Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Discovery of ferromanganese crust boundary and its genetic and ore prospecting significance*

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Received Nov. 10, 2004; revision accepted Apr. 6, 2005

Abstract: Evidences for the existence of ferromanganese crust boundary were found for the first time during the survey of the "DA YANG YI HAO" Vessel 2003. Some typical characteristics of the boundary are summarized and the significances of the finding of the boundary are included in the genesis discussion. Ore prospecting and assessment of the crust resources are described in this paper. The morphologic and extending characteristics of the crust boundary led to the recognition of two types of crust boundary: interpenetration crust boundary and closed crust boundary. According to the distribution and types of the crust, however, the boundaries are classified into three types: the boundary between ferromanganese crust and detrital sediment, the boundary between tabular crust and seamount nodules, and the boundary between tabular crust and rudaceous crust. This study revealed that the boundary between tabular crust and nodules was not formed under different regional environments but formed under different nucleation potential barriers between different initial growth (nucleation and germination) processes and between solid rocks and loose sediments. The rudaceous crusts are controlled spatially by fracture zones and the crusts' boundaries are controlled by the seamount structure and landform. The discovery of the crust boundaries reveals the crust's 'negative growth' phenomena (especially for some seamount nodules). The boundary investigation can be helpful in identifying the existence of tabular crust covered by detrital sediments and in calculating the area covered by the crust. The resource calculation error and the resource quality as well as resource exploration degree can be assessed through the survey of crust boundary.

Key words: Curst boundary, Crust type, Genetic and ore prospecting significance
doi:10.1631/jzus.2005.A0656 **Document code:** A **CLC number:** P736

INTRODUCTION

Cobalt-rich crust, one of the most important marine mineral resources, is a kind of mat-like ferromanganese oxide precipitated from seawater on seamount rocks and sediments. The three main morphologic types of crust are recognized as tabular crust, rudaceous crust and seamount nodules. Tabular crust with thickness varying over a large range from film-like to thick platy (30 cm), is more important as mineral resource than the other crusts. Previous survey once found distinct boundaries between hydrothermal tabular crusts and nodules (Akira and Masao, 1997). However, the discovery has not been paid attention to since then. The "DA YANG YI HAO" Vessel surveyed and videoed two sea-bottom seamounts of Marcus Ridge in the middle Pacific, two seamounts of Marcus Ridge and one seamount of Wake Ridge in West Pacific. The sea-bottom videos showed that there are distinct boundaries between crusts and sediments and even between different types of crusts on the five seamounts. The boundaries

*Project supported by the National Natural Science Foundation of China (No. 49976017), and the China Ocean Mineral Resources R & D Association (COMAR) (No. DY105-01-01-01) and the National Basic Research Program (973) of China (No. G2000046700)

between tabular crusts and sediments are shown to be obviously continuous. Nowadays, the measurement of the crust thickness and the measurement of its coverage rate are two problems for crust ore prospecting and the assessment of crust resources. We discovered the crust boundary, based on study of the genetic relationship among different crusts, and are committed to study the crust distribution tendency and its control factors and then construct the prospecting and assessment model of the cobalt-rich crust ore.

CRUST TYPES AND CHARACTERISTICS

Based on the statistics of 2003 exploration videos, according to the morphology and extending scale, the boundaries of crusts are classified into two types: interpenetration crust boundary and enclosed boundary. The former is of large scale, of good orientation and extension. The latter is of small scale and usually features smooth enclosed lines. But according to the crust distribution and type, the boundaries are classified into three types: the boundaries between crusts and sediments, the boundaries between tabular crusts and seamount nodules, and the boundaries between tabular crusts and rudaceous crusts. The boundaries between crusts and sediments can be classified into three subtypes: the boundaries between tabular crusts and sediments, the boundaries between seamount nodules and sediments, and the boundaries between rudaceous crusts and sediments. Only tabular crust boundary characteristics are discussed in this paper.

Characteristics of the boundaries between tabular crusts and sediments

Tabular crusts usually distribute in bands along seamount isobaths. This type of boundaries is usually present in tabular crust areas, and is occasionally present below the tabular crusts. The sediments usually are foraminiferal sands. This sort of boundary is interpenetration crust boundary, usually extending a long way. There are usually sporadic seamount nodules on the side of loose sediments. On the side of crusts, thin sediment layers covered occasionally the tabular crusts incompletely. The crust bases usually are lavas or limestone reefs. The near boundaries tabular crusts are usually rootless crusts which occur in the covering sediments (Fig.1a).

Characteristics of the boundaries between tabular crusts and seamount nodules

Seamount nodules mainly occur at the bottom edge of tabular crusts (Fig.1b), or in the holes of tabular crusts (Fig.1c). The nodules growing on the edges of tabular crusts sometimes distributing intensively, are mainly uniform size lenses. The nodules distribution area ranges on a large scale (10 m^2~n km^2). These boundaries between seamount nodules and tabular crust are continuous, and there are also cases that intensive seamount nodules are cemented together forming tabular crust, whose boundaries could be macroscopically recognized (Fig.1d). But the surface characteristics of such tabular crusts differ from those of the narrow-sense tabular crusts (Fig.1e). The nodules growing in the tabular crust interstices are usually dispersed in small areas (1~10 m^2). The boundaries between tabular crusts and seamount nodules are smooth and enclosed.

Characteristics of boundaries between tabular crusts and rudaceous crusts

Rudaceous crusts are also distributed in band pattern, but not so intensive in density. They are mainly below the tabular crust area, and occasionally distribute like string on sediments and rocks (Fig.1f). The boundaries between tabular crusts and rudaceous crusts are mainly untouched boundaries, so narrow blank areas usually appeared between them. There are also usually sporadic seamount nodules around individual rudaceous crusts above loose sediments. However, there are few seamount nodules around rudaceous crusts cemented on rocks. Rudaceous crusts which distributed on tabular crust are occasionally found, but the probability is low and they are usually mixed with fresh rocks. These individual or colony rudaceous crusts are sometimes cemented with tabular crusts forming unevenly warped-upward surface tabular crusts.

CONTROL FACTORS OF CRUST BOUNDARY

All sorts of crusts are of regular layer structure (usually 3 layers, occasionally 2 or 1 layer) or complicated laminar structure with distinct growing char-

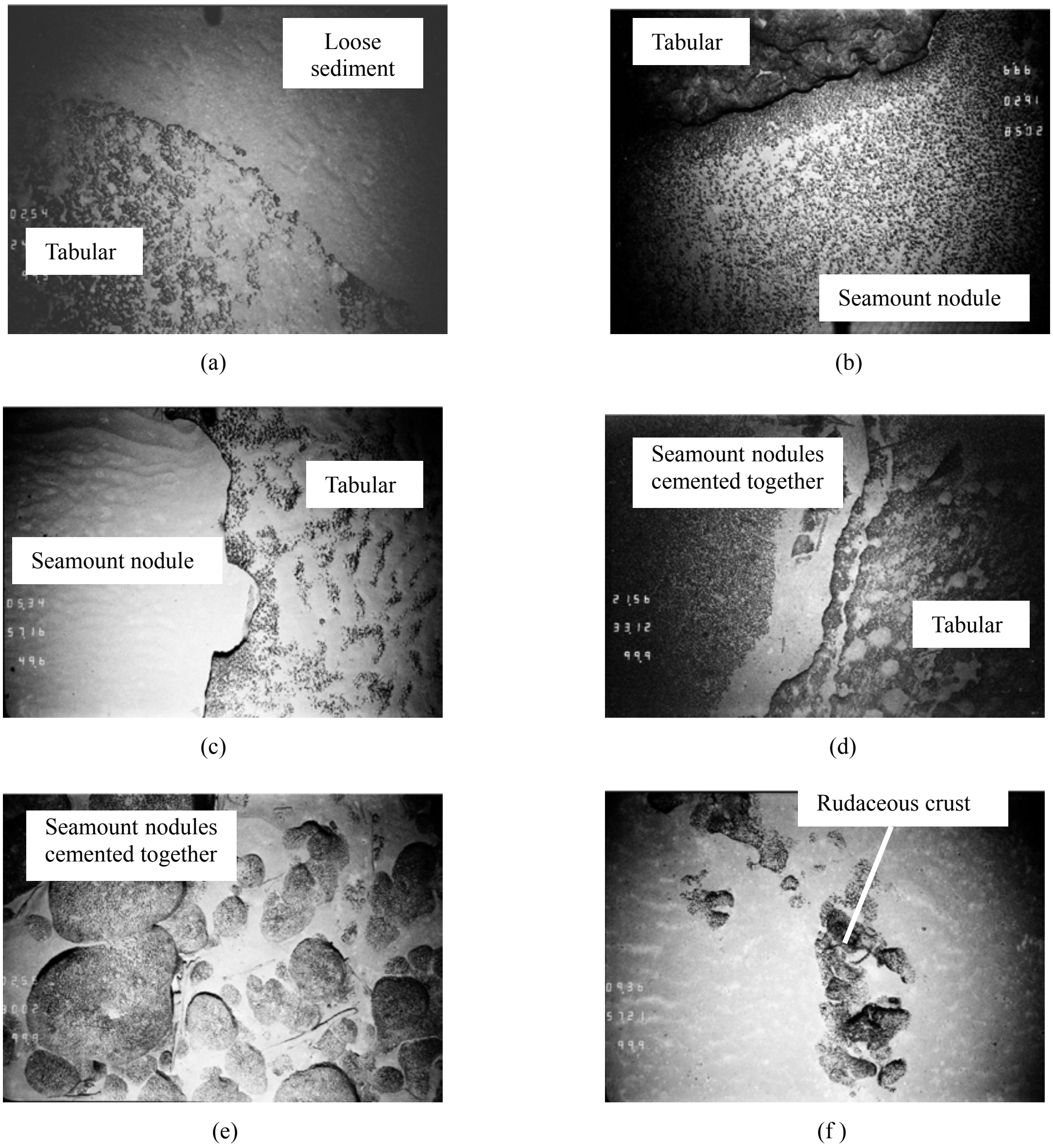

Fig.1 Types of crust boundary
(a) Boundary between tabular crust and loose sediment; (b) Boundary between tabular crust and seamount nodule; (c) Seamount nodule in the holes of tabular crust; (d) Boundary between tabular crust and cemented seamount nodule; (e) Surface feature of nodules cemented together; (f) Linearly distributed rudaceous crust

acteristics. Previous study on the crust (nodule) growing mechanism suggests that the layer structure reflects discontinuous growing of crust and environmental changes of the sea, and laminar structure is formed in chemical deposit and colloid absorption during crust growing. There are no clear differences between the inner grain structure of the crust and that of nodule, so it may indicate that there is no clear difference between the growing mechanism of crust and that of nodule (Usui, 1979; Lyle, 1982; Von Stackelberg and Beiersdorf, 1991; Zhang *et al.*, 1998). According to crystal growing theory, the structure thickness is a function of the growing rate and time. The rate is a vector whose direction is in the normal direction of the growing face. Therefore, the inner complicated laminar structure and combination feature are formed as a result. The continuous growing of crust in some areas generates continuous tabular crust, circle layer rudaceous crust and nodule.

The discovery of the boundaries reveals that there is no intergrowth relationship among different types of crusts although they are associated together. Different type crusts also indicate some genetic relationship, even like an interchangeable relationship, such as rudaceous crusts and seamount nodules can be formed around debris nucleus of tabular crust, and seamount nodules and rudaceous crusts can be cemented into tabular crusts (Fig.2).

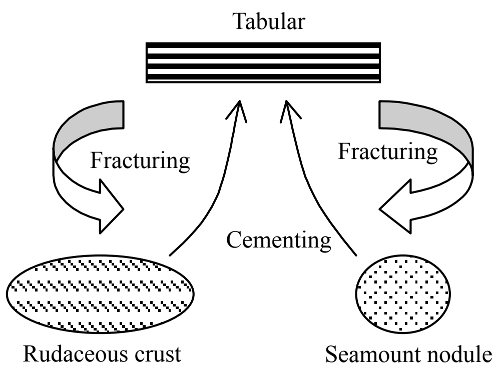

Fig.2 Transforming model of different types of crust

The morphology of the secondary crusts keeps the original growing features and their boundaries are clear. All these show that however their original growing conditions were different, their original morphologic characteristics were kept and inherited even during the later growth. The boundaries between tabular crust and nodule or the boundaries between nodule-free sediments and tabular crusts are caused by different initial growth (nucleation, germination). Rudaceous crusts are controlled by fracture zone, and their boundaries are controlled by seamount tectonics and landform. The forming mechanisms were studied, with tabular crusts and seamount nodules take for examples (Fig.3). The base of the tabular crusts is concreted rock or semi-cemented clay, while the seamount nodules grow nearly exclusively on the base of loose sands. Loose sandy sediments are controlled by the landform and micro-landform and distribute as bands along isobaths or partly distribute planarly, with clear boundaries between them and the exposed base rock. The distribution of crust boundaries is clearly related to these boundaries, which indicates the inheritance relationship between them. During the initial period, i.e. nucleation period, the growth of Fe and Mn mineral must overcome the potential barriers for nucleation, which differ for different types of bases; the nucleation patterns could be different for the minerals on concreted rock and for minerals on loose sediments. On the loose sandy base, Fe and Mn minerals tend to be nucleated, to grow into ball-size seamount nodules around granules; controlled by dissolution-absorption, which is helpful not for the growth of small-size seamount nodules but for larger ones, as small-size seamount nodules tend to be dissolved but correspondingly larger ones tend to grow in size by absorbing Fe and Mn elements. As a result, the size and distribution of seamount nodules tend to be uniform. Because the concreted and semi-cemented bases are not suitable for nucleation or germination of minerals, the sea bottom water above them will be concentrated with more Fe and Mn. When environment changes or the concentration of Fe and Mn reaches some value, the nucleus of the tabular crusts will be formed by their absorption and growing.

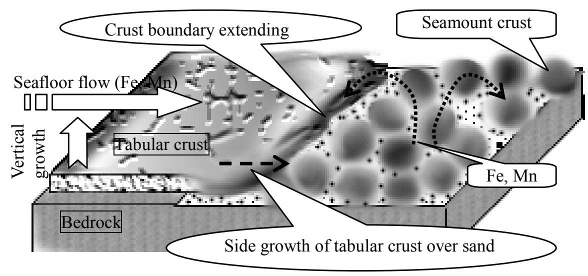

Fig.3 Model of the formation of crust boarder

What makes the difference in initial growing patterns and mineral nucleation is not the change of regional environment, but the local microenvironment. The differences between nucleation potential barriers and nucleation patterns of concreted rock and those of loose sediments led to the formation of crust boundaries.

GENETIC AND ORE PROSPECTING SIGNIFICANCES OF CRUST BOUNDARY

Just as tabular crust is the most important crust type, survey and research on crust is certainly very important for studying the genesis and ore prospecting significance of cobalt-rich crust.

Genetic significance of crust boundary

It is believed that tabular crusts grow mainly on concrete rocks. But in this study and survey on the Philippine Sea revealed that some tabular crusts growing on semi-cemented clay. The continuous distribution of crusts on concreted and semi-cemented base generally tended to be stable or to be gradually intergraded, whatever the thickness of the crusts ranges. Crusts on the exposed base rock will distribute continuously or turn into thin film. In spite of being affected by tectonic movement or volcanic action, there are few crust boundaries on exposed base rocks. In the adjacent areas of the base rocks and loose sediments, tabular crusts grow beside and cover loose sediments (usually foraminiferal sands), and then form boundaries parallel to the rocks and loose sediments, or form distinct boundaries between tabular crusts and seamount nodules or sediments. Because loose land bases, such as foraminiferal sands, are relatively beneficial for nucleation and growth of Fe and Mn minerals, the boundary's forming could be explained as indicating the negative growth of crusts, especially seamount nodules, which means that the growth of tabular crusts and seamount nodules near the boundaries would inhibit further nucleation on sediments and cause relatively small-size seamount nodules to be dissolved. The phenomenon of negative growth could explain the crust (nodule) growing mechanism that is, the crust grows in the environment when the concentration of Fe and Mn is below their solubility. In other words, crust (nodule) can form a local microenvironment to sustain the growing by the coupling of its growing and negative growing for a period and in the regional sense, which is so called fluctuating and non-linear growth of Fe and Mn (Yao *et al*., 1994). Around tabular crust holes and rudaceous crusts, the observed nonlinear growth phenomenon is much more clear. Notablely, the coupling of the growth and negative growth may influence the measurement accuracy of crust age and crust growth rate. The discovery of crusts developed on fish teeth and man-made articles also reveals that the crust (nodule) growth rate may be fairly high. However, the published data on the average crust growth rate is n~10n mm/Ma, which is surely low (Moore *et al*., 1981; Burnett and Morgenstein, 1976; Krishnaswai *et al*., 1982; Sharma and Somayjulu, 1982; Henderson, 1999; Qian *et al*., 1990; Qian and Wang, 1999), undoubtedly the consequence of growing interruption. However, the negative growth of crust cannot be neglected. Younger crust sometimes shows higher growing rate, which cannot be explained simply by the changes of sea environment being helpful to crust high-rate growth. The negative growth should be taken into account when sea-environment evolution information is collected. And the post-reconstruction feature, including structure and chemical composition, should not be ignored either.

Ore prospecting significance of crust boundaries

Previous statistics of net samples showed that the crust samples in every station had different thickness, and different types of crusts could be found at the same station. The discovery of crust boundaries suggests that the changes of thickness and types of net towage samples reflect the microenvironment changes of crust growth as a matter of fact (e.g. micro-landform changes) and reflect the stability and continuity of the ore body to some extent as well. The type of crusts sampled by towing net on some seamounts in Wake Ridge is simplex, of which mainly tabular crusts with uniform thickness varying within 6~8 cm. The survey of video and grab data in 2003 showed that the ore bodies of seamount crust were stable and promising from the resource perspective.

This study on the crust boundary-forming mechanism suggested that tabular crusts may be fairly thick due to the cementing together of rudaceous crusts and seamount nodules or their partial reconstruction. As the tow net prefers these crusts to other sample materials, the average thickness of crusts in some regions may in fact be smaller than the statistical values of crusts sampled by previous tow net. At the same time, the identification of crust boundaries is an effective method to estimate the existence of crusts covered by sediments. The tabular crust boundary is characteristic of the projective edge of the crust boundary (growing aside, Figs.1a~1d). Even when there is no projective boundary, there may be tabular crust covered by sediment which should be further studied with TV grab or core drill.

Significance of assessment of crust resources

Currently the parameters of seamount-slope area, crust coverage rate and crust abundance are used to calculate and assess the crust resources. The value of its abundance is achieved by calculating the tabular crust thickness or seamount nodule (rudaceous, nodule) size (Zhang, 2001). But it has been long controversial whether the crust coverage rate can be obtained directly from the investigation. So some scientists have tried to introduce parameters such as ore-bearing efficiency and probability of ore-occurrence to supplement the coverage rate. To some extent, the discovery of crust boundary indicates well what are as follows. Firstly, tabular crust distributes continuously to an extent. As the essential part of these resources, the spread area of ore bodies mainly conforms to the distribution area of tabular crusts. Secondly, tabular crust may have natural boundaries. And the most probable distribution pattern is strip-like or banding distribution, or mat-like or planar distribution along the boundary line of rock and sediments. Finally, because of the distribution of sediments, especially foraminiferal sands, controlled by seamount landform, the extent of crust distribution may be decided directly by the survey on crust boundary.

The distribution extent of tabular crusts can be obtained directly by survey of the interpenetration crust boundaries. As a matter of fact, the distribution area of tabular crust can be used to calculate the crust resources, instead of using the outdated measurement of the area of the seamount slope. In this way, the error of the crust resources calculation, which resulted in reducing the coverage rate, and the crust resources can be simply calculated by some parameters including area, thickness and density. Survey of the enclosed crust boundary and the statistics of the area (usually small scale) of seamount nodules or sediments without seamount nodules can be achieved within the spread of the tabular crusts, so that error analysis of crust resources calculation and assessment of the resources quality can be carried out.

$$\sigma = S_0/S \times 100\% \quad (1)$$

σ refers to the error range of crust resources calculation, S the distribution area of crust, S_0 the distribution area of seamount nodules and sediments in tabular crust distribution area, while S_0/S can be estimated simply through the statistics of video line-measurement data.

$$S_0/S \approx \sum l/L \quad (2)$$

$\sum l$ refers to the sum of the length of seamount nodules and that of sediments in the whole measurement line. L refers to the length of line or the ribbon length of tabular crusts. The value of σ varies with the degree of survey and increases gradually when the survey degree increases, but tends to be stable when the survey degree reaches a certain level (Fig.4). The crust survey degree and crust resources quality can be assessed through numerical and statistical analysis on the value of σ.

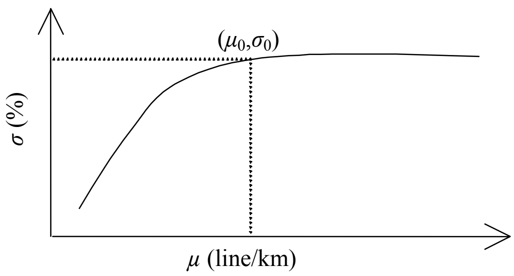

Fig.4 The μ and σ relationship of crust resources
μ: measuring line density of measuring station; μ_0: ideal value of net intensity, the lower the value of μ_0, the higher the quality of ore body; σ: the error range of crust resources calculation; σ_0: resources error

CONCLUSION

1. Two types of crust boundary were recognized: one is the interpenetration crust boundary, and the other is the enclosed boundary, according to their morphologic and extending characteristics. The former is of large scale, and is characterized by directionality and extensibility. The latter is of small scale and usually is characterized by smooth enclosed lines. Whereas, according to the crust distribution and the crust type, the boundaries are classified into three types: the boundaries between crusts and sediments, the boundaries between tabular crusts and seamount nodules, and the boundaries between tabular crusts and rudaceous crusts. The boundaries between crusts and sediments can be classified into three sub-types also.

2. The boundaries between tabular crusts and nodules, and the boundaries between nodule-free sediments and tabular crusts are caused by the difference in initial growth (nucleation, germination).

Whereas, rudaceous crusts are controlled by fracture zone, and their boundaries are controlled by seamount structure and landform. What makes the initial growing manner and mineral nucleation (germination) different is not the differences of regional environment, but local microenvironment. The differences between potential barrier for nucleation and nucleation process of concreted rock and those of loose sediment contribute to the crust boundary formation.

3. The discovery of crust boundary indicates the negative growth phenomenon of crusts (especially of some seamount nodules), which is important for studying the depositing mechanism and the evolution of the environment where crusts formed. The identification of crust boundary is an effective way for determining the existence of crust covered by sediments. Survey of crust boundary can yield data on crust area for calculating the error in estimation of crust resources and assessing the crust resources quality.

ACKNOWLEDGMENTS

The paper is based on 2003 cruise report of the "DA YANG YI HAO" Vessel. The Association of China Oceanic Ore Resources Study and Exploitation Office offered a large amount of basic data. Professor Guo Shiqin, Professor Lian Dehua, Professor Xu Dongyu, Professor Pan Jiahua, Associate Professor Cui Ruyong, Academician Qin Yunshan and Academician Chen Yuchuan provided the participants in this study with much valuable advice. Assistant Engineer Zhang Kai, Assistant Engineer Jin Xiaobing, Professor Gu Yumin and Senior Engineer Li Yunda offered a lot of photographic data. The authors would like to thank all of them and thank all the people who held discussions with us on the issue of crust boundary.

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