

# Research Article

# Characteristics and Research Direction of Triassic in the South Yellow Sea Basin, China

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Received 9 January 2022; Revised 25 February 2022; Accepted 26 February 2022; Published 17 March 2022

Academic Editor: Zheng Sun

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To advance oil and gas exploration in the South Yellow Sea Basin, characteristics of Triassic, including its correlation with regional strata, distribution, lithology characteristics, and karst development characteristics, are studied by geological mapping. Results show that there exist Zhouchongcun Formation and Qinglong Formation in the Triassic. Zhouchongcun Formation corresponds to Dongma Formation in the lower Yangtze Region, Badong Formation in the middle Yangtze Region, and Lekoupo Formation in the upper Yangtze region. The upper Qinglong Formation corresponds to the Nanlinghu Formation and Longshan Formation in Xiyanzi district, and Jialingjiang Formation in the middle and upper Yangtze region. Its lithology is limestone, intercalated with marl, mudstone, and argillaceous siltstone. The lower Qinglong Formation corresponds to the Yinkeng Formation at the lower Yangtze group. The lower Qinglong group has the complex lithologic characteristics, which can be divided into six categories from top to bottom, including limestone weathering crust layer, limestone, marl with mudstone, mudstone with limestone, marl with limestone, and mudstone interbedding limestone and mudstone. Karst phenomenon is well developed in the lower Qinglong Formation, and the thickness of weathering crust, revealed by cz35-2-1 well, reaches 60.5 m. Triassic in the South Yellow Sea Basin is mainly distributed in the central uplift and southern depression, showing the regional differences in distribution. Karstification is probably the main reason for this significant difference. Identification of karst phenomenon and stratigraphic division method towards Triassic drilling coring are two important directions of Triassic study in the South Yellow Sea Basin.

# 1. Introduction

Triassic system was founded by von Alberti, a German geologist in 1834 [1–3], according to the characteristics of three sets of stratigraphic units in southern Germany and other parts of Europe [4, 5]. According to the international chronostratigraphic table (2020) [6–9], the limit of Triassic geological age ranges from 251.902 ma~201.3 ma. Triassic is widely distributed in the world and in China [10], for example, the Tarim Basin, Ordos Basin, and Junggar Basin in northern China, western Guizhou, Eastern Yunnan, and western Yunnan. Moreover, there are also well-developed Triassic systems in northern Tibet, such as the Zhehala group in the middle of the Bangong Lake-Nujiang junction zone [6]. Triassic is one of the most important geological periods in the process of tectonic evolution in China [4]. Volcanic events and biological extinction in the early Triassic Indian stage have always been the focus of many researchers [11–13]. The Triassic system is rich in mineral resources, such as the enrichment of minerals in the Triassic System on both banks of the middle and lower reaches of the Yangtze River [5]. Xujiahe Formation of Upper Triassic, Leikoupo Formation of Middle Triassic, Jialingjiang Formation, and Feixianguan Formation of Lower Triassic are developed in Triassic in the Sichuan Basin. Recently, major oil and gas reservoirs are discovered in the Triassic in Sichuan Basin [12, 13], including Puguang, Yuanba, Moxi, and other (large) gas fields. Triassic carbonate rocks are the reservoir rock type of these (large) gas fields. The South Yellow Sea Basin has a promising broad oil and gas exploration

prospect, and the Triassic carbonate rock is suitable for the formation of oil and gas reservoir. It is of great significance to make a major breakthrough in oil and gas exploration in the South Yellow Sea Basin as soon as possible and carry out in-depth research on Triassic in the basin. From the perspective of oil and gas exploration, this paper studies the characteristics of Triassic in the South Yellow Sea Basin of China, including lithologic characteristics, karst development characteristics, relevant correlation with regional strata, and distribution characteristics.

#### 2. Overview of the Study Area

The South Yellow Sea Basin is located at the Yangtze fault block area (Figure 1). According to the trough platform theory, it belongs to the Yangtze quasiplatform. The Yangtze quasiplatform is further divided into the upper, middle and lower Yangtze areas, and the South Ring Basin is located at the lower Yangtze area.

The South Yellow Sea Basin can be divided into three major internal structural units, including the northern depression (Yantai depression), central uplift (Laoshan uplift), and southern depression (Qingdao depression). The Subei Basin is adjacent to the South Yellow Sea Basin. In fact, the southern depression of the South Yellow Sea Basin can be regarded as the marine extension of the Subei Basin.

The South Yellow Sea Basin has developed for a long time. The caprock deposition began in the Sinian period, and many sets of extremely thick carbonate rock strata developed, such as Sinian Cambrian, Middle Carboniferous Lower Permian, and lower Triassic carbonate rock strata. Indianan movement is the most important tectonic activity, experienced by the Yangtze fault block area, which makes the Yangtze fault block area transform from large-scale marine basin to small continental basin.

As depicted in Figure 2, the South Yellow Sea Basin covers a large area of about 300,000 square kilometers, with a geographical range of  $32^{\circ} - 34^{\circ}$  N as well as  $120^{\circ} - 124^{\circ}$ . It has a wide exploration area, few exploration wells have been drilled, and the degree of exploration is low.

#### 3. Triassic Characteristics

The Triassic in the South Yellow Sea Basin includes Zhoucun Formation and Qinglong Formation, and Qinglong Formation can be further divided into the upper Qinglong Formation and lower Qinglong Formation. Characteristics of Triassic in the South Yellow Sea Basin, as discussed below, include lithologic characteristics, karst phenomenon, stratigraphic regional correlation, and distribution.

3.1. Correlation with Regional Strata. The lower Yangtze region can be divided into five stratigraphic divisions (Figure 3), including Xianning-Anqing-Nanjing division, Jiuhuashan-Wuxi-Nantong division, Changsha-Nanchang division, Duchang-Dongzhi division, Wuyuan-Huangshan division, and Huaiyushan-Tianmu Mountain layer division [15]. Notably, only the limestone of the lower Triassic Qinglong Formation can be seen in Duchang-Dongzhi division,

and only the upper Triassic Sanqiutian Formation and the upper Triassic Tianmu mountain layer division can be seen in Wuyuan-Huangshan division and Huaiyushan-Tianmu layer division. The Permian-Jurassic Duojiang formation is characterized by coarse clastic rock series. Xianning-Anqing-Nanjing, Jiuhuashan-Wuxi-Nantong, and Changsha-Nanchang zones are the major areas, where carbonate rocks developed in the lower Triassic.

According to Figure 3, the South Yellow Sea (southern depression) belongs to the Northeast seaward extension of Xianning-Anqing-Nanjing zone. It is urgent to investigate the characteristics of Triassic in the South Yellow Sea Basin (southern depression) and fully understand the research results of Triassic stratigraphic division. In order to achieve comprehensive knowledge, it is necessary to systematically sort out the problems related to Triassic strata.

Triassic system is located at Anhui Province. Bounded by Mountain-Zhangbaling denudation area, it is divided into the North type and the South type. The Triassic System on both sides of the Yangtze River and southern Anhui belongs to the southern type and belongs to the Xianning-Anqing-Nanjing stratigraphic division (Figure 3), respectively [15–17]. The stratigraphic groups, including Xiaoliangting Formation, Tashan Formation, Nanlinghu Formation, Fenshuiling Formation, Longtoushan Formation, Hujiawu Formation, Chenjiawu Formation, Yueshan Formation, Tongtoujian Formation, Lalijian Formation, Yinkeng Formation, Helongshan Formation, and Wutian Formation, Wuzhishan Formation, have been found at early times.

The traditionally utilized stratigraphic division scheme, in terms of Triassic, is lower Triassic Yinkeng Formation, Helongshan Formation, Middle Triassic Biandanshan Formation, Upper Triassic Yueshan Formation, Tongtoujian Formation, and Lalijian Formation. The scheme is later altered as the lower Triassic Yinkeng Formation, Helongshan Formation, Nanlinghu Formation, Yueshan Formation, Tongtoujian Formation, and Upper Triassic Lalijian Formation.

According to the results of the regional survey team of Anhui Bureau of Geology and mineral resources (1987) [1], the standard profile and main lithological characteristics of the Yinkeng Formation, Helongshan Formation, Nanlinghu Formation, Yueshan Formation, Tongtoujian Formation, and Lalijian Formation in the lower Yangtze subregion are as follows.

The Yinkeng Formation and Longshan Formation were created by Guichi stratigraphic research team of Anhui Province in 1965. The standard zone is located at Guichi county. The lithology of Yinkeng Formation is yellow green and grayish green calcareous mudstone, interbedded with dark gray thin to medium thick limestone, and argillaceous limestone. The thickness of the upper limestone falls in the range of 83~286 m. Lithology of Helongshan Formation is mainly light gray banded limestone, intercalated with a small amount of yellow green calcareous shale, and thin limestone, with a thickness of 21-235 m. Nanlinghu Formation was founded by Wang Changyi in 1964. The standard section is located at Nanlinghu, Nanling County. Its lithology is characterized by thin to medium thick limestone in the lower part, purplish red or yellow green nodular limestone



FIGURE 1: Tectonic location of the South Yellow Sea Basin.

in the bottom, and cyan gray medium thick dense limestone in the upper part, mixed with thin soft wrinkled limestone. The East Maanshan Formation was found by Wang Guixiang in 1979. The standard section is located at Yueshan, Huaining County. The lower part is mainly dolomite, and the upper part is mainly salt soluble breccia. It is generally 110-200 m thick and can reach more than 675 m in the end. The lower part of Yueshan Formation contains Middle Triassic Badong fauna fossils, which are similar to the Zhouchongcun Formation in Ningzhen mountains. The Yueshan Formation, Tongtoujian Formation, and Lalijian Formation were named by Huaining 326 team in 1966. The standard profile of Yueshan Formation is in Yueshan, Huaining County. The main lithology is grayish white and grayish green siltstone and silty shale, intercalated with bluish gray dolomitic limestone and its convex mirror. The Yueshan Formation is only found in Wuhu-Anging stratigraphic community. Standard section of Tongtoujian Formation is located at Tongtoujian near the Yueshan mountain, Huaining County. The main lithology is purplish red siltstone and silty mudstone mixed with fine sandstone, with a thickness of about 1735 m. The distribution of Tongtoujian Formation is limited, which is only found in Wuhu-Anqing stratigraphic community. This formation is rich in bivalve fossils, and its characteristics are similar to those of the lower part of Huangmaqing Formation in Jiangsu Province.

The standard section of Lalijian Formation is located at Lalijian near Yueshan mountain, Huaining County. It is mainly gray to gray black sandstone, siltstone, sandy shale, and gray black carbonaceous or carbonaceous shale, intercalated with unstable coal seams, with a thickness of 18-75 m. The distribution of this group is limited, and the surface is rarely exposed.

Zhu and Wang (1992) [18] summarized the division scheme of the Early Triassic in Jiangsu and Anhui, and the other three division schemes reflect the current division and correlation relationship. The lithologic characteristics of the lower Triassic in Jiangsu and Anhui may change in different regions. From top to bottom, the main petrological characteristics of the lower Triassic in Ningzhen area are vermicular limestone nodular limestone mudstone, and shale with thin limestone. The main lithological characteristics of the lower Triassic in the area are limestone, thin limestone, and large wormhole limestone, mixed with a small



FIGURE 2: Plane distribution of Triassic wells drilled in the South Yellow Sea Basin [14].

amount of nodular limestone-thin limestone. The change of lithology reflects the different paleogeographic environment. The appearance of oolite limestone and gravelly limestone reflects that its sedimentary environment has the characteristics of marginal facies.

The Huangmaqing Formation, belonging to Middle Triassic Latin stage to the Late Triassic Kani stage, is a set of continental clastic rock, dominated by purplish red in the middle and lower reaches of the Yangtze River [18]. There are large areas of exposed areas on both north and south sides (Figure 4). Various phenomena show that after entering the late Middle Triassic, the large set of limestone of Qinglong Formation of Lower Triassic and evaporite series of Zhouchongcun Formation of Middle Triassic are in an environment of extensive denudation and weathering leaching, which is conducive to the karst phenomenon.

In short, many researchers have carried out the comparative study of Triassic between different units in the Yangtze paraplatform [10, 15, 20]. The Qinglong Formation in the lower Yangtze region corresponds to the Daye Formation in the middle Yangtze region. The upper Qinglong Formation, including Nanlinghu Formation and Helongshan Formation, in the lower Yangtze region corresponds to the Jialingjiang Formation in the middle and upper Yangtze region, and the lower Qinglong Formation in lower Yangtze region corresponds to Feixianguan Formation in middle and upper Yangtze region.

3.2. Lithologic Characteristics. The main lithological characteristics of Shangqinglong Formation are limestone mixed with marl, mudstone, and shale. Main lithological characteristics of Shangqinglong Formation are limestone, mixed with mudstone. The main characteristics of Shangqinglong Formation are interbedding of limestone and marl, limestone mixed with marl, mudstone, and argillaceous siltstone. These wells reveal a common feature of Shangqinglong Formation, demonstrating that the limestone is generally mixed with mudstone, even shale, as well as siltstone.

The main lithological characteristics of Xiaqinglong Formation are limestone weathering shell (well section 1185.5-1246 m, thickness 60.5 m), limestone, marl, and mudstone (well section 1246-1327 m, thickness 81 m), large limestone section (well section 1327-1676 m, thickness 349 m), mudstone mixed with limestone and marl (well section 1676-1779 m, thickness 103 m), limestone and mudstone interbedding (1779-2036.5 m well section, 257.5 m thick), and mudstone mixed with limestone (2036.5-2077 m well section, 40.5 M thick). The lithology of Xiaqinglong Formation, encountered by csdp-2 well, is characterized by limestone mixed with mudstone, mudstone, and



FIGURE 3: Stratigraphic map of lower Yangtze region [15].



FIGURE 4: Sedimentary facies of Huangmaqing Formation in Jiangsu and Anhui [19].

dolomite. It should be emphasized that the lithology characteristics of the lower Qinglong Formation, revealed by three wells drilled in the South Yellow Sea Basin, are very different.

3.3. Karst Development Characteristics. The Well wx5-st1 reveals that the lithology of Zhouchongcun Formation is karst breccia, belonging to developed karst phenomenon, and the thickness of karst breccia is 70 m. Well cz35-2-1 reveals that the of Xiaqinglong Formation, ranging from well section 1185.5-1246 m, is gray white, light gray, and gray limestone weathering crust section. Two of the five wells, drilled in Triassic revealed karst phenomenon, indicate that the drilling rate of karst phenomenon is still very high. The thickness of karst interval, revealed by well cz35-2-1, is beyond 60 m, indicating that the influence depth of karstification is relatively large.

As for carbonate areas with obvious karst phenomena, there exist many argillaceous fillings in underground solution gaps and caves through weathering and leaching, and many silty fillings, formed by groundwater, can be seen. For the study of karst phenomena, the identification of karst filling is very important, especially cave filling. Cave fillings have different classifications. Loucks (1999) divided cave fillings into crack breccia, mixed breccia, and cave sedimentary fillings [21]. Xiao et al. (2003) divided cave sediments and deposits into three categories [22], including the flowing mechanical deposits, chemical deposits, and gravity collapse deposits. Specifically, flowing mechanical deposits can be divided into transportable conglomerate facies deposits and transportable sandstone deposits, the latter including fine sandstone, siltstone, and mudstone. For carbonate rock areas with significant karst, large influence depth, and serious sand mud filling, drilling coring is required. The fine sandstone, siltstone, and mudstone encountered can be characterized as interlayer of carbonate rock. In the previous studies focusing on the karst phenomenon of Ordovician carbonate rocks in outcrop area and Tahe oilfield, Tarim Basin, there are many examples in this research scope [23-25]. However, in the previous achievements and understanding of the characteristics of Triassic in the South Yellow Sea Basin [26, 27], these phenomena are basically not involved.

3.4. Distribution Characteristics. Among the five Triassic wells (cz24-1-1, cz35-2-1, wx4-2-1, wx5-st1, and csdp-2), only one well (wx5-st1) encountered Zhouchongcun Formation, only three wells (cz24-1-1, wx4-2-1, and wx5-st1) encountered Qinglong Formation, and only three wells (cz35-2-1, wx5-st1, and csdp-2) encountered Shangqinglong Formation. And the Zhoucun Formation, Shangqinglong Formation, and Xiaqinglong Formation are locally distributed.

According to the three-point scheme of the South Yellow Sea Basin (Northern depression, central uplift, and southern depression), the Triassic is mainly distributed in the central uplift and southern depression, showing significant regional differences in distribution (Figures 5 and 6). The regional comparison results show that the lithology of the Triassic in the South Yellow Sea Basin, revealed by drilling, is significantly different from that in the region. In southern depression of the South Yellow Sea Basin, the Triassic is seriously cut by faults, showing the distribution characteristics of blocks. Relevant studies show that (Figure 6) the residual thickness of Triassic in the southern depression of the South Yellow Sea Basin exceeds 1250 m [14, 28, 29].

#### 4. Discussion

Well wx5-st1 encountered Zhouchongcun Formation at 1340-1410 m, with a thickness of 70 m. The lithology is calcareous breccia, with a particle size of 20-30 mm [25]. Regionally, the main lithology of Zhouchongcun Formation is gypsum breccia, including small insect trace limestone and dolomite. In terms of Genesis, karst breccia and gypsum breccia are also very different. Therefore, the lithology of Zhoucun Formation, drilled in the South Yellow Sea Basin, is very different from that of the regional standard section. The main lithology of Nanlinghu Formation is characterized by thin to medium thick limestone in the lower part, purplish red or yellow green nodular limestone in the bottom, and green gray medium thick dense limestone in the upper part. The main lithology of Helongshan Formation is light gray banded limestone, mixed with a small amount of yellow green calcareous shale and thin limestone, with a thickness of 21-235 m.

It can be seen from the comparison that the main characteristics of Shangqinglong Formation, reflected by wells cz24-1-1, wx24-2-1, and wx5-st1, are quite different from the regional lithological characteristics. This difference is mainly reflected in the widespread existence of mudstone interlayer in all wells, and some wells (well wx5-st1) also have argillaceous siltstone interlayer. In the lower Yangtze region, the lower Qinglong Formation corresponds to the Yinkeng Formation. On the standard section, the lithology of Yinkeng Formation is yellow green and grayish green calcareous mudstone interbedded with dark gray thin to medium thick limestone and argillaceous limestone. According to comparison, the main lithologic characteristics of Xiaqinglong Formation, reflected by well cz35-2-1, are very different from those of the region. First, the thickness of Yinkeng Formation on the standard profile is only 83-286 m, while the thickness of cz35-2-1 well is 891.5 m. Second, a large set of limestone, with a thickness of 56 m, was encountered when drilling well cz35-2-1, which is a typical lithology of Shangqinglong Formation.

In short, mudstone intercalation generally appears in the upper part of Qinglong Formation in wells, drilled in Qinglong Formation. These phenomena may be the result of primitive sedimentation or late karst. A large set of carbonate rocks and karst phenomena are widely developed in the lower Triassic in the Yangtze paraplatform, for example, large-scale karst cave group developed in Longwanggang, Hunan Province, the large-scale karst cave group developed in Yixing, Jiangsu Province, and the large-scale karst cave group developed in Xingguo, Anhui Province. Many karst caves are also distributed in the vicinity of the cave. The important karst caves include Dashan rock (cave), Huimao Cave, Rhinoceros cave, Tianhe cave, and Guanyin cave. These karst caves form a large karst cave group. In terms



FIGURE 5: Profile distribution of Triassic in the South Yellow Sea Basin [14].



FIGURE 6: Triassic residual thickness and its distribution in the southern depression of the South Yellow Sea Basin [14].

of Longwang cave and its large-scale karst caves nearby, the area, where these holes are located, is about  $14 \text{ km}^2$ .

There are abundant karst phenomena in Longwang cave (Figure 7). Fractures in the cave are well developed [28, 29]. It is found that the development of fractures has a positive correlation with the development degree of karst. The development degree of karst phenomena in different locations is different. At the fault or fracture turning point, medium and large stalactites are less developed.

Karst caves are densely developed in Yixing, Jiangsu Province. The soluble rock series in the area are carbonate rocks, and faults are very developed, including NW, NW, NE, and NE direction. The developed large-scale karst caves include Shanjuan cave, Zhanggong cave, Yuquan cave, Linggu cave, Muli cave, and Xishi cave (Figure 8). Among them, Shanjuan cave, Lyon cave in France, and Han cave in Belgium are known as the three wonders of the world. Large-scale karst caves are mainly developed in areas where large-scale carbonate rocks of Qinglong Formation of lower Triassic are exposed, such as Shanjuan cave, Zhanggong cave, Yuquan cave, and Linggu cave.

As mentioned earlier, for carbonate rock areas with significant karstification, sand mud filling, the fine sandstone, siltstone, and mudstone drilled in the drilling coring can



(a) Stalactite, stone pillar

(b) Stalactite, the cave top



(c) Stalactites, pillars and waterfalls

(d) Stalactites

FIGURE 7: Karst morphological types and characteristics in Longwang cave.



FIGURE 8: Distribution diagram of large karst caves in Yixing, Jiangsu.

be characterized as interlayer of carbonate rock. Tahe oilfield in Tarim Basin is a world-famous large oilfield; the Ordovician Karst carbonate rock series is the main reservoir. This set of carbonate rock series is distributed on the long-term uplift, with significant karst development, and the depth of karst zone can reach more than 250 m. At least two cave filling intervals are developed in well section 5548–5553 m of well T403 in block 4 of Tahe oilfield. Among them, one section is distributed in well section 5539.5-5548.5 m. The other section is distributed at 5505.5-5539.5 m. In a large set of



FIGURE 9: Karst filling in well section 4929.00-4980.78 m of yq3 well in Yuqi Area of Tahe Oilfield.

carbonate formations, these cave filling deposits appear in the form of interlayer (Figure 9(a)). Three cave filling intervals also appear in well t615 in block 6 of Tahe oilfield in well section 5560~5580 m (Figure 9(b)); it is characterized by interlayer in Ordovician carbonate rocks. In the well section 4929.00-4980.78 m of yq3 well in Yuqi area of Tahe oilfield, there are two large karst filling layers, which are characterized by large thickness, and the Ordovician carbonate rocks are characterized by interlayer (Figure 9(c)).

In the carbonate rock distribution area with strong karstification, great influence depth, serious sand mud filling, and the lithology can change greatly due to the transformation of karstification, from a large set of carbonate rocks to intercalated with clastic rocks. This change in lithology will increase difficulties in stratigraphic division and lead to wrong stratigraphic division results. This problem is very prominent for the upper and lower Qinglong Formation of Triassic in the South Yellow Sea Basin. The study is of great significance for carbonate reservoir evaluation.

#### 5. Conclusions

(1) The lithological characteristics of Triassic groups in the South Yellow Sea Basin are significantly different from those in the region. The lithology of Zhouchongcun Formation in the South Yellow Sea Basin, revealed by drilling, is karst breccia, which is characterized by gypsum breccia and dolomite. The lithology of Shangqinglong Formation in the South Yellow Sea Basin revealed by drilling is limestone mixed with marl, mudstone, and argillaceous siltstone. Lithological characteristics of this formation area are mudstone, mudstone, and marl interbedding. The limestone, intercalated with syngenetic breccia, is developed in some areas

- (2) The Triassic karst in the South Yellow Sea Basin is developed, the thickness of karst breccia of Zhouchongcun Formation is up to 70 m, and the thickness of weathered crust of Xiaqinglong Formation is up to 60.5 m. Triassic strata in the South Yellow Sea Basin are locally distributed, mainly in the central uplift, and southern depression of the South Yellow Sea Basin
- (3) The lithologic characteristics of the upper and lower Qinglong Formation revealed by drilling in the South Yellow Sea Basin may be the result of karstification transformation. In-depth study of the genesis and formation period of its lithologic characteristics is not only a karstification problem in carbonate rock area but also a very important stratigraphic division and correlation problem

## **Data Availability**

Data are available on request.

# **Ethical Approval**

On behalf of all the co-authors, the corresponding author states that there are no ethical statements contained in the manuscripts.

## **Conflicts of Interest**

The authors declare that there is no conflict of interest regarding the publication of this paper.

#### Acknowledgments

The authors acknowledge the SINOPEC for the permission to publish this work.

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