

Article

Quantitative Description of Size and Mass Distribution of Polymetallic Nodules in Northwest Pacific Ocean Basin

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Abstract: Metals in deep-sea polymetallic nodules are indispensable for battery production and play a crucial role in facilitating the socio-economic green transition. A three-dimensional laser scanning model of nodules in the northwest Pacific Ocean has yielded an amount of data on volume, shape, and particle size. To deeply mine the correlation between the characteristics of the nodules, a joint probability density function (JPDF) based on copula theory is used. A univariate probability density function (PDF) linked to the particle size, buried depth, shape factor, and mass of the ores is established. The trend of nodule density with particle size is analyzed. Then, bivariate joint distribution using the copula method is constructed for mass and particle size. Furthermore, trivariate joint distribution using the copula method for nodule mass, particle size, and shape factor is derived. The results of this paper provide data to support the resource assessment of polymetallic nodules and optimize the design of mining systems.

Keywords: polymetallic nodule; NW pacific; probabilistic modeling; three-dimensional scanning



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1. Introduction

Key metals, namely, cobalt, nickel, copper, and manganese, are abundant in polymetallic nodules, and play a crucial role in green transition [1]. These metal reserves in nodules in the Clarion–Clipperton Zone (CCZ) of the northeast Pacific Ocean alone are estimated to be 3 to 9 times more than the total reserves found in the global terrestrial region [2]. As valuable deep-sea mineral resources with important industrial applications, polymetallic nodules are still undergoing optimization and refinement in terms of their exploration and mining methods [3]. Polymetallic nodules usually form at the water–sediment interface of deep-sea plains in the form of two-dimensional deposits [4]. By using optical images captured at an elevation of 3 m above the seafloor, the two-dimensional size of the exposed manganese nodules on the sediment can be automatically and reliably detected. However, this method is unable to provide information regarding the burial depth and density of the nodules [5], leading to an impediment to a precise resource estimation. The limited individual characteristics of the nodules not only affect resource estimation but also result in a lack of basis for mining systems design.

The size, shape, burial depth, and density of polymetallic nodules are crucial factors that influence the design of mining vehicles and lifting systems [6]. Currently, the hydraulic lifting mining system exhibits promising commercial potential [7]. This system consists of several components, specifically mining vehicles, flexible risers, buffers, pipes, lifting pumps, and mining vessels [8] (Figure 1). The energy consumption and design of the pump are affected by the ore slurry concentration and the size distribution of polymetallic nodules [9]. The presence of large nodules poses risks of clogging when conveying them through the centrifugal pump and the collection head [10]. The burial depth affects the

design of the flow field surrounding the collection head, as well as the resulting disturbance depth. The deeper the nodule burial depth, the higher the jet flow velocity that is required, yielding a greater depth of sediment disturbance. The settling velocity and transport velocity of polymetallic nodules during the hydraulic lifting process in vertical risers are directly associated with their form, density, and mass properties [11]. To ensure the collection efficiency and the reliability of the mining system, it is necessary to conduct an analysis and quantitative characterization of the particle size, mass, shape, density, and burial depth of nodules in the mining area. The selection of appropriate designing parameters, including the collection head diameter, the riser pipe inner diameter, and the flow velocity and other parameters, can improve system performance and avoid clogging, and this can be achieved by utilizing statistical models that consider the physical characteristics of nodules.

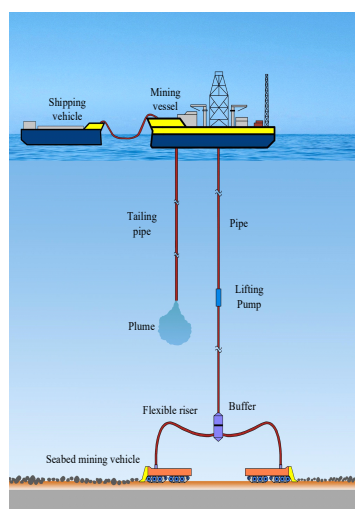


Figure 1. Schematic of a mining system for seafloor polymetallic nodules.

Extensive research has been conducted on the characteristics of nodules of the CCZ in the northeast Pacific, the Peru Basin in the southeast Pacific, and the central Indian Ocean [12]. For example, the relationship between the particle size of the CCZ nodules and the smoothness of both the upper and the lower surface was explored [13]. The relationship between the long axis and mass of CCZ nodules was fitted by a log-linear model, the Gaussian curve, and the Rayleigh curve, respectively [14–16]. The joint distribution of nodule size and mass in the CCZ area was estimated by using the copula method; however, the influence of nodule shape on the dependence between its size and mass was not considered [17]. Spherical and discoidal nodules predominated in the Peru Basin, whereas a greater concentration of small ellipsoidal and irregular nodules was observed in close proximity to seamount slopes [18]. The relationship between shape, Mn/Fe ratio, and topography of Peru Basin nodule was studied [19], as well as the spatial distribution of nodules with different cores in the Peru Basin [20]. The relationship between different genetic types of nodules, particle size, and underlying sediments in the Central Indian Ocean was researched [21], along with the shape, particle size, density variation, porosity, water content, and other characteristics of Central Indian Ocean nodules [22]. Central Indian Ocean nodules mainly exhibited a spherical morphology with dimensions ranging from 2 to 4 cm. As the particle size increased, the spherical nodules gradually transformed into discoidal and elongated shapes [23]. Disparities in the physical and distribution characteristics of nodules are observed across diverse marine regions. Presently, the research on nodules in the Pacific Northwest is still insufficient.

The rest of the paper is organized as follows. In the next Section, the location of the polymetallic nodule samples and the post-processing techniques used for the three-dimensional scanning models are described. In Section 3, the PDF, spatial distribution, and

correlation relationships of nodule characteristics, including particle size, shape, burial depth, mass, and density are analyzed. Furthermore, reasoning is carried out on the geological factors that might contribute to this distribution phenomenon. In Section 4, the JPDE, considering the nodule size, mass, and shape, was introduced using copula to capture the intricate nonlinear interdependence among those attributes. The differences and similarities between the fitted results and the CCZ Korea contract area are compared in the discussion Section, and the paper is concluded in Section 5.

2. Materials and Methods

2.1. Polymetallic Nodule Contract Area and Samples

The polymetallic nodule contract area of The Beijing Pioneer Hi-tech Development Corporation (BPC) lies in the intermountain basin that lies between the Magellan Seamounts and the Marcus–Wake Seamounts chain in the western Pacific. The BPC has four exploration areas, C1, C2, M1, and M2, totaling 74,052 km² (Figure 2). The nodule samples used in this paper were collected from block M2, which is predominantly composed of hydroformed nodules. The central part of block M2 constitutes a relatively large plain with a water depth of 5100–5700 m. The northwest of block M2 is close to the southern part of the Magoshichi Seamount, where landslide landforms are comparably developed, and the water depth is between 4500 and 5500 m. The sediments in the contract area are yellowish-brown deep-sea clay, with a siliceous clay sedimentation rate of less than 0.5 mm/ky. The summer surface productivity is less than 3000 mg C/m²/day. Those factors make the region under investigation an ideal metallogenic belt for polymetallic nodules [24].

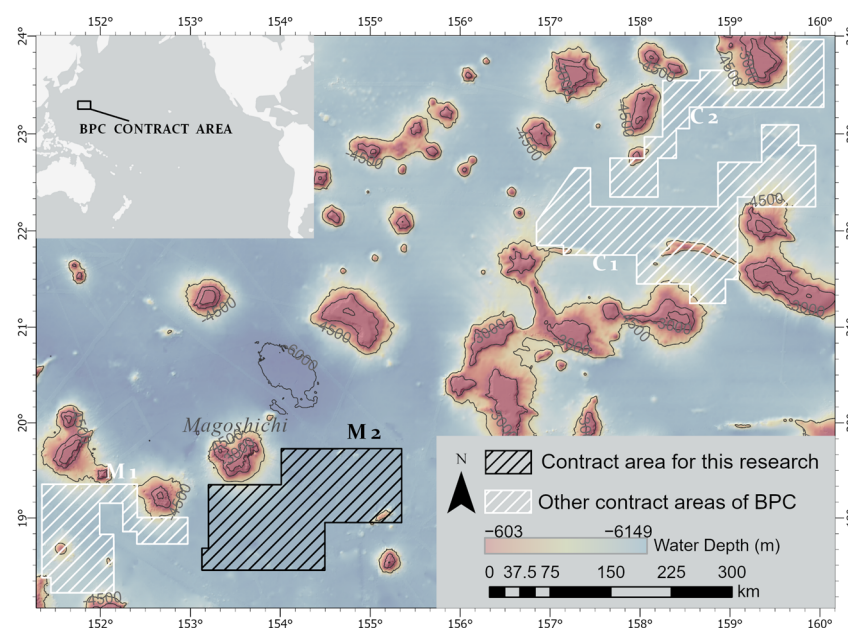


Figure 2. Location map of BPC contract area for polymetallic nodules.

During DY-75 cruises in 2022, 8798 nodules were collected by box-corer at 80 stations, encompassing the triaxial axis length, mass, and shape data. The distance between each two adjacent stations is 10–20 km. Each nodule at each station undergoes high-precision 3D laser scanning to accurately obtain the nodule's three-axis dimensions and volume information. During scanning, the nodules are placed on a rack arranged in 4 rows and 7 columns. In the post-processing stage, the spatial bounding box for each individual nodule is first obtained based on its preset position (Figure 3). Then, each nodule is cropped out using the spatial bounding box, and a clustering algorithm is applied to automatically separate the polymetallic nodule model from the rack. Finally, the Open3D library is used to automatically calculate the nodule's three-axis dimensions and volume. The traditional immersion-based drainage method encounters inefficiencies and diminished precision

when applied to nodules. Employing a non-contact 3D scanner to comprehensively record the surface morphological information of samples not only enhances volume measurement precision and efficiency but also mitigates sample damage and contaminations. Several unrealistic measurements that could have resulted from entry errors while manually recording masses are screened out.

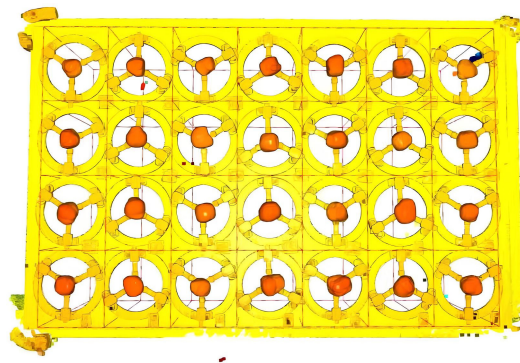


Figure 3. Three-dimensional scanning model of polymetallic nodules. The yellow surface patches represent the rack model, the orange surface patches represent the nodule model, and the red lines indicate the spatial bounding box used in the post-processing stage.

2.2. Univariate Probability Distribution

Distributions such as normal, log-normal, gamma, Weibull, extreme value type I, and generalized extreme value (GEV) distributions are used for fitting the characteristics of nodules, including size, mass, shape factor, burial depth, and density (Table 1). To assess the extent of correlation among various nodule characteristics, the Spearman correlation coefficient (r_s) is employed. This coefficient is robust when dealing with non-normally distributed data [25]. It assesses the monotonic relationship between variables through the fractional ranking difference d_i and sample size n :

$$r_s = 1 - \frac{6 \sum_{i=0}^{i=n} d_i^2}{n(n^2 - 1)} \quad (1)$$

Table 1. Candidate probability distribution functions (the tail shape is classified according to the index proposed by Rojo [26]).

Distribution	Probability Density Function	Parameters Range	Properties of Distribution
Normal	$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$	$-\infty < \mu < \infty, 0 < \sigma < \infty$	Symmetrical, Medium-tailed
Log-normal	$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left\{-\frac{(\log x - \mu)^2}{2\sigma^2}\right\}$	$-\infty < \mu < \infty, 0 < \sigma < \infty$	Skewed, Long-tailed,
Gamma	$f(x) = \frac{1}{b^a\Gamma(a)} x^{a-1} e^{-\frac{x}{b}}$	$0 < a < \infty, 0 < b < \infty$	Skewed, Medium-tailed
Weibull	$f(x) = abx^{b-1} e^{-ax^b}$	$0 < a < \infty, 0 < b < \infty$	Skewed, Long-tailed,
Extreme value	$f(x) = \frac{1}{\sigma} e^{\left(\frac{x-\mu}{\sigma}\right)} e^{-e^{\left(\frac{x-\mu}{\sigma}\right)}}$	$-\infty < k < \infty, 0 < \sigma < \infty$	Skewed, Short-tailed
GEV	$f(x) = \frac{1}{\sigma} e^{-\left(1+k\left(\frac{x-\mu}{\sigma}\right)\right)^{-\frac{1}{k}}} \left(1+k\left(\frac{x-\mu}{\sigma}\right)\right)^{-1-\frac{1}{k}}$	$-\infty < k < \infty, 0 < \sigma < \infty$ $-\infty < \mu < \infty$	Skewed, Short-tailed

2.3. Copula Based Joint Distribution

The JPPDF of nodule size, mass, and shape was constructed using the copula function. Copula is a mathematical object that captures the dependency structure among random variables. Therefore, the multivariate joint distribution model can be efficiently derived given a marginal distribution. Although the multidimensional normal distribution is a more commonly used joint distribution, it assumes that each variable follows a normal distribution and the correlation between variables is linear [27]. The mass distribution of

polymetallic nodules is pronounced skewed, and the complex composition of the nodules leads to a non-linear dependence between nodule mass and nodule size. As a result, fitting functions with multivariate normal distributions are prone to deviations. The copula method shows a more flexible capability for joint distribution modeling because it imposes no restrictions on either the type of marginal distribution or the dependencies between variables.

Based on Sklar's theorem, the copula model decomposes the joint distribution of random variables in any dimension into marginal distribution functions and a copula function. According to Sklar's theorem [28], if F is a joint distribution function of d dimensions with marginal distributions $F_1(x_1), F_2(x_2), \dots, F_d(x_d)$, then there exists a copula function C that satisfies the equation for all random variables $x_1, x_2, \dots, x_d$:

$$F(x_1, x_2, \dots, x_d) = C(F_1(x_1), F_2(x_2), \dots, F_d(x_d)) \quad (2)$$

The Archimedean copulas and the elliptical copula function are two big copula families. In this paper, Gaussian and t copula from the elliptical classes, as well as Clayton, Gumbel, Frank, and Joe copula from the Archimedean classes, are selected as candidate copula models (Table 2). Given $u_d = F_d(x_d)$, $u_d \in [0, 1]$. The value of C ranges from 0 to 1. Here, Φ^{-1} denotes the inverse function of the standard normal distribution function and t_{τ}^{-1} is the inverse function of the univariate t distribution with degrees of freedom τ .

Table 2. Candidate Copula-based joint distribution.

Dimension	Copula	Cumulative Distribution Function	Parameter Range	Tail Dependence
Bivariate	Gaussian	$C(u_1, u_2 \rho) = \Phi_{\rho}(\Phi^{-1}(u_1) + \Phi^{-1}(u_2))$	$-1 \leq \rho \leq 1$	No tail
Bivariate	t	$C(u_1, u_2 \rho, \tau) = t_{\rho, \tau}(t_{\tau}^{-1}(u_1), t_{\tau}^{-1}(u_2))$	$-1 < \rho < 1,$ $1 \leq \tau < \infty$	Symmetric tail
Bivariate	Clayton	$C(u_1, u_2 \theta) = (u_1^{-\theta} + u_2^{-\theta} - 1)^{-1/\theta}$	$0 < \theta < \infty$	Lower tail
Bivariate	Gumbel	$C(u_1, u_2 \theta) = \exp(-[(-\ln u_1)^{\theta} + (-\ln u_2)^{\theta}]^{1/\theta})$	$1 \leq \theta < \infty$	Upper tail
Bivariate	Joe	$C(u_1, u_2 \theta) = 1 - [1 - (1 - (1 - u_1)^{1/\theta})(1 - (1 - u_2)^{1/\theta})]^{1/\theta}$	$1 \leq \theta < \infty$	Upper tail
Trivariate	Gaussian	$C(u_1, u_2, u_3 \rho) = \Phi_{\rho}(\Phi^{-1}(u_1) + \Phi^{-1}(u_2) + \Phi^{-1}(u_3))$	$-1 \leq \rho \leq 1$	No tail
Trivariate	t	$C(u_1, u_2, u_3 \rho, \tau) = t_{\rho, \tau}(t_{\tau}^{-1}(u_1), t_{\tau}^{-1}(u_2), t_{\tau}^{-1}(u_3))$	$-1 < \rho < 1,$ $1 \leq \tau < \infty$	Symmetric tail
Trivariate	Clayton	$C(u_1, u_2, u_3 \theta) = (u_1^{-\theta} + u_2^{-\theta} + u_3^{-\theta} - 2)^{-1/\theta}$	$0 < \theta < \infty$	Lower tail
Trivariate	Gumbel	$C(u_1, u_2, u_3 \theta) = \exp(-[(-\ln u_1)^{\theta} + (-\ln u_2)^{\theta} + (-\ln u_3)^{\theta}]^{1/\theta})$	$1 \leq \theta < \infty$	Upper tail
Trivariate	Joe	$C(u_1, u_2, u_3 \theta) = 1 - [1 - (1 - (1 - u_1)^{1/\theta})(1 - (1 - u_2)^{1/\theta})(1 - (1 - u_3)^{1/\theta})]^{1/\theta}$	$1 \leq \theta < \infty$	Upper tail

With the above-mentioned theories and the candidate functions, the process of calculating the JPDP using copula on the MATLAB (2023b) platform can be divided into three steps [23]: (1) Fitting the optimal PDF for the marginal distribution $f(x)$, as well as the marginal cumulative probability density distribution function $F(x)$. (2) Based on the estimated parameter θ of the copula function C calculated from $F(x)$, the joint cumulative distribution function $F(x_1, x_2, \dots, x_d)$ was obtained:

$$F(x_1, x_2, \dots, x_d) = C(F_1(x_1), F_2(x_2), \dots, F_d(x_d) | \theta) = C(u_1, u_2, \dots, u_d | \theta) \quad (3)$$

By taking the derivative of the copula function C with respect to the variables, the probability density function c of the copula is obtained, then the PDF model can be calculated by multiplying c with $f(x)$:

$$c(u_1, u_2, \dots, u_d | \theta) = \frac{\partial^2 C(u_1, u_2, \dots, u_d | \theta)}{\partial u_1 \partial u_2 \dots \partial u_d} \quad (4)$$

$$f(x_1, x_2, \dots, x_d) = c(u_1, u_2, \dots, u_d | \theta) \prod_{d=1}^D f_d(x_d) \quad (5)$$

2.4. Parameter Estimation and Goodness of Fit

It has been accepted that there is no significant difference in the parameter values of the copula model obtained using the full maximum likelihood (FML) and the inference function for the margins (IFM) [27]. Considering that estimating a large number of parameters simultaneously is not conducive to optimization, IFM is generally used to acquire the parameters for the copula model. The steps of obtaining model parameters by IFM can be decomposed into two stages: First, the parameters a and b of the marginal distribution were estimated, and $\hat{a}$ and $\hat{b}$ were substituted into the copula function to estimate the parameter $\hat{\theta}$:

$$\hat{a}, \hat{b} = \operatorname{argmax}_{\mu, \sigma} \sum_{i=1}^n \ln f(x^i; a, b) \quad (6)$$

$$\hat{\theta} = \operatorname{argmax}_{\theta} \sum_{i=1}^n \ln c(F_1(x_1^i; \hat{a}_1, \hat{b}_1), F_2(x_2^i; \hat{a}_2, \hat{b}_2), \dots, F_d(x_d^i; \hat{a}_d, \hat{b}_d); \theta) \quad (7)$$

The likelihood function $f(x_i; a, b)$ can be directly derived from the PDF. By taking the log logarithm of likelihood, the product of the likelihood for independent and identically distributed variables transforms into a summation form, facilitating parameter optimization. The AIC is utilized as the evaluation index for the univariate distribution:

$$\text{AIC} = 2k - 2 \ln L \quad (8)$$

where L is the maximum likelihood value of the candidate function, and k is the number of parameters of each candidate distribution. The copula model is evaluated by using the Kolmogorov–Smirnov (K–S) test and the Root Mean Square Error (RMSE):

$$\text{KSE} = \max_{i=1,2,\dots,n} |C(F(x_1^i), F(x_2^i), \dots, F(x_d^i)) - \tilde{C}(x_1^i, x_1^i, \dots, x_d^i)| \quad (9)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n [C(F(x_1^i), F(x_2^i), \dots, F(x_d^i)) - \tilde{C}(x_1^i, x_1^i, \dots, x_d^i)]^2} \quad (10)$$

$$\tilde{C}(x_1^i, x_1^i, \dots, x_d^i) = \frac{\#(X_1 \leq x_1^i, X_2 \leq x_2^i, \dots, X_d \leq x_d^i) - 0.44}{n + 0.12} \quad (11)$$

C and $\tilde{C}$ are the theoretical frequency and empirical frequency, respectively. n is the sample size. C is calculated from the copula distribution. $\tilde{C}$ is estimated using the Gringorten formula [29]. $\#(X_1 \leq x_1^i, X_2 \leq x_2^i, \dots, X_d \leq x_d^i)$ is the number of samples satisfying $X_1 \leq x_1^i, X_2 \leq x_2^i, \dots, X_d \leq x_d^i$ in the observation sample.

3. Results

3.1. Nodule Size Distribution

The particle size of a nodule is characterized by its long axis. It can be proved that the long axis is an important parameter for the design of the collection head. The histogram of the quantity and weight statistics of the long axis are shown in Figure 4a. It can be seen that the size of the nodules associated with a collection rate of 90% is 5.12 cm, and the size at which the mass of nodules corresponding to a mass collection rate of 90% is 6.11 cm. The particle size distribution of nodules at 80 stations in block M2 shows that medium-sized nodules are mainly distributed in the middle basin area of block M2, while large-sized nodules are predominantly concentrated on the south side of the Magoshichi Seamount (Figure 5).

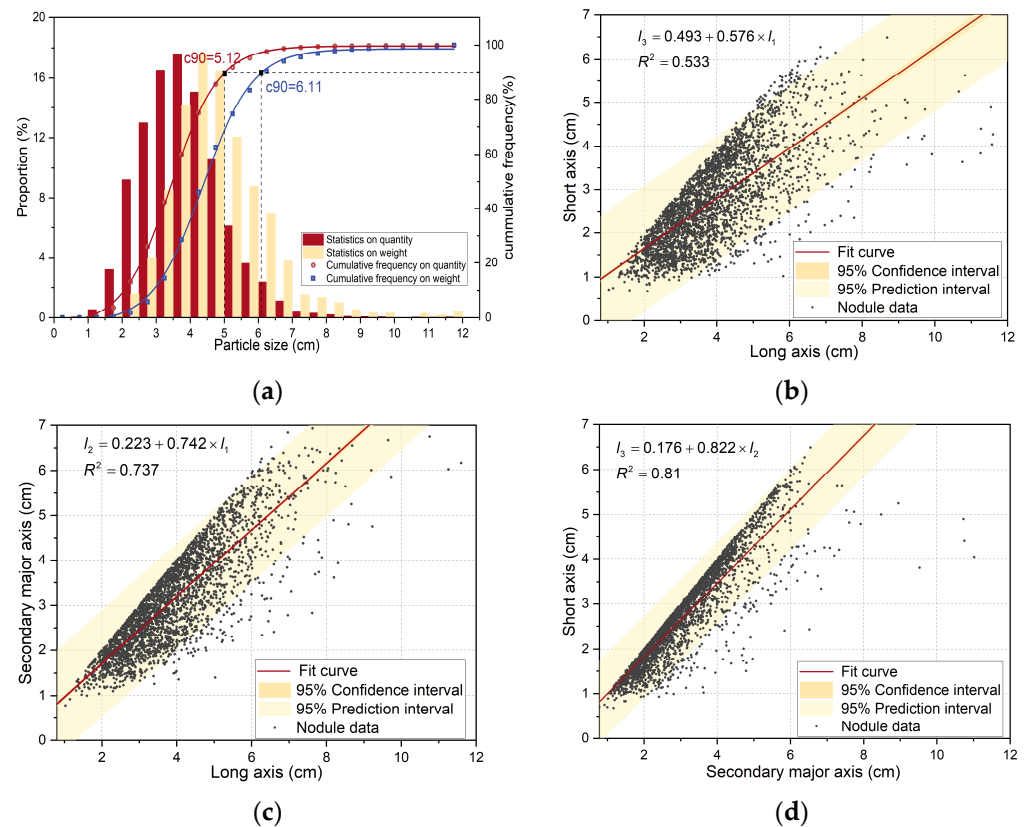


Figure 4. (a) Cumulative proportions of the number and mass of nodules in different particle sizes. (b) The relationship between the long axis and the short axis. (c) The relationship between the long axis and the secondary major axis. (d) The relationship between the secondary major axis and the short axis.

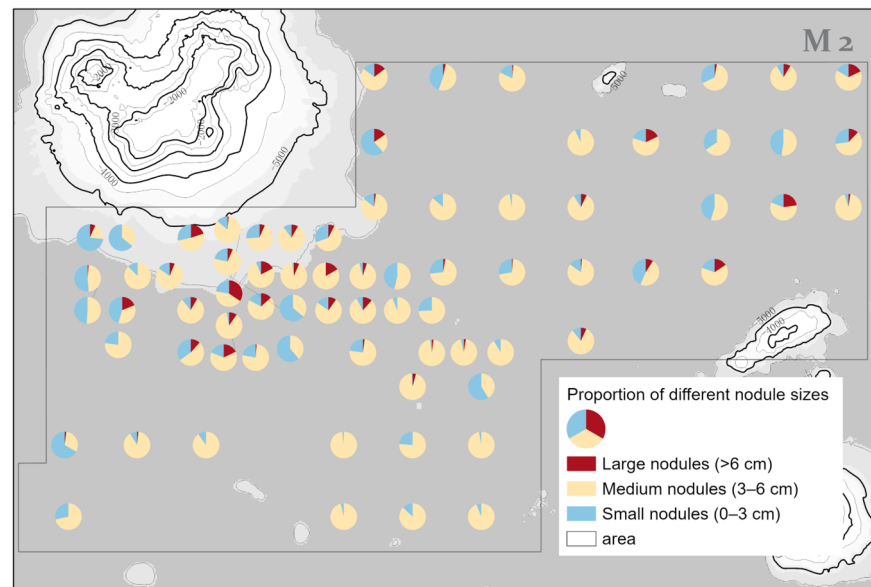


Figure 5. Spatial distribution of the proportion of different nodule sizes in the M2 area.

The mineralization mechanisms of polymetallic nodules mainly include three types: hydrogenic precipitation, diagenetic precipitation, and hydrothermal precipitation. The first two mechanisms are the most common. Hydrogenic precipitation occurs when dissolved Mn^{2+} and Fe^{2+} in seawater precipitate to form nodules, while diagenetic precipitation involves the adsorption of Mn, Fe, and other metal ions from pore water to form nodules.

Most polymetallic nodules in the BPC contract area are hydrogenic nodules. Based on the mineralization mechanisms, a preliminary analysis of the spatial distribution patterns of the polymetallic nodule size in the BPC region can be conducted. The biological productivity in the vicinity of seamounts exceeds that observed in basins, resulting in enhanced organic matter deposition on the seabed and consequently elevating the rate of oxygen consumption. Environments with lower oxygen levels favor the dissolution, migration, and redeposition of manganese elements in sediments, thereby accelerating the growth of nodules. It is speculated that nodules near seamounts are more significantly influenced by diagenesis compared to those in the central basin, greatly increasing the probability of larger nodules appearing compared to those in the central basin.

The relationship among the three characteristic axis lengths of nodules, namely, the long axis, the secondary major axis, and the short axis, extends significant reference for optical survey methods that can only obtain two-dimensional information. The long axis and secondary major axis represent the axial lengths of the largest horizontal cross-section of nodules. The short axis often represents the vertical length of the nodule burial direction. The interrelationship among the three axes is illustrated through linear fitting in Figure 4b–d, with the confidence interval and prediction interval of the fitting results presented. The R^2 value of the linear regressions between the short axis and the secondary major axis is 0.81. The R^2 value of the linear regressions between the short axis and the long axis is 0.53. The narrow confidence interval indicates a relatively high level of certainty. Consequently, the linear fit between the short axis and the secondary major axis outperforms that between the short axis and the long axis. The slope between the short axis and the secondary major axis is 0.822, with an intercept of 0.176.

3.2. Nodule Shape Analysis

At the initial stage of nodule formation, the shape of the nodule typically follows that of the nucleating material. As growth proceeds, the nodule gradually transforms into an ellipsoidal or discoidal shape [30]. In some cases, smaller nodules can aggregate to form conjoined nodules. Among 8798 samples of polymetallic nodules, ellipsoidal nodules accounted for 71.4%, conjoined nodules constituted 16.2%, spherical nodules made up 11.6%, and discoidal nodules accounted for 0.8% (Figure 6a). Shape factor ξ was used to describe the shape characteristics of nodules:

$$\xi = l_3 / \sqrt{l_1 l_2} \quad (12)$$

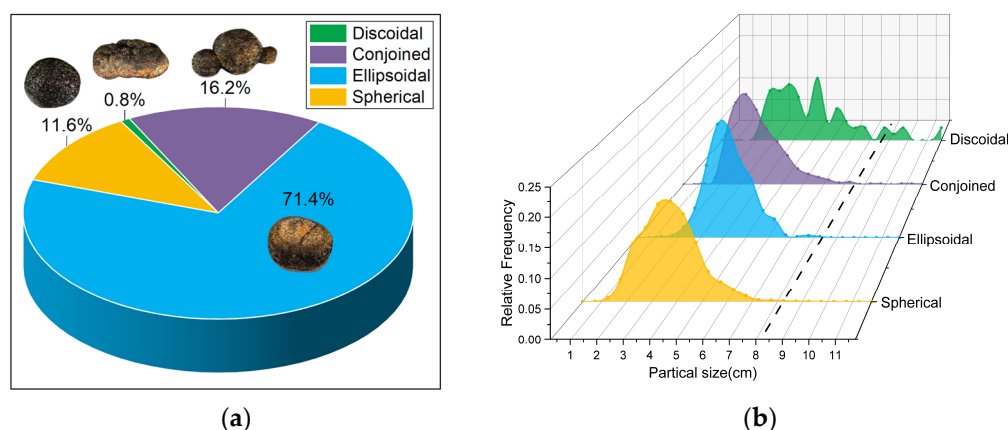


Figure 6. (a) The proportion of polymetallic nodules with different shapes. (b) Particle size distribution of nodules with different shapes.

l_1, l_2, l_3 are the long axis, secondary major axis, and short axis of nodules, respectively. $\xi \in [0, 1]$, as ξ approaches one, the shape is more spherical, while as ξ tends to zero, the shape becomes flatter or elongated (Figure 7). Figure 7 shows that the highest frequency of the shape factor for spherical and ellipsoidal nodules is 0.9–1.0, for conjoined nodules is 0.7–0.8, and for discoidal nodules shifts to 0.4–0.5.

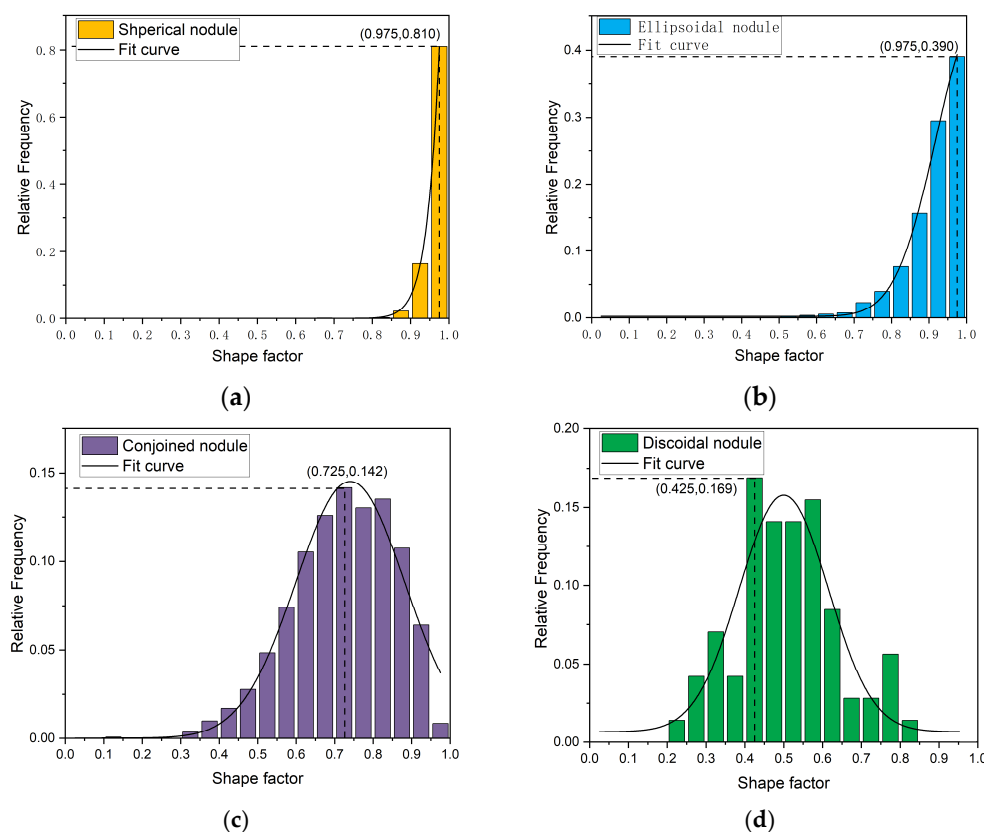


Figure 7. (a–d) Distribution range of shape factors for different shapes of nodules.

Analysis of the relationship between shape factor and size revealed that nodules smaller than 8 cm were predominantly ellipsoids, while nodules larger than 8 cm exhibited a significantly higher proportion of discoidal shapes (Figure 6b). This phenomenon can be attributed to the fact that, as nodules grow to a certain size, the buried part of the nodules reaches the depth of the redox boundary [31]. The lower parts of nodules experience a faster growth rate in the diagenetic environment, while the exposed part on the sediment surface undergoes slower growth. This discrepancy in the growth rates results in the asymmetric growth of nodules.

The shape of nodules at each station in the M2 area reveals that the middle area of the basin is dominated by ellipsoids, while a greater variety of the shape types are observed on the south side of the seamount. Notably, spherical, conjoined, and plate-shaped are more concentrated on the south side of the seamount (Figure 8). This observation leads to the speculation that the debris produced by the landslide on the south side of the seamount has provided diverse forms of nucleation materials, fostering the growth of nodules in various forms.

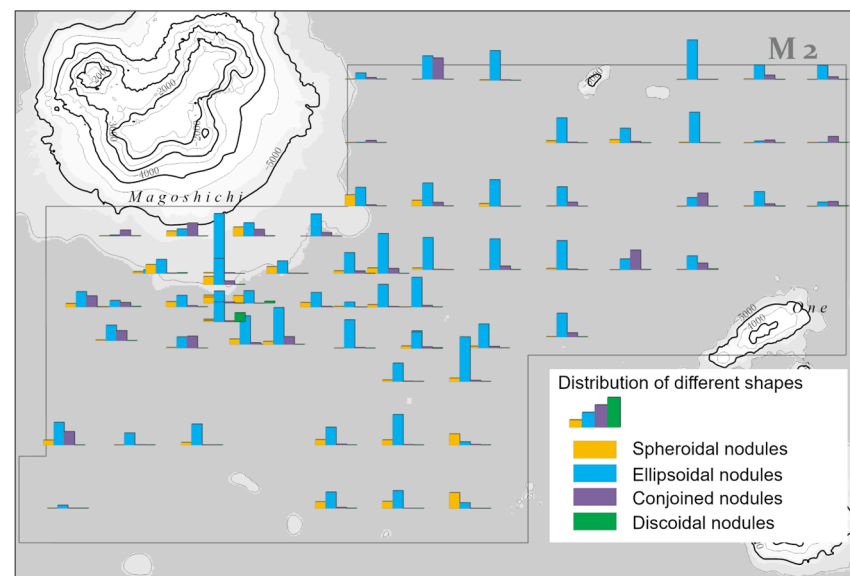


Figure 8. Spatial distribution of different shapes of nodules in the M2 area.

3.3. Nodule Mass Analysis

The Pearson correlation coefficient (r) between the mean long axis and mass of nodules in the KR5 area of the eastern Pacific is 0.84, which indicates a strong correlation between nodules mass and size [8]. In our study, r between the long axis and mass is only 0.31 (Table 3), while r_s is 0.92 (Table 4), suggesting a significant linear correlation in KR5, but a non-linear relationship in the western Pacific. This may be due to differences in nodule shape in different marine areas, as most of the nodules in the KR5 area are discoidal, while the BPC area is predominantly ellipsoidal [8]. Additionally, r and r_s between the sub-long axis and mass in the BPC region are higher than those for the long and short axes, reaching 0.86 and 0.97, respectively.

Table 3. Matrix of Pearson's rank correlation coefficients for different characteristic parameters of nodules.

	Long Axis	Secondary Major Axis	Short Axis	Mass	Shape Factor
Long axis	1	0.33	0.3	0.31	−0.12
Secondary major axis	0.33	1	0.94	0.86	0.21
Short axis	0.3	0.94	1	0.77	0.45
Mass	0.31	0.86	0.77	1	0.07
Shape factor	−0.12	0.21	0.45	0.07	1

Table 4. Spearman rank correlation coefficient matrix of different characteristic parameters of nodules.

	Long Axis	Secondary Major Axis	Short Axis	Mass	Shape Factor
Long axis	1	0.89	0.82	0.92	−0.04
Secondary major axis	0.89	1	0.96	0.97	0.31
Short axis	0.82	0.96	1	0.96	0.45
Mass	0.92	0.97	0.96	1	0.25
Shape factor	−0.04	0.31	0.45	0.25	1

Notable variations in the nonlinear relationship between the mass and size are observed among different types of nodules (Figure 9a). This suggests that the shape of nodules also plays a significant role in affecting the relationship between the mass and size. Due

to the partial overlap in the scattering distribution of nodules with different shapes and sizes, it would be clearer to establish a joint probability distribution model between mass and size by dividing cases based on shape factors (Figure 9b). The marginal histogram in Figure 9 also shows that the mass distribution of nodules is obviously right-skewed, with notable long-tail characteristics.

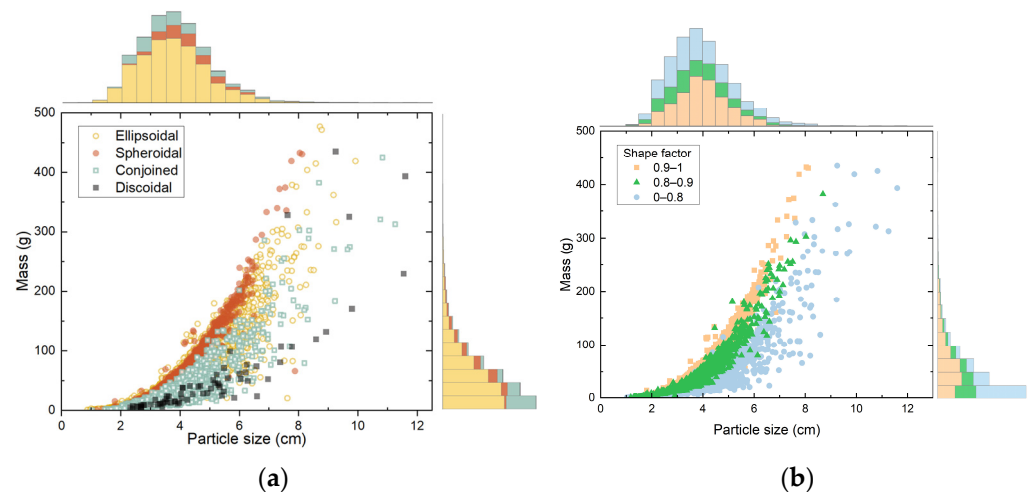


Figure 9. (a) Marginal histograms of mass and particle size of polymetallic nodules with different shapes. (b) Marginal histograms of mass and particle size of polymetallic nodules with different shape factors.

3.4. Nodule Density Analysis

The scatter plot of the nodule density and the long axis reveals that the nodule density gradually stabilizes at around 1970 kg/m^3 as the size increases (Figure 10). An exponential function was fitted to the upper and lower boundaries on the variation between the nodule density and the long axis, where y_{up} is the upper boundary of the nodule density, y_{down} is the lower boundary of the nodule density, and x represents the length of the nodule's long axis:

$$y_{up} = \begin{cases} 3.0 & x \leq 3.7 \\ 1.97 + 9.0e^{-0.59x} & x > 3.7 \end{cases} \quad (13)$$

$$y_{down} = \begin{cases} 1.2 & x \leq 3.7 \\ 1.97 - 6.08e^{-0.58x} & x > 3.7 \end{cases} \quad (14)$$

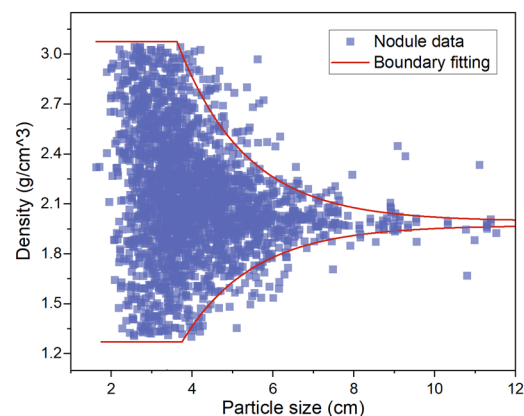


Figure 10. Envelope function fitting results of polymetallic nodules density.

The complexity of nodule composition and structure results in variations in nodule density. The core of the nodules exhibits high porosity, with its constituents comprising irregularly shaped rock debris, indurated sediment, nodule fragments, shark teeth, etc. [32,33]. Rock debris includes feldspar and quartz, with quartz being larger and granular, while feldspar mainly is plate-like with pores in the middle and partially altered. The densities of shark teeth, quartz, and feldspar are 2.71, 2.65, and 2.55 g/cm³, respectively. However, the nodule shell exhibits a relatively uniform composition, with closely arranged constituents, and pores are either scarce or poorly developed [4]. The micro-textural features of the shell can be classified into columnar, dendritic, finely laminar, mottled, and dense block types [34]. The mineral composition of the shell consists of iron and manganese minerals with low crystallinity, including Vernadite, Birnessite, and Todorokite. The mineral densities are 2.9, 3.0, and 3.67 g/cm³, respectively (the density data can be referred to the link <https://mindat.org>, accessed on 29 September 2024).

The reason for the greater stability in the density of larger nodules is speculated to be attributed to the overall volume occupied by the shell structure, which results in a more uniform porosity and water content of the nodule [4,35,36]. Jiang et al. measured the core density of nodules in the Western Pacific region. For nodules where core volume accounted for 2.42%, the difference between the overall nodule density and the core density was 0.21 g/cm³ [37]. For nodules where the core volume accounted for 1.03%, the difference in density between the overall nodules and the core was 0.04 g/cm³. The measured data indicate that smaller nodules have a relatively larger proportion of the inner core, leading to a greater influence of the inner core on nodule density.

3.5. Statistic Model of Characteristics

The PDF of polymetallic nodule characteristics can predict the probability of ore characteristics occurring within a certain interval. Based on experience and data distribution characteristics, six potential distribution functions were preselected. The nodule size and burial depth are symmetrically distributed, while the mass has a pronounced right-skewed distribution, and the shape factor has a distinct left-skewed distribution (Figure 11). The fitting results are assessed by using AIC, and the most suitable PDF is chosen through comprehensive consideration of both the fitting performance and function complexity (Table 5). The PDFs for nodule size l and burial depth h follow a normal distribution, and the PDFs for nodule shape factor ξ and mass m are characterized by the generalized extreme value distribution and Weibull distribution, respectively. The frequency distribution of nodule burial depth shows that most nodules are buried at depths of 0 to 4 cm, exhibiting a semi-buried state, with half of the nodule volume exposed above the sediment and half buried beneath it.

Table 5. Results of PDF parameter fitting process for different characteristics of polymetallic nodules.

Characteristic	Probability Distribution Function	AIC ($\times 10^3$)	R ²
Particle size	$f(l) = 0.001 + 0.35e^{-2(\frac{l-3.65}{2.22})^2}$	28.08	0.98
Buried depth	$f(h) = -0.005 + 0.73e^{-2(\frac{h-1.54}{1.13})^2}$	15.97	0.98
Shape factor	$f(\xi) = \frac{1}{0.12}e^{(-1+\frac{(\xi-0.881)}{0.12})}$	−15.51	0.96
Mass	$f(m) = 0.02(\frac{m-2.96}{51.83})^{0.053}\exp\{- (\frac{m-2.96}{51.83})^{1.05}\}$	86.42	0.97

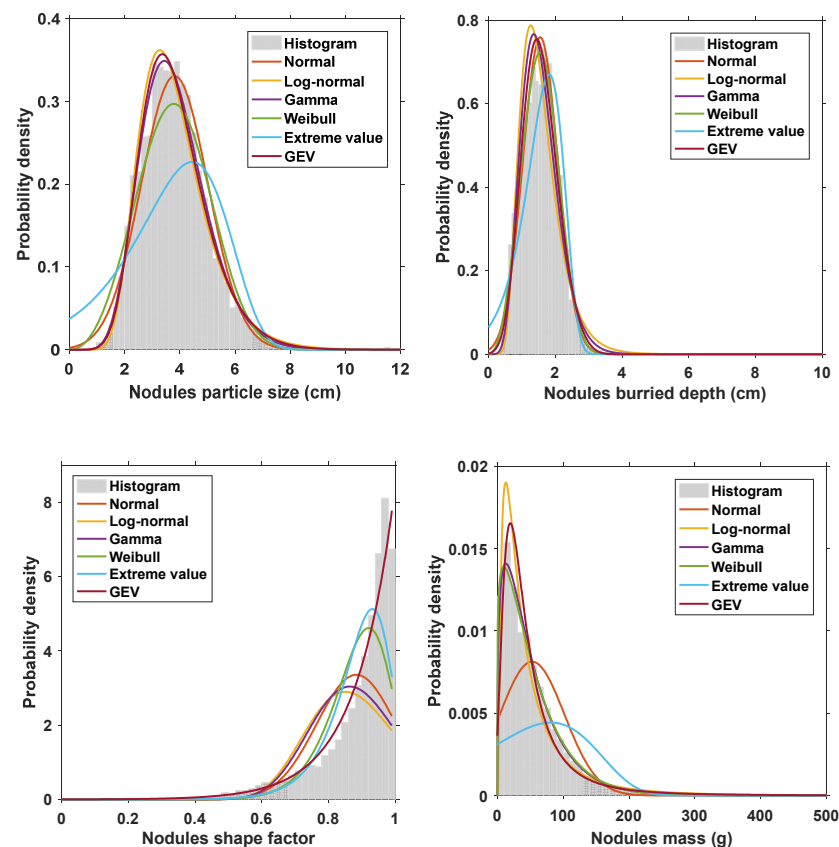


Figure 11. PDF fitting results of particle size, burial depth, shape factor, and mass characteristics.

4. Discussion

It was found that there exists a strong correlation between the mass and size characteristics, and it is often necessary to consider multiple characteristics of the nodules during the exploration and mining process. The nodules are categorized into three groups based on the range of the shape factor intervals, and the joint PDF of mass and particle size are established by using copula. The nodules with a shape factor of 0.9–1 are mostly spherical, the nodules with a shape coefficient of 0.8–0.9 are mainly ellipsoidal, and the conjoined and discoidal nodules are mainly distributed within the range of shape factor 0–0.8. The J PDF achieves the best fit when the marginal distributions of nodule size and mass follow a logarithmic distribution function (Table 6).

Table 6. Results of copula parameter fitting process for bivariate case.

Shape Factor	Gaussian Copula	Log-Normal Distribution	
		Particle Size	Mass
0.9–1	$\rho = 0.99$	$\mu = 1.35, \sigma = 0.27$	$\mu = 3.96, \sigma = 0.81$
0.8–0.9	$\rho = 0.98$	$\mu = 1.28, \sigma = 0.33$	$\mu = 3.47, \sigma = 1.02$
0–0.8	$\rho = 0.94$	$\mu = 1.33, \sigma = 0.37$	$\mu = 3.06, \sigma = 1.11$

The K-S and RMSE of various copula estimation results indicate that the Gaussian copula is the best-fit model, with the KSE value below 0.06 and RMSE value under 0.03 (Table 7). The findings from the BPC contract area confirm that the Gaussian copula is the optimal fitting model for the relationship between particle size and quality, consistent with the KR5 results. This supports the Gaussian copula's applicability in describing the two-dimensional joint probability distribution of polymetallic nodules. In the BPC region, ρ values of the Gaussian copula for shape factors of 0.9–1, 0.8–0.9, and 0–0.8 are 0.99, 0.98,

and 0.94, respectively, which overall maintains a certain consistency with the 0.96 value observed in the KR5 contract area.

Table 7. KSE and RMSE of multidimensional copula fitting of polymetallic nodule samples.

Copula	KSE ($\times 10^{-2}$)				RMSE ($\times 10^{-2}$)			
	SF 0.9–1	SF 0.8–0.9	SF 0–0.8	SF 0–1	SF 0.9–1	SF 0.8–0.9	SF 0–0.8	SF 0–1
Gaussian	5.94	3.83	4.29	5.42	2.54	1.48	1.66	1.91
t	5.89	3.85	4.32	5.36	2.64	1.49	1.67	1.84
Clayton	5.88	5.15	5.89	87.97	3.02	1.71	3.08	44.24
Gumbel	5.92	4.14	4.70	18.14	2.65	1.69	2.05	8.28
Joe	19.50	22.21	22.78	15.68	14.40	14.15	13.92	5.95

The two-dimensional probability density contours illustrate differences in the joint PDF between nodule mass and size across different shape factor ranges. A smaller shape factor value corresponds to the lower tangent slope on the bottom contour (Figure 12a–c). Additionally, the dispersion of the tails in the probability density contours is proportional to the range of shape coefficients; i.e., nodules with a shape coefficient of 0.9–1 and 0.8–0.9 exhibit more concentrated contour tails compared to the nodules ranging from 0 to 0.8.

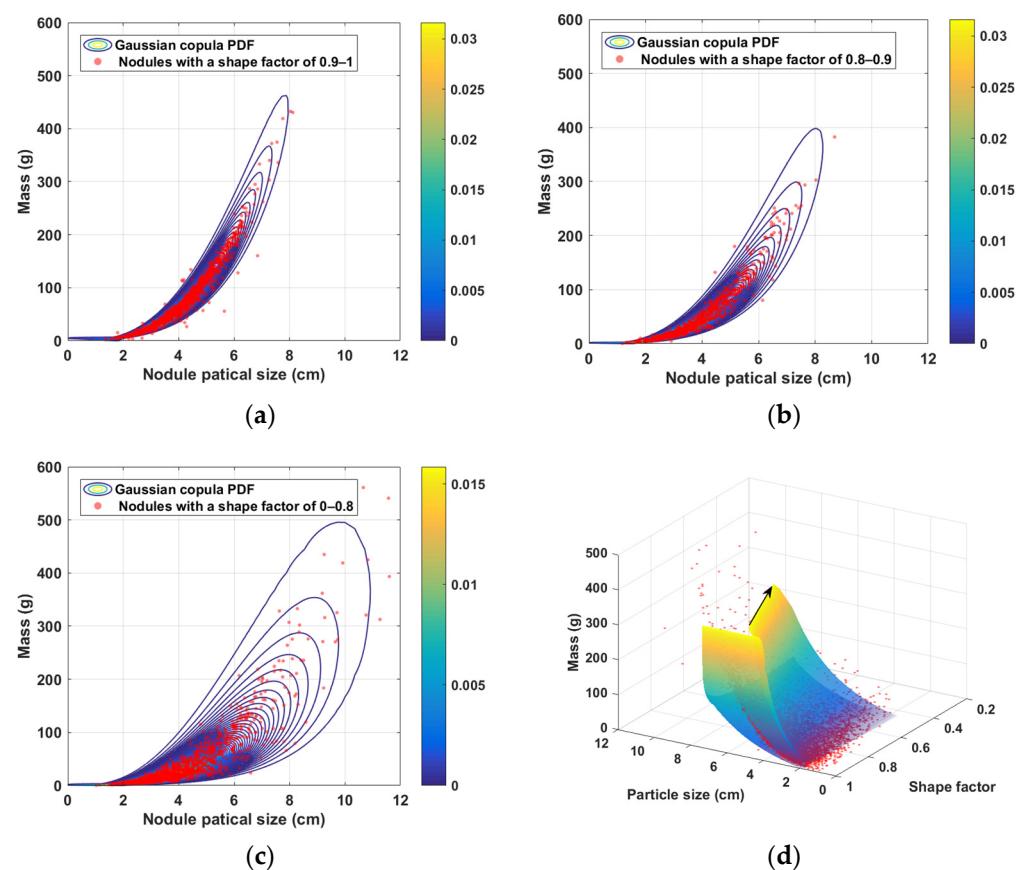


Figure 12. (a–c) Estimated joint PDF using copula for the size and mass of polymetallic nodules of different shapes. Nodules with shape factors of 0.9 to 1.0 are primarily spherical; shape factors of 0.8 to 0.9 are predominantly ellipsoidal; and with shape factors less than 0.8, conjoined and discoidal nodules are more common. (d) Estimated joint PDF using copula for the size, mass, and shape factor of polymetallic nodules. The arrow shows a gradual decrease in the slope of the mass and particle size components as the shape factor decreases. The colours represent different probability values.

To establish a more continuous description of the relationship between the shape factor, size, and mass, the data of shape factor, size, and mass of nodules were then fitted with a three-dimensional copula function. The marginal distribution is derived from the characteristic distribution function calculated in Section 3.5, and the Gaussian copula remains the most suitable probability distribution model. The probability density isosurface plot also demonstrated that the slopes of the mass and particle size sections gradually decrease as the shape factor diminishes (Figure 12d). The copula function for the three variables of polymetallic nodules is as follows:

$$F(l, \zeta, m) = \Phi_{\rho}(\Phi^{-1}(f(l)) + \Phi^{-1}(f(\zeta)) + \Phi^{-1}(f(m))) \cdot \rho = \begin{bmatrix} 1.00 & -0.06 & 0.92 \\ -0.06 & 1.00 & 0.92 \\ 0.92 & 0.24 & 1.0 \end{bmatrix} \quad (15)$$

The statistical results and probabilistic distribution models presented in this paper can be applied to the reliability-based design optimization (RBDO) of mining systems. Taking the design and optimization of the core component of mining vehicles—the pick-up devices for deep-sea mining—as an example, ellipsoidal nodules can be elevated in fluids with lower resistance compared to other nodule shapes [38]. The statistical results indicate that the majority of polymetallic nodules in the BPC contract area are ellipsoidal, supporting the application of hybrid-type hydraulic pick-up devices. These hydraulic pick-up devices utilize the Coanda effect, where fluid flow tends to bend and adhere to nearby solid surfaces, allowing for nodule collection with reduced environmental disturbance compared to mechanical systems.

For hydraulic pick-up devices, the volumetric flow rate of the nozzle, in conjunction with the shape and particle size of the polymetallic nodules, jointly influences the lift generated. The mass of the nodule determines whether the lift is sufficient to collect the nodule into the system. An excessively high volumetric flow rate leads to increased energy consumption, negatively impacting mining costs, while an excessively low flow rate results in inadequate collection efficiency to meet mining demands. By using a joint probabilistic distribution model of particle size and mass for different nodule shapes, it is possible to generate representative nodule data samples characteristic of the region, thereby calculating the optimal volumetric flow rate for pick-up devices suited to that area, achieving a balance between efficiency and energy consumption [8].

5. Conclusions

Statistical analysis was conducted on the existing status of polymetallic nodules. In the BPC M2 contract area of northwest Pacific, the nodule size corresponding to 90% of the nodule number collection rate is 5.12 cm, while the size corresponding to 90% nodule mass collection rate is 6.11 cm. In terms of nodule shape, ellipsoidal nodules accounted for 71.4%, conjoined nodules accounted for 16.2%, spherical nodules accounted for 11.6%, and discoidal nodules accounted for 0.8%. The central region of the contract area is dominated by medium-sized ellipsoids. A greater variety of shape types of nodules is observed on the southern side of the Magoshichi Seamount, where spherical, conjoined, and plate-shaped nodules are more concentrated. Furthermore, a distinct correlation can be found between the nodule shape and size, with a notable increase in the proportion of discoidal nodules among those larger than 8 cm. The burial depth of the majority of nodules is distributed between 0 and 4 cm. The dispersion degree of nodule density correlated with the size of nodules where small-sized nodules exhibit notable variation in density, while large-sized nodules maintain a relatively constant density.

Uncertainties in the shape, size, and quality of polymetallic nodules can significantly affect the collection efficiency of collection equipment. The nodules' characteristics were quantitatively described by using PDFs, and the best-fitting function was selected based on the AIC. The normal distribution serves as the best-fitting function for nodule size and burial depth, and the generalized extreme value distribution and Weibull distribution are the best-fitting functions for the shape factor and mass, respectively, with R^2 values exceeding 0.96.

Spearman's rank correlation coefficient between the nodule mass and the long axis is 0.97, indicating a strong correlation between nodule mass and size characteristics. Two-dimensional copula and three-dimensional copula were employed to capture the dependence relationship between the size, mass, and shape factor of nodules. The best-fitting function was selected based on KSE and RMSE. Gaussian copula is the optimal copula model, with the KSE value below 0.06 and RMSE value under 0.03. The model fitting results conform to the distribution trend of the sampling data, which provides a quantitative basis for the design optimization of the mining system.

This paper utilizes the probabilistic analysis of polymetallic nodule shape, size, and mass distributions to inform reliability-based design optimization (RBDO) for deep-sea mining systems. Given that nodules in the BPC contract area are predominantly ellipsoidal, this supports the application of hydraulic pick-up devices in this region. By generating representative data samples of nodules based on the joint probability distribution of nodule size and mass, the optimal volumetric flow rate parameters for pick-up devices can be calculated, enhancing system reliability and efficiency.

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