Stratigraphic Framework of the Cryogenian in China

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Abstract: The Cryogenian is a critical period in the history of the Earth. It is marked by multiple extreme climate changes that caused alternating global glacial and interglacial intervals. These dramatically changed the sedimentary system, and metal ores and source rocks distributed widely during this period. Therefore, studying the Cryogenian stratigraphic framework and sedimentary basins is important to improve the stratigraphic resolution for metal mineral and hydrocarbon prospecting and exploration in China. This review paper firstly divides three tectonic-stratigraphic regions in China in the Cryogenian, including the tectonic-stratigraphic regions of Great South China, Xingmeng-Tarim, and North China. Secondly, geochronologic data and geological records are combined to clearly depict the Cryogenian sedimentary sequence of continental blocks and micro-continental blocks in different tectonic-stratigraphic regions. The results were used to propose a new comparison scheme of stratigraphy for the Cryogenian in China. Finally, according to differences of sedimentary evolution and tectonic evolution, sedimentary basins and their lithofacies paleogeography are identified and summarized, respectively.

Key words: Cryogenian, stratigraphic framework, correlation, basin, palaeogeography, China


1 Introduction

The Cryogenian (~720–635 Ma) is a unique period of the evolutionary history of the Earth. Along with the breakup of the Rodinia supercontinent, the Earth experienced at least two rapid conversions between extreme glaciation and greenhouse climate. An ice-covered snowball Earth had been hypothesized since glaciers reached tropical oceans and the Earth approached a mostly or completely frozen condition (Hoffman, 1999; Hoffman et al., 1998, 2017; Li et al., 2013; Macdonald et al., 2010). This extreme climate event became both filter and bottleneck for the evolution of life, where most eukaryotic lineages went extinct, while others (especially prokaryotic clades) survived in unknown refugia (Hoffman et al., 1998), and influenced the subsequent radiation of multicellular eukaryotic life (Xiao et al., 2014; Yuan et al., 2011). During the same period, both banded iron formation (BIF), which had disappeared for more than one billion years (Basta et al., 2011; Hoffman et al., 2011a; Isley and Abbott, 1999; Yan et al., 2010), and sedimentary manganese ore occurred (Yu et al., 2017). Moreover, a large quantity of organic matter-rich shale deposition occurred, which served as an important hydrocarbon source rock during the Neoproterozoic period (Lin et al., 2016; Zhu et al., 2017). Thus, understanding the stratigraphic framework of the Cryogenian in China is beneficial for the study of earth science and the prediction of metal mineral, oil, and gas deposits.

The notion of widespread glaciations during the late Precambrian had been recognised as early as 1930s (e.g., Kulling, 1934; Lee, 1936; Mawson, 1949). Several terms (e.g., the Infracambrian and the Varangian System) were proposed when Brian Harland (Harland, 1964a, b) suggested to use glacial deposits to define a new addition to the international geological time scale (Dunn et al., 1971; Harland et al., 1982, 1990). In 1989, the Neoproterozoic Era (1000 Ma–Cambrian) had been divided into three periods, i.e., the Tonian Period (1000 Ma–850 Ma), the Cryogenian Period (850 Ma–650 Ma), and the unnamed “Neoproterozoic III” Period (650 Ma–Cambrian) (Plumb and James, 1986; Plumb, 1991). After nearly a decade, the Neoproterozoic III was redefined as the Ediacaran Period and its initial GSSP was marked by the base of the cap carbonate that overlies Marinoan diamictites in South Australia (Cloud and Glaesner, 1982), which also defined the end of the Cryogenian Period and could be correlated throughout the world (Knoll et al., 2004). The initial GSSP of the Ediacaran Period, for the first time, was defined at the stratigraphic level with dramatic geochemical and paleoclimatic changes rather than biological evolution, which is of great significance on the expansion of the GSSP definition (Shields-Zhou et al., 2012). In the absence of index fossils and/or characteristic biotas/ assemblages, the ICS
advocated a chronostratigraphic definition for the Cryogenian Period, of which began at the base of the Sturtian glacial interval and terminated at the basal Ediacaran GSSP (Knoll, 2000). Over the two following decades, how to define the bottom boundary of the Cryogenian Period is still a matter of debate. In 2016, the base of the Cryogenian Period was revised from 850 Ma to ca. 720 Ma (Ogg et al., 2016; Hoffmann et al., 2017). In addition, based on the glacial event stratigraphy and isotope chronostratigraphy, two globally synchronous glacial units (i.e., Sturtian and Marinoan) and the intervening warm interglacial interval divide the Cryogenian into three units. The onset and termination of the Sturtian glaciation are tightly constrained in ca. 717–660 Ma, the end of the Marinoan glaciation was strictly limited to 635 Ma, while the initial time of the Marinoan glaciation was broadly limited to ~650 Ma (Fig. 1; Fanning and Link, 2004; Kendall et al., 2006; Bowring et al., 2007; Bertoni et al., 2014; Lan et al., 2015b; Hoffman et al., 2017; Bao et al., 2018).

Cryogenian successions were widely outcropped in China. Glacial deposits developed in late Neoproterozoic were first defined as the lower Sinian Series (Lee, 1936). At the third national stratigraphic congress of China in 2000, in response to the new global division scheme of the Neoproterozoic, the original Sinian System had been fragmented into two parts. The former upper Sinian Series was redefined as the “Sinian System” which equals the Ediacaran System, while the former lower Sinian Series was independently established as a new system, and named the “Nanhua System”. The top boundary of the Nanhua System, which is the same for that of the Cryogenian System, was dated at ~635 Ma. However, there are still different competing ideas about the age of the bottom boundary of the Nanhua System, which was previously placed at the bottom of the Liantuo Fm. and its equivalent strata, dated to ~780 Ma (Fig. 1; Zhang et al., 2015). Recently, research increasingly tends to define its bottom boundary at the basal of the Chang’an Fm. or Jiangkou Gp., which dated to ~720 Ma and represented the earliest glacial deposits in the South China block (e.g., Lan et al., 2014, 2015b; Zhou, 2016). This review supports the latter idea to put the bottom boundary of the Cryogenian/Nanhua Period at the age of ~720 Ma.

As an important carrier of geological events, the widely outcropped Cryogenian successions on various blocks and micro-continental blocks in China present a wide range of records, including biological, chronological, and environmental information. In recent years, attempts to establish a stratigraphic and sedimentological framework for the Cryogenian in China have been made by numerous publications (e.g., Wang et al., 2003; Xiao et al., 2004; Xu et al., 2009; Zhu and Wang, 2011). However, notable uncertainties remain, especially regarding the following aspects: Firstly, current studies of the Cryogenian in China mainly focused on the Yangtze and Tarim Blocks, while the understanding of the Cryogenian sedimentary sequence on various micro-continental blocks in China remains limited. Secondly, systematic stratigraphic correlation of the Cryogenian strata under an identical chronological framework in a whole China scale needs to be updated. Moreover, sedimentary basins and their lithofacies paleogeography during this period has not been systematically studied to date.

Fig. 1. Evolution of stratigraphic terms covering the Neoproterozoic-Cambrian interval.
This review summarizes many of the representative stratigraphic sections of the Cryogenian (99 sections in Table 1) and provides a sedimentological interpretation and a new comparison scheme of stratigraphy across China. On this basis, the sedimentation and their lithofacies paleogeography were further discussed.

2 Materials and Method

A total of 99 Cryogenian sections from different blocks of China are presented in this review (Fig. 2). Gathered section information includes lithology, thickness, lithofacies, carbon isotope characteristics, isotope ages, and fossils (Tables 1 and 2). Most sections were summarized from Yangtze (a total of 44 sections, sections 38–81), Tarim (a total of 12 sections, sections 11–22), and North China blocks (four sections, sections 34–37) since these are hotspots for the study of the Cryogenian in China. For these micro-continental blocks (where the study is comparatively weak), a total of 29 sections were briefly summarized based on previous data and field investigations by the authors. Among these sections, most of the successions distributed in Qinghai-Xizang and western Yunnan areas are temporarily classified as Cryogenian because of their high metamorphic level and lack of accurately reported glaciogenic diamictite. It should be noted that the typical Cryogenian lithostratigraphy of each block and micro-block is described based on 1–3 representative sections. More details of other relevant sections can be found in Tables 1 and 2.

3 Geological Settings and Tectonic-Stratigraphic Divisions of China in Cryogenian

3.1 Distribution of main oceans in China during the Cryogenian period

The final breakup of the Rodinia supercontinent penetrated the entirety of the Cryogenian period (Hoffman, 1999; Li et al., 2008; Zhao et al., 2018). This breakup event might have been triggered by an independent super mantle plume event, which led to the birth of a series of new oceans (Torsvik and Cocks, 2013; Zhao et al., 2018). Among these new oceans that are directly related to the breakup of the Rodinia, the Proto-
Table 1 The outcrop sections referred to in this study

<table>
<thead>
<tr>
<th>Num.</th>
<th>Location of section</th>
<th>Longitude and latitude</th>
<th>Formation</th>
<th>Thickness</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fushai, Xinjiang</td>
<td>89°30'00&quot;E, 43°12'10&quot;N</td>
<td>Fuyan Gp.</td>
<td>&gt;1107 m</td>
<td>IGC-Xinjiang</td>
</tr>
<tr>
<td>2</td>
<td>Arxan, Inner Mongolia</td>
<td>116°15'00&quot;E, 49°00'03&quot;N</td>
<td>Jiageda Fm.</td>
<td>&gt;576 m</td>
<td>IMTG; 2010a</td>
</tr>
<tr>
<td>3</td>
<td>Enhe, Inner Mongolia</td>
<td>119°12'10&quot;E, 50°30'03&quot;N</td>
<td>Jiageda Fm.</td>
<td>&gt;673 m</td>
<td>IMTG; 2010b</td>
</tr>
<tr>
<td>4</td>
<td>Mordaga, Inner Mongolia</td>
<td>120°51'38&quot;E, 51°35'57&quot;N</td>
<td>Jiageda Fm.</td>
<td>&gt;2000 m</td>
<td>Zhao et al., 2016</td>
</tr>
<tr>
<td>5</td>
<td>Jifeng, Jilin</td>
<td>123°10'31&quot;E, 50°24'16&quot;N</td>
<td>Xinling-Xiguiti melange</td>
<td>&gt;2200 m</td>
<td>Feng et al., 2016</td>
</tr>
<tr>
<td>6</td>
<td>Xinlin, Heienglish</td>
<td>124°19'37&quot;E, 51°31'13&quot;N</td>
<td>Xinling-Xiguiti melange</td>
<td>&gt;1500m</td>
<td>Feng et al., 2019</td>
</tr>
<tr>
<td>7</td>
<td>Huma, Heienglish</td>
<td>126°04'10&quot;E, 50°50'38&quot;N</td>
<td>Tiemaozhen Fm.</td>
<td>&gt;1168 m</td>
<td>BGRMR-Heilongjiang, 1997</td>
</tr>
<tr>
<td>8</td>
<td>Yilan, Heienglish</td>
<td>123°19'37&quot;E, 51°31'13&quot;N</td>
<td>Heienglish melange</td>
<td>&gt;1000 m</td>
<td>Yang et al., 2015</td>
</tr>
<tr>
<td>9</td>
<td>Xinxing, Heienglish</td>
<td>130°27'00&quot;E, 44°50'51&quot;N</td>
<td>Heienglish melange</td>
<td>&gt;1000 m</td>
<td>Xie et al., 2008</td>
</tr>
<tr>
<td>10</td>
<td>Chenning, Heienglish</td>
<td>129°22'05&quot;E, 45°19'44&quot;N</td>
<td>Hongquin Fm.</td>
<td>Unspecified</td>
<td>Quan et al., 2013</td>
</tr>
<tr>
<td>11</td>
<td>Guozigou, Xinjiang</td>
<td>44°28'10&quot;N, 81°07'23&quot;E</td>
<td>Talisayi Fm.</td>
<td>79-414 m</td>
<td>Gao et al., 2011</td>
</tr>
<tr>
<td>12</td>
<td>Keguqinshan, Xinjiang</td>
<td>80°31'00&quot;E, 44°40'00&quot;N</td>
<td>Biexibastao Fm.</td>
<td>34 m</td>
<td>Nie et al., 2013</td>
</tr>
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<td>13</td>
<td>Shaerbuer Mountain, Xinjiang</td>
<td>89°54'22&quot;E, 43°25'58&quot;N</td>
<td>Xinglongshan Fm.</td>
<td>91m</td>
<td>Quan, 2017</td>
</tr>
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<td>14</td>
<td>Yuermeink, Xinjiang</td>
<td>79°27'40&quot;E, 40°40'04&quot;N</td>
<td>Yuermeink Fm.</td>
<td>10-80 m; 175 m;</td>
<td>Gao et al., 2013; Zhu, et al., 2011</td>
</tr>
<tr>
<td>15</td>
<td>Keping, Xinjiang</td>
<td>79°29'10&quot;E, 40°55'27&quot;N</td>
<td>Dongwu Fm.</td>
<td>94 m</td>
<td>Quan, 2017</td>
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<tr>
<td>16</td>
<td>Xishankou, Xinjiang</td>
<td>86°37'30&quot;E, 41°33'10&quot;N</td>
<td>Hangguling melange</td>
<td>&gt;1250 m</td>
<td>Huang et al., 1995</td>
</tr>
<tr>
<td>17</td>
<td>Qiakemarktieshi, Kuluketag, Xinjiang</td>
<td>87°27'41&quot;E, 41°22'20&quot;N</td>
<td>Tereeken Fm.</td>
<td>915 m</td>
<td>He et al., 2014; Shi et al., 2017; Wei et al., 2017</td>
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<td>18</td>
<td>Zhaobishan, Kuluketag, Xinjiang</td>
<td>87°50'27&quot;E, 41°31'00&quot;N</td>
<td>Tereeken Fm.</td>
<td>471 m</td>
<td>Kou et al., 2011; Shi et al., 2017</td>
</tr>
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<td>19</td>
<td>Yuergeumblac, Kuluketag, Xinjiang</td>
<td>89°15'10&quot;E, 40°59'10&quot;N</td>
<td>Tereeken Fm.</td>
<td>499 m</td>
<td>GSI-Xinjiang, 2010; Shi et al., 2017</td>
</tr>
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<td>20</td>
<td>Yaerdangshang, Kuluketag, Xinjiang</td>
<td>82°17'20&quot;E, 40°00'10&quot;N</td>
<td>Tereeken Fm.</td>
<td>404 m</td>
<td>GSI-Xinjiang, 2010; Shi et al., 2017</td>
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<td>21</td>
<td>Yecheng, Xinjiang</td>
<td>77°07'00&quot;E, 36°40'00&quot;N</td>
<td>Beiyixi Fm.</td>
<td>182 m; 339 m</td>
<td>Zhu et al., 2011</td>
</tr>
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<td>22</td>
<td>Chuck Markick, Yecheng, Xinjiang</td>
<td>77°07'00&quot;E, 36°40'00&quot;N</td>
<td>Beiyixi Fm.</td>
<td>183 m; 441 m</td>
<td>Ma et al., 1989</td>
</tr>
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<td>23</td>
<td>Zeluma, Subei, Gansu</td>
<td>96°08'00&quot;E, 41°22'00&quot;N</td>
<td>Yutang Fm.</td>
<td>904 m</td>
<td>Shi et al., 2017</td>
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<td>24</td>
<td>Mazongshan, Gansu</td>
<td>97°09'59&quot;E, 41°44'45&quot;N</td>
<td>Beiyixi Fm.</td>
<td>181 m; 903 m</td>
<td>Shi et al., 2017</td>
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<td>25</td>
<td>Xichangjiang, EjinBanner, Gansu</td>
<td>99°15'00&quot;E, 41°16'15&quot;N</td>
<td>Beiyixi Fm.</td>
<td>118 m; 339 m</td>
<td>Zhu et al., 2011</td>
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<td>26</td>
<td>Biamaguo, Subei, Gansu</td>
<td>95°48'00&quot;E, 39°31'30&quot;N</td>
<td>Beiyixi Fm.</td>
<td>183 m; 441 m</td>
<td>Ma et al., 1989</td>
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<td>27</td>
<td>Baiyanggou, Sunan, Gansu</td>
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<td>Shaozhonggou Fm.</td>
<td>&gt;950 m</td>
<td>BGRMR-Gansu, 1999</td>
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<td>28</td>
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<td>101°24'00&quot;E, 38°41'00&quot;N</td>
<td>Shaozhonggou Fm.</td>
<td>842 m</td>
<td>BGRMR-Inner Mongolia, 1996</td>
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<td>Mafangzigou, Yongcheng, Gansu</td>
<td>101°56'00&quot;E, 38°32'00&quot;N</td>
<td>Shaozhonggou Fm.</td>
<td>472-511 m</td>
<td>IGC-Gansu, 2017</td>
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<td>Ourobrook, Qinghai</td>
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<td>&gt;1300 m</td>
<td>Sun et al., 2014;</td>
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<td>Bolinmu Fm.</td>
<td>370 m</td>
<td>Xu et al., 2008</td>
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<td>Hualong, Qinghai</td>
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<td>Mahuanmou Fm.</td>
<td>430 m</td>
<td>Wang et al., 2014</td>
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<td>Thickness</td>
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<td>34</td>
<td>Dadianzi, Liaoning</td>
<td>124°11′42″E, 42°15′00″N</td>
<td>Yintun Fm.</td>
<td>805 m</td>
<td>Lu et al., 2015</td>
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<td>35</td>
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<td>Kangjia Fm.</td>
<td>228 m</td>
<td>Ao et al., 2016</td>
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<td>Wafangdian, Liaoning</td>
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<td>Kangjia Fm.</td>
<td>403 m</td>
<td>Ao et al., 2016</td>
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<td>Liuhe, Jilin</td>
<td>127°15′48″E, 42°20′00″N</td>
<td>Qiaofo Fm.</td>
<td>528 m</td>
<td>GSI-Jilin, 1971</td>
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<td>Guanjiagou, Wenzian, Gansu</td>
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<td>Guanjiagou Fm.</td>
<td>&gt; 2033 m</td>
<td>IGC-Gansu, 2017</td>
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<td>Wenzian, Gansu</td>
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<td>Guanjiagou Fm.</td>
<td>&gt; 1300 m</td>
<td>IGC-Gansu, 2017</td>
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<td>Sanjiang, Guangxi</td>
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<td>655 m</td>
<td>Wang et al., 2016</td>
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<td>41</td>
<td>Xiaoyangba, Shanxi</td>
<td>107°53′51″E, 32°32′16″N</td>
<td>Datangpo Fm.</td>
<td>30–50 m</td>
<td>Wang et al., 2016</td>
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<td>42</td>
<td>Shiwan-Keji, Shanxi</td>
<td>Unspecified</td>
<td>Dogong Fm.</td>
<td>300–2000 m</td>
<td>Zha et al., 2014</td>
</tr>
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<td>43</td>
<td>Yunxian, Hubei</td>
<td>111°04′31″E, 32°56′25″N</td>
<td>Dogong Fm.</td>
<td>1199 m</td>
<td>BGRM-Hubei, 2017</td>
</tr>
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<td>Xixia, Henan</td>
<td>111°29′33″E, 33°09′06″N</td>
<td>Dogong Fm.</td>
<td>2400 m</td>
<td>Zha et al., 2014</td>
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<td>Xincheng, Hubei</td>
<td>114°16′41″E, 31°29′38″N</td>
<td>Dogong Fm.</td>
<td>Unspecified</td>
<td>Mao et al., 2016</td>
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<td>&gt; 299.94 m</td>
<td>Ye et al., 2015</td>
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<td>Maoyeping, Badong, Hubei</td>
<td>110°08′22″E, 30°51′59″N</td>
<td>Nantuo Fm.</td>
<td>43 m</td>
<td>Zhang et al., 2008</td>
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<td>60 m</td>
<td>Liu et al., 2015</td>
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<td>111°13′18″E, 29°54′06″N</td>
<td>Nantuo Fm.</td>
<td>17 m</td>
<td>Liu et al., 2015</td>
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<td>109°53′40″E, 28°33′48″N</td>
<td>Nantuo Fm.</td>
<td>4 m</td>
<td>Liu et al., 2015</td>
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<td>51</td>
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<td>108°48′04″E, 28°03′57″N</td>
<td>Nantuo Fm.</td>
<td>90 m</td>
<td>Wang et al., 2015</td>
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<td>108°56′35″E, 27°42′43″N</td>
<td>Nantuo Fm.</td>
<td>12 m</td>
<td>Wang et al., 2015</td>
</tr>
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<td>53</td>
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<td>106°49′16″E, 27°09′04″N</td>
<td>Nantuo Fm.</td>
<td>4 m</td>
<td>Wang et al., 2015</td>
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<td>54</td>
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<td>108°27′16″E, 27°12′13″N</td>
<td>Nantuo Fm.</td>
<td>95 m</td>
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<td>Nantuo Fm.</td>
<td>20 m</td>
<td>Wang et al., 2015</td>
</tr>
<tr>
<td>56</td>
<td>Songzao, Anhui, Hunan</td>
<td>111°20′22′E, 28°40′11″N</td>
<td>Nantuo Fm.</td>
<td>51 m</td>
<td>Wang et al., 2015</td>
</tr>
<tr>
<td>57</td>
<td>Nanhu, Yiyan, Hunan</td>
<td>112°14′01″E, 28°24′38″N</td>
<td>Nantuo Fm.</td>
<td>20 m</td>
<td>Wang et al., 2015</td>
</tr>
<tr>
<td>58</td>
<td>Jishan, Xinggan, Hunan</td>
<td>112°36′45″E, 27°37′22″N</td>
<td>Nantuo Fm.</td>
<td>5 m</td>
<td>Wang et al., 2015</td>
</tr>
<tr>
<td>59</td>
<td>Liangfengao, Guizhou</td>
<td>107°49′25″E, 26°05′00″N</td>
<td>Nantuo Fm.</td>
<td>0–250 m</td>
<td>Wang et al., 2015</td>
</tr>
<tr>
<td>60</td>
<td>Lijiao, Congjiang, Guizhou</td>
<td>108°57′27″E, 25°39′60″N</td>
<td>Lijiao Fm.</td>
<td>2340 m</td>
<td>Lu et al., 2010</td>
</tr>
<tr>
<td>61</td>
<td>Sanjiang, Guangxi</td>
<td>109°36′10″E, 25°48′10″N</td>
<td>Lijiao Fm.</td>
<td>4.53 m</td>
<td>Lu et al., 2010</td>
</tr>
<tr>
<td>62</td>
<td>Sizhiyan, Chenzhou, Huanan</td>
<td>112°37′09″E, 26°02′04″N</td>
<td>Lijiao Fm.</td>
<td>314 m</td>
<td>Lu et al., 2010</td>
</tr>
<tr>
<td>63</td>
<td>Sanheji, Quanzhou, Anhui</td>
<td>118°02′24″E, 32°09′14″N</td>
<td>Lijiao Fm.</td>
<td>299 m</td>
<td>Lu et al., 2010</td>
</tr>
<tr>
<td>64</td>
<td>Jixi, Anhui</td>
<td>118°13′40″E, 29°35′20″N</td>
<td>Lijiao Fm.</td>
<td>1286 m</td>
<td>Lu et al., 2010</td>
</tr>
<tr>
<td>65</td>
<td>Yinhuan, Lianan, Zhejiang</td>
<td>119°43′02″E, 30°11′50″N</td>
<td>Yinhuan Fm.</td>
<td>65.9 m</td>
<td>IGC-Anhui, 1985</td>
</tr>
<tr>
<td>66</td>
<td>Hongfeng, Dongzhi, Anhui</td>
<td>117°06′33″E, 29°57′14″N</td>
<td>Yinhuan Fm.</td>
<td>115 m</td>
<td>IGC-Anhui, 1985</td>
</tr>
<tr>
<td>67</td>
<td>Pengshan, De'an, Jiangxi</td>
<td>118°42′26″E, 29°20′30″N</td>
<td>Yinhuan Fm.</td>
<td>5.0 m</td>
<td>IGC-Anhui, 1985</td>
</tr>
<tr>
<td>68</td>
<td>Tongshan, Hubei</td>
<td>114°27′48″E, 29°39′99″N</td>
<td>Nantuo Fm.</td>
<td>2 m</td>
<td>Song et al., 2016</td>
</tr>
</tbody>
</table>
Tethys Ocean (PTO) and the Paleo-Asian Ocean (PAO) played an important role in the formation and evolution of the continental blocks of China (Figs. 2, 3).

The PTO originated at ~750 Ma at the breakup of Rodinia and closed during the early Paleozoic at ~500–420 Ma (Zhao et al., 2018). In the Chinese literature, different areas of the Proto-Tethys Ocean have different names, including the AltynTagh Ocean in the southeastern margin of the Tarim craton (Liu et al., 2013a), the Northern Qilian Ocean in the southern margin of the Alxa (Song et al., 2013, 2014, 2017), and the Shandian Ocean between the North China craton and South China craton (Li et al., 2008, 2016, 2018b; Liu et al., 2013b; Dong et al., 2015, 2016; Dong and Santosh, 2016; Figs. 2, 3).

The PTO is a wide Panthalassa, which separates continental blocks into North China, Tarim, and Alxa from those in eastern Europe and Siberia (Xiao et al., 2003, 2014; Wilhem et al., 2012; Xiao and Santosh, 2014; Xiao and Zhao, 2016). In the Chinese literature, the Xinlin -Xiguitu Ocean between Erguna Block and Xing’ an Block (Feng et al., 2016, 2018) and the Heilongjiang ocean in the western margin of the Jiamusi Block (Xie et al., 2008) are all belong to PTO. In the adjacent area, the Bayankhongor Ocean in central Mongolia (Wilhem et al., 2012), the Enganepe ocean in Polar Urals (Scharow et al., 2001), and the Baikal-Muya ocean in Siberia (Kuzmichev et al., 2008; Kuzmichev and Larionov, 2013; Kröner et al., 2015; Powerman et al., 2015), are all different names for PTO. It’s worth noting that arc-related magmatic rocks and SSZ-type ophiolite (700–630 Ma) indicate that the subduction of PAO was existed in Cryogenian (Figs. 2, 3; Feng et al., 2018), which make it great differ from to PTO.

### 3.2 Positions of main blocks of China in Rodinia

In recent years, research on the paleogeographic reconstruction of the Rodinia achieved great progress. Several reconstruction models such as "SWEAT" (Dalziel, 1991; Hoffman, 1991; Moores, 1991; Hoffman et al., 2011b), "Missing-link "(Li et al., 1995) and "AUSWUS" (Brookfield, 1993; Direen and Crawford, 2015) have been proposed. However, due to poor geological and paleomagnetic constraints, no consensus has been reached regarding its configurations. In the Cryogenian (~720–635 Ma), the paleogeographic locations of Tarim, South China, and North China Blocks in China have been given various placement schemes by predecessors (eg., Li et al., 1996, 1999, 2008, 2013; Zhao et al., 2018; Zhang et al., 2013). This study mainly adopted the model of configurations of Rodinia (~700Ma) proposed by Zhao et al. (2018) as the prototype and place the Tarim, South China, and North China Blocks in the northwest of India and Australia (Fig. 3a, Zhao et al., 2018). As for those micro-continents in China, the detrital zircon age spectra in Cryogenian/Neooproterozoic sedimentary successions are collected to reconstruct their tectonic evolution and discuss their affinity relationship with other blocks in China. Thus, these micro-continental blocks are placed in their appropriate places (Fig. 3a), as follows.

It is generally accepted that the CathaysiaBlock and the Yangtze Block collided to form South China Block between 825 and 815 Ma (Li et al., 2009; Shu et al., 2008a, 2008b, 2011; Zhang L et al., 2012; Yin et al., 2013; Zhang G W et al., 2013; Zhao et al., 2018). The detrital zircon age spectra from Neoproterozoic strata of other
### Table 2 Age compilations of Cryogenian in China

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude and latitude</th>
<th>age</th>
<th>Rocks</th>
<th>Group/Formation</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chengjiang, Yunnan</td>
<td>102°55′34″E, 11°47′23″N</td>
<td>&lt;725±11 Ma</td>
<td>Tuff</td>
<td>Upper Chengjiang</td>
<td>SHRIMP U-Pb</td>
<td>Cui et al., 2013</td>
</tr>
<tr>
<td>Yannnenzhu, Hainan</td>
<td>116°34′40″E, 28°40′30″N</td>
<td>717±2.8 Ma</td>
<td>Tuff</td>
<td>Upper Bai</td>
<td>SIMS U-Pb</td>
<td>Bo et al., 2015</td>
</tr>
<tr>
<td>Ganluo, Sichuan</td>
<td>109°24′40″E, 32°11′00″N</td>
<td>715±9.8 Ma</td>
<td>Tuff</td>
<td>Upper Kainianqiao</td>
<td>SHRIMP U-Pb</td>
<td>Jiang et al., 2016</td>
</tr>
<tr>
<td>Sibao, Guanzhi</td>
<td>None</td>
<td>7159±2.8 Ma</td>
<td>Tuffaceous slate</td>
<td>Below Chang'an</td>
<td>U-Pb ID-TIMS</td>
<td>Lan et al., 2014</td>
</tr>
<tr>
<td>Siduping, Huanan</td>
<td>110°20′53″E, 28°50′05″N</td>
<td>&lt;714±6.5 Ma</td>
<td>Sandstone</td>
<td>Upper Bai</td>
<td>LA-ICP-MS U-Pb</td>
<td>Song et al., 2017</td>
</tr>
<tr>
<td>Tianjiayanzhi, Hubei</td>
<td>None</td>
<td>&lt;714±8 Ma</td>
<td>Tuffaceous siltstone</td>
<td>Upper Lantuo</td>
<td>SIMS U-Pb</td>
<td>Lan et al., 2015</td>
</tr>
<tr>
<td>Yangjiang, Huanan</td>
<td>None</td>
<td>6919±8 Ma</td>
<td>Tuffaceous siltstone</td>
<td>Upper Xieshuhe</td>
<td>SIMS U-Pb</td>
<td>Lan et al., 2015</td>
</tr>
<tr>
<td>Yuxian, Hubei</td>
<td>110°49′51″E, 32°54′35″N</td>
<td>685±5 Ma</td>
<td>Rhyolite</td>
<td>Yaolinghe Group</td>
<td>LA-ICP-MS U-Pb</td>
<td>Ling et al., 2007</td>
</tr>
<tr>
<td>Zhalanghao, Guizhou</td>
<td>108°48′04″E, 32°03′57″N</td>
<td>663±4 Ma</td>
<td>Tuff</td>
<td>Datanggo</td>
<td>SHRIMP U-Pb</td>
<td>Zhou et al., 2004</td>
</tr>
<tr>
<td>Jiangjunchen, Guizhou</td>
<td>108°53′51″E, 28°03′47″N</td>
<td>662±7.6 Ma</td>
<td>Tuff in Mn shale</td>
<td>Lower Datanggo</td>
<td>LA-ICP-MS U-Pb</td>
<td>Yu et al., 2017</td>
</tr>
<tr>
<td>Daotuo, Guizhou</td>
<td>None</td>
<td>660±6.75 Ma</td>
<td>Black shale</td>
<td>Lower Datanggo</td>
<td>Re-Os</td>
<td>Pei et al., 2017</td>
</tr>
<tr>
<td>Jiangjunchen, Guizhou</td>
<td>108°34′56″E, 28°55′05″N</td>
<td>658±8.0 Ma</td>
<td>Tuff</td>
<td>Lower Datanggo</td>
<td>CA-ID-TIMS</td>
<td>Zhou et al., 2019</td>
</tr>
<tr>
<td>Changyang, Hubei</td>
<td>111°03′56″E, 30°32′35″N</td>
<td>654±2.7 Ma</td>
<td>Tuff</td>
<td>Datanggo</td>
<td>SIMS U-Pb</td>
<td>Liu et al., 2015</td>
</tr>
<tr>
<td>Maopingdong, Huanan</td>
<td>109°51′30″E, 28°33′48″N</td>
<td>655±3.8 Ma</td>
<td>Tuffaceous siltstone</td>
<td>Datanggo</td>
<td>SHRIMP U-Pb</td>
<td>Zhang et al., 2008</td>
</tr>
<tr>
<td>Maopingdong, Huanan</td>
<td>109°51′30″E, 28°33′48″N</td>
<td>636±4.9 Ma</td>
<td>Tuffaceous siltstone</td>
<td>Lower Nantungo</td>
<td>SHRIMP U-Pb</td>
<td>Zhang et al., 2008</td>
</tr>
<tr>
<td>Eshan, Yunnan</td>
<td>102°28′31″E, 30°48′28″N</td>
<td>634±5.8 Ma</td>
<td>Tuffaceous mudstone</td>
<td>Upper Nantungo</td>
<td>CA-ID-TIMS</td>
<td>Zhou et al., 2019</td>
</tr>
<tr>
<td>Gaojiashui, Hubei</td>
<td>111°01′36″E, 30°48′28″N</td>
<td>632±5.0 Ma</td>
<td>Volcanic ash</td>
<td>Upper Nantungo</td>
<td>U-Pb ID-TIMS</td>
<td>Condon et al., 2005</td>
</tr>
<tr>
<td>Gaojiashui, Hubei</td>
<td>111°01′36″E, 30°48′28″N</td>
<td>632±5.1 Ma</td>
<td>Volcanic ash</td>
<td>Upper Nantungo</td>
<td>U-Pb ID-TIMS</td>
<td>Schmitz, 2012</td>
</tr>
</tbody>
</table>

**Cryogenian stratigraphic age in Tarim**

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude and latitude</th>
<th>age</th>
<th>Rocks</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xinger, Xinjiang</td>
<td>88°35′47″E, 41°27′12″N</td>
<td>740±7 Ma</td>
<td>Lowest felsic bed</td>
<td>Lower Beiyixi</td>
<td>SHRIMP U-Pb</td>
</tr>
<tr>
<td>Xishankou, Xinjiang</td>
<td>86°32′46″E, 41°35′18″N</td>
<td>725±10 Ma</td>
<td>Andesite</td>
<td>Upper Beiyixi</td>
<td>SHRIMP U-Pb</td>
</tr>
<tr>
<td>Yukengou, Xinjiang</td>
<td>87°27′43″E, 41°22′14″N</td>
<td>655±4.4 Ma</td>
<td>Rhyolite</td>
<td>Upper Altungo</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
<tr>
<td>Mochia-Khutuk, Xinjiang</td>
<td>87°47′18″E, 41°24′24″N</td>
<td>654±9.9 Ma</td>
<td>Andesite</td>
<td>Upper Altungo</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
<tr>
<td>Kurukgak, Xinjiang</td>
<td>87°48′14″E, 41°26′02″N</td>
<td>636±2 Ma</td>
<td>Tuff</td>
<td>Upper Tereeken</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
</tbody>
</table>

**Cryogenian stratigraphic age in Other block**

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude and latitude</th>
<th>age</th>
<th>Rocks</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moldaoha, Inner Mongolia</td>
<td>120°51′58″E, 51°35′57″N</td>
<td>&lt;764 Ma</td>
<td>Quartz two-mica schist</td>
<td>Jiagedi</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
<tr>
<td>Jiageda, Inner Mongolia</td>
<td>120°34′38″E, 51°34′16″N</td>
<td>723±42 Ma</td>
<td>Andesite</td>
<td>Jiagedi</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
<tr>
<td>Zhiyan, Gansu</td>
<td>104°00′40″E, 35°46′42″N</td>
<td>713±824 Ma</td>
<td>Basic volcanic rock</td>
<td>Upper Xinglango</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
<tr>
<td>Changting, Fujian</td>
<td>None</td>
<td>650±635 Ma</td>
<td>Sandstone</td>
<td>Upper Louziba</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
<tr>
<td>Naxiong, Jiangxi</td>
<td>None</td>
<td>640±635 Ma</td>
<td>Sandstone</td>
<td>Upper Xifang</td>
<td>LA-ICP-MS U-Pb</td>
</tr>
</tbody>
</table>

**Intrusive rocks and ophiolites age of Cryogenian in China**

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude and latitude</th>
<th>age</th>
<th>Rocks</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shangnan, Shanxi</td>
<td>110°44′57″E, 33°35′12″N</td>
<td>655±9 Ma</td>
<td>Eclogite (protolith age)</td>
<td>LA-ICP-MS U-Pb</td>
<td>Liu et al., 2013</td>
</tr>
<tr>
<td>Yingluosi, Altyn-Tagh</td>
<td>None</td>
<td>730±11 Ma</td>
<td>Garnet peridotite (protolith age)</td>
<td>LA-ICP-MS U-Pb</td>
<td>Chao et al., 2011</td>
</tr>
<tr>
<td>Jiefeng, Heilongjiang</td>
<td>123°30′31″E, 50°24′16″N</td>
<td>647±1.64 Ma</td>
<td>Gabbro</td>
<td>LA-ICP-MS U-Pb</td>
<td>Feng et al., 2015</td>
</tr>
<tr>
<td>Gaxian, Heilongjiang</td>
<td>123°32′34″E, 50°37′47″N</td>
<td>628±10 Ma</td>
<td>Pyroxenite</td>
<td>LA-ICP-MS U-Pb</td>
<td>Feng et al., 2018</td>
</tr>
<tr>
<td>Huang’erku, Heilongjiang</td>
<td>124°00′05″E, 50°59′16″N</td>
<td>697±3 Ma</td>
<td>Gabbro</td>
<td>LA-ICP-MS U-Pb</td>
<td>Feng et al., 2018</td>
</tr>
<tr>
<td>Balutansai, Xinjiang</td>
<td>86°51′16″E, 43°06′58″N</td>
<td>630±5 Ma</td>
<td>Gneissic granite</td>
<td>LA-ICP-MS U-Pb</td>
<td>Chen et al., 2012</td>
</tr>
<tr>
<td>Korla, Xinjiang</td>
<td>None</td>
<td>628±6.6 Ma</td>
<td>Mafic dyke</td>
<td>SHRIMP U-Pb</td>
<td>Zhu et al., 2008</td>
</tr>
<tr>
<td>Korla, Xinjiang</td>
<td>None</td>
<td>634±6.6 Ma</td>
<td>Mafic dyke</td>
<td>SHRIMP U-Pb</td>
<td>Zhu et al., 2011</td>
</tr>
<tr>
<td>Korla, Xinjiang</td>
<td>None</td>
<td>642.8±6.9 Ma</td>
<td>Mafic dyke</td>
<td>SHRIMP U-Pb</td>
<td>Zhu et al., 2008</td>
</tr>
<tr>
<td>Korla, Xinjiang</td>
<td>None</td>
<td>652±7.4 Ma</td>
<td>Mafic dyke</td>
<td>SHRIMP U-Pb</td>
<td>Zhu et al., 2008</td>
</tr>
<tr>
<td>Zhoushan, Huabei</td>
<td>110°12′33″E, 32°52′30″N</td>
<td>679±3 Ma</td>
<td>Mafic dyke</td>
<td>LA-ICP-MS U-Pb</td>
<td>Ling et al., 2007</td>
</tr>
</tbody>
</table>
micro-continental Blocks, such as Qilian, Quanji, Arjin, and Qinglin, yielded a dominant peak between ca. 950 and 750 Ma (Gehrels et al., 2011; Zhang et al., 2012; Wang et al., 2013; Li et al., 2018). Combined with the Hf isotopes and regional geological data (Zhang et al., 2006), these micro-continental blocks have been suggested to have had close tectonic affinities to South China during the Neoproterozoic Era (Liu et al., 2008; Qin et al., 2018).

The arc-related Neoproterozoic magmatism in Beishan and Dunhuang (1014–845 Ma), Yili and Tarim Block (830–580 Ma), is possibly the result of a southward on-going subduction-accretion process (Liu Q et al., 2015). In particular, the dominant peak of 700–580 Ma in the age spectra of detrital zircons from Yili, is similar to the 660–630 Ma magmatic event in northern Tarim which is related to an early Pan-African retreating accretionary orogeny with back-arc extension (Ge et al., 2012, 2014; He et al., 2015; Zhu et al., 2019). Therefore, these micro-continental blocks and the Tarim Block may have similar crustal evolution histories and close paleogeographic relationships during the Neoproterozoic (Zhu et al., 2019). It is therefore reasonable to place these micro-continental blocks near the northwest margin of Tarim. Micro-continental blocks of northeastern China such as Erguna, Xing’an, and Jiamusi were originally assumed to be affiliated to Siberia or North China. However, the characteristic Mesoproterozoic to Neoproterozoic age peaks (~1.0–0.75 and 1.5–1.3 Ga) within detrital zircon ages for these blocks were similar to those of the Tarim Block (Wu et al., 2011; Guo et al., 2013; Zhao et al., 2016; Hao et al., 2017; Luan et al., 2017). Combined with the fact that the subduction may have existed in 690–620 Ma (Feng et al., 2016, 2018), these blocks could be placed on the northern side of the Tarim and Yili blocks (Fig.3).
3.3 Tectonic stratigraphic division of Cryogenian in China

In conclusion, combined with previous studies on the stratigraphic regionalization of the Cryogenian in China (Wang et al., 1985; Wang et al., 2005), and based on the distributions of the PTO and the PAO during the Cryogenian, as well as the paleogeographic distribution and tectonic background of different continental blocks and microcontinental blocks in China, this review divided the Cryogenian into three tectonic stratigraphic region: the Great South China tectonic stratigraphic super region (GSSR), the Xingmeng-Tarim tectonic stratigraphic region (XTSR), and the North China tectonic stratigraphic region (NCSR). Among these, the GSSR was located at the southern side of the Proto-Tethys Ocean and mainly formed in the rift-extension tectonic background under the influence of the breakup of Rodinia. Both the XTSR and NCSR were located at the north of the Proto-Tethys Ocean. Of these, the XTSR was seated between the Proto-Tethys and the Paleo-Asian oceans, where the tectonic background was complicated since subduction and extension coexisted in these areas. NCSR has been far from Rodinia and their continental margins on each side are passive (Figs. 2, 3).

4 Cryogenian Sedimentary Sequence and Lithostratigraphic Correlation in China

Cryogenian strata are widely distributed in China (Fig. 2). This chapter reviews both old and recent studies, with a specific focus on the stratigraphy of the Cryogenian/Neoproterozoic diamicite successions of the Yangtze Block, Tarim Block, North China Block, and a dozen micro-continents, such as Qilian, Quanji, and Dunhuang. Using detailed lithostratigraphic, geochronological, and chem stratigraphic data, correlations of the Cryogenian successions of China are discussed, in an attempt to supplement or update the comparison scheme of stratigraphy for the Cryogenian in China.

4.1 Great South China tectonic-stratigraphic region

4.1.1 Stratigraphic sequence and correlation of the Yangtze Block

(1) Stratigraphic sequence and glaciogenic diamictites in the southeastern marine of Yangtze

The Cryogenian successions show obvious differences from the center to the edge of the southeastern Yangtze basin (Fig. 4). It was well developed in the basin center at the border of Hunan, Guizhou, and Guanxi Province, where the Cryogenian succession reaches up to 4000 m, and is composed of the Chang’an Fm., Fulu Fm., Tiesi’ao Fm., Datangpo Fm., and Silikou Fm. (Sections 51 and 61 in Fig. 4). The Chang’an Fm. is composed of diamicite and thin interbeds of sandstone and silty mudstones with a thickness of ~2000 m. The diamicite consists of 5~15% clasts of sandstone, slate, chert, quartzite, which are randomly organized, sub-angular, or sub-rounded. The diameter of these clasts varies from 0.5~1.5 cm, with a maximum diameter of 15 cm. Fulu Fm. overlies the Chang’an Fm. which is marked by banded iron or iron-rich sedimentary rock at the bottom, and characterized by sandstone, siltstone, and slate without clasts. The Tiesi’ao Fm. and its equivalent strata (i.e., Dongshanfeng Fm., Gucheng Fm., and Xiayabu Fm. in Zhejiang or Anhui) is a distinct interval that consists of massive diamicite with a thickness ranging from 0~10 m (Peng et al., 2004; Lu et al., 2010; Zhang Q R et al., 2006). In the Jinping and Zhaliaogou areas, the diamicite of Tiesi’ao Fm. contains 1~2% clasts the average diameter of which ranges from 0.5~1 cm. The clasts predominantly consist of metasandstone. The shapes of the clasts are generally sub-angular to angular. Several clasts show striation marks and lacunules on the surface (Sections 49, 50, and 51 in Fig. 4). Datangpo Fm. and its equivalent strata (i.e., Xiangmeng Fm. in western Hunan, and Yang’an Fm. at the west of Zhejiang and the northeast of Jiangxi) are dominated by black shale and carbonaceous shale. Manganese deposits and cap carbonate are developed at the bottom in southeast Guizhou and southwest of Hunan (Yu et al., 2017). This formation has its largest thickness at Minle in Huayuan, and at the border of Hunan and Guizhou provinces (i.e., Songtao), where it reaches more than 200 m (Sections 50 and 51 in Fig. 4). In other areas, such as Sanjiang in northern Guangxi, Congjiang in southeastern Guizhou, Zhangjiajie, Changde, Yangjiangping in Shimen of northwestern Hunan, Changyang in Hubei, Jiande in western Zhejiang, and Zhuji–Fuyang in Zhejiang, the sedimentary thickness of these interglacial sediments generally ranges between 8 m and 200 m (Sections 47~50, 61, and 64 in Fig. 4). Nantuo Fm. and its equivalent strata (Silikou Fm. in northern Guangxi, Hongjiang Fm. in southwestern Hunan, Leigongwu Fm. in western Zhejiang, northeastern Jiangxi, and southern Anhui) are characterized by massive diamicite and laminated mudstone and siltstone with dropstones. The sediment of Nantuo Fm. is controlled by the paleogeographic background, and the thickness and lithology of these formations vary greatly across the basin. At the border of the Hunan, Guizhou, and Guangxi area, the thickness of this formation could reach 1000~2000 m, and decreases gradually in a west and north direction.

(2) Stratigraphic sequence and glaciogenic diamictites in the northern marine of Yangtze Block

The Neoproterozoic Yaolinghe volcanic-sedimentary sequences outcrop extensively in northern Hubei, western Henan, and southern Shanxi provinces (e.g., Zhu et al., 2008; Ling et al., 2008; Xia et al., 2012; Wang et al., 2013). It is unconformably overlain by the Sinian strata and intruded by voluminous mafic intrusions, which are mainly composed of meta-sedimentary and meta-volcanic rocks, with protoliths of basalt, mafic tuff, and volcaniclastic rocks (Bader et al., 2013). In the Gaomiao section, the diamicite at the bottom and the top of the Yaolinghe Group were previously assumed to be glaciogenic (Section 43 in Fig. 4; Wang et al., 1989; IGC-Hubei, 2018; Liu, 1991). The diamicite are massive, with a matrix of low maturity, and include clasts of acid volcanic rock, basic volcanic rock, sandstone, and granite, which have never been found in the Wudang area. The clasts are generally 1~3 cm with the largest being ~200 cm in diameter. Clasts with stepped fractures, glacial striations, and polished
Fig. 4. Representative stratigraphic sections of the Cryogenian succession in Yangtze. Formation numbers match those in Appendix 1 and Fig. 2.
surface have been observed. Dropstones of various lithologies occur in laminated tuffaceous siltstone (Wang et al., 1989). These diamictites are distributed across a limited area near Yunxi to Gucheng of Hubei province. The thickness of diamictite units in the Yaolinghe Group gradually decreases from west to east.

(3) Stratigraphic sequence and glaciogenic diamictites in the western marine of Yangtze Block

In western Yangtze, Cryogenian successions exposures are limited and incomplete. In western Sichuan, Ganluo–Xichang are limited area, the Cryogenian Lieguliu Fm., which unconformably overlies the Tonian Kajianqiao Fm./Suxiong Fm., consists of two different members. The lower member is characterized by massive diamictite, while the upper member is marked by purple mud shale (Jiang et al., 2016; Section 83 in Fig. 4). The Lieguliu diamictite consists of 20–50% clasts of rhyolitic volcanic rock. The diameter of these clasts varies from 0.5 to 30 cm, and the largest diameter reaches 100 cm. These clasts show striation marks, and rolling cracks on the surface. These clasts were interpreted as glaciolake by Liu et al. (1991) and Jiang et al. (2016). However, Wu et al. (1991) suggested that sediments may be deposited in a fault–depression rather than the glacial water flow.

In eastern Yunnan and Southern Sichuan, the Cryogenian Nantuo Fm. overlies the Tonian Chenguang Fm./Niutoushan Fm. and is dominated by massive diamictite and shale (Section 84 in Tabel 1; Zhou et al., 2019). This diamictite shows distinct glaciogenic features, such as striated clasts or dropstones. It contains 5–40% clasts with average diameters ranging from 0.5 to 60 cm. The diameters of the largest clasts reach up to 100 cm. These clasts are generally sub-angular and sub-rounded, and dominated by sandstone and siltstone. It is noteworthy that the cap dolostone, which occurs widely atop the Nantuo diamictite in the southern Yangtze area, is always absent in many areas of the western Yangtze area (eastern Yunnan and central Sichuan provinces). Instead, it is represented by discontinuous dolostone nodules (Zhou et al., 2019).

(4) Correlation and geostratigraphical constraints on the diamictites of Yangtze Block

Based on stratigraphic descriptions of these three areas, Cryogenian successions are relatively well-developed in the southeastern margin of the Yangtze Block. These consist of at least two episodes of glaciation and can be used as a framework for the stratigraphic correlation of the Cryogenian strata in the GSSR. The first episode of glaciation is characterized by Chang’an diamictite and Tiesi’ao/Gucheng diamictite. Both formations are more likely to deposit at different stages of the same ice age (i.e., Jiangkou glaciation; Zhang et al., 2006; Lan et al., 2014, 2015a, b; Zhou, 2016) since no definite cap carbonate and inter-glaciational sediments exist between them (Zhou et al., 2004, Zhou, 2016).

The complete sedimentary records of the Chang’an-Tiesi’ao formations occur in northern Guangxi, eastern Guizhou, and central-western Hunan. The strata were best developed in the Dongkou and Tongdiao areas of Hunan Province, with a thickness exceeding 4000 m. The total thickness of these strata in Sanjiang of Guangxi and southeastern Guizhou was 2000–3000 m (Section 61 in Fig. 4) and gradually thinned to the northwest. In Jishou and Shimen of Hunan province, there is only Tiesi’ao Fm. and its equivalent strata developed (Sections 49–51 in Fig. 4).

The non-glacioidal deposition Datangpo Fm. has the largest thickness at Minle in Huayuan, and at the border of Hunan and Guizhou provinces (i.e., Songtiao), where it reaches more than 200 m (Section 51 in Fig. 4). In other areas, such as Sanjiang in northern Guangxi, Congjiang in southeastern Guizhou, Zhangjiajie, Yangjia in Shimen of northwestern Hunan, Changyang in Hubei, Jiande in western Zhejiang, and Zhi–Fuyang in Zhejiang, the sedimentary thickness generally ranges between 8 m and 50 m (Sections 47–50, 61, and 64 in Fig. 4).

The second glaciation is characterized by Nantuo Fm., with a thickness up to 1000–2000 m at the border area of Hunan, Guizhou, and Guangxi and decreases gradually in west and north direction.

The onset of the Jiangkou glaciation and the terminations of both Jiangkou glaciation and Nantuo glaciation are tightly constrained by U-Pb and Re-Os geochronology in the southeastern Yangtze Basin. While the cyclothetographic data suggest that the Nantuo (Marinoan) glaciation in South China initiated at ~650 Ma (Bao et al., 2018). The time limit of the Jiangkou glaciation is ~717–663 Ma and that of the the Nantuo glacial period is ~650–635 Ma (Fig. 4; Table 1).

Compared with that of the southeastern marine of Yangtze, U-Pb age of 768 ± 7 Ma, 731±11 Ma and 685±5 Ma were obtained from the Yaolinghe volcanic rocks in northern Yangtze Block(Ling et al., 2007; Zh et al., 2014), indicating that the Yaolinghe Fm. could contains Cryogenian sediments. In Gaomiao section, 645.1 ± 9 Ma and 636.1 ± 5.9Ma for acidic volcanic rocks in the upper and lower part of the section, respectively (IGC-Hubei, 2018), shows that diamictites of Yaolinghe Group is most likely the deposition of the Nuotuo glaciation. However, whether there is Jiangzou / Sturtian diamictite remains to be explored.

In western Yangtze, the diamictites out crop in the Ganluo area are usually considered as the deposits of Nantuo glaciation (Wu et al., 1991). However, the U-Pb zircon age obtained from tuffaceousdiamictite at the bottom of the Lieguliu Fm. is 715 ± 9.8 Ma and 718.8 ± 9.4 Ma (Jiang et al., 2017). Hence, the Liegulidi anomalous are most likely deposited in Jiangkou glaciation. In the Eshan area of Yunnan Province, a remarkable U-Pb ages 634.57 ± 0.88 Ma within the top of diamictite, indicated that it could be deposited in Nantuo glaciation (Zhou et al., 2019).

4.1.2 Stratigraphic sequence and correlation of Cathaysia Block

No typical glacial diamictite has been reported for the Cathaysia Block. Newly chronostratigraphic data show that Louziba and Xiafeng formations outcrop in Fujian and Jiangxi provinces might belong to Cryogenian. The Louziba Fm. is over 6317 m thick and mainly consists of thick sandstone, mudstone, and siliceous rocks in the
Changting area (Section 79 in Table 1). To southeast Shanghang, Tongkang and Zaiouk areas, the main lithology of Louziba Fm. is clastic rocks and its total thickness is over 2423 m. The two youngest detrital zircon ages of 655 ± 6 Ma and 646 ± 10 Ma from the basal Louziba Fm. in Wuyi area (Qi et al., 2018; Wang et al., 2018) and Ediacaran microfossils from its overlying strata (Zhang et al., 2005) constrain the deposition time of Louziba Fm. between 650 Ma and 630 Ma. Its sedimentological characteristics and CIA values indicate a cold event within the formation, suggesting that Louziba Fm. could be correlated with Nantuou Fm. in Yangtze Block (Qi et al., 2018).

In southeastern Jiangxi Province, the Xiafang Fm. can be divided into three lithologic members. The lower Gujia conglomerate member is mainly composed of tuffaceous conglomerate and conglomerate-bearing tuffaceous slate, with a thickness reaching 1039 m in Pingxiang, which decreases significantly to 22 m to the east of Jiliulongshan in Xinyu. The middle member is characterized by Xinyu-type iron-bearing rocks (BIF), which occasionally contains manganese and is rich in volcanic matter. It outcrops in the areas of Pingxiang, Xinyu, Xiajiang areas with a thickness of 400–700 m. The upper Dashajiang conglomerate member of Xiafang Fm. is dominated by conglomerate-bearing tuffaceous slate with carbonate phyllite, with the thickness of 20–2000 m (IGC-Jiangxi, 2017).

Conglomerate-bearing tuffaceous slate of Xiafang Fm. contains 1–5% clasts with average diameters ranging from 0.5 to 20 cm. The clasts are generally sub-rounded. However, there are no distinct glaciogenic features in these members. In the middle member, the BIFs from the Xinyu area lack Ce negative anomalies and show heavy Fe isotope enrichment, which may be the result of the Neoproterozoic ‘Snowball Earth’ condition when the ice cover began to melt early and the ocean and atmosphere did not fully exchange the material (Li et al., 2014). This characteristic BIF is also widely developed in Fulu Fm. in the Yangtze Block. Hence, three members of Xiafang Fm. could more likely be compared with Changang–Fulu–Nantuou formations of the Yangtze Block. This correlation was also confirmed by the age of detrital zircons from the upper Xiafang Fm. (640 ± 12 Ma) (Qi et al., 2018).

4.1.3 Stratigraphic sequence and correlation of Qilian Block

In the northern Qilian area, the Baiyanggou Fm., outcrops at Erdaogoukou and Baiyanggoukou in Gansu Province. At the Baiyanggoukou section in Subei of Gansu Province, Baiyanggou Fm. is unconformably overlies the Tonian Daliguou Group (Section 27 in Figs. 5, 6d). The lower part of Baiyanggou Fm. consists of phyllite–slate grade sandstone, siltstone, and diamictite. At Baiyanggou in Subei, Gansu Province, the thickness of Baiyanggou Fm. is more than exceed 240 m. At least four individual diamictite units can be recognized. These units are intercalated with, laminated silty marine mudstones and carbonates (Fig. 6c, f). The lower diamictite unit (I) of Baiyanggou Fm. is dominated by massive diamictite with 30–70% sub-angular or sub-rounded clasts of dolostone, which originates from the Daliguou Group. Clasts are dominated by pebbles of 2–15 cm in diameter, with a maximum diameter of 40 cm (Fig. 6b). Influenced by metamorphism and tectonics, the muddy matrix was subject to phyllitization, and the gravel was elongated and oriented. It may be the basal conglomerate, and no clear evidence has been found to confirm the glaciogenic nature of the lower diamictite unit was glaciogenic. The other three individual diamictite units can be recognized within the upper diamictite interval of Baiyanggou Fm. These diamictites showing glaciogenic features, striated clasts, and dropstones throughout (Fig. 6g). Clasts in the diamictites are dominated by carbonate, slate, and marble, and silticlastic clasts are more abundant in comparison to the lower diamictite interval.

Noradiometric ages have been published for Baiyanggou Fm. Previously, a number of microfossils from the Baiyanggou Fm. have been reported (Section 27 in Fig. 5); however, these fossils are dubious and have limited biostratigraphic significance. In this paper, according to the stratigraphic features, a previous research result was adopted, suggesting that the Baiyanggou Fm. may roughly be equivalent to the Nantuou Fm. of the Yangtze Block (IGC-Gansu, 2017, Section 27 in Fig. 5). Moreover, the Bianmagou Fm., outcropped in Yaodonggou and Bianmagou of Central Qilian, also contains several diamictite units, which were identified as glacial deposits (IGC-Gansu, 2017). In addition, sedimentary iron ore layers were identified between two diamictite units, indicating that Baiyanggou Fm. could be compared with the Cryogenian successions of the Yangtze Block (Section 26 in Fig. 5).

4.1.4 Stratigraphic sequence and correlation of the Quanji Block

The Neoproterozoic sedimentary succession in the Quanji area is represented by the Quanji Group, which is well preserved in the Ulongbrook, Shihuiou, and Quanjishan of the northern margin of the Qaidam Basin in Qinghai Province. It consists of seven lithologic units, including Mahuanggou, Kubaimu, Shiyinglejiang, Hongzaoshan, Heitupo, Hongtiegou, and Zhoukou formations in ascending order, with a total thickness of 1489 m (Section 31 in Fig. 5). Among these, the Mahuanggou and Kubomu formations are dominated by conglomerate/diamictite and quartzarenite. The Shiyinglejiang Fm. disconformably overlies the Kubaimu Formation, and has a thickness of ~200 m in the Quanjishan area. The Shiyinglejiang Fm. mainly consists of basaltic and andesitic volcanics, quartzite, and siltstone. The bottom of Shiyinglejiang Fm. consists of ferruginous quartzite sandstone. The iron-bearing mineral is oolitic or pisolithic hematite. Hematite lens developed locally. The maximum thickness is 0.7 m, which can extend to more than 10 m (BGMR-Qinghai, 1997).

The diamictite in Kubomu Fm. might be glaciogenic with features such as a variety of lithic compositions, angular and irregular shapes of the clasts, and sand dropstones with scratch marks; this explanation is supported by the characteristic CIA value, which represents a cold environment (Sun et al., 2014, 2016 a, b). The age of 738 ± 28 Ma (single zircon U-Pb) obtained
Fig. 5. Representative stratigraphic sections of the Cryogenian succession in Xing’an–Inner Mongolia, North China, Qinling–Qilian–Kunlun area. Formation numbers match those in Table 1 and Fig. 2.
from the basic rock and the presence of sedimentary iron ore of Shiyingliang Fm. (Lu, 2002; Li et al., 2003a), indicated that Mahuanggou and Kubomu formations may have been deposited during Cryogenian Jiangkou glaciation. However, Shen et al. (2010) and Sun et al. (2019) confirmed that the diamictite’s glaciogenic provenance remains uncertain, and would be deposited in a high energy foreshore or nearshore setting. Therefore, it remains to be proved whether the Quanji Group contains Cryogenian strata.

4.2 Xingmeng–Tarim tectonic–stratigraphic region

4.2.1 Stratigraphic sequence and correlation of Cryogenian in the Tarim Block

(1) Kuruktag area

The Cryogenian successions are well developed in the Kuruktag area. They unconformably overlie the Tonian Paergangtag Group and are composed of five formations: the Beiyixi Fm., the Zhaobishan Fm., the Altungal Fm., the Huangyanggou Fm., and the Tereeken Fm. (Sections 17–20 in Fig. 7).

The Bayisi Fm. is 640–1670 m thick and predominantly consists of siliciclastic and volcanic rocks with several intervals of diamictite. The Beiyixi diamictite was interpreted as glacimarine in origin by clasts with different shapes, scratch marks, and unidirectional striations (Gao and Zhu, 1984). However, unequivocal evidence for a glacial origin, such as glacial striations on boulders, is missing. In addition, no typical cap carbonates outcrop from the overlying strata. The Zhaobishan Fm., with a thickness of 358–570 m, is comprised of sandstones and calcareous siltstones. The Altungal Fm. is characterized by several massive diamictite intervals associated with sandstones, siltstones, and shales. The thickness of the formation decreases from east to west. Clasts of Altungol diamictite have an angular shape and are dominated by granite, cherts, and quartz. The average diameter of these clasts varies from 0.2–1 cm, while the diameter of the largest clasts could reach up to 15 cm (Zhu and Wang, 2011). Several clasts show striation marks and rolling cracks on their surfaces (Kou et al., 2008). The Huangyanggou Fm. represents interglacial deposits between the diamictites of the Altungol Fm. and the Tereeken Fm. (Cao, 1991; Kou et al. 2008). The base of the Huangyanggou Fm. is marked by ~2 m grey-purplish micritic dolostone, which represents a cap carbonate above the Altungol diamictite (Xiao et al., 2004). The upper part of the Huangyanggou Fm. is mainly composed of fine clastic rocks. The Tereeken Fm. is characterized by massive grey diamictites with thicknesses ranging from 689 m to 1845 m. The diamictite is separated into several units by thin interbeds of finely laminated silty mudstones and carbonates. The diamictite in the Tereeken Fm. shows clear glaciogenic features since dropstones and striated clasts are distributed throughout (Xiao et al., 2014). The diamictite contains 20–70% clasts with average diameters ranging from 2–5 cm, while the largest clasts could reach up to 40 cm in diameter. Clasts in the diamictite consist of carbonate, granite, and other igneous rocks; marble and siliciclastic clasts are more abundant in comparison to Beiyixi and Altungol diamictites (Zhu and Wang, 2011).
Fig. 7. Representative stratigraphic sections of the Cryogenian successions in the Tarim block and Yili micro-continental block. Formation numbers match those in Table 1 and Fig. 2.
(2) Aksu area
In the Aksu area, Cryogenian successions are composed of five formations with a total thickness exceeding 3000 m: the Xifangshan, Dongjiaoebrak, Muyangtan, Dongwu, and Youerreinark formations. The Xifangshan Fm. has a thickness of ~1700 m and is characterized by feldspathic quartz sandstone, feldspathic sandstone, and siltstone. The Dongjiaoebrak Fm. mainly consists of a conglomerate with interbeds of sandstone and massive diamictite. The diamictite is matrix-supported with 20–80% clasts of various lithologic compositions such as felsite, dacite, granite, and sandstone. Clasts are dominated by ca. 10-cm-sized pebbles with a maximum diameter of 60 cm. Clasts are randomly organized and sub-rounded and striated marks have been observed on the surface. Thus, the Dongjiaoebrak diamictite is usually interpreted as a glacial origin (Section 14 in Fig. 7; Zhu and Wang, 2011). However, rapid deposits of submarine debris flows may result in similar diamictites (Gao et al., 1993), leading to uncertainties about the cause of diamictite. The Muyangtan Fm. is 107 m thick and is composed of calcareous siltstone and quartz sandstone with parallel and cross-stratification. The overlying Dongwu Fm. is mainly comprised of feldspathic sandstone. A 1–2-m-thick conglomerate bed was found at the base of the Dongwu Fm., which is dominated by sub-rounded or rounded cobbles and was considered as glaciogenic by Quan et al. (2017). The Yulmeinak Fm. is mainly composed of purplish massive diamictite with a maximum thickness of 70 m. Poorly sorted and sub-angular to angular shaped clasts (20–30%) appears in the silty and muddy matrix. Clasts mostly include volcanic rocks, blueschists, granites, and sandstone, derived from the underlying strata. Clast sizes are predominantly 6–40 cm in diameter. Striated clasts and dropstones are well preserved throughout the Yulmeinak Fm., and a large abraded surface at its base, with scouring and striations, indicates its glaciogenic origin (Zhu and Wang, 2011).

(3) Tiekelike area
In the Tiekelike area, the Cryogenian strata consist of the Yalaguzi, Bolong, Kelixi, and Yutang formations, with a total thickness of ~3000 m. Two diamictite intervals (i.e., the Bolong and Yutang Fms.) have been interpreted as glaciogenic (Section 21 in Fig. 7).

The Yalaguzi Fm. consists of conglomerate, feldspathic sandstone, and silty mudstone. The Bolong Fm. is dominated by purplish-brown massive diamictite with a thickness of ~900 m. Clasts of diamictite are randomly organized, with angular to sub-angular shapes, and are composed by porphyry, chert, quartzite, dolostone, and granite. Their diameter varies between 2 cm to 10 cm with a maximum diameter of 100 cm. Glaciogenic features include striated marks and notches on the surface of cobbles, and parallel cracks of clasts. Laminated mudstone and siltstone with dropstones can be observed in the middle and top of the Bolong Fm. The Kelixi Fm. consists of laminated mudstone and siltstone, purple quartz sandstone, and purple interbeds of feldspathic sandstone and conglomerate. The Yutang Fm. consists of mudstone, conglomerate, and diamictite with a thickness of 30–200 m.

(4) Correlation and geochronological constraints on the diamictites of the Tarim block
The relatively well-developed Cryogenian successions in Kurukutag can provide a basis for the stratigraphic correlation of the Cryogenian in the Tarim Block. Two unambiguous episodes of Cryogenian glaciation (i.e., Altungol and Tereeken glaciations) have been recorded in this area (Xiao et al., 2004; Zhu and Wang, 2011; Gao et al., 2013). The onset and terminations of both glaciations were roughly constrained to ~725–654 Ma and ~654–616 Ma by geostratigraphic data (Xu et al., 2009; He et al., 2014a). However, it remains unclear whether the Beiixi diamictite belongs to the Cryogenian. Two U-Pb ages of 740 ± 7 Ma and 725 ± 10 Ma have been obtained from the lower part and the upper part of the Biexibastao Fm., respectively (Xu et al., 2009). However, the 740 ± 7 Ma U-Pb age might be inherited from underlying volcanic rocks of ~750 Ma (Rooney et al., 2015). In addition, considering that the Beiixi diamictite more closely resembles Altungol diamictite in clast composition, degree of metamorphism, and thickness of individual diamictite beds, it would be more likely that the Altungol and Beiixi diamictites represent two pulses of glacializations of a single ice age if the diamictite in Beiixi Fm. were found to be glaciogenic (Xiao et al., 2004). Compared with the Kurukutag area, the Cryogenian and Ediacaran successions of the Tieliid area are more similar to those of the Aksu area. However, both diamictite intervals of these two areas lack chronological constraints. Based on the chemostratigraphy of the overlying Ediacaran Sugetblaq and Qigeblaq formations, Zhu and Wang (2011) suggested a correlation of the Dongjiaoeblaq and Yulmeinak glaciations with Altungol and Tereeken glaciations, respectively.

4.2.2 Stratigraphic sequence and correlation of Cryogenian in the Yili-central Tianshan Block
The middle-late Neoproterozoic strata in the Guozigou-Keguqinshen area of Yili have been subdivided into six formations. From bottom to top, these are the Kulutieliket Fm., the Tulasu Fm., the Biexibastao Fm., the Keyindi and Targat formations, and the Talisayi Fm. (Sections 11 and 12 in Fig. 6; Zhu and Wang, 2011; Gao et al., 2013). Among these, the Kulutielik Fm., the Biexibastao Fm., and the Talisayi Fm. consist of diamictite, and a reliable SHRIMP U-Pb age of 642 ± 6 Ma has been identified for the bottom of the Taersayi Fm. (Gao et al., 2011). This indicates that the diamictites of the Kulutielik-Tulasu-Biexibastao formations could be time-equivalent with the Beiixi-Jhaobishan–Altungal formations in the Kurukutag area. However, He et al (2015) believed that Talisayidiamictite should compared with Hankalchoudiamicidite which shows the existence of an Ediacaran glaciation, based on the youngest concordant detrital zircons in the Talisayi yield weighted mean ages of 592 ± 5 Ma. In addition, the underlying Biexibasitao and Kulutieliketidiamictites may be correlated with the Marinoan and Sturtian glaciations respectively, indicating the Biexibasitao–Tereeken and Kulutieliketi–Bayisi connection between Yili and Tarim (Zhu and Wang, 2011; He et al., 2015).
4.2.3 Stratigraphic sequence and correlation of Cryogenian in the Dunhuang Block

At the Dunhuang-Beishan area, the exposed Cryogenian succession is of the Xichangjing Group, which unconformably overlies the dolostone of the Tonian Dahuoluoshan Group. The total thickness of the Xichangjing Group is ~200–700 m and gradually decreases from the west to the east. It could be divided into a lower member and the upper member. The lower member is mainly composed of carbonaceous shale, siltstone, and diamictite (Section 23 in Figs. 5, 8a). Three diamictite units can be recognized from the lower member, of which the clasts are sub-angular to sub-rounded in shape and range from fine gravel to cobbles (2–45 cm) (Fig. 8b, g). Clast are predominantly carbonatite and the matrix is mainly composed of micrite dolomite. Striated clasts and dropstones, preserved throughout the diamictite, indicate a glacial origin (Fig. 8c, d). Three individual diamictite units are separated by two interglacial deposits. The lower interglacial sediment is mainly composed of carbonaceous slate with thin interbeds of limestone, while the upper interglacial sediment consists of black carbonaceous slates with manganese (Fig. 8e, f). The upper member is a set of dolomitic limestone with calcareous siltstone. It contains microfossils that are common for the Ediacaran such as Micrhystridium (IGC-Gansu, 2017), suggesting that the lower member of the Xichangjing Group may have deposited in the Cryogenian Period. The characteristic sedimentary manganese ore and dark shale deposits can be well compared with the Datangpo Fm. of the Yangtze Block and the Huangyanggou Fm. of the Tarim Block.

4.2.4 Stratigraphic sequence and correlation of Cryogenian in Alxa Block

The Cryogenian Shaohuotonggou Fm., sporadically outcropped in Shandan County of Gansu province, which is the border area of the Alxa Right Banner of the Inner Mongolia, and Minqin in Qinghai Province, is characterized by multi-layered diamictites, siltstones, and carbonaceous phyllite (Section 28, 29 in Table 1). It is best exposed in the Alxa Right Banner with a thickness of ~841 m and contains three units of massive diamictite. From west to east, the strata thickness follows gradually.
thinning trend and diamicite units gradually disappear. The exact deposition age and stratigraphic correlation of the Shaohuotonggou Formation are not clear to date (Xie et al., 2013; IGC-Gansu, 2017). Microfossils of Laminarites santiquissimus, Leioufus bicornuta and Synsphaeridium conglutinatum have been collected from the Shaohuotonggou Fm. (IGC-Gansu, 2017); however, their stratigraphic significance remains ambiguous. This review temporarily tends to put the Shaohuotonggou Fm. in the Cryogenian Period in terms of a Rb-Sr isochron age of 593 ± 39 Ma that was obtained from the bottom of the overlying Caodaban Formation (IGC-Gansu, 2017).

4.2.5 Stratigraphic sequence and correlation of the Cryogenian in the Xingmeng-Altaiv Block

The Jiageda Formation, which conformably underlies the overlying Ediacaran Ergunahe Group, is well exposed in northern Heilongjiang and northeastern Inner Mongolia (Guo et al., 2005). It consists of a sequence of volcano-sedimentary rocks and is dominated by mica-quartz schist and biotite schist with minor amounts of metamorphosed sandstone and volcanic rocks. On the holostratotype of the Jiageda Formation in Inner Mongolia, the thickness of this formation exceeds 2000–4000 m (Section 4 in Fig. 8). Strata thickness gradually decreases from northwest to southeast.

Based on evidence of single-grain zircon U-Pb dating (~723 ± 42 Ma) obtained from a meta-andesite interlayer, the youngest detrital zircon age was 757 ± 10 Ma from a metamorphosed sandstone, and the U-Pb age of 654 ± 46 Ma was obtained from the intruded megaporphyritic biotite granite (Guo et al., 2005; Zhao et al., 2016). It is therefore reasonable to assume that the Jiageda Fm. was most likely deposited between 757 Ma and 654 Ma, and thus belongs to the Cryogenian.

4.3 North China tectonic-stratigraphic region

Whether the Cryogenian successions outcropped on the North China Block remains inconclusive (Zhang et al., 2016b). In the Tieling area, the Yintun Fm. could be divided into three parts: The lower member is characteristic by massive diamicite with interbedded sandstone, the middle part consists of purple sandstones, and the upper part is dominated by purple slates (Section 34 in Fig. 5; Zhang et al., 2016b). The diamicite of Yintun Fm. is considered to be glaciogenic (Lu et al., 2015; Ao et al., 2016). The clasts are rounded to sub-rounded in shape, and have diameters from 2–20 cm, mainly consisting of quartz sandstone, and showing glacial features, such as cracks and glacial scratching. These diamicites have been thought to be redeposited sedimentary products of the Huronian glaciation (Zhang et al., 2016b). However, the Yintun Fm. unconformably overlies the Mesoproterozoic Wumishan Fm. in this region, and the detrital zircon age indicates that the forming ages of these diamicites are less than 1000 Ma (Lu et al., 2015). Therefore, the Yintun Fm. are temporarily classified as Cryogenian in this review. In addition, the Qiaotou Fm. in southern Liaoning province mainly consists of quartz sandstone, siltstone, and silty mudstone, with a total thickness of about 560 m. Dropstones were found in silty mudstone by predecessors, which shows possible glaciogenic features (Tian et al., 2018). It was temporarily classified as Cryogenian in The Stratigraphic Chart of China (Zhang et al., 2014). However, a diabase sill emplaced in the Qiaotou Fm. has a zircon secondary mass spectrometry U-Pb age of 947.8 ± 7.4 Ma (Zhao et al., 2019), which indicates that the depositional age of Qiaotou Fm. should exceed 948 Ma.

4.4 Stratigraphic sequence and correlation of Cryogenian in China

During the Cryogenian, two main glacial events were recorded on the Yangtze Block. These events are regionally known as the Jiangkou and Nantuo glaciations. With the degradation of Jiangkou glaciations, the Dongtangpano-glaciatical deposition sediment consist of black silty shale, and carbon shale with Mn-bearing shale. The base of Dongtangpo Fm. is composed of dark, organic-rich, roll-up structures with developed and finely laminated carbonates, and the carbon isotopic profiles of this cap carbonate record a positive δ13C excursion (Yu et al., 2017). All these features are reminiscent of Sturtian cap carbonate (e.g. the Tindelpina Fm. of south Australia; Rasthof Fm. of Namibia; Hoffman and Schrag, 2002; Fig. 9). The Datangpo Fm. is overlain by the glaciogenic Nantuo Fm. and subsequent Doushantuo Formation. The carbonate at the basal part of the Doushantuo Fm. shows classical Marinoan cap carbonate feathers, including pseudo-tepee structures, sheetcrack cements, bladed barite cements and typical δ13C values (e.g., Jiang et al. 2007, 2011; Kuang et al., 2019a, 2019b). The distinct association of glaciogenic diamicites and cap carbonates provides strong evidence for correlation of the Jiangkou and Nantuo glaciations to the globally known Sturtian and Marinoan glaciations (e.g. the Nuccaleena Fm. of south Australia; Keilberg Fm. of Namibia; Hoffman and Schrag, 2002; Xiao et al., 2016; Fig. 9). U-Pb and Re-Os geochronology tightly constrained the timing of Jiangkou and Nantuo glaciations in ~720–635 Ma, respectively, which are highly synchronous with the global Sturtian and Marinoan glaciations (Hoffmann et al., 2004; Calver et al., 2013; Prave et al., 2016).

Identical to the Yangtze Block, at least two glaciogenic diamicites interval with cap carbonates have been reported in the Cryogenian of the Kunlunqtagh area (Kou et al., 2008; Gao et al., 2013). Above the Altungaldiamictite, the base of Huanyanggou Fm. cap carbonate is mainly composed of dark-purple dolomite with a typical negative δ13C value feature (~2‰ PDB, Kou et al., 2008), and highly positive δ13C values (~10‰ PDB, Xiao et al., 2004) occurred in carbonates in the middle Huanyanggou Fm.. The Huanyanggou Fm. is overlain by the glaciogenic Tereeken Fm. and a 2–10 m carbonate unit above the diamicite of Tereeken Fm. has been described as the cap carbonate by Xiao et al. (2004), viaethe evidence of characteristic C-isotope variation. All these chemostratigraphic and sedimentary features are suggestive of acorrelation of Altungal and Tereeken glaciation with Jiangkou-Sturtian and Nantuo-Marinoan glaciation. In addition, the time limit of those two glaciation is ~725–654 Ma and 654–616 Ma in the Tarim
Block (Xu et al., 2009; He et al., 2014a), which is roughly identical to the Yangtze Block (Fig. 9).

The Cryogenian sedimentary sequence and glacial events of the Yangtze and Tarim show great similarities; however, differences still exist with regard to volcanic and metallogenic events. These divergences may be due to differences in the tectonic environment between both blocks. Since the Cryogenian (after 720 Ma) subduction may still exist in the northern margin of the Tarim block, the Yangtze Block was mainly controlled by the rift system. For instance, the volcanic layers have a wide distribution and a longer duration in the Tarim Block. Neutral-basic volcanic rocks emerged in Beiyixi Fm. (~725 Ma), Huangyanggou Fm. (~654 Ma), and Zhamoketi Fm. (~615 Ma) (Xu et al., 2009; He et al., 2014a, b, Fig. 9). However, in the Yangtze block, few reports identified volcanic activities after 720 Ma. Moreover, the ~660–630 Ma quartz syenite and syenogranite formed during continuous back-arc rifting were recorded in the northern Tarim Block (Ge et al., 2012, 2014; Zhu and Wang, 2011, Fig. 9). This magmatic event has never been reported for the Yangtze Block. In the XTSR, the neutral-basic volcanic layers developed in the Cryogenian successions of Kulutieliekti Fm. of Yili Block and Xichangjing Gp. in the Dunhuang Block, could be compared with the volcanic event layer of Tarim Block.

However, the characteristic sedimentary iron deposits of Cryogenian strata in the Yangtze block were rarely found in the Tarim block. In the Yangtze Block, the BIF is well documented at the bottom of Fulu Fm. This Neoproterozoic iron formation (IF) is widespread in many other continents, such as in Rapitan (North America) and Adelaide (Australia) (Fig. 9; e.g., Bekker et al., 2010; Lottermoser and Ashley, 2000). A genetic relationship between the snowball Earth condition and the reappearance of the Rapitan-type IF in the Cryogenian has been proposed (Kirschvink, 1992; Hoffman et al., 1998). This indicates IFs as good markers for regional stratigraphic correlation. These Neoproterozoic IFs are also documented in successions of micro-continental blocks in the GSSR, such as Xiafang Fm. in Cathaysia, Mahuanggou Fm. in Qilian, and Shiyinliang Fm. in Quanji. Consequently, these formations were compared to Cryogenian successions of the Yangtze Block.

In conclusion, a new comparison scheme of stratigraphy of the Cryogenian in China has been proposed in this review (Fig. 10). Thereinto, the “Ocean Plate Stratigraphy”, which is distributed near the mid-ocean ridge or volcanic islands, etc. (Zhang et al., 2016b, 2020), such as the Xinlin–Xiguitumelange with an age of 690–630 Ma in Northeast China, was classified into Cryogenian only under a chronostratigraphy framework.
Fig. 10. Stratigraphic correlation of Cryogenian in China.
5 Lithofacies Paleogeography of Cryogenian in China

The middle-late Neoproterozoic represents the peak period of the breakup of Rodinia. The primary frame of basins was mainly shaped by the rift during ~850–680 Ma in the Great South China region as well as the back-arc extension/rift at ~773–540 Ma in the Xingmeng-Tarim region (Ge et al., 2012; 2014; Xia et al., 2012; Mabi et al., 2018). Subsequent Cryogenian basins were largely inherited and developed from basins that formed during the Early Neoproterozoic. In this paper, major sedimentary basins of the Cryogenian from three tectonic-stratigraphic regions in China are classified and summarized. The lithofacies and paleogeography of those basins are also depicted in this paper (Figs. 2, 11, 12).

5.1 Lithofacies paleogeography of Great South China tectonic-stratigraphic region

During the Cryogenian, basins in the Yangtze area were controlled by the rift system. Three major rift basins developed in the northern, western, and southeastern margins (Fig. 2). The rift basin in the northern margin of the Yangtze (NYRB) started at ~746 Ma and continued throughout the entire Cryogenian (Ling et al., 2008; Wang et al., 2013; Zhu et al., 2014).

The Cryogenian basin in NYRB is dominated by basic volcanic-sedimentary rocks of the Yanglingle Formation and the Hong’an Group but show local variations (Mao et al., 2016; Zhao et al., 2017). Clastic rocks of shallow-marine facies with glacial deposits are abundant in the west, while calcium, silicon, and argillaceous sedimentary assemblages of bathyal facies and abyssal facies are well developed in the east, where the rift was more intensive (Fig. 11).

The rift basin in the western margin of the Yangtze (estern Sichuan and eastern Yunnan (Sections 83 and 84 in Fig. 4) WYRB) is characterized by the rift volcanic-clastic rock sedimentary sequence in the Suxiong–Kaijianqiao Formation between ~800 Ma and ~715 Ma (Li et al., 2002; Jiang et al., 2016). Here, sediment is generally absent due to the western part intensely uplifted because of the Chengjiang Movement. Until the late Cryogenian period, continental glacial debris flow facies (CGD) and glacial lake (GLa) sediment was preserved in western Sichuan and eastern Yunnan (Fig. 11).

The rift basin in the southeastern margin of the Yangtze (SYRB) developed between 830 and 740 Ma (Liu et al., 1995; Jian et al., 2003; Zhou et al., 2007). In the early Cryogenian, when the Jiangkou glaciation began, the basin was filled with glacial marine gravity flow facies (GGF) (Wang et al., 2003). Then, with the warming climate, the rift basin of the SYRB underwent at least two glacial retreat processes and sea water intruded into the coastal shallow plain area. The stratigraphic records of shelf facies (Sh) and lagoon facies (Lf), with manganese and abundant organic matter, formed during glacier retreat, leading to hydrocarbon accumulation and the occurrence of valuable ore-bearing strata (Sections 49–51 in Fig. 5). As controlled and influenced by syngenetic structural faults near the continental margin, the lithofacies and thicknesses of these interglacial sedimentary successions varied greatly, following a thinning trend from the west to the east. During the late Cryogenian, the Nantuo glaciation represents several glacier advances and a widespread glacial diamictite unit in the South China Block (Lang et al., 2018). Tillites were transported far from their origin and were deposited in the marine facies in Hunan, Guizhou, and the Guangxi area. To the north of the Xidong and Miaohao areas, the sedimentary facies changed to CGD (Cross-sections A–A’ and B–B’ in Fig. 12).

The micro-continental blocks, which are closely related to the South China Block, have similar developing and filling stages of the Neoproterozoic rift (Xia et al., 2012, 2016). For instance, Yingfeng basic dyke swarms formed at ~820 Ma in the rift environment in the northern margin of Quanjian Block (Lu et al., 2008). Basic volcanic rocks of the Xinglongshan Group (824–713 Ma) developed in the southern margin of the Gaolalan Block. Continental flood basalt (738 Ma) of the Zhulongguan Group in the Central Qilian Block (Mao et al., 1997) are closely relevant to the breakup of Rodinia (Xu et al., 2008). During the Cryogenian, glacial shelf facies, continental glacial debris flow facies, and nearshore-foreshore facies deposited in relevant rift basins of these areas (see cross-section C–C’ in Fig. 11).

5.2 Lithofacies paleogeography of Xingmeng-Tarim tectonic-stratigraphic region

The Tarim Block collaged quite late in the process of the Rodinia convergence and split away early during the late Neoproterozoic. Under the influence of both the Paleo Asian ocean subduction and the Rodinian breakup, the Tarim Block displays many records of glaciation and volcanic events (Zhou et al., 2012, 2015). Varied types of basins developed in the Tarim Block, including the Tielikeli rift basin (TRB), the Aksu back-arc extensional basin (ABB), and the Kurukutag back-arc extensional basin (KBB) (Fig. 2). Of these, the TRB developed first during the Neoproterozoic. Basic dyke swarms and bimodal magmatic rocks formed at 802–783 Ma and may represent the lower limit of the opening of the Tielikeli rift at the southern margin of Tarim (Wang et al., 2004; Zhang et al., 2004, 2006, 2009; Tong et al., 2013). The TRB is filled with piedmont alluvial fan facies deposits in the early Neoproterozoic and glacial shelf facies and interglacial nearshore-shelf facies deposits in the Cryogenian, which underwent a basin evolution from land to sea as a whole (see cross-section D–D’ in Fig. 12). The ABB shows similar sedimentary sequences and lithofacies variations than TRB; however, it developed later than TRB, after 759 Ma (Zhang et al., 2009).

Northeast of the Tarim Block, the age of volcanic rocks at the bottom of the Beiixia Formation in Kurukutag area is 740–725 Ma (Xu et al., 2009), representing the start of the KBB, which is about 20–40 Ma later than those of the southern part of Tarim. Additionally, it is worth noting that the age of the volcanic rocks in the middle Altungal Formation in the Kurukutag area of the northeastern Tarim Block is ~650 Ma (He et al., 2014a). This suggests that the back-arc extension in the northern margin of the Tarim lasted to the middle and late Cryogenian. During the early Cryogenian period, a set of marine volcanic facies and
glacial facies associations, represented by the Beiyixi–Altungal formations, were rapidly deposited in the central part of those basins. During the following stage, with the rapid intrusion of seawater and sediment accumulation, fine clastic rock deposits of shelf-nearshore facies formed between the extension centers and land. At the late Cryogenian, with the onset of Tereeken gelation, widespread glacial diamictite successions of glacial shelf facies are developed in the KBB (see cross-section E–E’ in Fig. 12).

In the Neoproterozoic, because of the Paleo-Asian Ocean subduction on the outer side of the Rodinia supercontinent, the north margin of the XMT was in a compressive environment. The sustained subduction and compression resulted in the intra-oceanic subduction in the Xinlin-Xiguitu Ocean between the Erguna Block and the Xing’an Block at ~690–620 Ma (Feng et al., 2016, 2018). During this process, the active continental marginal basin (EACB) developed at the southern side of the Erguna Block and was filled with clastic-volcanic rocks in littoral-shelf facies (Fig. 2; cross-section F–F’ in Fig. 12; Zhao et al., 2016). On the southern side of Erguna and Xing’an Blocks in XMT, the tectonic dynamic setting of the microcontinental blocks, such as Yili-Central Tianshan, Dunhuang-Beishan, and northern margin of the Tarim Block, already changed from compression to extension (Ge et al., 2014). Continuous back-arc rifting and lithospheric extension lasted until 660–630 Ma as evidenced by the Korla mafic dyke-quartz syenite-syenogranite association (Zhu et al., 2008, 2011; Ge et al., 2012, 2014). During this period, a series of back-arc extension basins were dominated by glacial facies-littoral-shelf facies/tidal flat facies depositions (see cross-section C–C’ in Fig. 12).

5.3 Lithofacies paleogeography of North China tectonic-stratigraphic region

Since the Mesoproterozoic uplift, sea water has withdrawn from the Yanshan area and most of the North China Block has been uplifted into oldland, which has eroded for a long time and thus lacks a large scale of sediments. Only the Liaojie passive continental margin basin (LPCB) developed on the eastern margin edge of North China. It contains the Yintun Formation of glaciomarine-normal littoral shallow marine facies deposition (Fig. 11, see cross-section G–G’ in Fig. 12).

6 Conclusions

(1) Three tectonic-stratigraphic regions of the Cryogenian in China have been specified, including the Great South China, the Xingmeng-Tarim, and the North China tectonic-stratigraphic regions. According to different tectonic environments, a variety of genetic types

Fig. 11. Cryogenian tectono–stratigraphy showing litho–facies of China (725–635 Ma).

Details of 99 outcrop sections collected in this study are given in Table 1 (China basemap after China National Bureau of Surveying and Mapping Geographical Information).
of basins were identified in the interior or edge of continental blocks and micro-continental blocks. Among these identified blocks, the North China Block was far from Rodinia and remained relatively stable, and only passive continental marginal basins were developed. The Yangtze Block and its related continental blocks were greatly affected by the continental breakup of Rodinia and thus, rift basins developed widely. Tarim and Tarim-affinitive blocks were influenced by the Paleo Asian ocean subduction and the Rodinian breakup; consequently, a series of basins developed in these areas, including the active continental marginal basin, the post-arc extension basin, and the rift basin.

(2) Based on a systematic analysis of the event stratigraphy, lithostratigraphy, chemistry stratigraphy, and chronostratigraphy, the comparison scheme of stratigraphy of the Cryogenian in China was updated. At least two comparable glacial events were identified in the Yangtze and Tarim Block in China; namely, the Jiangkou-Altungal glaciation and the Nantuo-Tereeken glaciation, and the initiation and termination of these two glaciations are highly synchronous with the global Sturtian and Marinoan glaciations. The micro-continental blocks, such as Qilian, Quanji, Dunhuang, and Yili, have close tectonic affinities to the Yangtze and Tarim blocks; however, the correlation of multi-stage glacial and volcanic events between those micro-continental blocks and the Yangtze and Tarim blocks remains to be further explored.

(3) Different genetic types of basins and climatic impacts controlled the basin-filling sequence and distribution of sedimentary facies. Although the Cryogenian sedimentary sequence and glacial events of the Yangtze and Tarim showed great similarities, great differences still exist. Firstly, the temporal and spatial distribution of volcanic event layers in the Tarim Block is wider than in the Yangtze Block. Secondly, the sedimentary iron ore and manganese ore mineralization of the Yangtze Block is stronger than that of the Tarim Block.

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References
58: 1064–1075.


