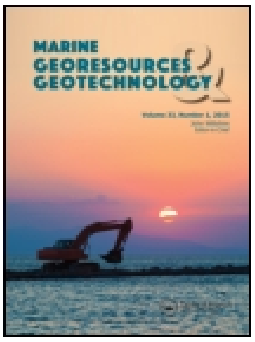

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Analysis and Evaluation of Coral Reef Integrity Based on Borehole Camera Technology

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Abstract

At present, very few drilling surveys have been conducted on coral reefs, and comprehensive geological info on coral reefs is difficult to obtain. However, research on coral reefs is of great importance to development and exploitation of maritime resources. In the survey of Chenhang Island in Paracel (Xisha) Islands, we applied the digital borehole camera technology the first time in China, which resulted in a large amount of first-hand geological data. We utilized the rock mass integrity index (RMDI) method in our analysis of coral reef integrity, and the value of coefficient α in the RMDI was determined to evaluate the size effect of cavities on coral reefs. We then developed the correlation between RMDI values and coral reef integrity with references to the rock mass classification standard, which enabled the engineering evaluation of coral reef integrity. By statistical analysis of camera data gathered along the CK2 borehole for approx. 1 km length, we

performed an integrity evaluation of the entire borehole length using the RMDI classification, and created a coral reef stratum development diagram that was consistent with the actual cores. The results indicated: (1) the RMDI is a feasible approach for the analysis of coral reef integrity; (2) the classification system based on RMDI is feasible in the integrity evaluation of coral reefs; (3) the values of coral reef integrity obtained using the RMDI method are accurate; and (4) borehole camera survey and statistical analysis are important in the study of coral reefs.

Keywords: borehole camera, classification standard, coral reefs, geological survey, rock mass integrity

INTRODUCTION

Coral reefs are rock and soil structures formed by the remains of scleractinian corals (see **Figure 1**) after long-term geological effects (Wei, Jia, and Meng 2008). They can be found widely and prominently around islands and certain coastlines in South China Sea. As the history of corals spans from the Paleozoic Era to the present, they can also be used as important indicators for stratum designation and analysis of past climate and geography. Coral reefs are affected by crust movements. They are generally formed in shallow areas 50 m below low tide line, with reefs above sea level indicating an upward movement of crust or lowering of sea level, and lower reefs indicating a downward crust movement. Coral reefs are also often found near abundant oil and natural gas resources. Coal, bauxite, manganese ore and phosphate rock have been found in the sediments of coral reefs and their lagoons, and strata-bound mineral deposits with multiple metals including copper, lead and zinc have been found through the rudaceous rocks of reef bodies. The coral limestone can be used as a raw material for lime and cement, the corals can also be used as decorations, and many coral reef regions have been developed for tourism (Ma 1994). In summary, the study of coral reefs is of great significance.

The main component of coral reefs is calcium carbonate ($CaCO_3$). As shown in **Figure 2**, it is porous and brittle, low in both hardness and strength. Drilling is an indispensable method in the background survey of coral reefs. Due to characteristics of their structure and limitations of technology, such as mechanical disturbances that may result in low or even zero coring rates, the geological info obtained is often incomplete, and traditional analytical methods are usually inaccurate. In addition, since the coral reef rocks is easily broken under high pressure, it is easy to cause the entire coral reef rocks crushing in the process of drilling. And it is hard to tell if the coral reef rocks are complete or broken from the core. Therefore, a singular reliance on drilling would affect the accuracy of coral reef research and even cause erroneous results. A better evaluation of the rock mass would require a combination of drilling and other complementary techniques. The digital borehole camera (Prensky 1999; Wang, Ge, and Bai 2001; Williams and Carole 2004) system has integrated digital video and computer control by using optical sensors for close observation of rock mass inside the borehole. The acquired information is then processed with computer to generate digital column-shaped image of the borehole walls (see **Figure 3**), which can solve the problems of integrity and accuracy in the collection of geological info in coral reef boreholes.

The basic quality of a rock mass is an inherent, fundamental property that affects its stability in engineering projects. It depends on internal factors of the rock structure, of which rock mass integrity is one of the controlling factors. The borehole camera system has enabled us to evaluate the geometric (macroscopic) intactness of a rock mass. Generally, the coral reefs contain no joints, fissures and fractures and tremendous amount of cavities exist within corals constituting the rocks. Therefore, despite the fundamental importance of rock mass integrity evaluation the existing evaluation methods are not applicable in investigation of coral reefs. This paper presents an analysis and evaluation of coral reef integrity based on borehole camera by introducing the rock mass integrity index (RMDI) (Wang, Hu, and Sun 2010)and re-determining the α value (Wang and Wang 2014), which enables the application of the RMDI approach on the evaluation of coral reef integrity. It provides an in-depth comparison between results of RMDI method and actual engineering, by comparing the RMDI values acquired from borehole CK2 at Chenhang Island, Xisha (Paracel) Islands with geological info obtained using other methods. The rock mass classification standard is then used to help determine the corresponding degrees of rock mass intactness for the RMDI values.

BOREHOLE CAMERA

The key to the digital panoramic borehole camera system lies in breakthroughs of panoramic (reflector on the conical surface) and digital (digital video and imaging) technologies. The panoramic technologies enable a 2-dimensional representation of the 360° borehole wall, which is overlayed with directional info, creating a panoramic image. Digital technologies allow the digitization of videos, which are processed with inverse transformation algorithms to construct a model of the borehole wall and generate a digital vertical image. The borehole camera image is an intuitive representation of the cavities and other geological info of the borehole wall. By processing this info, a complete database can be generated, which can be used to statistically determine the number and sizes of visible cavities in the image. **Figure 4** is a schematic diagram of borehole camera imaging.

RMDI METHOD

The Cavity Density Function

As the shapes of cavities in coral reefs can vary greatly, the cavities were treated approximately as rectangles for the purpose of calculation. Since there is remarkable difference between the axial and horizontal dimensions of the borehole, the borehole image has been compressed along the axial direction to make the image more readable. Therefore, the oblong in the image may not be the oblong in the summation. We defined the length of an oblong cavity to be **a**, and the width to be **b** in the summation.

We defined the degree of effect of cavities on coral reefs within unit depth as the coral reef cavity density. The cavity density function is a function that varies along the borehole axial direction, represented as ***g*(z)**, where **z** is depth of the borehole, the expression can be simplified into

$$g(\mathrm{z}) = \frac{\sum_{k=1}^{\mathrm{d}} (\mathrm{a}_k \cdot \mathrm{b}_k)}{\Delta h \cdot \Pi \cdot R} \qquad (1)$$

Where $\mathbf{a}_k$ is the length of the *k*th cavity; $\mathbf{b}_k$ is the width of the *k*th cavity; **d** is the total amount of cavities; Δh is the depth to be measured; $\prod$ is the circumference ratio; R is the diameter of the borehole.

The Lumpiness Function

The formation of coral reefs is affected by multiple factors. Its characteristics cause the rock mass to have multiple sections of intact rocks in addition to multiple hollow and broken sections. For the purpose of evaluating the maximum value of intact rock height within a unit depth, we established the lumpiness function $\ell(\mathrm{z})$, expressed as

$$\ell(z) = L/H \qquad (2)$$

Where **H** is the depth to be measured; **L** is the maximum height of intact rock within the depth to be measured; generally $0 \leq \mathbf{L} \leq \mathbf{H}$. If the value of the lumpiness function $\ell(z)$ is zero, it indicates the given section of rock mass is hollow.

The DIDF Function

Since the coral reefs is a complex entity formed from geological structures of the coral reef, the integrity shown in borehole images directly depends on its geological structures. A very small number of tiny cavities have little effects on the rock mass integrity, and its image shows even distribution of colours, which is an indication of high integrity, while a relatively high number of large cavities break up the rock mass, causing its image to show great variation in colours and signs of fragmentation. We established a single-variable function that varies along the borehole axial direction, the rock mass integrity index density function (DIDF), represented as ***f*(z)** where **z** is depth, expressed as

$$f(z) = \alpha \times 1 \qquad (3)$$

Where $0 \leq \boldsymbol{\alpha} \leq 1$. If the value of ***f*(z)** is 1 or approximating 1, it indicates the rock mass at the given depth has high integrity; the smaller the ***f*(z)** value is, the lower the integrity is, and the more fragmented the rock mass appears.

The Coefficient α

Due to the porosity of coral reefs, its integrity is affected not only by the size of lumpiness, but also by the cavities. The coefficient $\boldsymbol{\alpha}$ in the DIDF represents both effects, with their relations expressed as

$$\alpha = \ell(z)\cdot[1-g(z)] \quad (4)$$

The RMDI Value

The coral reefs integrity index density function DIDF is a reflection of rock mass intactness along borehole axial direction. The rock mass integrity index (RMDI) (Wang, Hu, and Sun 2010) refers to the proportion of intact rock bodies within a given range, expressed as a percentage, where the given range can be a part of the borehole or the entire depth. If the given depth range is ($\boldsymbol{h_1}$, $\boldsymbol{h_2}$), the RMDI can be expressed as a definite integral of DIDF within the range, expressed as

$$\mathrm{RMDI} = \frac{\int_{z}^{z+\Delta h} f(\mathrm{x})\mathrm{dz}}{\int_{h_1}^{h_2} 1\mathrm{dz}} \quad (5)$$

Analysis of an Example

During the geological survey on coral reef islands in the central northern parts of South China Sea, a panoramic digital camera survey was completed along the full length of the CK2 borehole in Chenhang Island, with the depth ranging from 22 to 924 m. An info database was created through acquisition of info from borehole walls and processed by computer to generate the borehole image. The sizes and numbers of visible cavities in the image were statistically analysed, and the rock mass integrity index was calculated in the following steps.

Step 1: establishing the cavity density function. Based on the sizes of cavities in the rock mass, the total area of cavities was determined, and the cavity density function was established with the ratio of cavity area to total area (see **Figure 5**)

Step 2: establishing the lumpiness function $\ell(z)$. In this instance, the maximum height of intact coral rock **L** within each meter was calculated by using the unit depth 1 m, and then the lumpiness function $\ell(z)$ was established (see **Figure 6**).

Step 3: establishing the rock mass integrity index density function. After the above-mentioned parameters had been determined, the $\boldsymbol{\alpha}$ value was calculated and, and the DIDF was established (see **Figure 7**).

Step 4: determining the rock mass integrity index value. As the CK2 is a relatively deep borehole approximating 1 km in depth, 10 m was used as the basic unit to simplify the calculation and assessment of RMDI (see **Figure 8**).

CORRELATION BETWEEN RMDI AND ROCK MASS INTACTNESS

Classification of Rock Mass Intactness

Rock mass intactness refers to the extent of development of various geological interfaces, mainly the fissures and faults. It is a generalized representation of the rock mass structures, and is determined by many factors including the shearing of structural planes, the sizes of structural bodies, and the cementation between bodies. A high-intactness rock mass has fewer faults, and a low-intactness rock mass contains more faults. It is one of the most important signs of rock mass quality, and used in rock engineering as an overall indicator. Thus it is important for rock engineering to find methods that allow simple and scientific evaluation of rock mass intactness.

Whether the qualitative classification or the quantitative assessment, the various classification of rock mass all are correlated with the integrity. The integrity is an important signifier for the strength and deformation of rock mass. The domestic engineering geologists have always used properties of joints and fissures (which directly affect rock mass integrity) to describe the engineering characteristics of rock mass, especially the distances between joints and fissures. **Table 1** shows the China's "Code for investigation of geotechnical engineering", "Technical code of railroad engineering geology", "Code of engineering geological survey", "Code for hydropower engineering geological investigations", and the joint spacing standard recommended by International Society for Rock Mechanism (Ministry of Geology & Mineral Resources of the People's Republic of China 1994; Ministry of Railways of the People's Republic of China 1996; Ministry of Water Resources of the People's Republic of China 2006; Ministry of Construction of the People's Republic of China 2009). **Table 2** shows the qualitative classification from "Standard for engineering classification of rock masses" (GB50218-94) (Ministry of Water Resources of the People's Republic of China 1995).

As the standards of classification of rock mass intactness differ in different area, and no prior examples exist for coral reefs, properly grading the intactness of coral reefs can be difficult. With the comprehensive geological info acquired by the borehole camera system, we attempted to conduct the rock mass integrity evaluation of coral reefs using the RMDI method, and explore the correspondence between the RMDI values and rock mass intactness.

Correlation Between RMDI and Rock Mass Intactness

As shown in **Figure 9**, the RMDI stayed relatively high in the segment of the CK2 hole depth from 82 to 229 m, with values above 0.85. Based on drilling log and rock core photos (see **Figure 7**), the rock cores of the segment were intact. Moreover, the heights of the intact cores were larger than 1 m (the cores shown in the figure have been broken up for the purpose of storage).

The spacing between joints or structural planes was evaluated by the length of intact cores, and this segment correspondedto the "intact" type in the qualitative classification of rock mass intactness in the **Table 2**. Therefore, this segment of coral reefs was considered to have high intactness.

For the segment from depth 319 to 339 m, the RMDI was below 0.4. Based on drilling log and rock core photos (see **Figure 10**), the cores from this segment were more fragmented. The heights of intact cores were less than 0.2 m, and the structures displayed weak cementation. These cores corresponded to the "highly fragmented" type in the qualitative classification. Thus the cores from this segment were considered to have low intactness.

For the segment from depth 469 to 509 m, the RMDI was between 0.55 and 0.75. Based on drilling log and rock core photos (see **Figure 11**), the intact cores from this segment had an average length around 0.5 m. The cores displayed bedded structures with medium thickness, and had an average cementation. It corresponded to the "moderately fragmented" type in the qualitative classification. Thus the cores from this segment were considered to have average intactness.

The feasibility and accuracy of the RMDI method in the evaluation of coral reefs integrity have already been studied. Through the comparison between the RMDI and other data shown above, with references to the classifications based on joint spacing (see **Table 1**) and qualitative classification of intactness, the correlation between the RMDI of coral reefs and the rock mass intactness can be formulated (see **Table 3**).

Evaluation of the CK2 Borehole

The intactness of the whole CK2 can be evaluated based on the correlation between RMDI and intactness in **Table 3**.The intactness of coral reefs can be deemed to be the degree of cementation in the coral reef. A comprehensive diagram of coral reef stratum development can be constructed using the RMDI, as shown in **Figure 12(b)**.

A comparison of actual rock cores and results of the RMDI-based assessment (see **Figure 12**) shows that the RMDI results were generally consistent with actual cores. Through the evaluation of rock intactness of the CK2 borehole, we discovered that the intactness in coral reef was alternately interleaved along the depth. The segments of 82 ~ 229 m, 560 ~ 700 m, and 880 ~ 924 m in depth had high intactness, strong cementation , high coring rates, and more intact cores, while the segments of 319 ~ 349 m, and 740 ~ 860 m had low intactness, weak cementation, low coring rates, and fragmented cores. The construction of coral reef development stratum structures can be of great importance to the identification of geological stratums, and investigation of climates and geography in the past.

CONCLUSION

We have utilized the rock mass integrity index (RMDI) method, where the value of coefficient α was re-determined in the analysis of the coral reef integrity. Through a detailed comparative analysis of the RMDI values and info from the entire CK2 borehole with an approximate length of 1 km, and with the references to the rock mass classification standards, we formulated the correlation between the RMDI values and the coral reef intactness. And we conducted an integrity evaluation of the CK2 boreholeand constructed a coral reef development stratum structure diagram. The results of the RMDI evaluation were also generally consistent with those from other evaluation methods. We conclude that: (1) the RMDI is a feasible approach for the analysis of coral reef integrity; (2) the classification system based on RMDI is feasible in the integrity evaluation of coral reefs; (3) the values of coral reef integrity obtained using the RMDI method are accurate; and (4) borehole camera survey and statistical analysis are of great importance in the study of coral reefs.

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Table 1. Classification based on rock mass joint spacing

Standard	Structure Type				
	Intact	Lumpy	Bedded	Fragmented	Granular
Code for investigation of geotechnical engineering GB50021-2001	>1.0 m	>1.0 m >0.4 ~ 1.0 m	0.4 ~ 1.0 m 0.2 ~ 0.4 m	0.2 ~ 0.4 m ≤0.2 m	
Technical code of railroad engineering geology TBJ12-85	>1.0 m	>0.4 m	<0.4 m	<0.2 m	
Code of engineering geological survey ZBJ14003-89	>1.0 m	0.5 ~ 1.0 m	0.3 ~ 0.5 m	<0.3 m	
Code for hydropower engineering geological investigations GB50287-2006	>1.0 m	0.5 ~ 1.0 m	0.3 ~ 0.5 m	0.1 ~ 0.3 m	<0.1 m
ISO/TC182/SC/WGI0	>0.6 m		0.2 ~ 0.6 m	<0.2 m	

Table 2. Qualitative classification of rock mass intactness

Name	Development of Structural Planes		Cementation of Main Structural Planes	Types of Main Structural Planes	Corresponding Structural Types
	No. of Groups	Mean Spacing			
Intact	1 ~ 2	>1.0 m	Strong or average	Joints, fissures, beddings	Intact or very thick bedded structure
Moderately intact	1 ~ 2	>1.0 m	Weak	Joints, fissures, beddings	Lumpy or thick bedded structure
	2 ~ 3	1.0 ~ 0.4 m	Strong or average		Lumpy structure
Moderately fragmented	2 ~ 3	1.0 ~ 0.4 m	Weak	Joints, fissures, beddings, minor faults	Fissured lumpy or medium thick bedded structure
	≥3	0.4 ~ 0.2 m	Strong		Mosaic fractured structure
			Average or weak		Medium & thin bedded structure
Fragmented	≥3	0.4 ~ 0.2 m	Weak	Various types	Fissured lumpy structure
		≤0.2 m	Average or weak		Fractured structure

Highly fragmented	Disordered		Very weak		Granular structure

Table 3. Correlation between RMDI and coral reefs intactness

Intactness	High	Moderately high	Average	Moderately low	Low
Homogeneity	1.00 ~ 0.85	0.85 ~ 0.70	0.70 ~ 0.55	0.55 ~ 0.40	<0.40

Figure 1. Remains of scleractinian corals.

Figure 2. Rock cores obtained from coral reefs.

Figure 3. Borehole camera images.

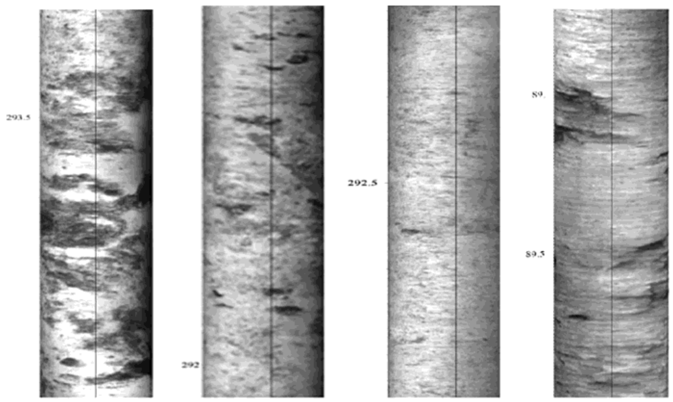


Figure 4. Schematic diagram of borehole camera imaging.

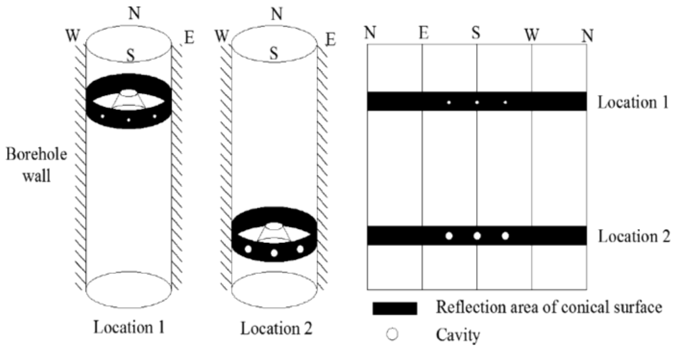


Figure 5. Coral reefs cavity density function.

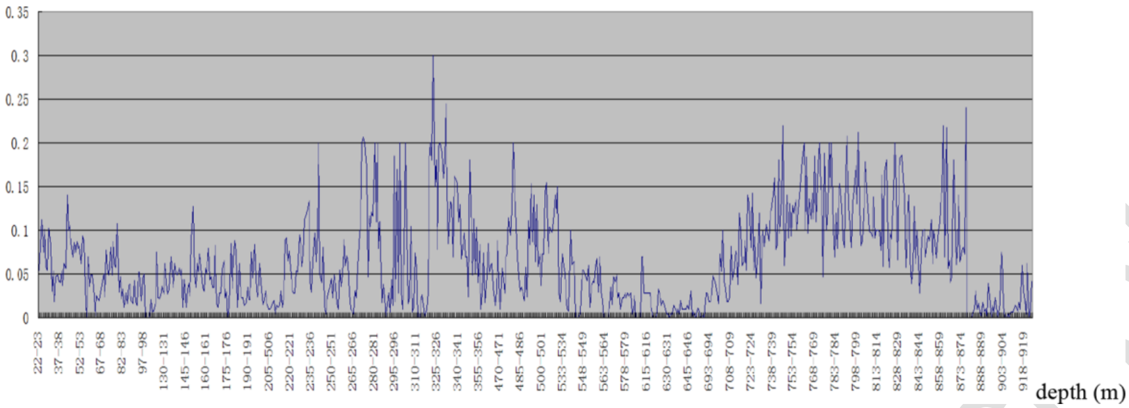


Figure 6. Coral reefs lumpiness function.

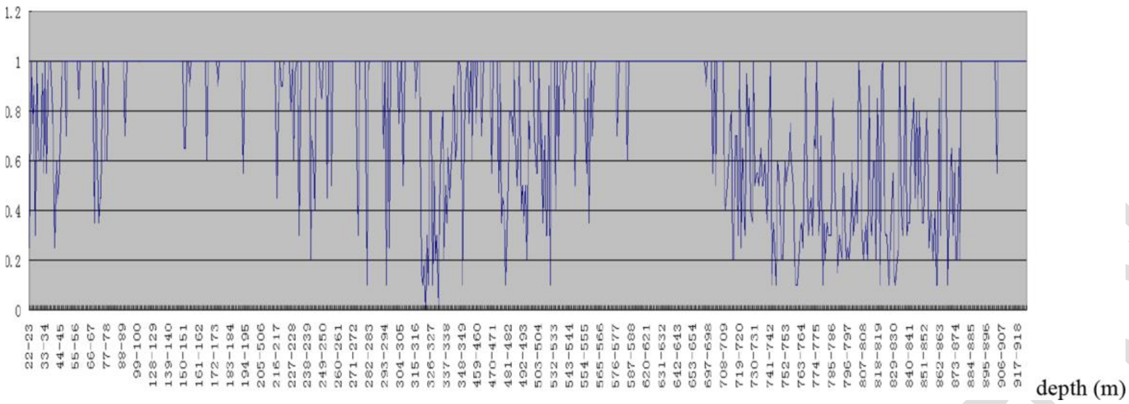


Figure 7. Coral reefs cavity density function.

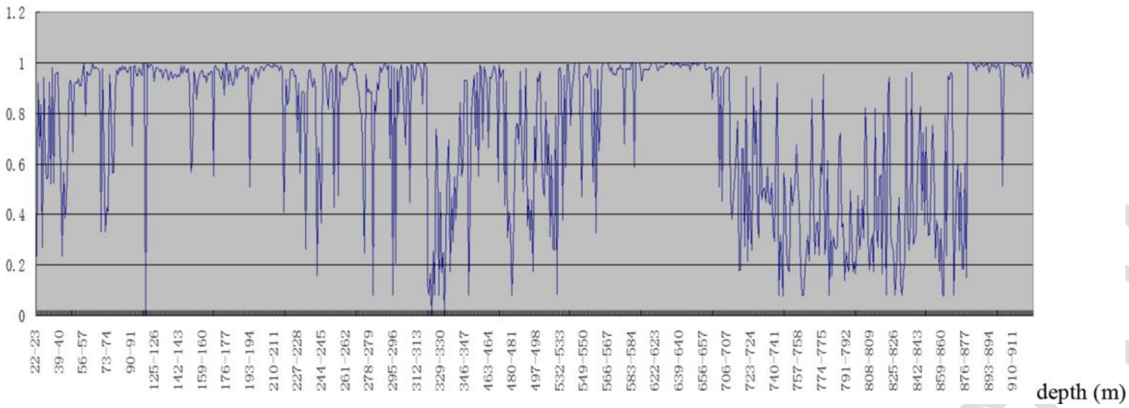


Figure 8. Coral reefs integrity index (RMDI).

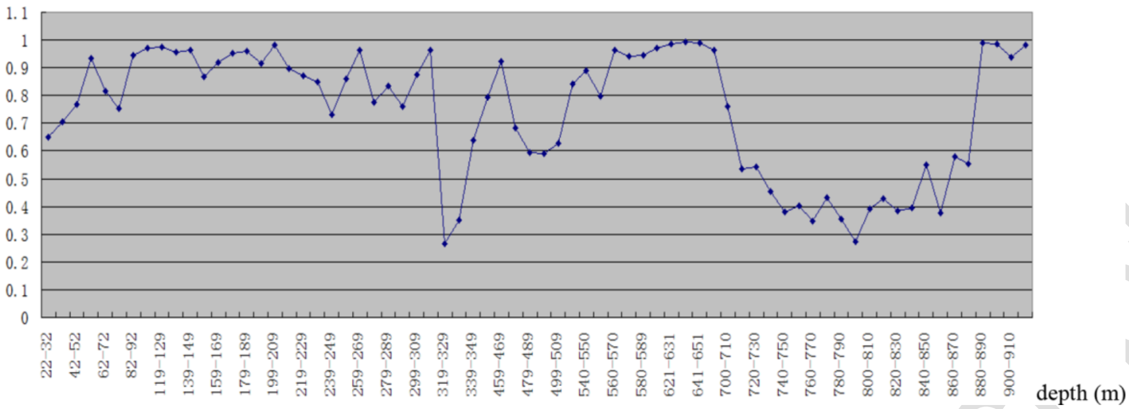
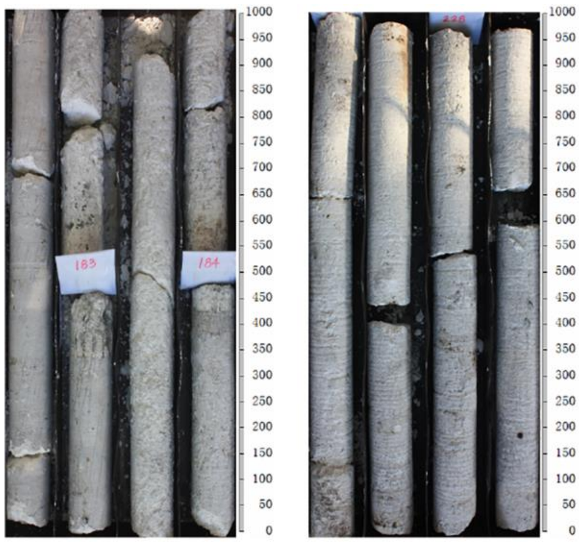


Figure 9. Some cores from coral reefs.



129~133m 169~173m

Figure 10. Some cores from coral reefs.

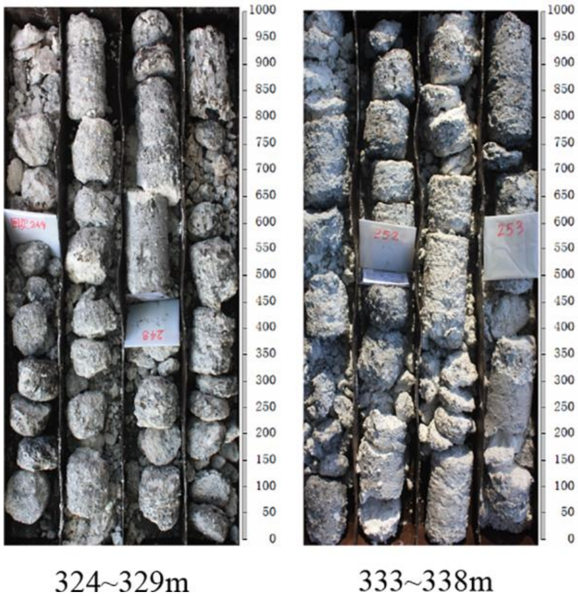


Figure 11. Some cores from coral reefs.

Figure 12. Comparison of rock cores and RMDI evaluation results.