Submarine Geomorphological Features and Their Origins Analyzed from Multibeam Bathymetry Data in the South China Sea

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Abstract: We processed the raw multi-beam bathymetry data acquired in the central and northeastern part of the South China Sea by eliminating noise and abnormal water depth values caused by environmental factors, and a high resolution bathymetric map with a 20-m grid interval was constructed. Various scales of seafloor geomorphological features were identified from the data, including an image of Shenhu canyon, which is located in the northern continental margin of the South China Sea; submarine reticular dunes in the north of the Dongsha atoll; submarine parallel dunes in the northeast of the Dongsha atoll; and several seamounts in the southwest sub-basin and in the east sub-basin. In the processing step, various anomalies in the multi-beam bathymetry data were corrected. The optimal swath filtering and surface filtering methods were chosen for different scales of seafloor topography in order to restore the true geomorphological features. For the large-scale features with abrupt elevation changes, such as seamounts (heights of ~111–778 m) and submarine canyons (incision height of ~90–230 m), we applied swath filtering to remove noise from the full water depth range of the data, and then surface filtering to remove small noises in the local areas. For the reticular dunes and parallel dunes (heights of ~2–32 m), we applied surface filtering to refine the data. Based on the geometries of the geomorphological features with different scales, the marine hydrodynamic conditions, and the regional structure in the local areas, we propose that the Shenhu submarine canyon was formed by turbidity current erosion during the Sag subsidence and the sediment collapse. The submarine reticular dunes in the north of the Dongsha atoll were built by the multi-directional flows caused by the previously recognised internal solitary waves around the Dongsha atoll. The submarine parallel dunes in the northeast of the Dongsha atoll were built by the repeated washing of sediments with the influence of the tidal currents and internal solitary waves. The conical, linear and irregular seamounts identified from the bathymetry data were formed during the spreading of the southwest sub-basin and the east sub-basin. The identified seamounts in the multi-beam bathymetry data are correlated to deep magmatic activities, the Zhongnan transform fault and the NE-trending faults.

Keywords: multi-beam bathymetry system; seamount; submarine canyon; submarine parallel dune; submarine reticular dune; South China Sea
1. Introduction

A multi-beam bathymetry system (MBS) is a kind of underwater measurement system with full coverage, high precision and high resolution. Compared to the early single-beam measurement system, the MBS can obtain seabed bathymetric values of multiple measurement points in a strip zone with each transmit acoustic pulse, as developed from “point-line” to “line-plane” measurement [1,2]. Due to its high-resolution imaging capability, MBS is widely used for seabed geomorphology surveying and scientific research with various purposes. The previous geomorphological surveying of seamounts was performed in the South China Sea basin [3–5], around the Mariana Trench [6], and on the Alaska seamount chains [7]. Studies of submarine canyons have been carried out in the northeastern Gulf of Mexico [8], in northwest Madagascar [9], and in Santa Monica Bay [10]. Morphological studies of submarine parallel dunes have been performed in San Francisco Bay [11], in Monterey Bay [12] and around Dongsha island of the South China Sea [13]. Research works about pockmarks have been reported in the northwest margin of the South China Sea [14], in the continental margin of western India [15], and in Saco Bay [16]. Early researchers performed detailed analysis on various seafloor morphological features and their origins in different seas. However, only a few early studies were mapped in the complex topography of the seafloor and various submarine geomorphic features with different scales in the South China Sea due to limitation of the data quality of the early systems.

The South China Sea is bounded by the Eurasian plate, the Pacific plate and the Indo-Australian plate [17–21]. Active neotectonic movements and different types of seafloor geomorphological features in the South China Sea were built with a complex tectonic background. According to previous studies, the South China Sea can be divided into the east sub-basin, the southwest sub-basin and the northwest sub-basin [22]. The topographic features and tectonic activities of the three sub-basins are different, and these three basins have undergone different evolution processes [18,22–27]. Seafloor topographic and geomorphological features are the products of the interaction between internal and external dynamic forces. The internal forces control the spatial distribution patterns of large-scale seafloor topography. Based on the seafloor topography formed by internal forces, the external forces transform the seafloor subsurface and build complex seafloor topographic features [28]. As a direct representation of submarine tectonic movements, submarine topography and geomorphology are of great scientific significance to the investigation of submarine resources, and the study of sedimentary process and tectonic activity. In 1986, Pautot [3] carried out the first multi-beam bathymetry surveying in the South China Sea, and identified some seamounts in the central sub-basin of the South China Sea. With the application of early multi-beam technology, some researchers identified a variety of submarine topographical features in the South China Sea, including submarine canyons in the Dongsha atoll area, in the Pearl River Mouth basin and in the southwest basin of Taiwan [29–32]. Mounds, mud volcanoes, pits and submarine cold seeps, which are related to gas hydrate leakage, were found in the southwest basin of Taiwan, in the Qiongdongnan basin, in the Shenhui and Xisha areas [33–35]. Other geomorphologic features such as submarine sand waves were identified in the Pearl River Mouth basin, in the southwest basin of Taiwan, and in the Dongsha atoll area [36,37]. Seamounts were identified in the southwest sub-basin, the east sub-basin and the northwest sub-basin of the South China Sea [26,38].

Most previous studies mainly used the processed multi-beam bathymetry data to directly analyze the seabed topographic features of the South China Sea [4,5,13,39], but the acquisition and processing of the multi-beam bathymetry data is rarely involved. The widespread understanding of large-scale and small-scale bathymetry features is still absent in the South China Sea at present. In this paper, we process the newly acquired multi-beam bathymetry data in the South China Sea by the R/V “Dongfanghong 3” in 2020. Radial anomalies and anomalies in the central beam area and the edge beam area are corrected and eliminated. Two optimal filtering methods are chosen to apply to
the raw bathymetry data for different scales of seafloor morphology in order to obtain precise submarine topographic maps. After the MBS data processing, we identified some typical submarine geomorphological features, including the Shenhu submarine canyon in the northern continental slope of the South China Sea, submarine parallel dunes in the northeast of the Dongsha atoll, submarine reticular dunes in the north of Dongsha atoll, and seamounts distributed in the South China Sea basin (Figure 1). We also analyzed and summarized the geometries of the submarine geomorphological features, and finally made an attempt to explain the origins of the submarine canyons, seamounts, submarine parallel dunes and reticular dunes in the South China Sea.

Figure 1. Bathymetric map in the South China Sea and the elevations in its surrounding area. The background bathymetric data is from the General Bathymetric Chart of the Oceans [40]. The geological setting is shown in the index map on the bottom-left. EU: Eurasian plate; PA: Pacific plate; PS: Philippine Sea plate; IN-AU: Indo-Australian plate. The geographic location and landform type of later Figures are shown in it.

2. Bathymetry Data Acquisition and Processing

We collected the multi-beam bathymetry data in the northeast and central part of the South China Sea from the R/V “Dongfanghong 3” from July to October, 2020. All of the ship track lines from the cruise are shown in Figure 1. We used CARIS HIPS and SIPS 9.1 software [41] to process raw multi-beam bathymetry data by correction and filtering steps. The final output was transformed to text files in ASCII format for plotting. Generics Mapping Tools (GMT) [42] were used to visualize the processed data. We used the GMT—specifically the xyz2grd command—to set appropriate grid spacing. The other GMT commands—such as grdimage and gradient, etc.—were used to map the final seabed topographic maps. The detailed data acquisition and processing steps are described in the following sections.

2.1. Multi-Beam Bathymetry Acquisition System

The Kongsberg EM122 Multi-beam echo sounder system was installed on the R/V “Dongfanghong 3”; EM122 is a full ocean depth MBS [43]. The EM122 is mainly composed of sonar transmitting and receiving arrays and processing units, real-time data processing and monitoring units, and various auxiliary equipment (a GPS navigation and positioning system, attitude sensors, a wave compensator, a compass, a sound velocity profiler, and a time synchronizer). The transmitting frequency of EM122 MBS is 12 kHz, and the measured
water depth ranges were from 20 to 11,000 m. The sounding accuracy is 0.3% water depths. The detailed parameters of the EM122 are summarized in Table 1.

Table 1. Main parameters of the multi-beam bathymetry system [43].

| EM122 (the R/V “Dongfanghong 3”) | Beam Forming |
|----------------------------------|--------------|
| **Basic Principle**              | **Beam Forming** |
| Main operational frequency       | 12 kHz       |
| Depth ranges from transducers    | 20–11,000 m  |
| Beam widths                      | 0.5 × 1°, 1 × 1°, 1 × 2°, 2 × 2°, or 2 × 4° |
| Coverage sector                  | 150°         |
| Maximum strip width              | Six times the water depth |
| Maximum coverage width           | 30 km        |
| Beam number                      | 288          |
| Range sampling rate              | 3 kHz        |
| Sounding resolution              | 10–40 cm     |
| Sounding accuracy                | 0.3% water depth |
| Beam spacing                     | Equidistant, equiangle or in between |
| Maximum operating speed          | 16 Knots     |

During the field surveying, the transverse direction of the transmitted beam was larger than the longitudinal direction, and the longitudinal direction of the received beam was larger than the transverse direction [2,44,45]. The arrays of transducers below the vessel send and reflect a fan-type sound beam with a narrow strip. The sound wave propagates in the water, and is reflected when it hits the interface of the seabed sediment. Due to the different distances between each reflection point and the transducer, the return time of each echo is also different. The echo that reaches the transducer contains information, such as the rough relief of the seafloor topography [45,46].

2.2. Bathymetry Data Processing

We collected and integrated different types of field data during the MBS acquisition, including the configuration data of the vessel, beam angles, two-way travel times, sound velocity, and the navigation of tracks. The raw multi-beam bathymetry data need several processing steps to obtain the accurate submarine topographic values.

2.2.1. Sound Velocity Correction

The tidal correction was made onboard by determining the instantaneous changes in the tide level through GPS carrier phase technology, and correcting the bathymetric data directly. The central beam is transmitted vertically to the seafloor, so its acoustic paths are regarded as a straight line, but the acoustic paths of the rest of the beams (larger than 45° emission angles) are significantly bent due to the refraction [47]. Seawater is a kind of flowing medium, and the difference of temperatures, salinities and depths (pressure) lead to the changes of sound velocities and produce the continuous refraction phenomenon. Therefore, the measurement beams emitted from different surveying areas reflect in different sound paths. We used the results of the sound velocity profile in the northern and central part of the South China Sea to obtain the variation curves of the seawater sound velocity with depth (Figure 2). The variation trend of the sound velocity with depth was similar in the two surveying region. From the sea surface to 1000 m depths, the sound velocity decreases sharply from 1540 m·s⁻¹ to 1480 m·s⁻¹, and continues to increase with an increasing depth. During the raw-data processing, the measured sound velocity profile is directly imported into the processing software to correct the sound velocity variations.
2.2.2. Bathymetry Data Editing and Filtering

We processed the raw multi-beam bathymetry data with manual editing and automatic filtering. We edited manually and deleted the problematic navigation data, odd attitude data from the R/V “Dongfanghong 3”, and part of the noise points in the bathymetric data. We chose swath filtering and surface filtering methods to filter the raw data (Figure 3). The minimum and maximum depth filters of different geomorphological features were set based on scales and real bathymetric variations during the filtering. The depth filters ranged from ~600 to 1650 m for the Shenhu canyon, from ~690 to 890 m for the reticular dunes, from ~370 to 440 m for the parallel dunes, and from ~3490 to 4330 m for the seamounts. The track distance was set to about three times the nadir depth, and the angles from the nadir depth were set to about 70 degrees. Swath filtering can perform filtering for whole-strip data, and is suitable for the removal of the strong noises in the data. By using the swath filtering method, noises caused by various environmental factors and unsuitable parameter sets are eliminated (Figure 3a,b). The surface filtering is suitable to remove noise in a small range for the small-scale morphology (Figure 3c,d). For large-scale seamounts and submarine canyons, we choose swath filtering and the surface filtering to process the data successively. In order to avoid deleting the actual data, surface filtering was only used for small-scale parallel dunes and reticular dunes. These filtering methods are useful to enhance the identification of different scale topography and geomorphology features.
2.2.3. Bathymetry Data Interpolation

In principle, the MBS can fully cover the measured area, but some areas with empty values were generated during the acquisition caused by the large line spacing, data loss, unreasonable parameter sets and error delete data during the data processing (Figure 4a). In order to make the dataset complete, the bathymetry data needed to be interpolated for the gaps (Figure 4b). We used the weighted average algorithm [48] to interpolate the processed data. The advantage of this algorithm is that it can determine the weight by the distance between the data unit in the null value area and the surrounding data unit, and it is suitable for the interpolation of multi-beam bathymetry data.

Figure 3. Two optimal swath filtering and surface filtering methods applied on the multi-beam bathymetry data: (a) noises in the raw multi-beam bathymetry data; (b) the filtering result after the swath filtering after (a); (c) the surface filtering interface of the bathymetry data after the swath filtering; (d) the filtering result after the surface filtering after (c).
Figure 4. Anomaly correction and data interpolation of the multi-beam bathymetry data. (a) Anomalies in the central beam area. The anomalies include abnormal bulges and data gaps. (b) The processed result after the filtering and interpolation of (a). (c) The raw bathymetry data for seamounts. (d) The processed bathymetry data of the seamounts. The abnormal bulges at the top of the seamounts were eliminated, and the data gaps around the seamounts were filled. (e) Anomalies in the edge-beam area. (f) The processed results of (e). The “wavy anomaly” was removed and the data gaps were interpolated.

3. Bathymetry Data Anomaly Correction

After the simple processing of the multi-beam bathymetry data, the final bathymetry map can be constructed directly, but some images may be distorted due to various errors [49]. In the central beam area, the multi-beam bathymetry data contains obvious narrow-band bulges and data gaps along the direction of the ship route (Figure 4a). In the strip splicing area, a linear data gap was found to be vertical to the track lines (Figure 4a). In the edge-beam area, the strip contains obvious “wavy” anomalies (Figure 4e) and radial anomalies caused by attitude changes during the vessel turn-around (Figure 5b). In order to accurately map the seabed topography, these anomalies require correction.
3.1. Anomaly Correction in the Central Beam Area

During the data acquisition, the central beam is emitted vertically downward, and its beam angle is generally small (~±5°) [47,50], such that the signals received in the central beam area are directly reflected from the seabed and the high acoustic intensity of the signal results in certain residual errors in this region. In our raw multi-beam bathymetry data, a large number of narrow band anomalies and data gaps exist in the central beam area (Figure 4a) and seamount area (Figure 4c). By applying the surface filtering method many times in the central beam area, abnormal bulges (Figure 4a) were eliminated (Figure 4b). The weighted average algorithm was used to interpolate the data. The data gaps in the central beam area and blank area (Figure 4a) are caused when separated data files are combined; they are completely filled by the interpolation process, as well as those around the seamounts (Figure 4d). After interpolation, the images of deep-sea plains (Figure 4b) and seamounts (Figure 4d) are smooth and continuous (Figure 4).

3.2. Anomaly Correction in the Edge-Beam Area

During the data acquisition, the sounding sheath of the R/V “Dongfanghong 3” showed vibration affected by strong wind and waves, and this caused a high frequency resonance between the transducers and the vessel. The acquired data was inconsistent with the real attitude of the transducer, and the bathymetric data did not receive effective compensation. The regular “jitter”—“wavy”—anomalies occur on the data in the edge-beam area (Figure 4e). This type of anomaly gradually increases to both sides perpendicular to the track direction, and seriously affects the accuracy of the data in the edge beams. To resolve this effect on the data, we applied a special filtering mode to remove the noise. We used the swath filtering method to eliminate the obvious “wavy” noise, and then used surface filtering to remove anomalies perpendicular to the track-line directions in the data. By calculating the average water depths of the false values in the edge beam area, the “wavy” anomaly was effectively removed by repeatedly running surface filtering on the average as the filtering parameter (Figure 4f).
3.3. Correction of Radial Anomalies

A large number of noises in the bathymetry data were generated when the attitude of the R/V “Dongfanghong 3” changed (Figure 3a,c). In the raw bathymetry data, the average water depths were of 3300–3500 m, and there were a lot of random noises in the data. The maximum water depth was 6000 m for these noises to appear in a deeper-than-average water depth in this region (Figure 3a). The noise in the data produce purple band anomalies in the geomorphology images (Figure 5a). After repeated swath filtering, the noises seemed to be completely removed, and the filter processing resulted in water depths ranging between 3340 and 3520 m (Figure 4b). The final bathymetry data show smoother variations of water depths with complete coverage, and the obscured scarps are clearly visible (Figure 5b). Some noises and false values still exist after swath filtering (Figure 4c), but by the further application of the surface filter, these random noises and abnormal values were successfully removed (Figure 4c). Radial anomalies are also removed using the surface filtering method for each anomaly stripe, and after local final surface filtering, the seabed topographic features appear smoother and continuous on the multi-beam bathymetric map (Figure 5c).

4. Results and Discussion

For a better understanding of the submarine geomorphological features, well-processed and high resolution bathymetric data are required. However, during the acquisition of the bathymetric data, the sea condition (strong wind and high waves), variations of ship speeds, the turning of the vessel and hull configuration designs (azimuth, pitch and roll) will change and cause the horizontal position changes of the multi-beam transducers on the hull. These factors will lead to systematic errors for the position of the beam footprint [45]. In addition, instrument noise, environmental noise and the unreasonable parameter setting of multi-beam system cause the acquisition of false values [51,52]. The attitude offsets of the R/V “Dongfanghong 3” were recorded in the configuration file during the surveying, and the mount angle of the azimuth was 359.98°, the mount angle of the pitch was 0.09°, and the mount angle of the roll was 0.05°. In our data processing steps, we used the configuration of the R/V “Dongfanghong 3” and corrected the attitude errors to eliminate the systematic errors, and then we filtered the random noise and false values for the multi-beam raw-data. Finally we obtained accurate bathymetry data for the further analysis of different submarine geomorphology features.

In our acquired bathymetry data, two different filtering methods were applied to the different scales of seabed topography (reference heights). We classified the different scales of the morphology features and sorted the different parameters for submarine canyons, seamounts, submarine reticular dunes and parallel dunes with small scales (Table 2). The incision depths of a submarine canyon are between 90 and 230 m, and we first used swath filtering to remove the noises of the whole strips, and then used surface filtering to remove noises in a small range. The heights of submarine reticular dunes are between 8 m and 32 m, and the heights of submarine parallel dunes are between 2 m and 20 m. The wave height variations are small for reticular dunes and parallel dunes, such that using swath filtering to correct water depth values would delete the real data values. Therefore, we adopted surface filtering for small-scale features that highlight the real geomorphology. The heights of seamounts (ranging in 111–778 m) are relatively large, so we chose both swath filtering and surface filtering to process the data successively. Based on the accurate bathymetry data after processing, we identified a submarine canyon, seamounts, very large submarine reticular dunes, and large or very large parallel dunes on the seabed topography of the South China Sea. There is a detailed discussion of the geometry and origins of these typical features in the following sections.
Table 2. Seabed geomorphology scales and the optimal filtering methods.

| Geomorphology Features | Length [m] | Width [m] | Height [m] | Filter Methods          |
|------------------------|------------|-----------|------------|-------------------------|
| Shenhu canyon          | ~21,000    | 2000–3000 | 90–230     | Swath and surface filtering |
| Reticular dunes         | 50–600     | 50–300    | 8–32       | Surface filtering        |
| Parallel dunes          | 100–1000   | 50–300    | 2–20       | Surface filtering        |
| Seamounts               | 8200–23,000| 2700–11,100| 111–778   | Swath and surface filtering |

4.1. Geometry and Origins of Submarine Canyons

Submarine canyons are significant negative topographies located on the seabed; they cut deep into the continental shelf and continental slope, and they indicate linear grooves perpendicular or diagonal to the coastline [53–56]. By applying the processing techniques to the acquired multi-beam bathymetry data, we identified a submarine canyon in the Shenhu area of the South China Sea, which we call the Shenhu canyon (Figures 1 and 6).

The Shenhu Canyon Group and the Pearl River canyon, located in the northern continental slope of the South China Sea, was found by the early bathymetry data [31,32], consisting of 17 small N–S trending canyons. The Shenhu Canyon Group connects the upper part of the northern continental slope of the South China Sea and the Pearl River canyon. Our identified Shenhu canyon is one of canyons of the Shenhu Canyon Group, and the tail of the Shenhu canyon is connected to the Pearl River canyon. The identified Shenhu canyon has incision depths of 680–1460 m, lengths of about 21 km, and widths of about 3–6 km. At the crest, the terrain of the canyon shows complex features with dense furrows, and steep cliffs are seen. The bottom of the canyon is relatively flat (Figure 6). In order to analyze the morphological characteristics of the Shenhu canyon, we extracted six vertical cross sections through the central axis of the canyon. In the upper portion of the canyon, the vertical cross sections show a V-shape incision geometry (profiles 2–3) and the
central axis of the canyon indicates a NNW–SSE trend with a narrow width and steep slope (Figure 6b). At the lower portion of the canyon, the water depths increase from 700 m to 1000 m, and the incision depth of the canyon ranged from 160 to 200 m. There is a turning point at a depth of 1100 m at the lower portion of the canyon, where the trending of the canyon changes from NNW to NS. From the turning point to the tail of the canyon, the shape of the canyon changes from a V-shape to a U-shape (Figure 6b, profiles 4–6). The incision widths of the canyon increase from ~0.4 to 1.4 km from the upper portion to the lower portion as the slope angles decrease from ~40 to 30 degrees down to the slope. The water depths in the canyon increase from 1000 m to 1460 m, and the incision depths of the canyon range from 90 to 230 m.

The formation, development and evolution of submarine canyons are a complex process, which is affected by internal dynamic forces caused by tectonic movement and external dynamic forces such as the river erosion, gravity flow erosion and sea level changes. Harris and Whiteway [57] divided submarine canyons into two types: the shelf-incising canyon and the slope-confined canyon. The shelf-incising canyon develops on the continental shelf. If its head is connected with the river system, it is affected by both shelf erosion and river erosion. If the canyon head is not connected to a river system, only the shelf erosion occurs. The slope-confined canyons appear and develop only on the continental slope. Shenhu canyon, which was identified in our study, was interpreted to be in the group of to the slope-confined type. It is still not clear whether or not, in the early stage of the formation of the Shenhu canyon, it was originated by shelf erosion. Greene and Hicks [58] suggested that the Monterey submarine canyon developed during the Oligocene to the early Miocene, and the head of the canyon was connected to the Salinas, Pajaro, and San Lorenzo rivers. These three rivers were the main sources of sedimentary material of the Monterey canyon [58–60]. With the frequent changes of the Pleistocene sea level and climate, the canyon was repeatedly filled and eroded by terrestrial sediment and gradually transformed into the present form [61]. The Gaoping submarine canyon in the southwest basin of Taiwan was believed to be formed by the fluvial erosion. The canyon was flooded in the late Pleistocene, and the controlling structural features are intrusions of mud diapirs and thrust faulting in the complex continental margin in the southwest Taiwan region [62–64]. The head of the Gaoping canyon is connected with the Gaoping river. The turbidities formed in the head of the canyon strongly eroded the Gaoping canyon [65,66]. Both the Monterey submarine canyon and the Gaoping submarine canyon are shelf-incising type submarine canyons. The head of the canyon is connected with rivers onland, and the main controlling factors are the shelf cutting and river erosion caused by the sea levels falling.

Compared with the Monterey and the Gaoping canyon, the submarine Shenhu canyon is located in the Baiyun Sag. Based on the stratigraphic characteristics and divisions of the Pearl River Mouth basin, the sea level of the South China Sea began to fall at 21 Ma [67]. At the same time, the Baiyun Sag rapidly began to subside, and submarine canyons were formed and developed with the increase of the slope degree of the South China Sea continental slope [68]. Due to the sedimentation of the Baiyun Sag, very thick sediments were deposited, and the fall of the sea level led the unconsolidated sediments to be unstable as they were saturated with water, and to slide along the slope. Under the erosion of the turbidity current, grooves or furrows were formed. The basal shapes of the erosional grooves are consistent with V-shaped surfaces identified on the vertical cross sections of the Shenhu canyon in the upper portion (Figure 6b, profiles 2–3). As the sediments on both sides of the furrows were subjected to continuous erosion and prone to collapse, the sediments were transported to the deep-sea basin and the embryonic geometry of the Shenhu canyon was build up with the major effect of long-term turbidity current erosion.

4.2. Geometry and Origins of Submarine Reticular Dunes

The types of surface sediments in the north and northeast of the Dongsha atoll are mainly fine sand and coarse silt, according to previous studies [68,69]. A large number of submarine dunes are distributed in the Dongsha atoll. Based on Ashley’s classification, the dunes were classified as small (0.6–5 m), medium (5–10 m), large (10–100 m) or very large (>100 m) according
The dunes in the Dongsha atoll may be sand dunes. The submarine reticular dunes distributed in the water depths of 370–440 m were identified in the northern part of the Dongsha atoll in the South China Sea (Figures 7 and 8). We chose an east–west profile to analyze the specific morphological features of the reticular dunes in this region. The topography of the reticular dunes (peak to trough) indicates that the reticular dunes in the west of the profile are more dense than those in the east (Figure 8d). The extending direction of the ridge lines of the reticular dunes is in E–W, NE and NWW (Figure 8c). The shape-types of reticular dunes are polygonal and elongated types. We found that the major morphological feature of reticular dunes is mainly banded type which are predominantly located at the west of the profile (Figure 8c). The difference in heights of these reticular dunes is relatively small, and the maximum height difference is only 17 m at the west of the profile shown in Figure 8f. The reticular dunes at the east of the profile are sparse in density, and their shape is mainly polygonal. The height difference of these reticular dunes is relatively large, and the maximum height difference reaches 32 m to the east of the profile shown in Figure 8e. The spacing of the reticular dunes in the northern part of the Dongsha atoll ranges between 20 and 500 m (Figure 8d–f). Based on Ashley’s classification, these reticular dunes belong to large or very large dunes.

**Figure 7.** Multibeam echo-sounder bathymetry in the narrow track line showing the reticular dunes and parallel dunes, overlapped on the background bathymetric data from the General Bathymetric Chart of the Oceans [40]. The locations of the reticular dunes and parallel dunes are marked with arrows.

We find that the reticular dunes are located at the areas between two parallel dune regions, and the reticular dunes are separated by the Dongsha atoll (Figure 7). The ridge lines of the submarine reticular dunes extend in two or more directions [30]. For the quadrilateral type, the ridge lines of the reticular dunes extend in two diagonal directions. For the pentagons, hexagons and other polygon types, the ridge lines of the reticular dunes extend in multiple directions. Previous studies showed that the ridges of reticular dunes were formed simultaneously, rather than by the later transformation [71]. According to Synthetic Aperture Radar (SAR) images
(Figure 8a), there are a large number of internal solitary waves [72,73] which appeared above submarine reticular dunes indentified in our data. The interaction of the internal solitary waves with the seabed causes the oscillation of the water body and produces dominant current flow in multiple directions (E–W and SE–NW). Based on the bathymetric map, the ridge lines of the reticular dunes show extensions in the N–S and NE directions, and these reticular dunes are affected by internal solitary waves propagated from the east to the west. The ridge lines of the reticular dunes in the E–W direction are affected by the bottom currents, which are generated by internal solitary waves at the Dongsha atoll. The multiple directions of the currents play a key role in the formation of reticular dunes. The small-size pockmarks of the cracks in the shallow water may indicate the small dunes in the unstable sediment environment; however, this is hard to prove using our bathymetric data. The unorganized network of flat surfaces separated by rectilinear troughs of dunes could be a polygonal network. These dunes could be small in size based on Ashley’s classification [70], and these dunes could be superimposition results of the variation of the bottom current and slow sediment transportation.

Figure 8. (a) Synthetic Aperture Radar (SAR) image around the Dongsha atoll (modified after [72]). The ripples represent the propagation of the internal solitary waves, and the black lines represent the wave fronts of the main internal solitary. The yellow triangle represents the distribution area of the submarine reticular dunes, and a yellow dot represents the areas where the parallel dunes are located. (b) Seismic reflection image collected in the northeast of the Dongsha atoll (modified after [13]). The image shows the development of the internal solitary waves with high frequency oscillation above the submarine reticular dunes. (c) Multi-beam bathymetric map of the submarine reticular dunes in the northeastern part of the Dongsha atoll (polygonal and elongated types). The purple solid lines represent the extending direction (E–W, NE and NWW) of the ridge lines of the reticular dunes. The detailed location of the reticular dunes is shown in Figure 1b. (d) The vertical cross section (A–A’) of the reticular dunes shown in (c). (e) The vertical cross section (B–B’) of the reticular dunes shown in (c). (f) The vertical cross section (C–C’) of the reticular dunes shown in (c). The maximum height difference of the reticular dunes is shown in the sections.
Reticular dunes (Figures 7 and 8) are mainly distributed in the active area of the internal solitary waves in the South China Sea. The internal solitary waves are formed by the interaction between the tides, the seabed, and the coastal topography in the Luzon Strait of the South China Sea, and spread westward to the Dongsha area in the northeast of the South China Sea [30]. According to the calculation of the X-Band radar data, multi-channel seismic reflection data, ADCP data and MODIS data, the propagation velocity of the internal solitary waves is usually between 50 and 300 cm·s$^{-1}$, and the maximum wave heights can exceed 100 m [14,74–76]. According to the statistics, the maximum velocity of the bottom currents caused by internal solitary waves in the north of the South China Sea can reach 200 cm·s$^{-1}$, and generally are above 100 cm·s$^{-1}$ [77]. Based on the analysis mentioned above, the movement of the bottom currents caused by the internal solitary waves can build the different shapes of the reticular dunes in our study area. Internal solitary waves can transport sediment particles with different particle sizes and affect the migration and accumulation of the sediments [78–80]. In the seismic profile around the Dongsha atoll, high-frequency internal solitary waves in the water column appear above the submarine reticular dune (Figure 8b). These high-frequency internal oscillation waves may be a manifestation of the interaction of multi-directional internal solitary waves. By the extraction and analysis of local bathymetric data along the profile (Figure 8c), the ridge lines of reticular dunes were identified, and their extension directions were defined to be in the E–W, NE and NWW directions. The shapes of the reticular dunes were classified as the polygonal (quadrilateral, pentagon, hexagon) and elongated types (Figure 8c). The shapes of these reticular dunes may be correlated to the propagation of the internal solitary waves. The early propagation of the internal solitary waves may be similar to the present based on the distribution and geomorphological features of the reticular dunes identified in our study.

4.3. Geometry and Origins of Submarine Parallel Dunes

Submarine parallel dunes are a kind of mound-shaped or crescent-shaped geomorphologic feature; the ridge lines of parallel dunes are perpendicular to the direction of the water flow. They are formed by the re-processing of sedimentary materials under various hydrodynamic interactions [81]. In our multi-beam bathymetry data, dense submarine parallel dunes were identified in the northeast of the Dongsha atoll (Figures 1, 7 and 9a). The parallel dunes are located at water depths of 690–880 m. The ridge lines of the parallel dunes in the west of the profile are N–S-trending and change to NE–NEE-trending in the east of the profile (Figure 9a). By the analysis of the vertical cross sections, we found that the wave heights of the parallel dunes are roughly between 2 and 20 m, and the wave heights and wavelengths gradually increase with the increase of the water depths (Figure 9b). The spacing of the parallel dunes is over 100 m (Figure 9b), and the parallel dunes belong to very large dunes according to Ashley’s classification.
Figure 9. Geometry of the submarine parallel dunes in the Northeast of the Dongsha atoll. (a) Multibeam bathymetry map of the parallel dunes. The detailed location of the parallel dunes is shown in Figure 1c. (b) Interpretation and classification of the parallel dunes. The blue circle represents the trochoidal type, the black circle represents the sinusoidal type, and the red circle represents the bimodal type. (c) Typical geomorphological classification of the submarine parallel dunes (modified after [82]).

There has been a strong hydrodynamic environment in the northern part of the Dongsha atoll area for the last 10,000 years, and the seafloor sediments have been washed and eroded by the underwater currents [36]. Based on the observational data around the Dongsha atoll, the hydrodynamic force in this region is mainly from the tidal current [83]. The main direction of the tidal current in each season is NW–NNW. Besides this, the internal solitary wave process is relatively developed, and it can certainly shape the movement effect on sediments in this region. In the Dongsha Islands and the surrounding areas, the surface topography is obviously an atoll and a quasi-shoal area with shallow water depths. The tidal currents accelerate in the Dongsha atoll and form strong underwater currents. The bottom currents have a strong scouring and erosional effect on the seafloor sediments [36].

The current flow velocity at the bottom of the South China Sea caused by internal solitary waves can usually reach 100 cm·s$^{-1}$ [77]; in the Dongsha atoll, there appeared to be a lot of movement of internal solitary waves [72,73]. Such hydrodynamic conditions are sufficient to produce the strong transport and deposition of sandy deposits. Therefore, we propose that the internal solitary wave increases the hydrodynamic conditions as it propagates from the Luzon strait to the east to the continental slope to the west, which has a strong shaping effect on the parallel dunes (Figure 8a). Based on the geomorphological features of parallel dunes [73], they are classified as sinusoidal, trochoidal or bimodal types (Figure 9c). The sinusoidal type has good symmetry on both sides and shows a regular shape (Figure 8c). The pattern of the trochoidal type is gentle on the upstream surface and steep on the downstream surface. Small dunes develop in the peaks of parallel dunes. The bimodal-type parallel dunes show the features of two peaks and second-order...
parallel dunes superimposed on the large parallel dunes between the two peaks. In our bathymetry data, the sinusoidal type is less developed, and is distributed in the local area with water depths of 730–745 m, which may indicate that the velocity of the rising tide is basically equal to the velocity of the ebb tide in this area. Parallel dunes with the trochoidal type are most common in the northeast of the Dongsha atoll (Figure 9b) [82]. Parallel dunes with the trochoidal type may be caused by internal solitary waves when tidal currents change direction and the movement of the tidal currents is unequal to the velocity of the ebb flow in this region. Parallel dunes with the bimodal type are basically distributed at the water depths of 740–750 m, and their formations are relatively complex. When underwater currents pass over the crest of parallel dunes, they often dissociate and produce a circulation flow on the horizontal axis [84]. We think that the circulation flow on the horizontal axis generates smaller parallel dunes and can form parallel dunes with the bimodal type.

4.4. Geometry and Origins of Seamounts

Seamounts are defined as seafloor atolls, and are distributed in the deep ocean. The top surface of seamounts is below the sea level, and the elevation differences from the bottom to the top of the seamounts are greater than 1000 m [85]. In the South China Sea, seamounts are widely distributed in the total sea area. The development and evolutionary process of seamounts can be related to the evolution of the South China Sea at different stages. A number of seamounts were identified in our multi-beam bathymetry data of the South China Sea basin (Figures 1 and 10). The morphological and geometrical parameters of the identified seamounts are summarized and analyzed in details including summit depths, basal depths, the summit radius, the basal radius, heights, the ratios between widths and heights, distribution area and flatness (Figure 11). The morphological parameters of seamounts can distinguish seamounts with different morphological features, and the relationship between them can reveal the evolution model of seamounts [86].

**Figure 10.** Multi-beam bathymetry map of seamounts in the southwest and east sub-basins. The background bathymetric data is from the General Bathymetric Chart of the Oceans [40]. The central band shows the bathymetry data acquired by the R/V “Dongfanghong 3”. The red dotted line represents the location of the inferred Zhongnan fault [18,87,88]. The purple dotted line represents the spreading center of the southwest and east sub-basins [88]. The magnetic anomaly stripes (labeled C5 and C6) are from deep-tow magnetic surveying [88]. ZS: Zhongnan Seamount; LS: Longbei Seamount; BS: Beiyue Seamount; ZBS: Zhenbei Seamount; HI: Huangyan Island; ZZS: Zhangzhong Seamount; SS: Shixing Seamount; XS: Xianbei Seamount; CSC: Changlong seamount chains; FSC: Feilong seamount chains.
We identified and interpreted eight seamounts (hereafter called M1–M8) on the processed multi-beam bathymetry map; the identified seamounts are mainly located in the northeastern part of the southwest sub-basin and the east sub-basin of the South China Sea (Figures 1 and 10). The parameters of the summit depths, basal depths, summit radius, basal radius, heights and areal distribution of the eight seamounts were measured (Table 3). The ratios between their widths and heights, and the flatness of the seamounts were also calculated (Table 3). Based on the processed bathymetry data and the geometry of the identified seamounts, we classified the seamounts into three types: irregular, linear and conical type. The M1–M2 seamounts are an irregular type, and M8 is a conical type. M3 to M7 are all of the linear type. The heights of the seamounts vary from 94 to 778 m, and the average height is 402 m. The summit depths of the seamounts are between 3485 and 4104 m, with an average depth of 3817 m. The distributed area of the seamounts varies from 8.5 km$^2$ to 119.8 km$^2$. By our calculation, the ratios between the widths and heights of the seamounts are between 0.05 and 0.22, with an average of 0.12. The flatness of the seamounts is between 0.22 and 0.54, with an average of 0.36. The scales and area of the seamounts identified in this study are relatively smaller than the surrounding seamounts found by the early bathymetric data [3–5].

Table 3. Geometry and types of the identified seamounts.

| Number | Lat/Lon         | Summit Depth [m] | Basal Depth [m] | Height [m] | Summit Radius [km] | Basal Radius [km] | Area [km$^2$] | Ratio | Flatness | Type   | Trend |
|--------|-----------------|------------------|-----------------|------------|--------------------|-------------------|---------------|-------|----------|--------|-------|
| M1     | 115°15'30"37"E 15°09'22"N | 3854             | 4283            | 435        | 2                  | 3.7               | 119.8         | 0.12  | 0.54     | Irregular | —     |
| M2     | 115°15'34"40"E 15°29'38"N | 4093             | 4263            | 543        | 2                  | 6.1               | 19.6          | 0.13  | 0.22     | Irregular | —     |
| M3     | 115°15'29"38"E 15°21'00"N | 3495             | 4263            | 579        | 2                  | 5.2               | 39.7          | 0.15  | 0.35     | Linear   | NEE   |
| M4     | 115°15'22"27"E 15°25'45"N | 3873             | 4238            | 565        | 2                  | 3.49              | 24.5          | 0.10  | 0.32     | Linear   | NEE   |
| M5     | 115°15'27"15"E 15°37'08"N | 3138             | 4245            | 543        | 2                  | 5.9               | 29.8          | 0.07  | 0.32     | Linear   | NE    |
| M6     | 115°15'47"39"E 15°31'38"N | 4048             | 4290            | 202        | 2                  | 2.5               | 10.9          | 0.22  | 0.26     | Linear   | NE    |
| M7     | 115°15'22"23"E 15°55'07"N | 4014             | 4198            | 94         | 0.5                | 1.9               | 8.5           | 0.05  | 0.26     | Linear   | NEE   |
| M8     | 115°15'47"35"E 15°33'39"N | 3666             | 4041            | 275        | 1.2                | 2.3               | 19.7          | 0.15  | 0.48     | Conical  | —     |

Note: Lat/Lon are the latitude and longitude of the seamounts. The height is the difference between the summit depth and the basal depth of the surrounding seabed. The summit and basal radius are the arithmetic mean values of the long and short axis radii of the seamounts. The ratios are the height compared to the basal radius. Flatness is the ratio of the summit radius to the basal radius. “—” indicates that the seamount has no obvious direction.

There are a great number of seamounts in the South China Sea basin. Although the seamounts in the different regions have different structures, scales and evolved processes, the formation of seamounts is most likely controlled by tectonic movements. The seamounts with the conical, linear and the irregular types are distributed in the southwest and east sub-basins. Although there is an absence of magnetic stripes in our seamount areas, the NE-trend of the identified linear seamounts is roughly parallel to the magnetic anomaly stripes [87,88], which imply that the formation of seamounts is controlled by the spreading of the southwest sub-basin (Figure 10). The Scarborough seamount (Zhenbei-Huangyan)
chains in the east sub-basin were formed by the spreading of the South China Sea [3].

The spreading of the South China Sea was ongoing from 32 to 16 Ma [85], from 32 to 15 Ma for the entire basin [88], and from 32 to 20.5 Ma in the Southwest sub-basin [27]. The NE-trending linear seamounts—the Changlong and Feilong seamount chains—are located in the southwest sub-basin, and their formations are related to the spreading of the southwest sub-basin. The linear seamounts identified in our study (M1–M8) are located in the northeast of the southwest sub-basin and the west of the east sub-basin (M1–M8; Figure 10). The geometry of the linear-type seamounts implies that our identified seamounts were formed during the spreading of the southwest sub-basin (Figure 12). The spreading ceased at 20.5 Ma in the southwest sub-basin [27]. The spreading ages imply that our identified seamounts were likely formed before the Miocene. At the locations of linear seamounts M3–M7, very weak magnetic anomalies were measured, and the accurate formation ages of the seamounts were difficult to determine.

The inferred Zhongnan transform fault [18,88] separated the South China Sea into the southwest sub-basin and the east sub-basin (Figure 10). Due to the spreading of the South China Sea, a large number of NE-trending fault structures were constructed [3,89]. The primary trends of the linear seamounts (Figure 12, M3–M7) are along the NE direction and parallel to the magnetic anomaly stripes in the southwest sub-basin. The formation of linear seamounts may be related to the deep magmatic activity and the movements of the NE-trending faults. The irregular (M1–M2) and conical type (M8) seamounts may be formed by deep magmatic activity along the NE- and NW-trending faults. The activity of the NW-trending Zhongnan fault could have had a key role in the formation of the seamounts in this region (Figure 12). The determination of the accurate ages and compositions of the seamounts require further drilling and sampling in the seamount domain areas in the future.
Figure 12. Multi-beam bathymetry map of the identified seamounts in the South China Sea basins. The three types of seamounts are interpreted as the conical, linear and irregular types. The (M1) and (M2) seamounts are the irregular type. The (M3–M7) seamounts are the linear type. The (M8) seamount is the conical type. The black lines indicate the ridge lines of the seamounts. The detailed locations of the seamounts are shown in Figures 1 and 10.

5. Conclusions

Newly acquired bathymetric data from 2020 by the R/V “Dongfanghong 3” in the South China Sea were processed by the correction and filtering methods; from the processed bathymetric data, several typical submarine geomorphological features were identified and interpreted. The optimal swath filtering and surface filtering methods were chosen to be applied to the large- and small-scale seabed geomorphological features to obtain an accurate seabed topography. A large-scale image of the submarine Shenhu canyon indicated a base morphology of a V-shape in the top segment and a U-shape in the bottom segment in the southern continental slope of the South China Sea. The incision depths of the Shenhu canyon range between 90 and 230 m along the slope. The large-scale seamounts
with heights ranging from 111 to 778 m were interpreted as being grouped into three types: conical, linear and irregular. The seamounts were identified in the northeast of the southwest sub-basin and in the west of the east sub-basin. The very large submarine parallel dunes with heights of 2–20 m and spacing of 20–500 m are found in the northeast of the Dongsha atoll. The shapes of the parallel dunes are the trochoidal, bimodal and sinuosoidal types. The very-large reticular dunes with heights of 8–32 m and spacing of over 100 m are found in the north of the Dongsha atoll.

The Shenhu canyon was formed by the turbidity current erosion during the Sag subsidence and sediment collapse. The reticular dunes were constructed by the multi-direction dominant currents caused by the internal solitary waves around the Dongsha atoll. The parallel dunes were built by the repeated washing of sediments with the influence of the tidal currents and internal solitary waves. The identified seamounts with the conical, linear and the irregular types were formed to the spreading of the southwest sub-basin and the east sub-basin. The geometrical characteristics of the seamounts imply that the seamounts are correlated to deep magmatic activity, the Zhongnan transform fault and the NE-trending faults.

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