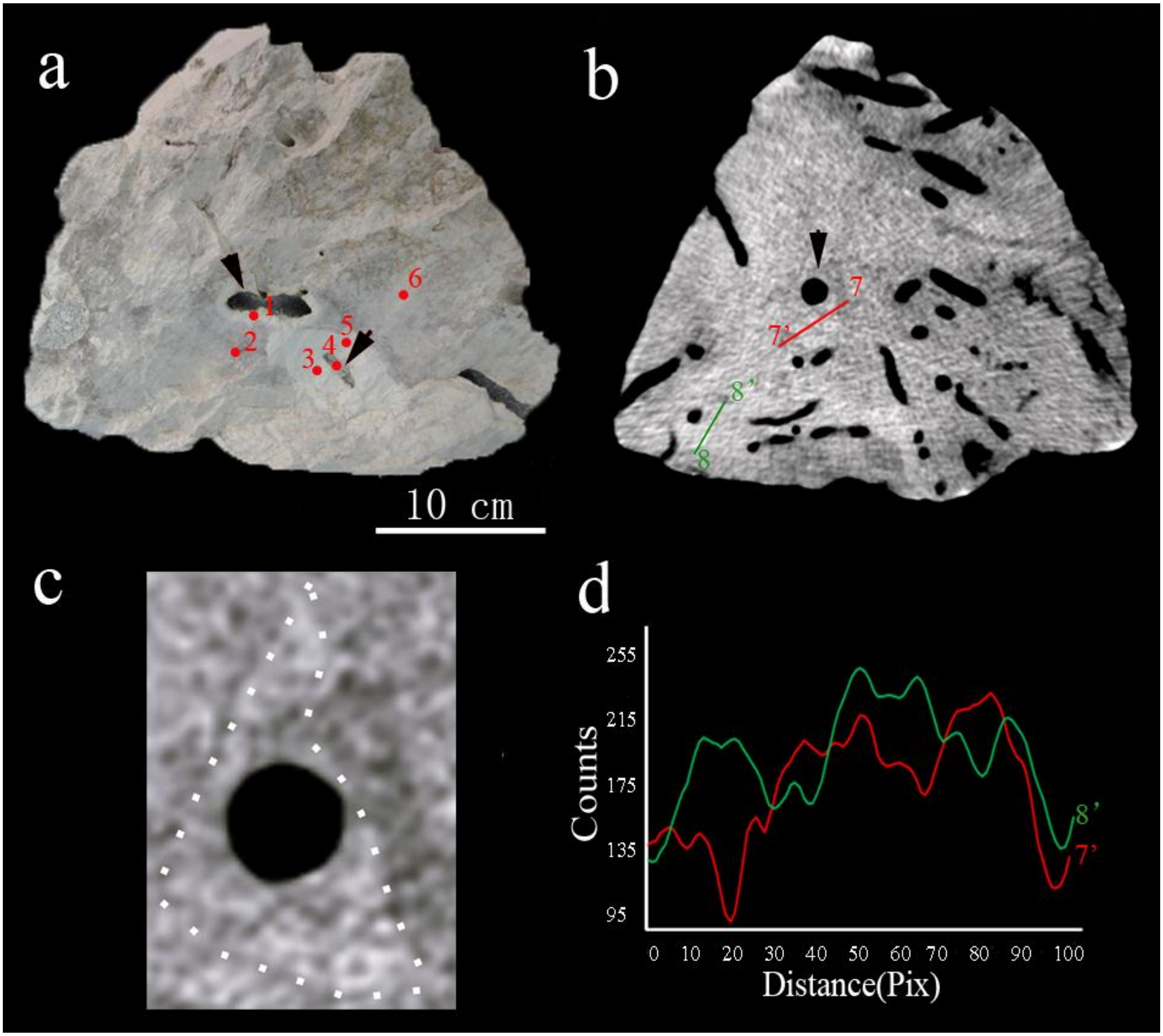

Figure 3: (a) A hand specimen shows the ~~enhancement~~ enhanced ~~of~~ brightness associated with burrow structures. Numbers of red dots indicate the subsamples for carbon and oxygen isotopic~~e~~ analysis in ~~table~~ Table 1. (b) Tomographic cross-section of the sample reveals that abundant burrows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

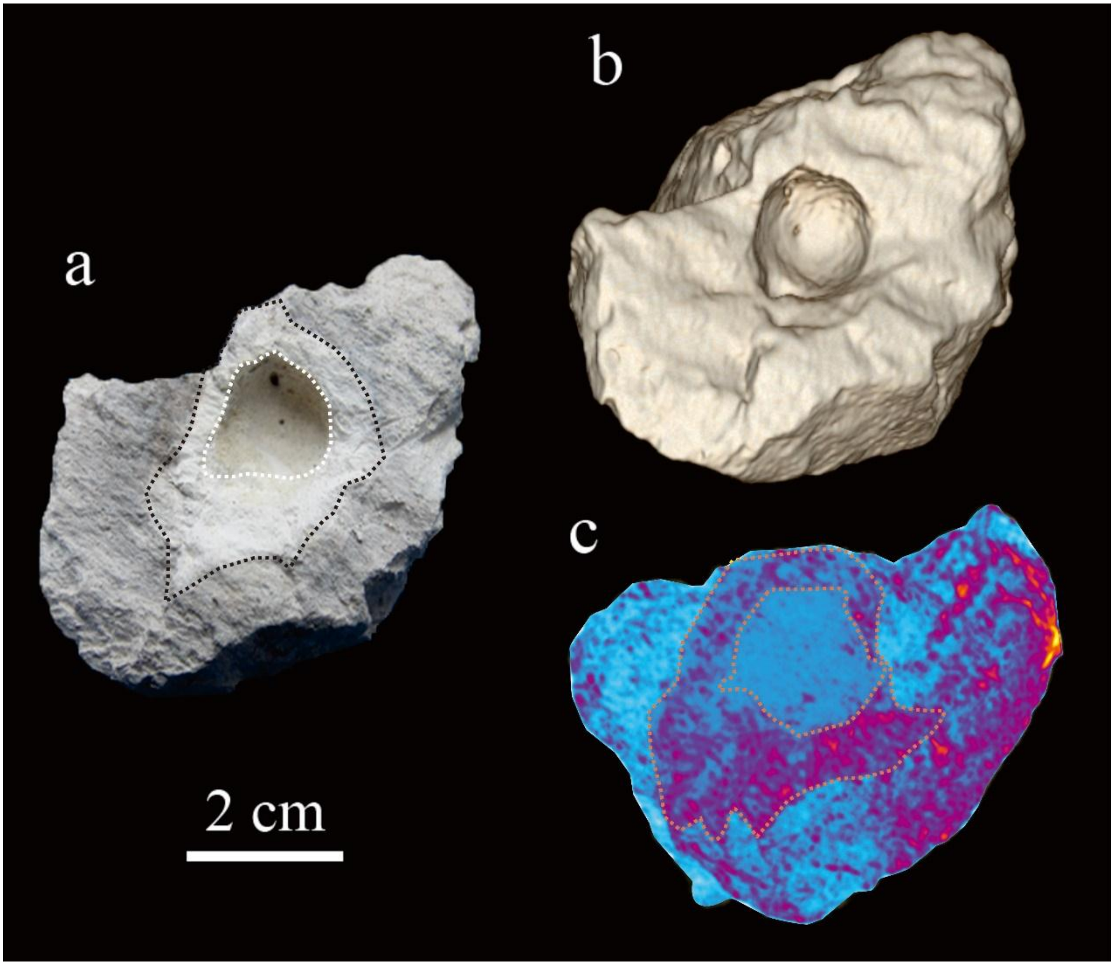

Figure 4: (a) A carbonate rock sample shows the ~~enhancement~~ enhanced of brightness associated with a burrow structure. (b) 3D reconstruction of the sample by CT shows the morphology of the sample. (c) 3D reconstruction of the sample by CT ~~exhibits~~ shows that the enhanced~~ment of~~ density is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

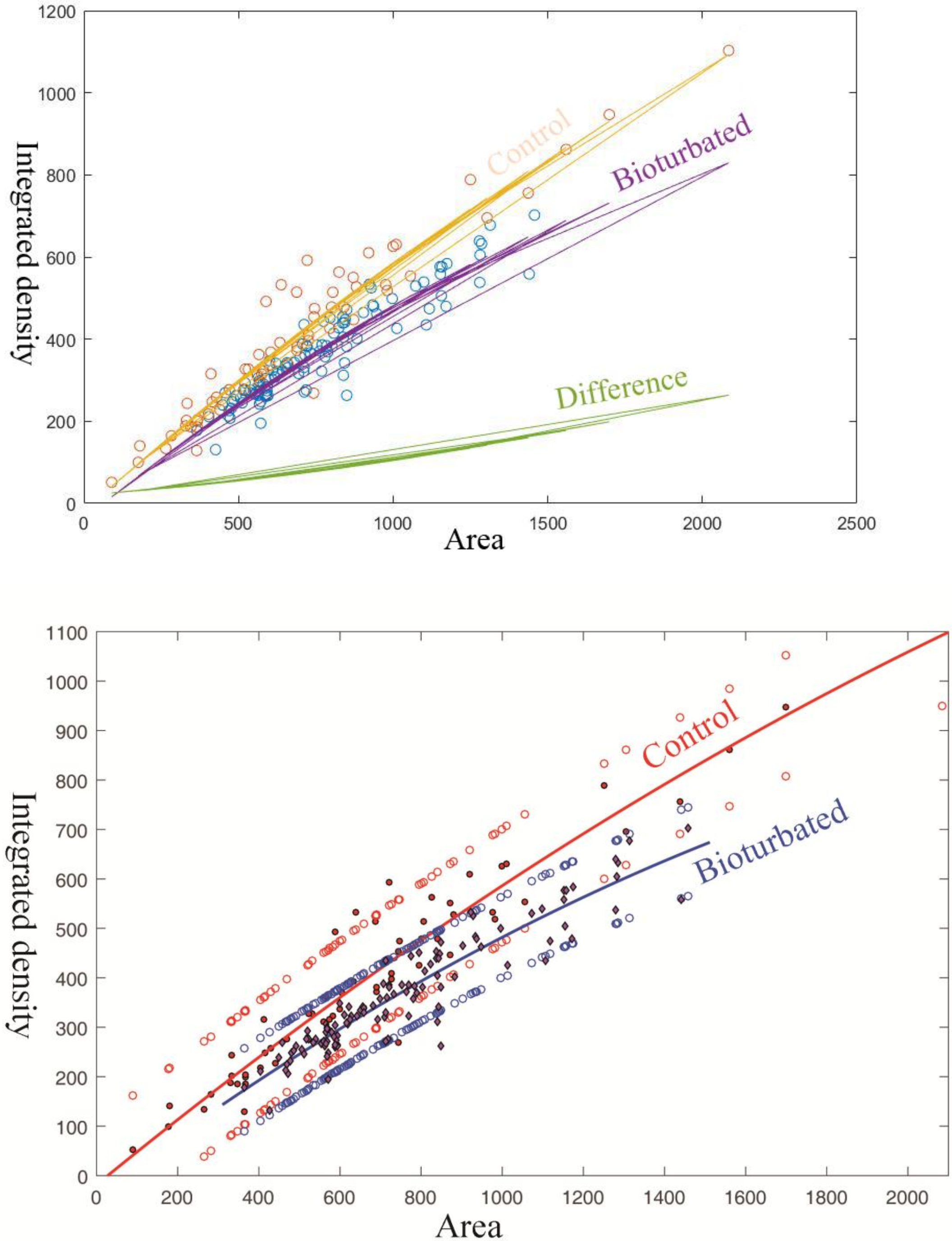

Figure 5: Statistical analysis of integrated density extracted from selected area around burrow and paralleled undisturbed area ~~clearly~~ shows different density around the burrows. Both images were inverted so that ~~bigger~~ a larger integrated density means a darker colo~~u~~r in the original CT image. The total number of analyzed burrows ~~are~~ is 113. Although 95% confidence bounds are

half overlain, ~~With 95% confidence bounds,~~ the statistical significance indicated by the change in density can be shown from the curves. ~~t~~The goodness of fit is shown~~ed~~ by $R^2_{bioturbate}$=0.9312 and $R^2_{control}$=0.8802.

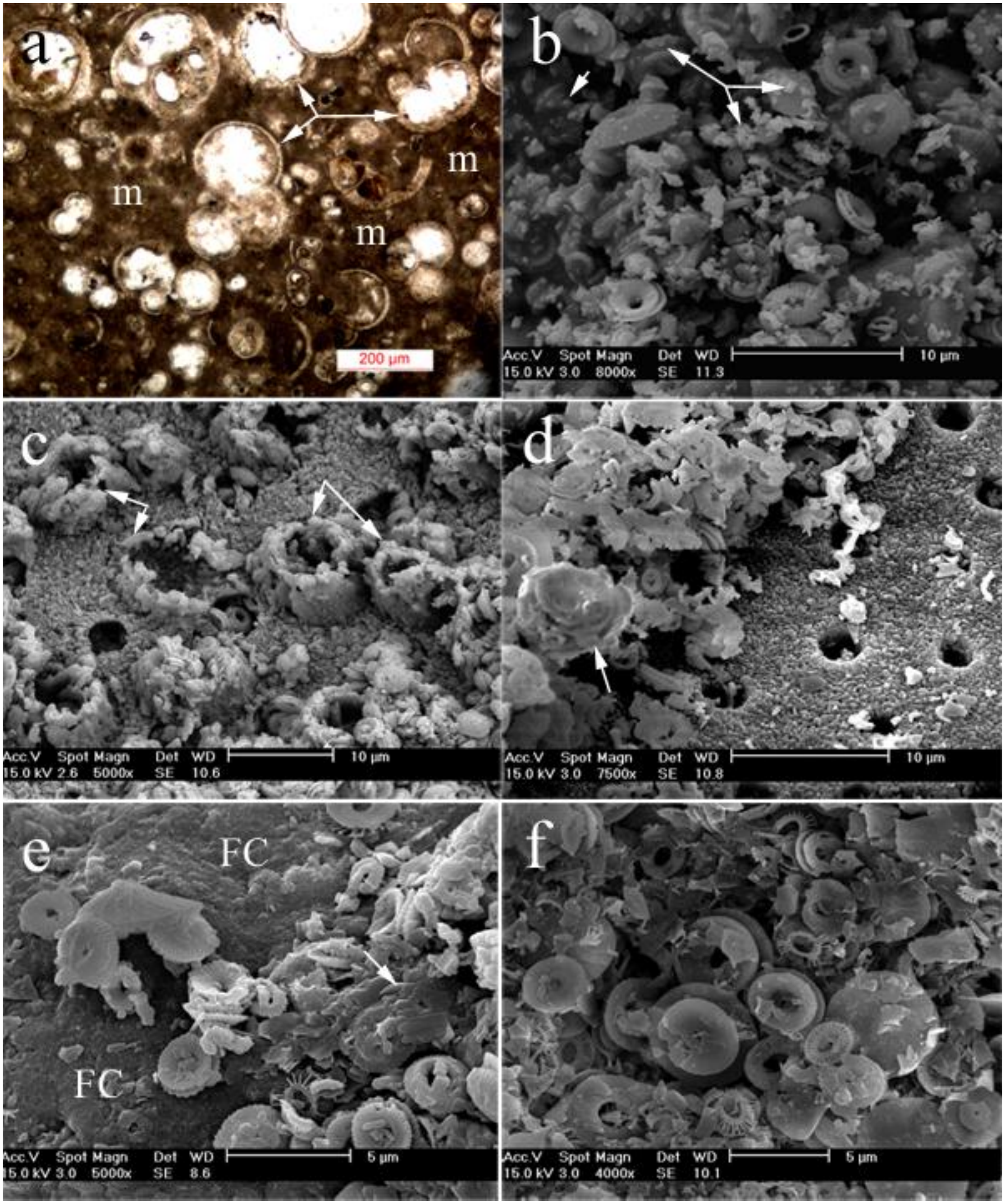

Figure 6: (a) ~~photomicrograph~~ Photomicrograph of thin sections of carbonate rocks shows a relatively high test (arrows) to matrix (m) ratio. (b) Scanning electron micrograph reveals abundant micritic carbonate particles (arrows) with many plates of coccoliths

in the interior of carbonate rocks. (c) Scanning electron micrograph shows overgrowths of calcites on the foraminifera~~l~~ 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 (FC). Arrow points out the dissolution of ~~the~~ coccoliths. (f) Scanning electron micrograph shows ~~grey~~ gray sediments ~~which~~ that infill the burrow. The s~~S~~mooth surfaces of the coccoliths indicate that ~~the~~ dissolution commonly occurs.

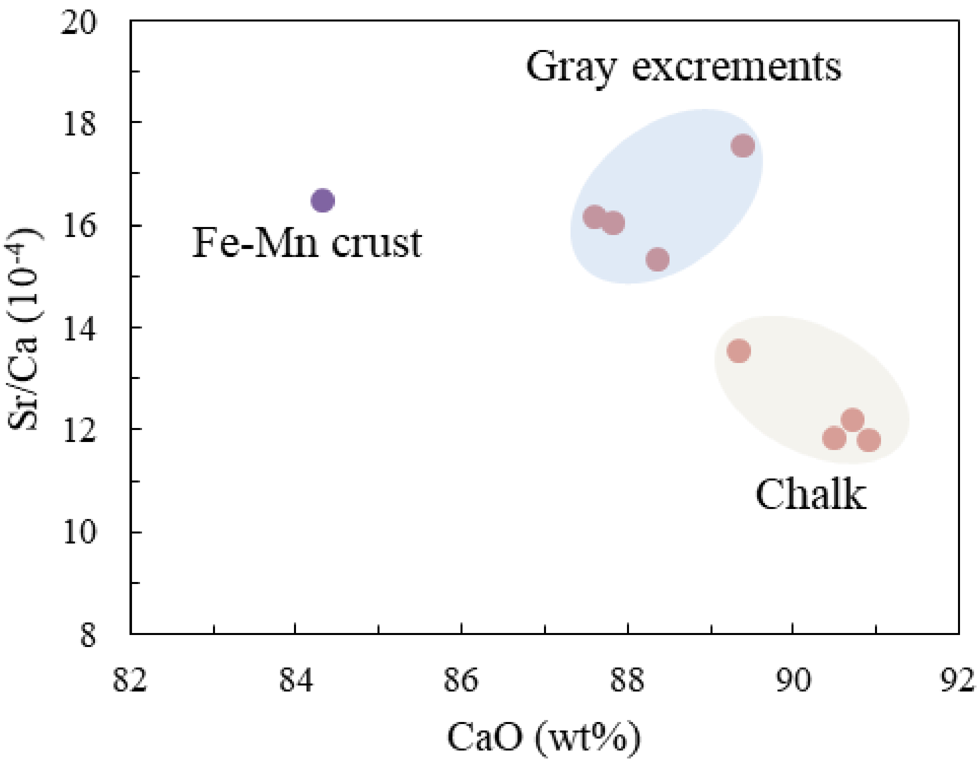

Figure 7: The lower ~~of~~ Sr/Ca values in chalk compared to those observed in the gray excrements represents the lithification of different portions of carbonate.

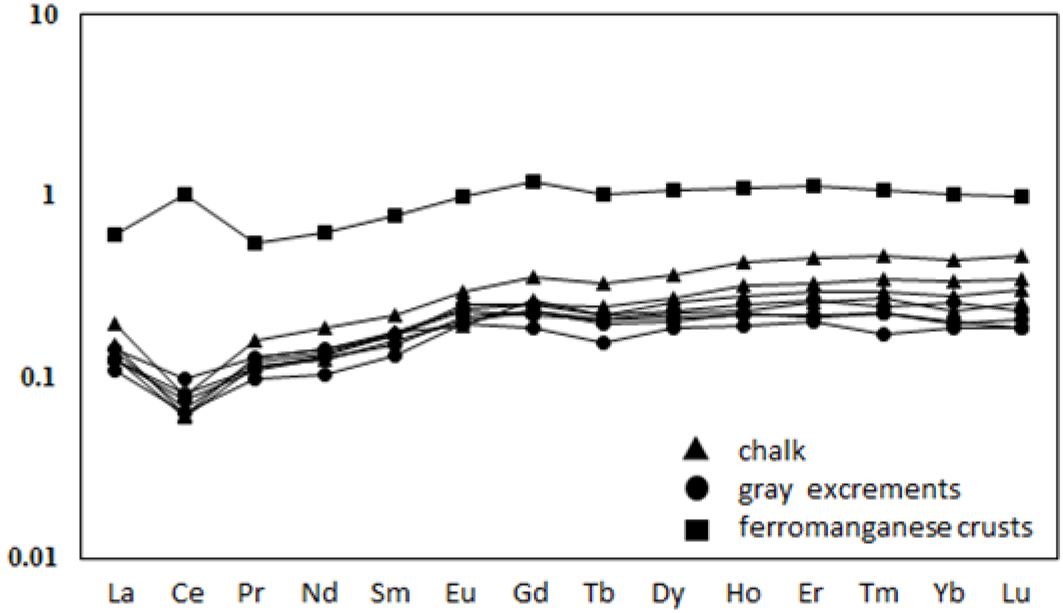

Figure 8: PAAS-normalized REE distribution patterns of selected samples from the SWIR.

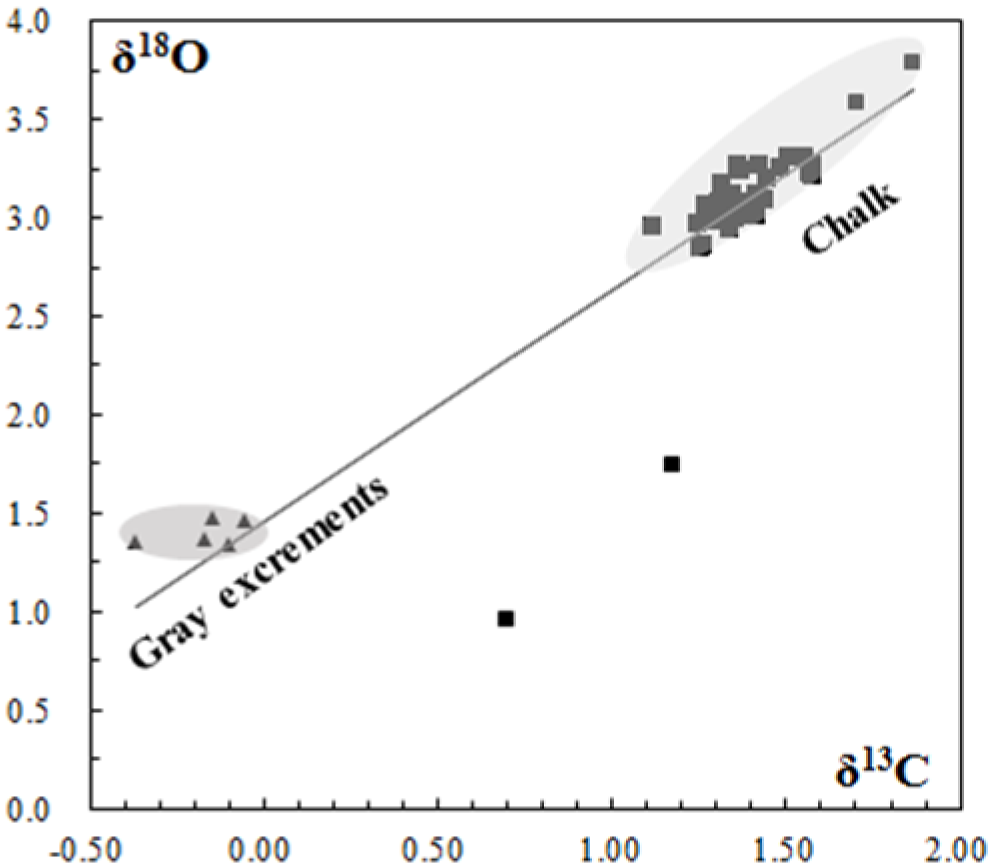

Figure 9: Oxygen and carbon isotopic composition of carbonate samples from the SWIR. Gray excrements contain ~~the~~ lighter carbon and oxygen isotopic values ~~compared to~~ than those in the chalk. The δ^{13}CPDB values of chalk and gray excrements are positively correlated with δ^{18}OPDB values (r=0.91).

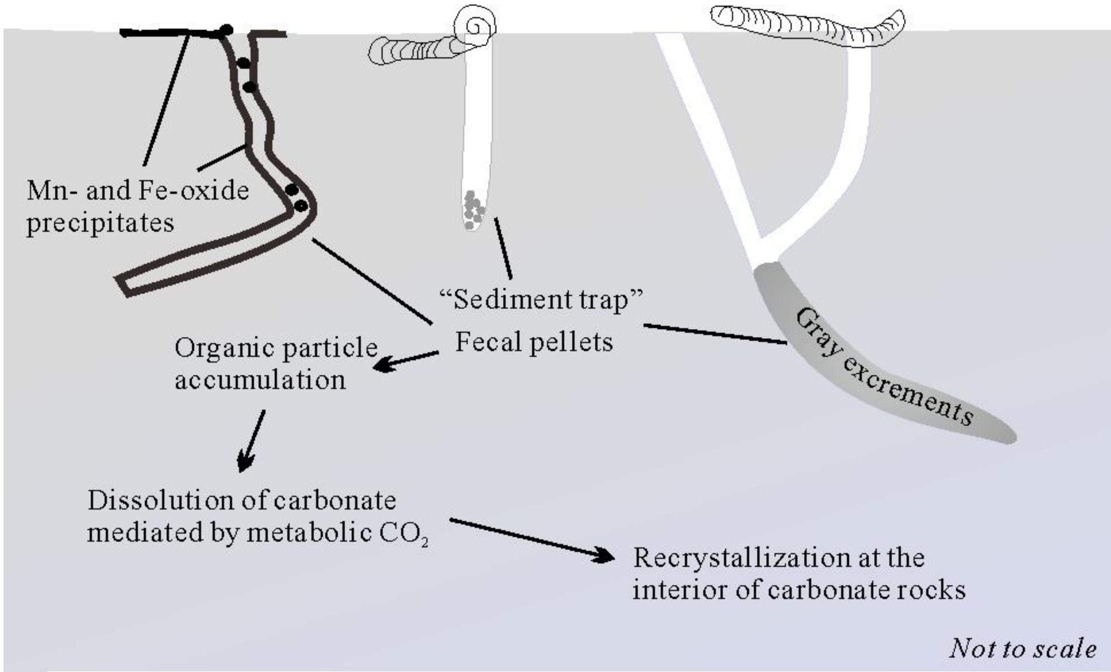

Figure 10: Schematic model for carbonate lithification influenced by bioturbation on the SWIR.

Sample NO.	$\delta^{13}C$ PDB	$\delta^{18}O$ 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: -Isotopic~~e~~ data for samples collected from ~~the~~ Figure 3a. 1, 3 and 5 represent ~~the~~ a higher density of influence~~d~~ by bioturbation compared to 2 and 6. 4 represents gray excrements infill~~ed~~ing in the burrows.