

# Fractal characteristics of resource quantity of cobalt crusts and seamount topography, the West Pacific

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**Abstract** This paper presents the fractal distribution of topography of seamounts from the West Pacific and the resource quantity of cobalt crust therein. The cobalt resource quantity has three to four variable fractal dimensions, corresponding to the distinct slopes and water depths of the seamount. The multiple fractal property of resource quantity may have resulted from various factors, such as types and components of cobalt crusts and ages of oceanic crusts hosting the seamounts. Individual seamounts display complex topography and quantity of cobalt crust, both in the same and different regions.

**Keywords** Pacific seamounts, cobalt crust, topography, resource quantity, multifractal

## 1 Introduction

The West Pacific seamounts and Mid-Pacific Mountains have been formed by a combination of various events, involving prolonged activity of super mantle plumes, progressive movement from the original equatorial Pacific to their present position due to the drift of the Pacific plate, and subsequent erosion and deposition. They vary in height from above sea level to water depths of about 1 400–1 700 m, with distinct depositional conditions at different depths throughout their history. These result in complex landform features of the seamounts, affecting distribution of cobalt crusts (Bannkar et al., 1997). Available data indicate that the slope and water depth are important factors affecting the distribution of cobalt

crusts capping seamounts. Hein et al. (1988) demonstrated that a stable environment is required for the growth of thick crusts, as gravity-flow and mass-wasting processes around seamounts prevent encrusting. Quantitative observation by stereo photographs and video data show that seamounts with slope angles of 0°–3°, 3°–7°, 7°–15° and over 15° are dominated by cobalt-rich nodules, sediments, coexisting nodules and crusts, and crusts, respectively (Yamazaki et al., 1994; Yamazaki and Taurusaki, 1995). Investigations from the CM2 seamount reveal that gentle or steep slopes of seamounts are unfavorable to the growth of cobalt crusts (Chu et al., 2005). The slope angles also have effect on the shape of cobalt crust, with platy crusts occurring on moderately steep slopes, whereas pebble-like or pillow-shaped crusts or nodules on gentle slopes or low-lying regions (Chu et al., 2005). This is confirmed by drilling cores from the cruise of *k/v* “Gelendzik” in the Magellan seamounts, showing that the thick and rich cobalt crusts are found in flat areas (Xu, 2002). However, existing studies yielded results that are essentially qualitative, far from satisfactory evaluation on a quantitative relationship between seamount topography and cobalt crust. In this paper, we report the fractal characteristics of both seamount topography and resource quantity of cobalt crusts in an attempt to provide information on the distribution of crusts. The results from this study are also important in our understanding of growth mechanism of cobalt-rich crusts.

## 2 Definition of fractal

The concept of fractals has been widely used in the geosciences for characterizing measures with scaling properties. The fractal is defined as

$$N(r) = Cr^{-D} \quad (1)$$

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where  $r$  is a characteristic linear dimension;  $D$  is the fractal dimension;  $C$  is constant of proportionality;  $N = N(\geq r)$  is number of objects with characteristic linear dimension  $\geq r$ . A plot of  $\lg N(r)$  versus  $\lg r$  produces a straight line with slope  $D$  (Bai and Wang, 2003).

### 3 Methods

Cobalt crusts are sampled irregularly, with variable sample density. This indicates that densely sampled areas may be over strengthened, whereas, others could be ignored when raw geological data are applied to analyzing the frequency distribution of slope data, causing problems in unraveling the intrinsic characteristics of geological fields. Such problems suggest that ordinary statistical methods cannot be used for analyzing spatial distribution and statistical characteristics of samples if spatial measure criterion mobility were taken into account (Cheng, 2001; Xie and Bao, 2002). The widely used concentration-area model (Cheng et al., 1994, 1996, 1997; Cheng, 1995, 2000; Shen, 2002) calculates the contour  $S(c_i)$  where all the concentrations  $C$  are greater than a given value  $c_i$  ( $i = 1, 2, \dots, n$ ,  $n$  is number of concentration groups) to study the power-law relationship between  $S(c_i)$  and  $c_i$  and then to discern the fractal features of geological distribution. This method can be effective when the data set and samples are collected irregularly. In this way, we substitute the square grid for the contour area. A common way to study the spatial structure of a measure is to cover the space by a square grid ( $0.01^\circ \times 0.01^\circ$ ) of slope and to partition the space into sub-areas or cells. The slope of computational method is from Wu (2002). According to the sampling station variables and areas of the nearest neighbor method controlling one, the sub-area or cell resources quantity is computed. We define  $N(s_i)$  as resources quantity with covering cells over slope ( $s_i$ ). The original data ( $N(s_1), N(s_2), \dots, N(s_n)$ ) and ( $s_1, s_2, \dots, s_n$ ) must be converted into  $\lg N(s_1), \lg N(s_2), \dots, \lg N(s_n)$  and ( $\lg s_1, \lg s_2, \dots, \lg s_n$ ) for estimation of fractal dimension  $D$  with slope if these data fit a straight line. When a log-log plot yields two or three segments of straight lines modeled

by least squares with corresponding slopes  $D_1, D_2$  or  $D_3$ , a dividing point is determined by using the optimum least-square regression method, i.e. the residual sum of squares ( $E$ )

$$E = \sum_{i=1}^{i1} [\lg N(s_i) + D_1 \lg s_i - \lg C_1]^2 + \sum_{i=1}^{i2} [\lg N(s_i) + D_2 \lg s_i - \lg C_2]^2 + \dots \rightarrow \min$$

where  $s_{i1}$  and  $s_{i2}$  are a dividing point defined as the threshold.

We study the distribution of resources from various water depths to show relationship between these two. Previous investigations indicate that cobalt crusts are generally distributed in the range of 300–3 500 m of water depth (Shen et al., 1999). Thus, we only compute resource quantity in seamount areas above 3 500 m of water depth. We define  $N(r_i)$  as resource quantity with covering cells over depth ( $r_i$ ).

### 4 Results

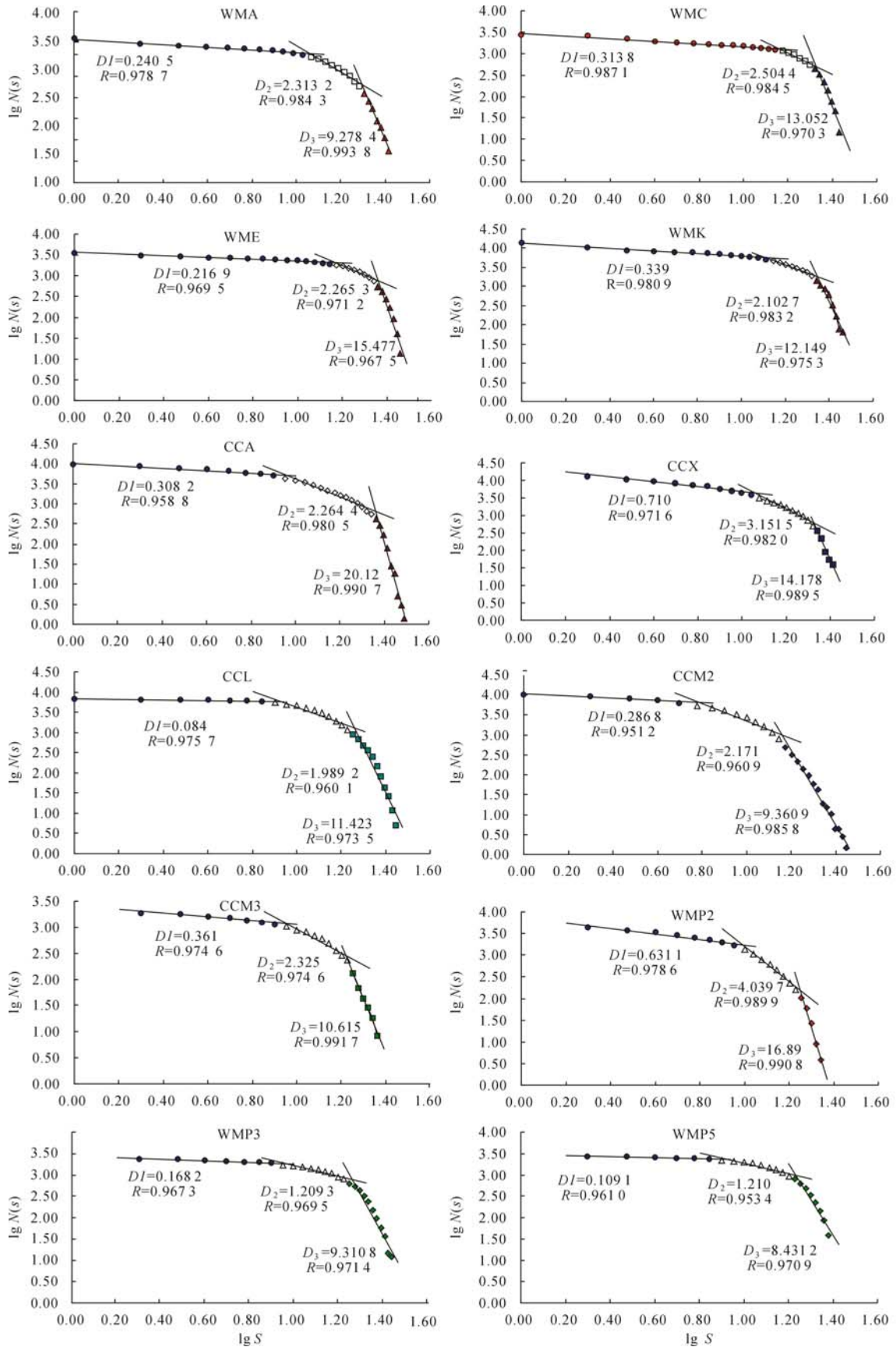
Fractal modeling was carried out on the resource quantity of cobalt crust from four Central-West Pacific seamounts, which are the Magellan seamounts, the Wake-Marcus Islands, the Mid-Pacific Mountains, and the Line Islands on the seamount terrain.

#### 4.1 Fractal distribution of resource quantity of cobalt crust on seamount slope

The log-log plot of  $N(s)$  against  $s$  of 12 seamounts (Table 1) are shown in Fig. 1. Three straight segments were obtained by least squares regression method. Two thresholds were modeled to achieve an optimal fit (Table 1, Fig. 1). The spatial distribution of cobalt crust displays three segments in the plot (Fig. 1), as best illustrated by the WME seamount, characterized by fractal dimension of 0.216 9 for slopes  $0^\circ$ – $15^\circ$ , 2.2653 for  $15^\circ$ – $23^\circ$ , and 15.477 for over  $23^\circ$ . By inference, one slope angle of  $5^\circ$  and  $23^\circ$  represent the thresholds

**Table 1** Fractal of seamount slope and resource quantity in various areas

Area	Seamount	First slope range	$D_1$	Second slope range	$D_2$	Third slope range	$D_3$	Residual
Magellan	WMA	$< 12^\circ$	0.240 5	$12^\circ \leq s < 21^\circ$	2.313 2	$\geq 21^\circ$	9.278 4	0.021
	WMC	$< 15^\circ$	0.313 8	$15^\circ \leq s < 21^\circ$	2.504 4	$\geq 21^\circ$	13.052 0	0.103
	WME	$< 15^\circ$	0.216 9	$15^\circ \leq s < 23^\circ$	2.265 3	$\geq 23^\circ$	15.477 0	0.140
	WMK	$< 14^\circ$	0.339 0	$14^\circ \leq s < 22^\circ$	2.102 7	$\geq 22^\circ$	12.149 0	0.103
Mid-Pacific	CCA	$< 9^\circ$	0.308 2	$9^\circ \leq s < 23^\circ$	2.264 4	$\geq 23^\circ$	20.120 0	0.166
	CCX	$< 12^\circ$	0.710 0	$12^\circ \leq s < 22^\circ$	3.151 5	$\geq 22^\circ$	14.178 0	0.052
Wake-Marcus	CCL	$< 8^\circ$	0.084 0	$8^\circ \leq s < 18^\circ$	1.989 2	$\geq 18^\circ$	11.423 0	0.326
	CCM2	$< 6^\circ$	0.286 8	$6^\circ \leq s < 15^\circ$	2.170 0	$\geq 15^\circ$	9.360 0	0.175
	CCM3	$< 9^\circ$	0.361 0	$9^\circ \leq s < 18^\circ$	2.325 0	$\geq 18^\circ$	10.615 0	0.039
Line	WMP2	$< 10^\circ$	0.631 1	$10^\circ \leq s < 18^\circ$	4.039 7	$\geq 18^\circ$	16.890 0	0.047
	WMP3	$< 9^\circ$	0.168 2	$9^\circ \leq s < 18^\circ$	1.209 3	$\geq 18^\circ$	9.310 8	0.216
	WMP5	$< 8^\circ$	0.109 1	$8^\circ \leq s < 17^\circ$	1.210 0	$\geq 17^\circ$	8.431 2	0.095



**Fig. 1** Log-log plot showing relationship between slope and resource quantity of cobalt resources from the 12 seamonts, central-west Pacific

to control resource distribution. A threshold is the index for evaluation of crust resources and delineation of ore blocks. The WME seamount from the Magellan seamounts and CCL seamount from the Wake-Marcus Islands, which were more densely stationed and sampled, are chosen to examine the types of crusts on different slopes (Table 2, Figs. 2–3).

The slopes from 0° to 15° are located on the summit plateau (< 1 700 m) and lower flanks (> 3 500 m) of the WME seamount. The crusts are developed in the summit plateau, characterized by platy crust (average thickness of 4.8 cm), pebble-like crust plus nodule, and pebble-like crust about 0.64 cm thick. The slopes of 15°–20° are located in the middle and lower flanks (1 700–3 500 m) of the seamount and dominated by platy-crust-rich layers 3.49 cm thick, pebble-like crusts, and few occurrences of nodules. Slopes greater than 23° are located in the outer summit margin and middle flanks on the seamount, characterized by platy-crusts (average thickness of 4.92 cm) and cobalt-rich pebbles.

As for the CCL seamounts, the 0°–8° slopes, located in the summit plateau and lower flanks (> 3 500 m), are characterized by platy crust and less abundant pebble-like crusts and nodules, which have an average thickness of 2.53 cm,

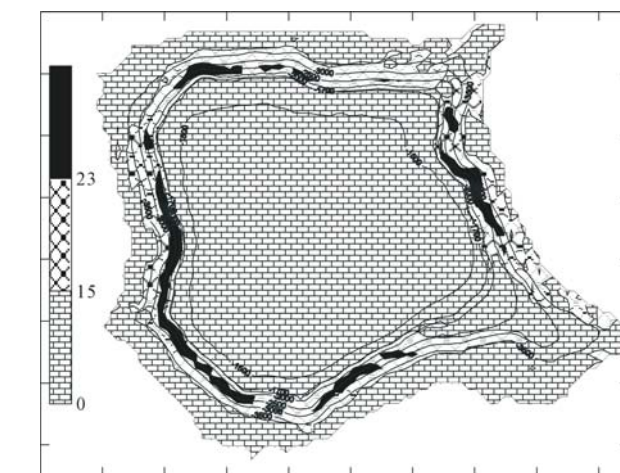


Fig. 2 Diagram showing slop distribution of the WME seamount

1.45 cm, and 1.27 cm, respectively. The 8°–18° slopes, located in the middle and lower flanks (1 500–3 500 m) of the seamount, have platy crusts next to pebble crust and nodules, which are 4.23 cm, 0.88 cm, and 0.95 cm thick on average.

Table 2 Statistics of different crust types in various seamount slopes

Seamount	Slope range/(°)	Distribution	Number of stations	Platy crust		Pebble-like crust		Nodule	
				Number of stations	Average thickness/cm	Number of stations	Average thickness /cm	Number of stations	Average thickness/cm
WME	0–15	Summit terraces and lower seamount flanks	33	25	4.80	4	0.64	6	0.56
	15–23	1 700–3 500 m on the middle and lower seamount flanks	21	16	3.49	1	0.08	0	0.00
	23–32	Upper seamount flanks	9	9	4.92	1	0.20	0	0.00
CCL	0–8	summit terraces and lower seamount flanks	15	10	2.53	8	1.45	6	1.27
	8–18	1 500–3 500 m on the middle and lower seamount flanks	38	31	4.23	13	0.88	12	0.95
	18–34	On the middle and upper guyot flanks and summit on conical seamount	5	3	3.22	0	0.00	0	0.00

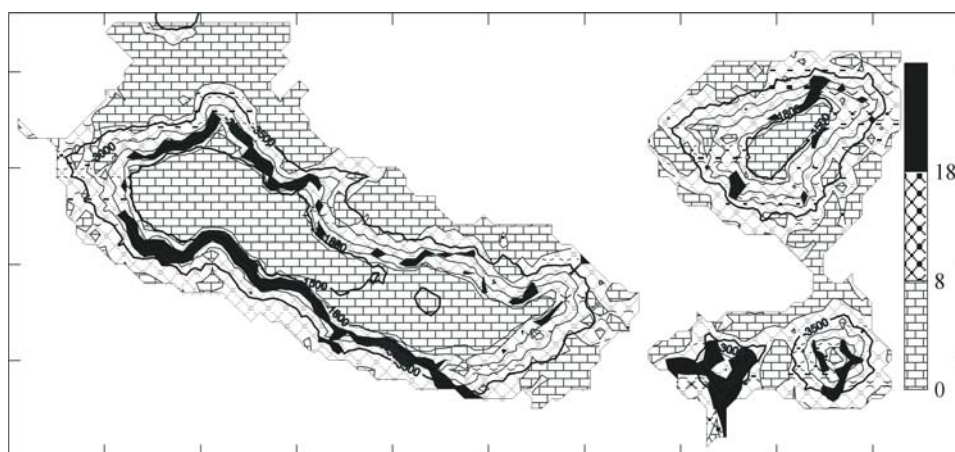


Fig. 3 Diagram showing slope distribution of the CCL seamount

The slopes greater than  $18^\circ$ , seated in the outer summit margin and the middle flanks on the guyot and summit on conical seamount, are scattered and characterized by steeper gradient, being developed with platy crust about 3.22 cm thick, cobalt-rich pebbles. Platy crusts on the conical seamount are richer than on the guyot.

The results suggest that the distribution of cobalt crusts is variable in the same area or even different areas, mainly dependent on the seamount topography. There are different crust types on different slopes on the same seamount. Three types of crusts are developed on the summit plateau and on the middle and lower seamount flanks, whereas only one on the outer summit that is steep. The pebbles and nodules are transported to the middle and lower flanks due to gravity flow, volcanic eruption and earthquake. This explains the fractal distribution of resources versus the seamount slope.

Based on the threshold range of slope versus resources quantity, the 12 seamounts can be divided into four areas: (1) area A is characterized by high slope threshold of lower boundary  $21^\circ$ – $23^\circ$  and upper boundary  $12^\circ$ – $15^\circ$  on WMA, WME, WMK and WMC in Magellan seamounts; (2) area B is characterized by low slope threshold of lower boundary  $15^\circ$ – $18^\circ$  and upper boundary  $6^\circ$ – $9^\circ$  on CCM3, CMC2 and CCL in Wake-Marcus Islands; (3) area C is characterized by high slope threshold of lower boundary  $22^\circ$ – $23^\circ$  and middle one of upper boundary  $9^\circ$ – $12^\circ$  on CCX and CCA in Mid-Pacific Mountains; (4) area D is characterized by medium one of lower boundary  $17^\circ$ – $18^\circ$  and upper boundary  $8^\circ$ – $10^\circ$  on WMP2, WMP3 and WMP5 in Line Islands. As a whole, the partition areas are distributed from northwest to southeast.

#### 4.2 Fractal distribution of resource quantity of cobalt crust and water depth of seamount

The log-log plot of resource quantity  $N(r)$  and water depth ( $r$ ), modeled by least squares regression, (Fig. 4) exhibits three to four straight-line segments, corresponding to the fractal dimensions ranging from 0.24 to 28.93 (Table 3). The fractal dimension of the 12 seamounts might be divided into two classes in terms of variation of water depth (Table 3). The first class, involving the WMC, CCM3, CCX, CCA, WMP2, WMP3, and WMP5 that are mostly located in the Mid-Pacific Mountains and Line Islands, has fractal dimension that are increasing progressively with the water depth. The second class, including WMK, WME, WMA, CCL, CCM2 are from the Magellan seamounts and Wake-Marcus Islands, is characterized by the initial increase and subsequent decrease of fractal dimension with water depth. In addition, the 12 seamounts can be classified into two types in light of the numbers of straight-line segments. The WMK, WME, WMC, CCA, WMP2, WMP3, WMP5 and CCX seamounts constitute the first type, which are distributed in regions of young oceanic crust ( $<165$  Ma). The remaining four seamounts, i.e., WMA, CCM3, CCM2 and CCL, have four straight-lines. These are distributed in the areas of old

oceanic crust ( $>165$  Ma). Such variation of fractal characteristics may have resulted from a combined effect of horizontal and vertical seamount uplift (Wu et al., 2003). The seamounts over old oceanic crust subjected to more frequent uplift than those standing from young oceanic crust; leading to more complicated fractal distribution of resource quantity of cobalt crust dependent on water depth, as reflected by the four straight-line segments. This in turn indicates that the fractal dimension of water depth versus resources quantity of cobalt crust may potentially serve as an indicator for ore distribution. For example, the WMA seamount has four segments, with fractal dimensions of 2.2438, 1.003, 4.6903, and 17.105, for the water-depth interval of  $<1700$  m, 1700–2700 m, 2700–3200 m, and  $>3200$  m, respectively. Thus, water depth of 1700 m, 2700 m, 3200 m can be taken as thresholds controlling distribution of resource quantity from different ranges. Such thresholds can further be used as a reference when computing resources quantity of cobalt crust based on geological blocks.

### 5 Application of fractal modeling to evaluation of resource quantity

Thresholds of seamount slope and water depth from this study may serve as a reference for partitioning geological blocks that are important in computing resource quantity. An integration of the neighbor-region technique and geological block approach cannot only estimate resource quantity of small rich spots and large ore district, but also quantitatively study distribution of cobalt crust from the different topography of seamounts (Wu et al., 2000). Resource quantity refers to amount of mineral accumulation within a certain area ( $S$ ) or volume ( $V$ ). The parameter  $T/S$  is defined as the resource quantity in a unit area, which can be called mineralization intensity (Zhang, 1993). Statistical data may provide valuable information on spatial distribution and variation of mineralization, useful for evaluation and exploration of mineral deposits. Tables 4 and 5 show the quantity of cobalt crust from various topographic seamounts, calculated by using the parameter  $T/S$  and the fractal distribution of water depth and slope of seamounts combined with the neighbor-region and geological block methods.

Based on the calculation of the  $T/S$  values, cobalt crusts resource from the 12 seamounts shows three general types of distribution. In the Line Islands and Wake-Marcus Islands (CCL and CCM2), cobalt crusts are rich on slopes of  $6^\circ$ – $18^\circ$ , but are relatively poor over slopes  $<6^\circ$  and  $>18^\circ$ . By contrast, the Magellan seamounts (WMA, WME and WMK) and the Mid-Pacific Mountain (CCX) have more abundant cobalt crusts both on gentle and steep slopes. In the WMC, CCA and CCM3 seamounts, the cobalt resource increases with the slope. Resource quantity of individual seamount varies to a large degree with increasing water depth. In general, the crusts of the Line Islands are richer in deep-seated areas than

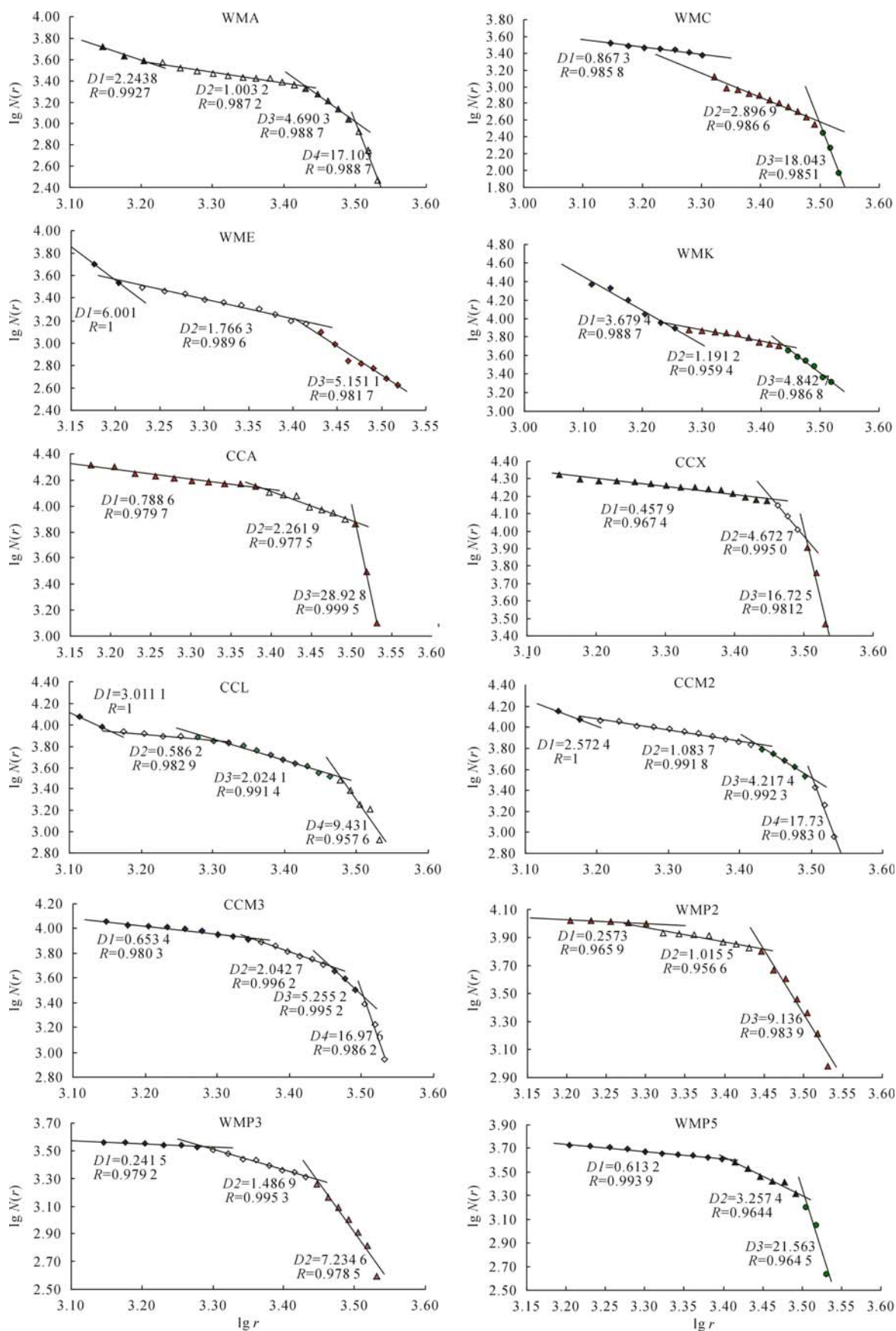


Fig. 4 Log-log plot showing relationship between water depth and resource quantity of 12 seamounts in Central-West Pacific

**Table 3** Fractal dimensions of the water depth and resource quantity on seamounts in various areas

Area	Seamount	First depth/m	$D_1$	Second depth/m	$D_2$	Third depth/m	$D_3$	Fourth depth/m	$D_4$	Residuals
Magellan	WMA	<1 700	2.243 8	1 700–2 700	1.003 2	2 700–3 200	4.690 3	≥3 200	17.105	0.005 0
	WMC	<2 100	0.867 3	2 100–3 200	2.896 9	≥3 200	18.04 3	—	—	0.011 1
	WME	<1 700	6.001	1 700–2 700	1.766 3	≥2 700	5.151 1	—	—	0.008 0
	WMK	<1 900	3.679 4	1 900–2 800	1.191 2	≥2 800	4.842 7	—	—	0.008 3
Mid-Pacific	CCA	<2 500	0.788 6	2 500–3 200	2.261 9	≥3 200	28.92 8	—	—	0.003 0
	CCX	<2 900	0.457 9	2 900–3 200	4.672 7	≥3 200	16.72 5	—	—	0.005 7
Wake-Marcus	CCL	<1 500	3.011 1	1 500–1 900	0.586 2	1 900–3 000	2.024 1	≥3 000	9.431	0.018 0
	CCM2	<1 600	2.572 4	1 600–2 700	1.083 7	2 700–3 200	4.217 4	≥3 200	17.73	0.005 0
	CCM3	<2 300	0.653 4	2 300–2 900	2.042 7	2 900–3 200	5.255 2	≥3 200	16.976	0.004 0
Line	WMP2	<2 000	0.257 3	2 100–2 800	1.015 5	≥2 800	7.234 6	—	—	0.011 6
	WMP3	<2 000	0.241 5	2 000–2 800	1.486 9	≥2 800	7.234 6	—	—	0.013 2
	WMP5	<2 600	0.613 2	2 600–3 200	3.257 4	≥3 200	21.563	—	—	0.013 9

**Table 4** Statistics of combined application of the nearest neighbor with geological block to cobalt crust resources on different seamounts (about the fractal of slope)

Area	Seamount	First		Second		Third	
		Slope range	$T/S/(10^4 \cdot \text{km}^{-2})$	Slope range	$T/S/(10^4 \cdot \text{km}^{-2})$	Slope range	$T/S/(10^4 \cdot \text{km}^{-2})$
Magellan	WMA	<12°	1.23	12° ≤ S < 21°	1.16	≥21°	1.44
	WMC	<15°	0.78	15° ≤ S < 21°	1.00	≥21°	1.04
	WME	<15°	2.25	15° ≤ S < 23°	2.11	≥23°	2.17
	WMK	<14°	3.90	14° ≤ S < 22°	3.34	≥22°	4.25
Mid-Pacific	CCA	<9°	0.96	9° ≤ S < 23°	1.36	≥23°	2.01
	CCX	<12°	3.44	12° ≤ S < 22°	3.07	≥22°	3.75
Wake-Marcus	CCL	<8°	1.18	8° ≤ S < 18°	2.07	≥18°	1.32
	CCM2	<6°	1.73	6° ≤ S < 15°	1.77	≥15°	1.59
	CCM3	<9°	2.85	9° ≤ S < 18°	3.36	≥18°	3.66
Lines	WMP2	<10°	0.88	10° ≤ S < 18°	1.24	≥18°	0.93
	WMP3	<9°	1.12	9° ≤ S < 18°	1.34	≥18°	1.04
	WMP5	<8°	0.83	8° ≤ S < 17°	1.08	≥17°	0.98

**Table 5** Statistics of combined application of the nearest neighbor with geological block to cobalt crust resources on different seamounts (about the fractal of water depth)

Area	Seamount	First		Second		Third		Fourth	
		Depth/m	$T/S/(10^4 \cdot \text{km}^{-2})$	Depth/m	$T/S/(10^4 \cdot \text{km}^{-2})$	Depth/m	$T/S/(10^4 \cdot \text{km}^{-2})$	Depth/m	$T/S/(10^4 \cdot \text{km}^{-2})$
Magellan	WMA	<1 700	1.15	1 700–2 700	1.35	2 700–3 200	1.27	≥3 200	1.06
	WMC	<2 100	0.65	2 100–3 200	1.11	≥3 200	1.09	—	—
	WME	<1 700	2.32	1 700–2 700	2.20	≥2 700	2.05	—	—
	WMK	<1 900	4.30	1 900–2 800	3.35	≥2 800	3.10	—	—
Mid-Pacific	CCA	<2 500	1.05	2 500–3 200	1.20	≥3 200	1.08	—	—
	CCX	<2 900	3.74	2 900–3 200	3.15	≥3 200	3.13	—	—
Wake- Marcus	CCL	<1 500	0.98	1 500–1 900	1.22	1 900–3 000	1.95	≥3 000	2.04
	CCM2	<1 600	1.65	1 600–2 700	1.62	2 700–3 200	1.83	≥3 200	1.92
	CCM3	<2 300	3.27	2 300–2 900	3.25	2 900–3 200	3.18	≥3 200	3.36
Line	WMP2	<2 000	0.53	2 100–2 800	1.04	≥2 800	0.95	—	—
	WMP3	<2 000	0.76	2 000–2 800	0.98	≥2 800	1.55	—	—
	WMP5	<2 600	0.65	2 600–3 200	1.16	≥3 200	1.34	—	—

shallow segments, whereas the opposite is observed in the Magellan seamounts, the Mid-Pacific Mountains and the Wake-Marcus Islands. The variation in cobalt resource quantity between seamounts may be interpreted in terms of

different structural evolution of individual seamounts. For example, the Line Islands have the smallest  $T/S$  value, possibly due to that the seamounts are young so that elapsed time has not been enough for the development of cobalt

crust. The difference of cobalt resource quantity is also present among seamounts from the same seamount province, as demonstrated by the CCX and CCA seamounts from the Mid-Pacific Mountains. Such differences may be related to distinct topography of individual seamount: the CCA seamount has a flat-top summit whereas the CCX has a conical summit. Results from this study demonstrate that fractal modeling of distribution of cobalt crusts in relation to slope and water depth of seamounts, combined with integrated usage of the nearest neighbor method and geological block method will be efficient to delineate rich ore segments.

## 6 Conclusion

Resource quantity of cobalt crust shows variable distribution among the 12 topographically distinct seamounts in the Central-West Pacific. The multi-fractal property of the slope and water depth of seamounts, when combined with the utilization of the neighbor-region and geological block methods, is instrumental in delineating rich blocks of cobalt crusts on the topographically distinct part of seamounts.

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