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Age of the Tuchengzi Formation in Western Liaoning Province and the Jurassic–Cretaceous Boundary from the Continuous Core Records of Well YD1, Jinyang Basin

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Abstract: The Tuchengzi Formation is widely distributed in western Liaoning Province with a clear top and bottom. It is the focal area for the delineation of the terrestrial Jurassic–Cretaceous boundary in China. Based on continuous core samples taken from well YD1, detailed lithostratigraphic sequences and zircon uranium–lead (U-Pb) dating WERE used to investigate the Tuchengzi Formation. The zircon U-Pb ages of the tuff samples taken from the First and Third Members of the Tuchengzi Formation ranged from 153.8 to 137.16 Ma, indicating that they were formed in the late Middle Jurassic–Early Cretaceous. Dating results from the bottom of the Second Member of the Tuchengzi Formation indicate that the sedimentary time of the stratum is no later than 145.7 ± 2.1 Ma. We concluded that the Jurassic–Cretaceous boundary of the Jinyang Basin in western Liaoning province may be located at the interface at a depth of 464 m in well YD1. This conclusion is consistent with the Jurassic–Cretaceous boundary that has been presumed by other researchers based on paleontological assemblage features found in recent years, and can provide useful geological marker beds for the future study of the terrestrial Jurassic–Cretaceous boundary. In addition, the authors also systematically sorted the potential development areas and layers of the terrestrial Jurassic–Cretaceous boundary line, which may also provide useful geological marker beds for the future study of the terrestrial Jurassic–Cretaceous boundary.

Keywords: Tuchengzi Formation; Jinyang Basin; Jurassic-Cretaceous boundary; western Liaoning region; YD1 well; zircon U-Pb dating

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1. Introduction

The definition and study of the Jurassic–Cretaceous boundary are primarily based on marine sedimentary sequences, and major advances have been made in recent years with respect to these subjects. The international stratigraphic tables published by the International Union of Geological Sciences (IUGS) and the International Commission on Stratigraphy (ICS) have changed the timeframe of the Jurassic–Cretaceous boundary from 135 Ma [1] to 145 Ma [2], further reflecting the progress and dynamics of Jurassic–Cretaceous boundary studies. The Jurassic–Cretaceous stratigraphy in China is primarily terrestrial [3], and studies on its boundary are an important part of international standard stratigraphic delineation, albeit with more regional characteristics and application values.

Northeast China has the most continuous marine and continental sedimentary records of the Jurassic–Cretaceous boundary. These areas include the Northern Hebei area (Jibei), the western Liaoning area (Liaoxi), the Songliao Basin, and eastern Heilongjiang Province. It is important to note that Late Jurassic–Early Cretaceous strata in the Jibei–Liaoxi area are the most continuous and have already been studied in detail. Therefore, the Jibei–Liaoxi area has become the key area for studying the continental Jurassic–Cretaceous boundary in China [4]. However, the true age and accurate position of the Jurassic–Cretaceous boundary at these eastern Chinese terrestrial sequences are still controversial, largely due to the large depth of the target layer, poor outcrop exposure, and discontinuous drill cores.

Although there is no unified understanding of the correlation between the bottom boundary of the terrestrial Cretaceous and the international stratigraphic table (145 Ma) [5–9], researchers believe that the Jurassic–Cretaceous boundary ought to be located in the Tuchengzi Formation in northern Hebei–western Liaoning Province, and they have made this hypothesis a study focus [3,10–13]. However, the Tuchengzi Formation is mostly composed of coarse clastic conglomerate and red beds, and fossils are rare, making it difficult to correlate findings with marine bed fossils. Therefore, the age of the Tuchengzi Formation and the identification of its sedimentary hiatus are both of particular importance in determining the Jurassic–Cretaceous boundary.

Well YangD1 (YD1) was drilled into the Jinyang Basin through 2000 m of continuous volcanic–sedimentary rock in the Tuchengzi and Tiaojishan Formations. Cores taken from YD1 provide a complete and continuous record of the Late Jurassic–Early Cretaceous period, providing unique material for studying the Tuchengzi Formation and the Jurassic–Cretaceous boundary in the Jibei–Liaoxi area. In the present work, by analyzing drilling core samples from well YD1, we were able to study the age of the Tuchengzi Formation in detail. The potential position of the Jurassic–Cretaceous boundary in the Jibei–Liaoxi area was also studied. Based on a comparative study of the various potential areas and layers that might contain the Jurassic–Cretaceous boundary in northeastern China, this study provides fundamental information for its further examination and its correlation with marine stratigraphy.

2. Recent Advances in the Study of the Jurassic-Cretaceous Boundary

2.1. Advances of the Global Marine Jurassic-Cretaceous Boundary

It is widely accepted that the Berriasian Stage is located at the base of the Lower Cretaceous, and the bottom of the stage in the Tethys Zone may represent the Jurassic–Cretaceous boundary [3]. The first occurrences of the calcareous nannofossils Nannoconus kamptneri minor and N. steinmannii minor have been widely used as place markers for the Tithonian–Berriasian and Jurassic–Cretaceous boundaries [14]. The Jurassic–Cretaceous boundary is at the base of magneto zone M18r, with a recommended age of 145.0 Ma according to the international stratigraphic chart [15]. Although this is only a recommended value and lacks actual support in the geological data, an increasing number of studies have proved that this value is rational. Mahoney et al. reported a 40 Ar/39 Ar age of 144.6 $\pm$ 0.8 Ma for the bottommost reversed-polarity basalt sill cored in the lowermost Berriasian sediments on the Shatsky Rise in the northwestern Pacific [16]. The sills were bounded by both calcareous nannofossil zone NK1 and the radiolarian Pseudodictyomitra carpatica zone. Liu et al. reported a zircon uranium–lead (U-Pb) age of 142–140 Ma for the lower part of the Sangxiu Formation in southern Tibet, China, which is located in the Nannoconus steinmannii minor zone above the Berriasian Stage, suggesting that the bottom boundary age of the Berriasian Stage may be older than 142–140 Ma [17]. Vennari et al. showed that the Jurassic–Cretaceous boundary in the Andean region is located in the Nannoconus kamptneri minor zone at the bottom of the Berriasian Stage. The tuff above about 22 m of shale yielded a zircon U-Pb age of 140 Ma, suggesting that the Jurassic–Cretaceous boundary in the Andean region may also be older than 140 Ma [18].

2.2. Recent Advances in the Terrestrial Jurassic-Cretaceous Boundary in the Jibei-Liaoxi Region

In recent years, research on the terrestrial Jurassic–Cretaceous boundary in the Jibei–Liaoxi region has experienced major progress, but the definition of both the boundary and its age limit is still controversial. There are two main opinions concerning this issue.

2.2.1. The Time Limit of the Terrestrial Jurassic-Cretaceous Boundary Line Is Earlier Than 145 Ma

A number of Chinese scientists have argued that the Jurassic–Cretaceous boundary is difficult to correlate directly with international marine standards based on terrigenous stratigraphic data, and they have proposed the use of 135 or 137 Ma as its age [10]. Chen placed the Jurassic–Cretaceous boundary between the Yixian and Jiufotang Formations and recommends a boundary age of 125 Ma [19]. The All-China Commission of Stratigraphy published a specification on the regional chronostratigraphic (geological) chronology of China in 2002, which set the boundary between the Dabeigou and Yixian Formations, with an age of 137 Ma [20]. Several researchers have set the Jurassic–Cretaceous boundary between the Dabeigou and Dadianzi Formations in the Luanping Basin, northern Hebei, limiting the boundary age to 130 Ma [6,9,21,22]. Wang et al. suggested that the Jurassic–Cretaceous boundary should be in the lower Yixian Formation and recommended an age of 124 Ma [23].

2.2.2. The Terrestrial Jurassic-Cretaceous Boundary Line Is Close to 145 Ma

According to new advances in international research on the Jurassic–Cretaceous boundary, an increasing number of Chinese scientists have gradually adopted the global time limit for this boundary. At the 4th China National Stratigraphic Conference in 2013, the age of the Jurassic–Cretaceous boundary was adjusted to 145 Ma [24]. As most of the isotopic ages measured in the Tuchengzi Formation have been found to be younger than 145 Ma, the terrestrial Jurassic–Cretaceous boundary may be located within the Tuchengzi Formation [25–29]. In addition, the terrestrial sporulation assemblage of the Tuchengzi Formation also has characteristics of the Late Jurassic–Early Cretaceous [30–35]. This evidence suggests that the Chinese terrestrial Jurassic–Cretaceous boundary is located within the Tuchengzi Formation [10,13,28,29,36–40]. However, whether the boundary is located between Members 1 and 2 or Members 2 and 3 is highly controversial. Wan et al. tentatively placed the Jurassic–Cretaceous boundary in the Yanliao region between Members 2 and 3 based on foliage, mesozoans, and sporulation [41].

3. Geological Background

Northeastern China is tectonically located at the intersection of three major plates: the Siberian, Pacific, and Mongolian–North China plates. Its northern region is connected to the Siberian plate through the Mongolia–Okhotsk suture zone, and its eastern region is connected to the Pacific plate through the Sikhote–Alin tectonic zone (Figure 1). Prior to the Late Paleozoic, a series of microplates, including the Erguna–Xing'an plate, the Songliao–Xilinhot microplate, and the Jiamusi microplate, assembled and formed the Heilongjiang plate [42]. In the Late Permian, the Heilongjiang–Mongolian plate was assembled with the northern margin of the North China Plate along the Xar Moron River suture zone (Figure 1a), which formed the basement of the Songliao Basin [43]. After these events, the Jibei–Liaoxi region at the northern margin of the North China Plate and the Songliao Basin were tightly connected.

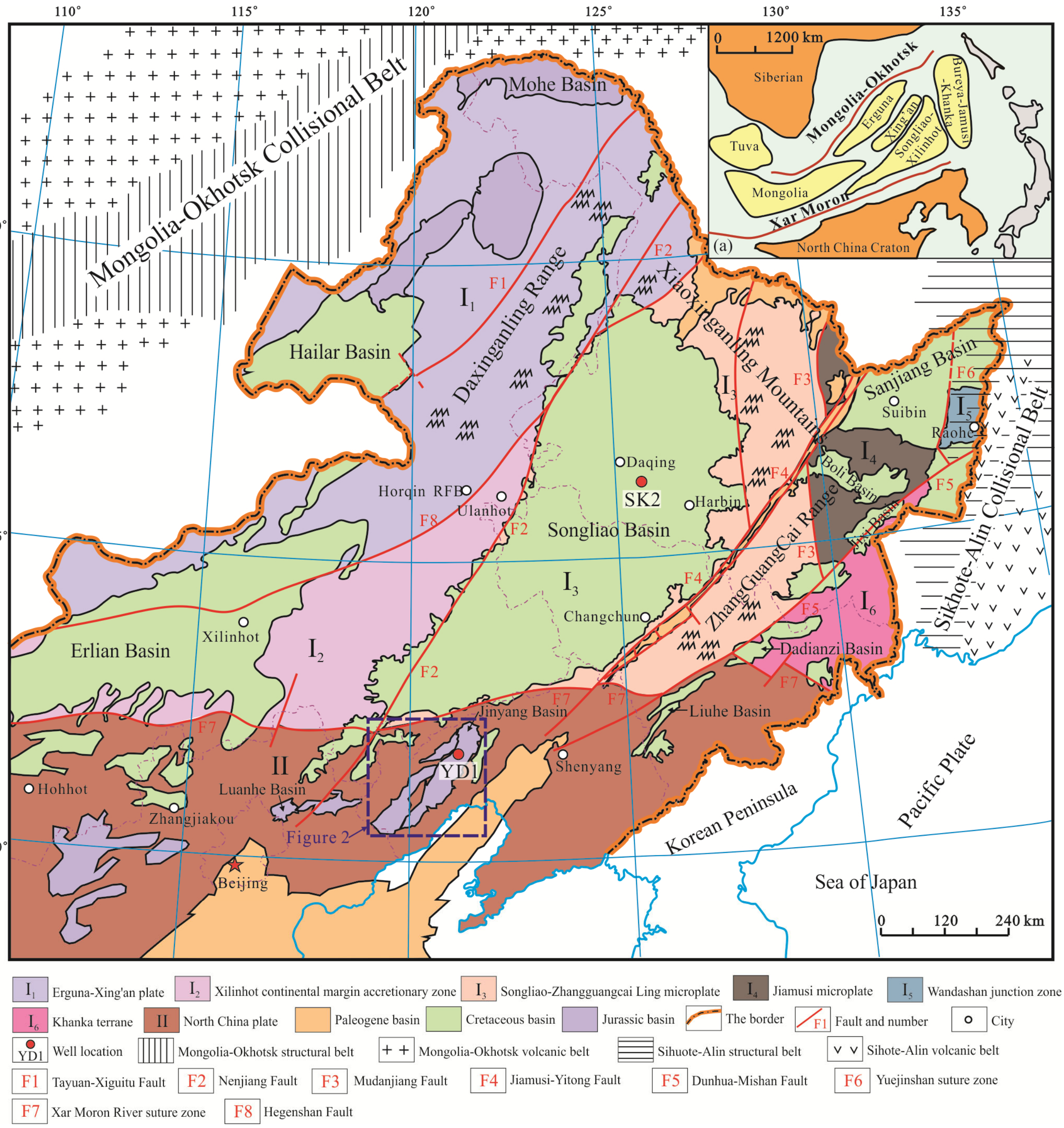

Figure 1. Simplified geological map of northeast China showing the geological tectonic units and location of the study area. (**a**) Tectonic sketch map showing the main subdivisions of eastern Asia (modified after [44]).

The Nenjiang Fault is a major fault controlling the formation of the Songliao Basin [45]. To the west of the Nenjiang fault are areas where Mesozoic Daxinganling volcanic rocks are widespread, in addition to a series of Jurassic–Cretaceous basins, including the Mohe and Hailar Basins [46]. The Jiamusi–Yitong Fault is the major basin-controlling fault of the Songliao Basin in the east. To the east of the Jiamusi–Yitong fault is the northeast-trending Dunhua–Mishan Fault, in addition to Cretaceous basins such as the Liuhe and Dadianzi Basins. The Mudanjiang Fault is north–south trending, and to the east, there is a series of Cretaceous basins, including the Sanjiang, Boli, and Jixi Basins. The Xar Moron River suture zone is on the southern boundary of the Songliao Basin, trending east–west, which belongs to the intraplate suture zone within the Mongolian–North China Plate [45]. The southern section of the belt primarily includes western Liaoning Province (Liaoxi) and the northern Hebei (Jibei) area, where a series of Mesozoic basins are located, including the Jinyang, Beipiao and Luanping Basins (Figure 1).

As a result of the Yanshanian Movement and the convergence of the East Asian multidirectional plates, the Mesozoic volcanic–sedimentary stratigraphy is most complete in western Liaoning, which is located on the eastern Yanshan orogenic belt [47,48]. The Jinyang Basin is the largest and most typical of all the basins [49–51].

Jurassic–Cretaceous strata are widespread in the Jinyang Basin, accounting for more than 90% (Figure 2b). Impacted by the Indosinian Movement and Early Yanshan orogeny, the upper basin formed in the Late Jurassic and the Tuchengzi Formation was filled with purple conglomerate, sandy conglomerate, siltstone, and argillaceous sedimentary formations. From bottom to top, the strata consist of the Xinglonggou and Beipiao Formations of the Lower Jurassic, the Haifangou and Tiaojishan Formations of the Middle Jurassic, and the Tuchengzi and Yixian Formations of the Upper Jurassic to Lower Cretaceous (Figure 2c). The contact interface between the Beipiao and Haifangou Formations is an angular unconformity, as is the interface between the Tuchengzi and Yixian Formations. However, the others are parallel unconformities. The angular unconformity between the Beipiao and Haifangou Formations and the Tuchengzi and Yixian Formations may represent Phases A1 and B of the Yanshanian Movement, respectively [52–57]. The Tuchengzi Formation was deposited during the transitional period between Phase A1 and B of the Yanshan orogeny [58,59].

The Jibei–Liaoxi area was located in a key position in the tectonic transition of East Asia during the turn of the Jurassic and Cretaceous (Figure 2a) [60]. The Yanshanian Movement triggered the Late Jurassic multidirectional extrusion and intra-land orogeny, Early Cretaceous massive extension, and lithospheric thinning. Regional tectonic and magmatic events at different times led to dramatic ecological changes [47,61], resulting in the extinction of the Yanliao Biota and the replacement of the Jehol Biota.

4. Lithologic Sections of the Tuchengzi Formation

The Tuchengzi Formation is divided into three lithologic members [62]. Based on the sedimentary environment and hiatus in this area, in addition to the core of well YD1, the boundary of Members 1 and 2 is set at the onset of gray-purple, complex-fine conglomerate, and the end of the red sand and mudstone. The boundary of Members 2 and 3 is set at the sedimentary hiatus between the green-gray lithic feldspar (intermediate-fine) sandstone and the gray-purple (complex-fine) conglomerate (Figure 2d).

At the top stratum of well YD1 is the Third Member of the Tuchengzi Formation, which is composed of gray-green aeolian sandstone. Well YD1 runs through the First and Second Members of the Tuchengzi Formation downward, and is primarily composed of sand–mudstone and polymictic conglomerates. Below the Tuchengzi Formation is the Tiaojishan Formation, which is primarily composed of neutral lava and pyroclastic. Due to the lateral differences between volcanic and sedimentary environments, the lithostratigraphy of the Tuchengzi Formation in western Liaoning Province is slightly different at each sedimentary basin. The lithostratigraphy of each member of the Tuchengzi Formation in well YD1 of the Jinyang Basin is divided as follows:

Member 1 (depth: 500.52–1207 m): The bottom is composed of gray-green, breccia-bearing, tuffaceous sandstone (medium-coarse), and gray-green andesite conglomerate (medium-coarse) with an alluvial fan facies, unconformably overlying the gray-green basaltic andesite of the Tiaojishan Formation. The middle and upper sections are brown, silty mudstone with gray-green siltstone and a thin tuff layer, which is dominated by lakeside–shallow lake subfacies.

Member 2 (depth: 50.45–500.52 m): The bottom is composed of gray-purple gravel complex conglomerate (medium-fine) with scour surface and massive bedding. The middle part is mainly gray-purple complex conglomerate. The top is gray-green lithic feldspar sandstone (medium-coarse) with grain sequence bedding, parallel bedding, and large plate crossbedding. The stratum is dominated by alluvial fan facies and conformable contact with Member 1.

Member 3 (depth: 0–50.45 m): Green-gray, lithic feldspar sandstone (medium-fine) interbedded with a thin layer of purple-red feldspar sandstone (medium-fine), with medium-large crossbedding (coarse-grained), make up Member 3. This member has an aeolian sedimentary sequence that has conformable contact with Member 2. Because the top strata of well YD1 are part of Member 3, the revealed strata in this section are incomplete. Comparing profiles near well YD1 shows that the revealed strata in this section form the bottom of the Tuchengzi Formation's Third Member.

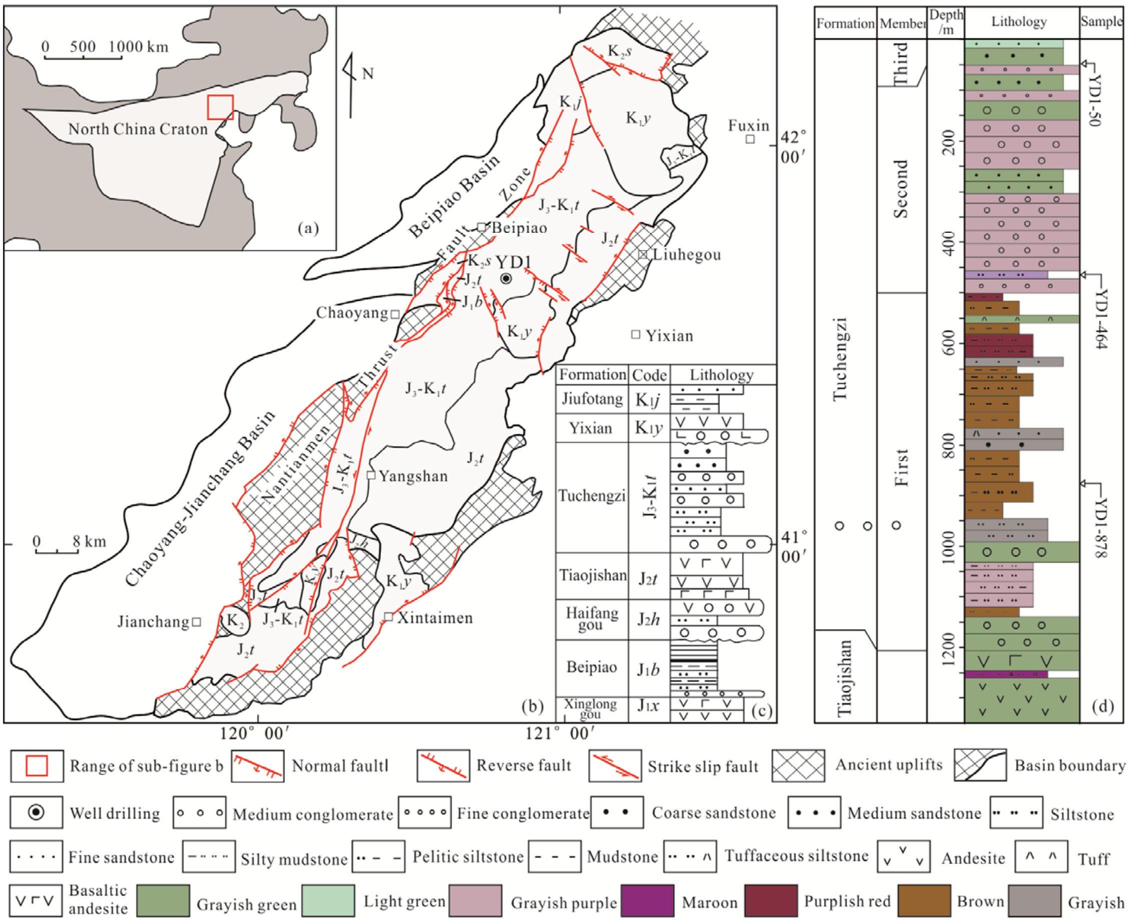

Figure 2. Geological sketch of Jinyang basin and its surrounding area and the core histogram of the Tuchengzi Formation in Well YD1. (**a**) Location of study area (modified after [63]); (**b**) geological sketch of Jinyang basin and its surrounding area modified after [64]; (**c**) filling sequence of main strata in Jinyang Basin; (**d**) the core histogram of well YD1 and sample location.

5. Analytical Methods and Sample Characteristics

5.1. Sample Characteristics

Three samples were chosen for zircon U-Pb isotopic dating. Vitreous crystalline tuff (YD1-50) at 50 m was taken from the bottom of Member 3 in well YD1. The other two samples were calcareous feldspar lithic sandstone (YD1-464) taken from a depth of 464 m at the bottom of Member 2, and rhyolitic tuff (YD1-878) at 878 m taken from the middle part of Member 1 (Figures 2d and 3).

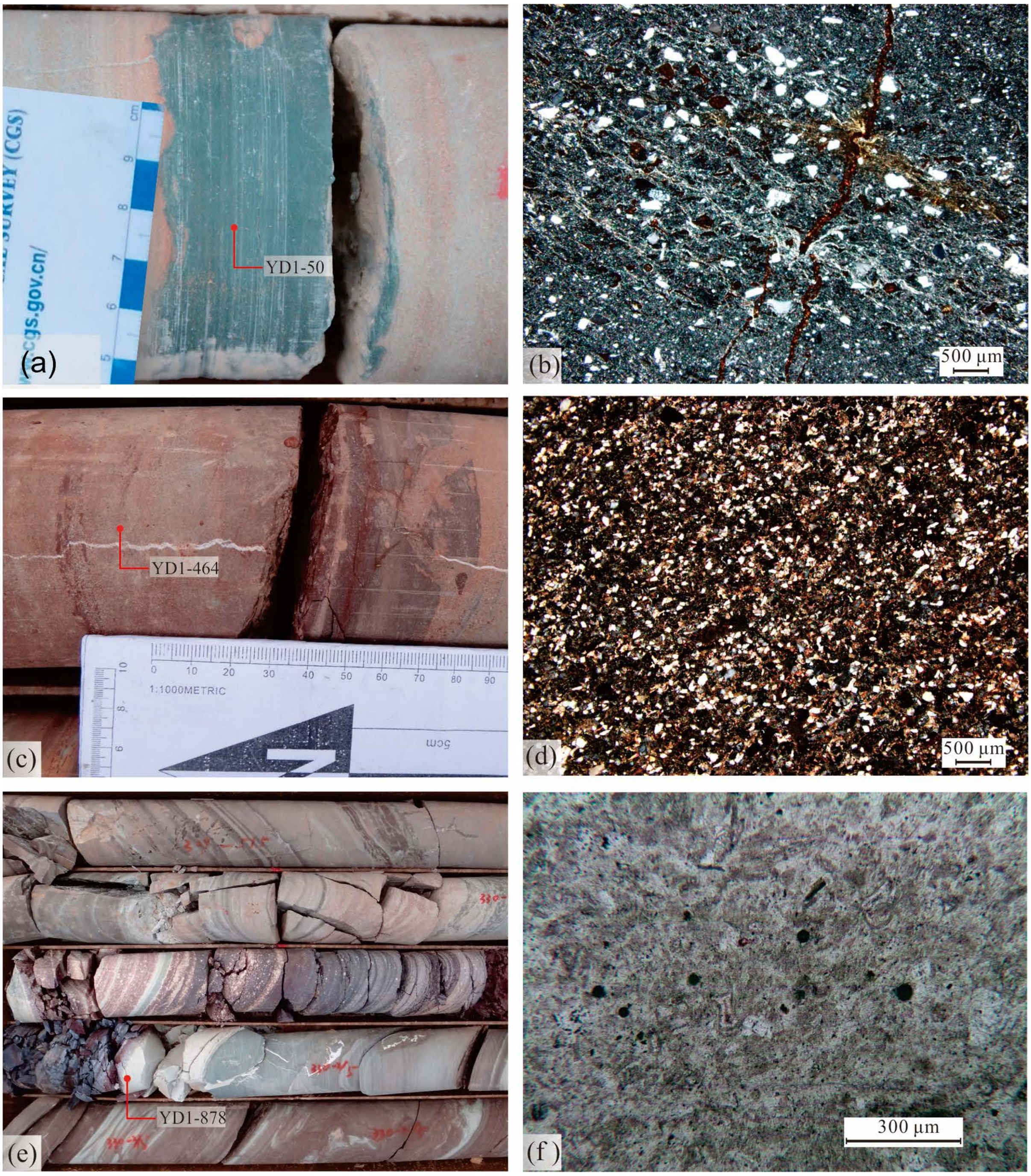

Figure 3. Photographs and microphotographs showing sampling core and its lithology. (**a**) Glassy crystal tuff (sample YD1-50), and (**b**) under transmitted light (sample YD1-50); (**c**) calcareous feldspar lithic sandstone (sample YD1-464), and (**d**) under transmitted light (sample YD1-464); and (**e**) rhyolitic tuff (sample YD1-878), and (**f**) under transmitted light (sample YD1-878).

5.2. Analytical Methods

Zircon crystals were separated at the Mineral Separation Laboratory of Langfang Regional Geological Survey, Hebei Province. First, each sample was ground, washed, dried, and sorted. Then, magnetic separation and heavy liquid separation technology were used to retrieve the zircon crystals. Relatively complete zircons crystals were then handpicked under a binocular microscope and mounted in epoxy. To reveal the internal texture, cathodoluminescence (CL) images were obtained.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) zircon U-Pb analyses were performed at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, using an Anlyitik Jena PQMS Elite ICP-MS equipped with a 193 nm laser. Analyses were performed with a beam diameter of 25 um, a laser frequency of 10 Hz, an energy of 2.31 J/cm^2, and He as a carrier gas. LA-ICP-MS laser denudation sampling was conducted using single point denudation [65]. GJ-1 was used as an unknown to evaluate the data quality, and SRM 610 silicate glass was applied for the external standard with silicon as the internal standard [66]. ICPMSdatacal [65] and ISOPLOT 3.0 [67] were used for data reduction. In data processing, most analysis points of $^{206}Pb/^{204}Pb > 1000$ were not corrected by ordinary lead, and analysis points with abnormally high ^{204} Pb content may be affected by ordinary Pb, such as inclusions. The analysis points with abnormally high ^{204}Pb were eliminated during calculation.

6. Results of Zircon U-Pb Dating

6.1. Glassy Crystal Tuff (YD1-50)

The zircon U-Pb data derived from 58 detrital zircons taken from sample YD1-50 are listed in Table S1 and illustrated in Figures 4 and 5a,b. Zircon grain CL images showed that most were euhedral to subhedral. The zircon grains showed clear oscillatory growth zoning. This kind of zircon grain is a homologous product with a single color, a concentrated crystal group, and a similar transformation distance. These properties, together with Th/U ratios (0.48–1.69), indicate these zircon grains had a magmatic origin [68,69]. For the analyzed samples, the concordant $^{206}Pb/^{238}U$ ages ranged from 142.3 to 132.3 Ma (Table S1). A U-Pb age frequency histogram (Figure 5a) shows that the detrital zircons had three main age peaks of 137.6, 252.9, and 2511 Ma, and secondary age peaks of 314.9, 410.3, 1700, and 1912 Ma. The age of the detrital zircons ranged from 2618.5 to 123.4 Ma, which reflects the diversity and complexity of the sediment sources. The weighted average age of $^{206}Pb/^{238}U$ was 137.16 ± 0.70 Ma (MSWD = 1.3, Figure 5b), which represented the age of magma crystallization.

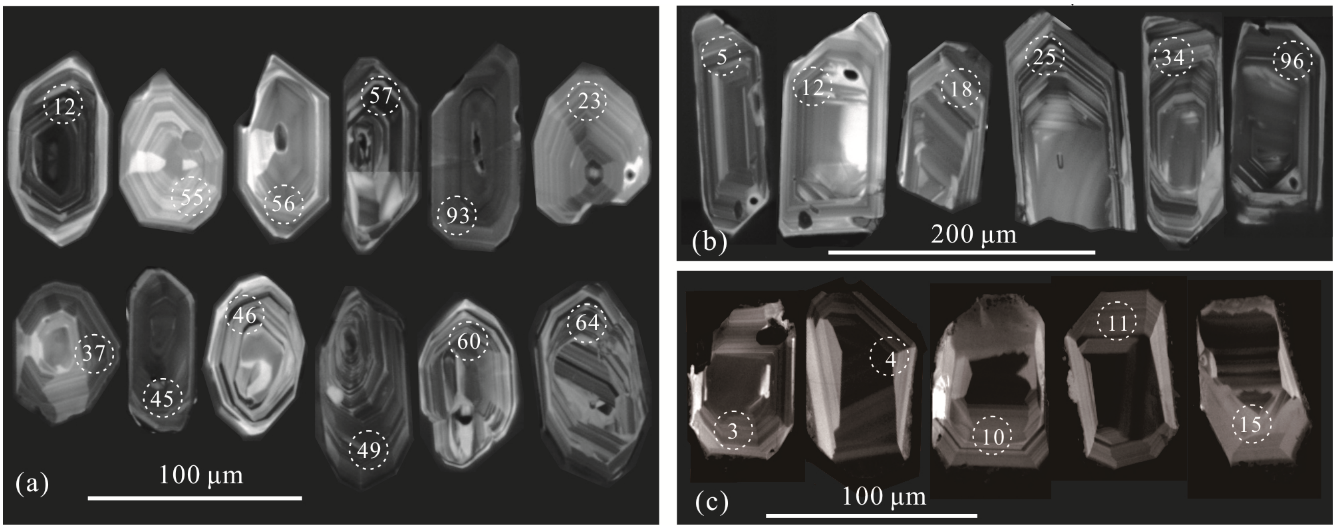

Figure 4. Cathodoluminescence (CL) images of typical detrital and magmatic zircons from the Tuchengzi Formation in well YD1. Circles indicate the location of laser ablation inductively coupled plasma source mass spectrometry, numbers in circles refer to the spot number. (**a**) Sample YD1-464; (**b**) sample YD1-50; and (**c**) sample YD1-878.

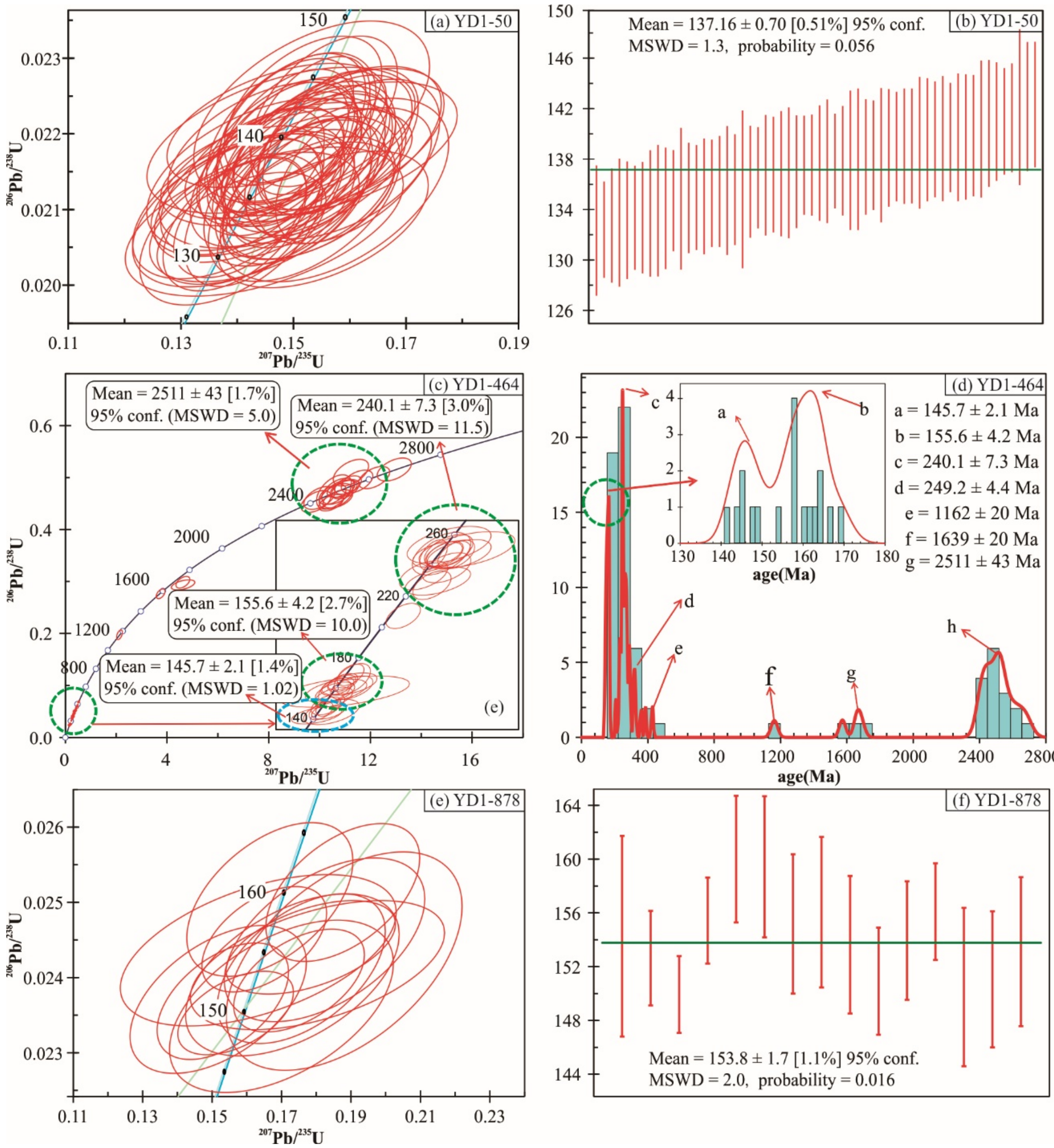

Figure 5. U-Pb Concordia diagram, frequency histogram, and weighted isochron diagram of zircon ages for samples from the Tuchengzi Formation. (**a**) U-Pb age Concordia diagram and (**b**) U-Pb weighted isochron diagram of YD1-50 magma zircon; (**c**) U-Pb age Concordia diagram and (**d**) U-Pb frequency histogram of YD1-464 detrital zircon; (**e**) U-Pb age Concordia diagram and (**f**) U-Pb weighted isochron of YD1-878 magma zircon.

6.2. Calcareous Feldspar Lithic Sandstone (YD1-464)

The zircon U-Pb data derived from 70 detrital zircons taken from sample YD1-464 are listed in Table S2 and illustrated in Figures 4 and 5c,d. Zircon grain CL images showed that most were euhedral to subhedral. The zircon grains showed clear oscillatory growth zoning. These properties, together with Th/U ratios (0.29–3.93), indicate that these zircon grains had a magmatic origin [68,69]. A total of 92 zircon grains were analyzed, and the concordant $^{206}Pb/^{238}U$ ages ranged from 2680.9 to 142.3 Ma (Figure 5c). The U-Pb age frequency histogram (Figure 5d) shows that the detrital zircons had four main age peaks of 145.7, 155.6, 240.1, and 2511 Ma and secondary age peaks of 294.2, 426.7, 1162, and

1639 Ma. The age range was large, which further reflects the diversity and complexity of the Tuchengzi Formation sediment sources.

6.3. Rhyolitic Tuff (YD1-878)

The zircon U-Pb data derived from 15 zircon grains taken from sample YD1-878 are listed in Table S3 and illustrated in Figures 4 and 5e,f. The zircon grains showed clear oscillatory growth zoning. These properties, together with Th/U ratios (0.59–1.81), indicate that these zircon grains had a magmatic origin [68,69]. A total of 15 zircon grains were analyzed, and the concordant $^{206}Pb/^{238}U$ ages ranged from 149.9 to 160.0 Ma (Table S3). The weighted average age of $^{206}Pb/^{238}U$ was 153.8 $\pm$ 1.7 Ma (MSWD = 2.0, Figure 5f), which represented the age of magma crystallization.

7. Discussion

7.1. Age of the Tuchengzi Formation

The Jurassic–Cretaceous strata in China are mostly terrestrial deposits. The high mountains formed by tectonic movements block communication between different lake ecosystems. As a result, the fauna and flora show remarkable regional differences and make it difficult to find biological markers for isochronous comparisons. This makes it difficult to reach a unified opinion on the biostratigraphic comparison of different phyla [32,33,70–77]. In terms of high precision isotopic dating, He et al. used the K-Ar and Rb-Sr methods to limit the age of the upper and lower strata of the Tuchengzi Formation to 156–145 Ma [78,79]. Davis et al. and Sun et al. limited its age to 156–139 Ma based on previous zircon U-Pb age data [26,28]. The National Stratigraphic Commission published the Manual of China's Regional Geochronology (Geochronology) table in 2014, which classified the strata of the Upper Jurassic in China as the Tuchengzi Formation. However, due to the difficulty in determining the exact attribution of the Tuchengzi Formation, they did not establish its stage [24,80].

Based on two tuff samples with zircon grains of magmatic origin, we further constrained the age of the Tuchengzi Formation in well YD1 between 137.16 $\pm$ 0.7 Ma (YD1-50) and 153.8 $\pm$ 1.7 Ma (YD1-878). However, the age of 137.16 $\pm$ 0.7 Ma in this study was the absolute age at the bottom of Member 3, where there was an aeolian dune deposition at least 1000 m above the interface [81]. Although the top age of the Tuchengzi Formation was not obtained, it can be inferred that the age of the top formation is later than 137.16 $\pm$ 0.7 Ma. Compared to the International Stratigraphic Chronology (2018), we suggest that the Tuchengzi Formation in western Liaoning province was formed between the middle–late Late Jurassic and Early Cretaceous.

7.2. The Boundary between Jurassic and Cretaceous

A total of 70 effective detrital zircons from sample YD-464, collected from the lower part of Member 2, were analyzed, among which, the ages of the six youngest zircon grains ranged from 142.3 to 149.5 Ma, with a weighted mean age of 145.7 $\pm$ 2.1 Ma (MSWD = 1.02, Figure 5c). The frequency histogram showed the youngest peak age at 145.0 Ma, which is consistent with the Jurassic–Cretaceous boundary of 145 Ma from the International Commission on Stratigraphy (ICS) [82]. It is also close to the minimum age (144.6 $\pm$ 0.8 Ma) of the Lower Cretaceous Berriasian Stage at the Shatsky Rise in the northwest Pacific [16]. The peak age and weighted-mean age of the samples were within the error range, which indicates that the sedimentary period of the strata was no later than 145.7 $\pm$ 2.1 Ma. Therefore, we concluded that the Jurassic–Cretaceous boundary of the Jinyang Basin in western Liaoning Province may be located at the interface at a depth of 464 m in well YD1. Based on the sedimentary facies analysis of the upper and lower strata, we believe that there may be a sedimentary gap between Members 1 and 2 and of the Tuchengzi Formation, which may be the Jurassic–Cretaceous boundary of the Mesozoic terrestrial strata in western Liaoning province (Figure 6a). This result is also consistent with Huang's opinion that the Jurassic–Cretaceous boundary is located in the upper part of the Tuchengzi Formation based on the paleontological assemblage characteristics [59,83].

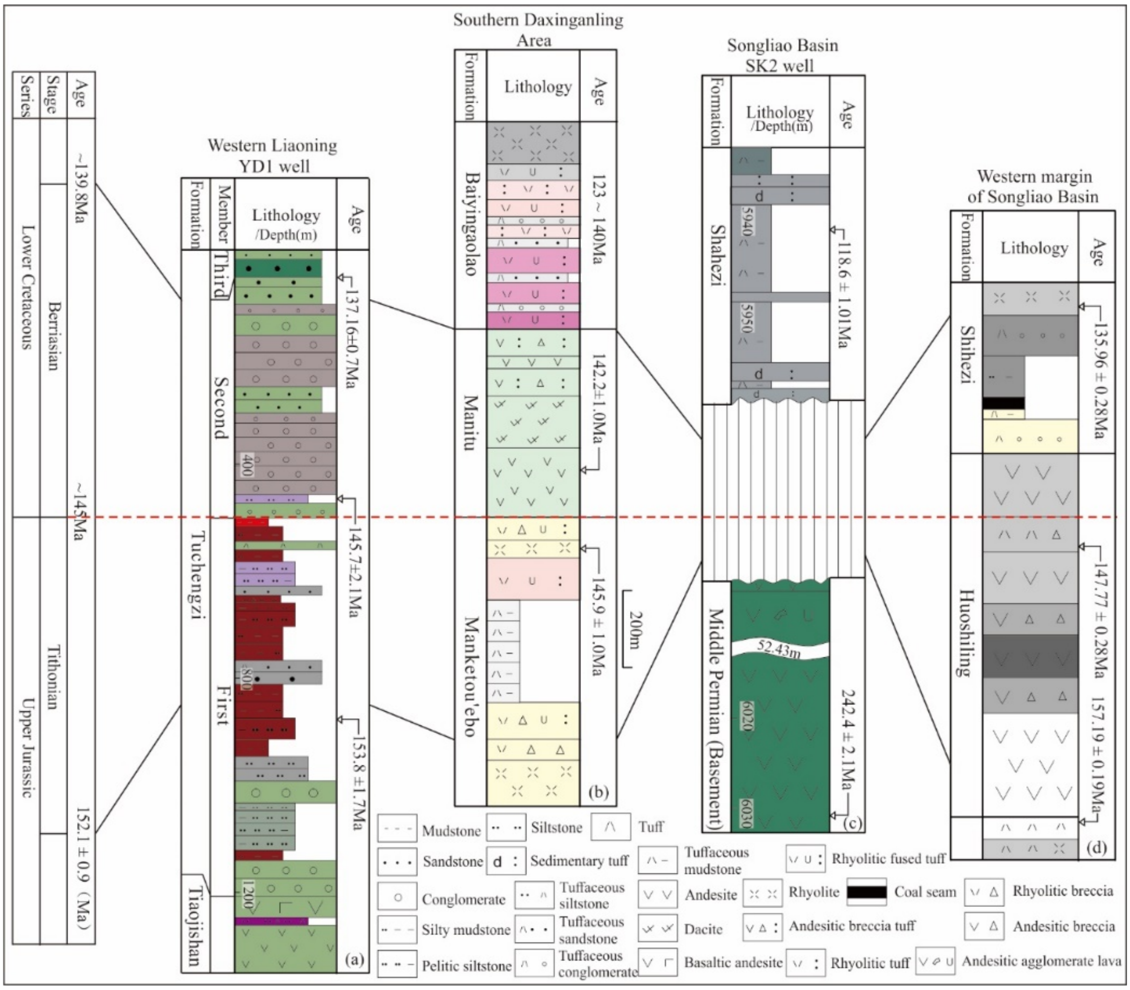

Figure 6. Potential layer comparison of terrestrial Jurassic–Cretaceous boundary in Northeast China. (**a**) Western Liaoning YD1 well; (**b**) Southern Daxinganling area; (**c**) Songliao Basin SK2 well; (**d**) Western margin of Songliao Basin.

Although a final determination of the international Jurassic–Cretaceous boundary age requires more accurate age data and the support of further research results, the latest research results indicate that 145 Ma can be used as the international Jurassic–Cretaceous boundary age. Considering that the Tuchengzi Formation was formed between 154 and 137 Ma ago, we further verified that the Jurassic–Cretaceous boundary exists within the Tuchengzi Formation in the northern Hebei area and western Liaoning Province regions. The results can provide detailed and basic geological data for the future study of the terrestrial Jurassic–Cretaceous boundary.

7.3. Potential Areas and Layers for the Development of the Terrestrial Jurassic-Cretaceous Boundary

It is generally accepted that the closure of the Mongolian–Okhotsk Ocean was the most important geotectonic event in northeast Asia during the Mesozoic, and it is characterized by a west-to-east scissor-like closure [84–86]. Its eastern closure process lasted until the Late Jurassic–Early Cretaceous [87,88].

To the west of the Nenjiang fault, i.e., the Daxinganling area, the Manketou'ebo Formation is a volcanic system that was formed by the collapse of thickened crust or delamination extension after the closure of the Mongolia–Okhotsk Ocean. Numerous isotopic dating results taken from the Manketou'ebo Formation have been reported in recent years, with age results ranging from 157 to 132 Ma [89–92]. Of note, Jia et al. performed zircon U-Pb dating on two Manketou'ebo Formation rhyolite samples from the Horqin Right Front Banner area, and the results were 145.9 ± 1.0 Ma and 146.0 ± 1.3 Ma (Figure 6b) [93]. The Manketou'ebo Formation overlies the Manitu Formation, of which the ages of volcanic rocks are between 139 and 148 Ma [94,95]. Tao et al. reported an age of 142.2 ± 1.0 Ma for the andesite of the Manitu Formation near Ulanhot in southern Daxinganling (Figure 6b) [96]. Judging from the dating results, the Manketou'ebo and Manitu formations have diachronous phenomena, which may be attributed to a younger trend from the southwest to the northeast in the spatiotemporal distribution of the Manketou'ebo Formation [93]. However, the overlying volcanic rocks of the Baiyingaolao Formation are between 123 and 140 Ma in age and belong to the Early Cretaceous (Figure 6b) [97]. Therefore, the Manketou'ebo and Manitu formations in southern Daxinganling are noteworthy formations for the study of the terrestrial Jurassic–Cretaceous boundary in these regions.

Andesite taken from a depth of 6031.9 m in well SK2, located in the Xujiaweizi fault depression in the Songliao Basin, yielded an age of 242.4 ± 2.1 Ma (Middle Triassic) [98]. The age of rhyolitic tuff approximately 88.71 m above the andesite (5943.19 m) was 118.6 ± 1.0 Ma [99]. Based on these two dating results, we suggest that, in the Xujiaweizi fault trap, where well SK2 was located, the Middle Triassic–Early Cretaceous sediments were in hiatus for around 123.8 Ma (Figure 6c). This also indicates that, after the closure of the Mongolian–Okhotsk ocean, no extensional basin was formed in the Songliao Basin. Consequently, there is no extensive Late Jurassic–Early Cretaceous continuous sedimentation in the Songliao Basin. Instead, numerous Late Jurassic volcanic rocks have been reported in the Changjiaweizi and Melisi fault depressions on the western margin of the Songliao Basin [100,101]. Qu et al. established sedimentary sequences for the Huoshiling Formation based on a detailed study in the Xujiaweizi fault depression [102,103]. The lower part is primarily composed of sedimentary rocks, whereas the upper part is composed of volcanics rocks interlayered with sedimentary sequences. Based on the established sequences, Wang et al. and Qu et al. suggested its diachronous nature (Figure 6d) [103,104]. Therefore, the Huoshiling Formation in the southern Songliao Basin is a key area in the study of the Jurassic–Cretaceous boundary.

The Jibei–Liaoxi area adjacent to the Songliao Basin is an important area for the study of the terrestrial Jurassic–Cretaceous boundary. With intensive studies and deeper stratigraphy revealed by drilling, there is an increasing amount of evidence suggesting that the terrestrial Jurassic–Cretaceous boundary in the Jibei–Liaoxi area is located in the upper portion of the Tuchengzi Formation's First Member. Zhang et al. reported a zircon U-Pb age of 142.6 ± 1.3 Ma for the welded tuff at the base of the Second Member of the Tuchengzi Formation in the Luanping Basin, Hebei [27]. Lin and Li reported a spodumene assemblage at the top of the First Member in the Luanping Basin, Hebei Province, and suggested that it is of Early Cretaceous (middle–late-stage Valanginian) origin, and the Jurassic–Cretaceous boundary in northern China is located in the upper portion of the First Member [105]. Another report suggested that the sporulation assemblage of Member 3 near Beipiao Sihetun is similar to that of the lower portion of the Yixian Formation in western Liaoning Province; no discernable differences could be found between the appearance of flora within the two formations [83]. These latest results are consistent with the conclusion that the Jurassic–Cretaceous boundary is located in the upper part of the Tuchengzi Formation's First Member. The lateral comparison of the formation in western Liaoning Province is crucial for reconstructing the sedimentary and evolutionary history of the Jurassic–Early Cretaceous in northern China.

Transgressions occurred in the Late Jurassic–Early Cretaceous Valanginian Stage in eastern Heilongjiang Province, but they were limited to the Dong'an-Sui'bin line and its northern area. Among them, the Donganzhen Formation in the Raohe and the Dongrong Formation in Suibin are two potential areas that may contain the Jurassic–Cretaceous boundary [106–109]. Marine fossil data from the interfacial strata can be compared with the international marine Jurassic–Cretaceous boundary. In contrast, the sporopollen fossil assemblage can be compared with the terrestrial Jurassic–Cretaceous boundary, thus establishing a bridge between the marine and terrestrial comparison of the Jurassic–Cretaceous boundary. Therefore, eastern Heilongjiang is a key area for making terrestrial and international marine comparisons with respect to the Jurassic–Cretaceous boundary in the Jibei–Liaoxi region. The next step of this work should be focused on the isotope chronology, biostratigraphy, magnetic stratigraphy, and cyclic stratigraphy of the Jibei–Liaoxi region and eastern Heilongjiang.

8. Conclusions

(1) The zircon U-Pb dating of two tuff samples from Members 1 and 3 of the Tuchengzi Formation in well YD1 constrained the sedimentary age range from 153.8 to 137.16 Ma, although the upper age may be much later than 137.16 Ma. According to the International Stratigraphic Chronology (2018), the age of the Tuchengzi Formation in western Liaoning province was determined to be from the middle–late Late Jurassic to the Early Cretaceous.

(2) A total of six zircon grains collected from the bottom of Member 2 of the Tuchengzi Formation (YD-464) yielded a weighted mean age of 145.7 $\pm$ 2.1 Ma, which is consistent with the peak age of the sample within the error range, and can be roughly used as the sedimentary period for this formation. Therefore, there may be a depositional gap between Members 2 and 1 of the Tuchengzi Formation, or at the top of Member 1, which can be regarded as the Jurassic–Cretaceous boundary of the Mesozoic terrestrial strata in western Liaoning Province. This conclusion is consistent with the Jurassic–Cretaceous boundary inferred by paleontological assemblage characteristics in recent years.

(3) The Tuchengzi Formation in the Jibei–Liaoxi region, the Dongrong Formation, and the Dong'anzhen Formation in eastern Heilongjiang are key layers that may contain the terrestrial Jurassic–Cretaceous boundary. The Jurassic–Cretaceous boundary may be only locally developed in the Songliao Basin, and the Huolshiling Formation in the south is a key layer in the study of the Jurassic–Cretaceous boundary.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/min12080953/s1, Table S1: LA-ICP-MS zircon U-Pb data of the glassy crystal tuff (YD1-50); Table S2: LA-ICP-MS zircon U-Pb data of the calcareous feldspar lithic sandstone (YD1-464); Table S3: LA-ICP-MS zircon U-Pb data of the rhyolitic tuff (YD1-878).

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References

1. Remane, J. International stratigraphic chart, with explanatory note. In Proceedings of the 31st International Geological Congress, Rio de Janeiro, Brazil, 6–17 August 2000; pp. 1–16. (In Chinese with English Abstract)
2. Cohen, K.M.; Finney, S.C.; Gibbard, P.L.; Fan, J.X. The ICS international chronostratigraphic chart. *Phase* **2013**, *36*, 199–204. [CrossRef] [PubMed]
3. Wan, X.Q.; Gao, L.F.; Qin, Z.H.; Cui, C.; Li, W.; Xi, D.P. Jurassic-Cretaceous boundary and its terrestrial issue in Northern China. *Earth Sci. Front.* **2016**, *23*, 312–322. (In Chinese with English Abstract)
4. Zheng, Y.J.; Chen, S.W.; Ding, Q.H.; Li, Y.F.; Zhang, J.; Wang, J.; Li, X.H.; Su, F.; Gao, X.Y. Chronostratigraphy of the Jurassic Tuchengzi Formation in Northern Hebei and Western Liaoning, China. *Geol. Resour.* **2010**, *19*, 293–295. (In Chinese with English Abstract)
5. Pang, Q.Q.; Li, P.X.; Tian, S.G.; Liu, Y.Q. Discovery of ostracods in the Dabeigou and Dadianzi Formations at Zhangjiagou, Luanping County, northern Hebei Province of China and new progress in the biostratigraphic boundary study. *Geol. Bull. China* **2002**, *21*, 329–338. (In Chinese with English Abstract)
6. Liu, Y.Q.; Pang, Q.Q.; Li, P.X.; Tian, S.G.; Niu, S.W. Advances in the study of non-marine Jurassic-Cretaceous biostratigraphi cal boundary and candidate stratotype in Luanping basin,northern Hebei. *Geol. Bull. China* **2002**, *21*, 176–180. (In Chinese with English Abstract)
7. Wang, Q.F.; Chen, P.J. A brief introduction to the Cretaceous chronostratigraphic study. *J. Stratigr.* **2005**, *29*, 114–123. (In Chinese with English Abstract)
8. Tian, S.G.; Niu, S.W.; Pang, Q.Q. Redefinition of the Lower Cretaceous terrestrial Yixianian Stage and its stratotype candidate in the Luanping basin, northern Hebei, China. *Geol. Bull. China* **2008**, *27*, 739–752. (In Chinese with English Abstract)
9. Tian, S.G.; Pang, Q.Q.; Niu, S.W.; Li, P.X.; Liu, Y.Q. Terrestrial Jurassic-Cretaceous boundary stratotype candidate in Luanping basin, northern Hebei. *Geol. Bull. China* **2004**, *23*, 1170–1179. (In Chinese with English Abstract)
10. Ji, Q.; Liu, Y.Q.; Ji, S.A.; Chen, W.; Lu, J.C.; You, H.L.; Yuan, C.X. On the terrestrial Jurassic-Cretaceous Boundary in China. *Geol. Bull. China* **2006**, *25*, 336–339. (In Chinese with English Abstract)
11. Zhou, Z.H.; He, H.Y.; Wang, X.L. The continental Jurassic-Cretaceous Boundary in China. *Acta Palaeontol. Sin.* **2009**, *48*, 541–555. (In Chinese with English Abstract)
12. Xu, H.; Liu, Y.Q.; Kuang, H.W.; Jiang, X.J.; Peng, N. U-Pb SHRIMP age for the Tuchengzi Formation, northern China, and its implications for biotic evolution during the Jurassic-Cretaceous transition. *Palaeoworld* **2012**, *21*, 222–234. [CrossRef]
13. Wan, X.Q.; Li, G.; Huang, Q.H.; Xi, D.P.; Chen, P.J. Division and correlation of terrestrial cretaceous stages in China. *J. Stratigr.* **2013**, *37*, 457–471. (In Chinese with English Abstract)
14. Casellato, C.E. Calcareous nannofossil biostratigraphy of Upper Callovian—Lower Berriasian succession from the southern Alps, North Italy. *Riv. Ital. Di Paleontol. Stratigr.* **2010**, *116*, 357–404.
15. Gradstein, F.M.; Ogg, J.G.; Schmitz, M.D. *The Geologic Time Scale*; Elsevier: Amsterdam, The Netherlands, 2012; pp. 795–813.
16. Mahoney, J.J.; Duncan, R.A.; Tejada, M.L.G.; Sager, W.W.; Bralower, T.J. Jurassic-Cretaceous boundary age and mid-ocean-ridge–type mantle source for Shatsky Rise. *Geology* **2005**, *33*, 185–188. [CrossRef]
17. Liu, Y.Q.; Ji, Q.; Jiang, X.J.; Kuang, H.W.; Ji, S.; Gao, L.F.; Zhang, Z.G.; Peng, N.; Yuan, C.X.; Wang, X.R. U-Pb zircon ages of early Cretaceous volcanic rocks in the Tethyan Himalaya at Yangzuoyong Co Lake, Negarze, Southern Tibet, and implications for the Jurassic/Cretaceous boundary. *Cretac. Res.* **2013**, *40*, 90–101. [CrossRef]
18. Vennari, V.V.; Lescano, M.; Naipauer, M.; Aguirre-Urreta, B.; Concheyro, A.; Schaltegger, U.; Armstrong, R.; Pimentel, M.; Ramos, V.A. New constraints on the Jurassic-Cretaceous boundary in the High Andes using high-precision U-Pb data. *Gondwana Res.* **2014**, *26*, 374–385. [CrossRef]
19. Chen, P.J. Comments on the Classification and Correlation of Non-marine Jurassic and Cretaceous of China. *J. Stratigr.* **2000**, *24*, 114–119. (In Chinese with English Abstract)
20. All China Commission of Stratigraphy. *Specification of Regional Chronostratigraphic (Geological) Chronology in China*; Geological Press: Beijing, China, 2002; pp. 1–72. (In Chinese with English Abstract)
21. Pang, Q.Q.; Tian, S.G.; Li, P.X.; Niu, S.W.; Liu, Y.Q. Ostracod biostratigraphy of the Dabeigou and Dadianzi formations and Jurassic-Cretaceous boundary in the Luanping basin, northern Hebei, China. *Geol. Bull. China* **2006**, *25*, 348–356. (In Chinese with English Abstract)
22. Niu, S.W.; Tian, S.G.; Pang, Q.Q. Conchostracan biostratigraphy of the Dadianzi Formation in the Luanping basin, northern Hebei, China and the boundary of continental Jurassic and Cretaceous strata. *Geol. Bull. China* **2010**, *29*, 961–979. (In Chinese with English Abstract)
23. Wang, W.L.; Zhang, L.J.; Zheng, S.L.; Ren, D.; Zheng, Y.J.; Ding, Q.H.; Zhang, H.; Li, Z.T.; Yang, F.L. The age of the Yixianian Stage and the boundary of Jurassic-Cretaceous—The establishment and study of stratotypes of the Yixianian Stage. *Geol. Rev.* **2005**, *51*, 234–242. (In Chinese with English Abstract)
24. Yin, H.F. Notes on the compilation of China stratigraphic table and the revision of China stratigraphic guide. *J. Stratigr.* **2014**, *38*, 123–125. (In Chinese with English Abstract)
25. Swisher, C.C., III; Wang, Y.L.; Zhou, Z.H.; Wang, Y.Q.; Jin, F.; Zhang, J.Y.; Xue, X.; Zhang, F.C.; Wang, Y. New evidence of isotopic age of Yixian Formation and 40Ar/39Ar dating of Tuchengzi Formation. *Chin. Sci. Bull.* **2001**, *46*, 2009–2012. (In Chinese with English Abstract)

26. Davis, G.A. The Late Jurassic "Tuchengzi/Houcheng" Formation of the Yanshan fold-thrust belt: An analysis. *Earth Sci. Front.* **2005**, *12*, 331–345.
27. Zhang, H.; Yuan, H.L.; Hu, Z.C.; Liu, X.M.; Diwu, C.R. U-Pb Zircon dating of the Mesozoic volcanic strata in Luanping of North Hebei and its significance. *Earth Sci. J. China Univ. Geosci.* **2005**, *30*, 707–720. (In Chinese with English Abstract)
28. Sun, L.X.; Zhao, F.Q.; Wang, H.C.; Gu, Y.C.; Ji, S.P. Correlationship of Tuchengzi Formation and implications of the Basin Tectonic Evolution in the Intracontinental Yanshan Orogenic Belt. *Acta Geol. Sin.* **2007**, *81*, 445–453. (In Chinese with English Abstract)
29. Xu, H.; Liu, Y.Q.; Kuang, H.W.; Peng, N. Ages of the Tuchengzi Formation in northern China and the terrestrial Jurassic-Cretaceous boundary in China. *Earth Sci. Front.* **2014**, *21*, 203–215. (In Chinese with English Abstract)
30. Shen, Y.B.; Chen, P.J. Late Middle Jurassic conchostracans from the Tuchengzi Formation of W. Liaoning, NE China. Bulletin of Nanjing Institute of Geology and Palaeontology. *Chin. Acad. Sci.* **1984**, *9*, 309–326. (In Chinese with English Abstract)
31. Wang, S.N. Correlation of the continental Jurassic in The North of China to the Paralic Jurassic in Northwest Scotland, United Kingdom with a discussion of the stratigraphic subdivision and correlation of the Jurassic in the North of China. *Acta Geol. Sin.* **1998**, *72*, 11–20.
32. Wang, W.L.; Zhang, H.; Zhang, L.J.; Zheng, S.L.; Yang, F.L.; Li, Z.T.; Zheng, Y.J.; Ding, Q.H. *Standard Sections of Tuchengzi Stage and Yixian Stage and Their Stratigraphy, Palaeontology and Tectonic-Volcanic Actions*; Geological Publishing House: Beijing, China, 2004; pp. 21–91. (In Chinese with English Abstract)
33. Wang, S.E.; Li, G. New fossil clam shrimps from the Tuchengzi formation of Northern Hebei and Western Liaoning. *Acta Palaeontol. Sin.* **2008**, *47*, 319–325. (In Chinese with English Abstract)
34. Wang, S.E.; Gao, L.Z.; Wan, X.Q.; Song, B. Ages of Tuchengzi formation in western Liaoning-northern Hebei area in correlation with those of international strata. *Geol. Bull. China* **2013**, *32*, 1673–1690. (In Chinese with English Abstract)
35. Deng, S.H.; Lu, Y.Z.; Zhao, Y.; Fan, R.; Wang, Y.D.; Yang, X.J.; Li, X.; Sun, B.N. The Jurassic palaeoclimate regionalization and evolution of China. *Earth Sci. Front.* **2017**, *24*, 106–142. (In Chinese with English Abstract)
36. Li, G.; Matsuoka, A. Searching for a non-marine Jurassic/Cretaceous boundary in northeastern China. *J. Geol. Soc. Jpn.* **2015**, *121*, 109–122.
37. Li, W.; Wan, X.Q.; Atsushi, M.; Zhang, S.Q.; Qu, H.Y.; Tsubasa, T.; Kohei, Y. Jurassic-Cretaceous boundary strata of the Somanakamura Group in NE Japan and their correlation with coeval terrestrial deposits in China. *Acta Geol. Sin.* **2015**, *89*, 285–299.
38. Deng, S.H.; Wang, S.E.; Yang, Z.Y.; Lu, Y.Z.; Li, X.; Hu, Q.Y.; An, C.Z.; Xi, D.P.; Wan, X.Q. Comprehensive Study of the Middle–Upper Jurassic strata in the Junggar Basin, Xinjiang. *Acta Geosci. Sin.* **2015**, *36*, 559–574. (In Chinese with English Abstract)
39. Wang, D.N.; Wang, X.R.; Ji, Q. The Palynoflora alternation and the Paleoclimate change at the turning time between Late Jurassic and Early Cretaceous in Northern Hebei and Western Liaoning. *Acta Geosci. Sin.* **2016**, *37*, 449–459. (In Chinese with English Abstract)
40. Liu, S.F.; Lin, C.F.; Liu, X.B.; Zhuang, Q.T. Syn-tectonic sedimentation and its linkage to fold-thrusting in the region of Zhangjiakou, North Hebei, China. *Sci. China Earth Sci.* **2018**, *61*, 681–710. [CrossRef]
41. Wan, X.Q.; Sun, L.X. Terrestrial Fossil Assemblages of Tuchengzi Formation and Jurassic-Cretaceous Boundary chronostratigraphy in Yanliao Area. *Acta Palaeontol. Sin.* **2020**, *59*, 1–12. (In Chinese with English Abstract)
42. Liu, Y.J.; Zhang, X.Z.; Jin, W.; Chi, X.G.; Wang, C.W.; Ma, Z.H.; Han, G.Q.; Wen, Q.B.; Li, W.; Wang, W.D.; et al. Late Paleozoic tectonic evolution in Northeast China. *Geol. China* **2010**, *37*, 943–951. (In Chinese with English Abstract)
43. Wang, C.W.; Sun, Y.W.; Li, N.; Zhao, G.W.; Ma, X.Q. Tectonic implications of late Paleozoic stratigraphic distribution in Northeast China and adjacent region. *Sci. China Ser. D Earth Sci.* **2009**, *52*, 619–626. [CrossRef]
44. Zhou, J.B.; Wilde, S.A.; Zhang, X.Z.; Zhao, G.C.; Zheng, C.Q.; Wang, Y.J.; Zhang, X.H. The onset of Pacific margin accretion in NE China: Evidence from the Heilongjiang high-pressure metamorphic belt. *Tectonophysics* **2009**, *478*, 230–246. [CrossRef]
45. Wang, P.J.; Zhao, R.L.; Meng, Q.A.; Qu, X.J.; Zhu, D.F.; Gao, Y.F. The Cretaceous Songliao Basin: Dynamic background from volcanic rift to interior sag basin. *Earth Sci. Front.* **2015**, *22*, 99–117. (In Chinese with English Abstract)
46. Zhang, X.Z.; Guo, Y.; Zeng, Z.; Fu, Q.L.; Pu, J.B. Dynamic evolution of the Mesozoic-Cenozoic basins in the northeastern China. *Earth Sci. Front.* **2015**, *22*, 88–98. (In Chinese with English Abstract)
47. Dong, S.W.; Zhang, Y.Q.; Chen, X.H.; Long, C.X.; Wang, T.; Yang, Z.Y.; Hu, J.M. The formation and deformational characteristics of East Asia multi-direction convergent tectonic system in Late Jurassic. *Acta Geosci. Sin.* **2008**, *29*, 306–317. (In Chinese with English Abstract)
48. Dong, S.W.; Zhang, Y.Q.; Li, H.L.; Shi, W.; Xue, H.M.; Li, J.H.; Huang, S.Q.; Wang, Y.C. The Yanshan orogeny and late Mesozoic multi-plate convergence in East Asia—Commemorating 90th years of the "Yanshan Orogeny". *Sci. China Earth Sci.* **2018**, *61*, 1888–1909. [CrossRef]
49. Xing, D.H.; Sun, C.L.; Sun, Y.W.; Zhang, L.D.; Guo, S.Z.; Zhang, C.J.; Peng, Y.D.; Jia, B.; Chen, S.W.; Ding, Q.H. Stratigraphic sequence of Tuchengzi Formation in Jinlingsi-Yangshan Basin, Western Liaoning Province. *Geol. Resour.* **2006**, *15*, 166–173. (In Chinese with English Abstract)
50. Xing, D.H.; Zhang, L.D.; Guo, S.Z.; Zhang, C.J.; Peng, Y.D.; Jia, B.; Chen, S.W.; Ding, Q.H.; Zheng, Y.J. Sequence stratigraphy of the Tuchengzi Formation in the northern part of the Jinlingsi-Yangshan basin, western Liaoning, and basin evolution. *Chin. Geol.* **2001**, *28*, 5–12. (In Chinese with English Abstract)

51. He, B.; Li, M.F.; Liu, Y.X. Jinlingsi-Yangshan Basin Beipiao Formation hydrocarbon source rock characteristics. *Coal Geol. China* **2008**, *20*, 25–27. (In Chinese with English Abstract)
52. Wong, W.H. Tectonic studies on Beipiao area of Jehol. *Geol. Rep.* **1928**, *11*, 23. (In Chinese with English Abstract)
53. Wong, W.H. Crustal movements and igneous activities in eastern China since Mesozoic time. *Bull. Geol. Soc. China* **1927**, *6*, 9–37. [CrossRef]
54. Zhang, H.R.; Zhang, Y.K.; Cai, X.M.; Qu, H.J.; Li, H.L.; Wang, M. The triggering of Yanshan Movement: Yanshan Event. *Acta Geol. Sin.* **2013**, *87*, 1779–1790.
55. Huang, D.Y. Yanliao Biota and Yanshan Movement. *Acta Palaeontol. Sin.* **2015**, *54*, 501–546. (In Chinese with English Abstract)
56. Zhang, R.H. The phasing of Yanshan Movement and its several important questions. *Acta Geol. Sin.* **2016**, *90*, 2176–2180. (In Chinese with English Abstract)
57. Zhu, J.C.; Feng, Y.C.; Meng, Q.R.; Wu, F.C.; Li, H.; Liu, H.T.; Zhang, F.P.; Wang, T.Y.; Wu, G.L.; Zou, C.N.; et al. Late Mesozoic tectonostratigraphic division and correlation of Bohai Bay basin: Implications for the Yanshanian Orogeny. *Sci. China Earth Sci.* **2020**, *62*, 1783–1804. [CrossRef]
58. Xi, D.P.; Wan, X.Q.; Li, G.B.; Li, G. Cretaceous integrative stratigraphy and timescale of China. *Sci. China Earth Sci.* **2019**, *62*, 256–286. [CrossRef]
59. Huang, D.Y. Jurassic integrative stratigraphy and timescale of China. *Sci. China Earth Sci.* **2019**, *62*, 223–255. [CrossRef]
60. Xu, W.L.; Wang, F.; Pei, F.P.; Meng, E.; Tang, J.; Xu, M.J.; Wang, W. Mesozoic tectonic regimes and regional ore-forming background in NE China: Constraints from spatial and temporal variations of Mesozoic volcanic rock associations. *Acta Petrol. Sin.* **2013**, *29*, 339–353. (In Chinese with English Abstract)
61. Dong, S.W.; Zhang, Y.Q.; Long, C.X.; Yang, Z.Y.; Ji, Q.; Wang, T.; Hu, J.M.; Chen, X.H. Jurassic tectonic revolution in China and new interpretation of the Yanshan Movement. *Acta Geol. Sin.* **2007**, *81*, 1449–1461. (In Chinese with English Abstract)
62. Yang, X.D.; Li, X.Y. *Stratigraphy (Lithostratic) of Liaoning Province*; China University of Geosciences Press: Wuhan, China, 1997; pp. 1–247. (In Chinese with English Abstract)
63. Zhai, M.G.; Hu, B.; Zhao, T.P.; Peng, P.; Meng, Q.R. Late Paleoproterozoic–Neoproterozoic multi-rifting events in the North China Craton and their geological significance: A study advance and review. *Tectonophysics* **2015**, *662*, 153–166. [CrossRef]
64. Sun, S.L.; Li, Y.F.; Gao, X.Y.; Zhou, T.S.; Zhang, T.; Wang, S.H. An analysis of the genesis and geochemical characteristics of shale gas in Lower Jurassic Beipiao Formation in Jinyang Basin. *Geol. Bull. China* **2017**, *36*, 575–581. (In Chinese with English Abstract)
65. Liu, Y.S.; Hu, Z.C.; Zong, K.Q.; Gao, C.G.; Chen, H.H. Reappraisement and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS. *Chin. Sci. Bull.* **2010**, *55*, 1535–1546. [CrossRef]
66. Liu, Y.S.; Gao, S.; Hu, Z.C.; Gao, C.G.; Zong, K.Q.; Wang, D.B. Continental and oceanic crust recycling-induced melt-peridotite interactions in the Trans-North China Orogen:U-Pb Dating,Hf isotopes and trace elements in zircons from mantle xenoliths. *J. Petrol.* **2010**, *51*, 537–571. [CrossRef]
67. Ludwig, K.R. *ISOPLOT 3.0: A Geochronological Toolkit for Microsoft Excel*; Special Publication: Berkeley, CA, USA, 2003; p. 70.
68. Belousova, E.A.; Griffin, W.L.; O'Reilly, S.Y.; Fisher, N. Igneous zircon: Trace element composition as an indicator of source rock type. *Contrib. Mineral. Petrol.* **2002**, *143*, 602–622. [CrossRef]
69. Hoskin, P.W.O.; Ireland, T.R. Rare earth element chemistry of zircon and its use as a provenance indicator. *Geology* **2000**, *28*, 627–630. [CrossRef]
70. Pang, Q.Q. Ostracods from middle and Upper Jurassic in Yanshan area, Hebei Province and their stratigraphic significance. *J. Hebei GEO Univ.* **1982**, *Z1*, 89–110. (In Chinese with English Abstract)
71. Pu, R.G.; Wu, H.Z. Palynopollen assemblage of middle and late Jurassic in western Liaoning Province. *J. Shenyang Inst. Geol. Miner. Resour.* **1982**, *4*, 169–184. (In Chinese with English Abstract)
72. Yang, R.Q. Jurassic-Cretaceous ostracods assemblage in Hebei Province and its stratigraphic significance. *J. Hebei GEO Univ.* **1984**, *4*, 30–46. (In Chinese with English Abstract)
73. Xiao, Z.Z.; Yang, H.L.; Shan, Q.S. *Mesozoic Strata and Biota in Beijing*; Geological Press: Beijing, China, 1994; pp. 119–121. (In Chinese with English Abstract)
74. Hong, Y.C. Discovery of fossil insects from Houcheng Formation of Hebei Province and establish of Houcheng Entomofauna. *Beijing Geol.* **1997**, *1*, 1–7. (In Chinese with English Abstract)
75. Zheng, S.L. *Division, Correlation and Age of Tuchengzi Formation in Northern Hebei and Western Liaoning: Editorial Board of Theses of the Third National Stratigraphic Conference//Proceedings of the Third National Stratigraphic Conference*; Geological Press: Beijing, China, 2000; pp. 227–232. (In Chinese with English Abstract)
76. Zheng, S.L.; Zhang, W.; Ding, Q.H. Discovery of fossil plants from Middle-Upper Jurassic Tuchengzi Formation in Western Liaoning, China. *Acta Palaeontol. Sin.* **2001**, *40*, 67–85. (In Chinese with English Abstract)
77. Wang, S.E.; Ji, Q. *A Comprehensive Study of the Continental Upper Jurassic Tuchengzi Stage in China//the Third National Stratigraphic Commission: A Study Report on the Establishment of the Main Chronological Strata In China*; Geological Press: Beijing, China, 2008; pp. 105–114. (In Chinese with English Abstract)
78. He, Z.J.; Wang, Z.Q.; Ren, J.S. A preliminary research on sedimentary features and genetic mechanism of frontal basins before Jurassic large-scale nappe in the Northern Region of North China. *Chin. J. Geol.* **1999**, *34*, 186–195. (In Chinese with English Abstract)

79. He, Z.J.; Li, J.Y.; Niu, B.G.; Ren, J.H. A late Jurassic intense thrusting-uplifting event in the Yanshan—Yinshan area, Northern China, and its sedimentary response. *Geol. Rev.* **1998**, *44*, 407–418. (In Chinese with English Abstract)
80. Wang, Z.J.; Huang, Z.G.; Yao, J.X.; Ma, X.L. Characteristics and main progress oft the stratigraphic chart of China and directions. *Acta Geosci. Sin.* **2014**, *35*, 271–276. (In Chinese with English Abstract)
81. Huang, Z.A.; Pan, Y.Q.; Yang, Y.J. *Regional Geological Survey Report of 1:250,000 Zone in Jinzhou*; Liaoning Provincial Institute of Geology and Mineral Resources Investigation: Dalian, China, 2003; pp. 1–391. (In Chinese with English Abstract)
82. Fan, J.X.; Chen, D.Y.; Hou, X.D. The International Chronostratigraphic Chart (v 2016/04), Its color model and application. *J. Stratigr.* **2016**, *40*, 341–348. (In Chinese with English Abstract)
83. Lin, M.Q.; Li, J.G.; Peng, J.G. Early Cretaceous palynological assemblages from the Third Member of the Tuchengzi Formation at Sihetun, Beipiao County, Western Liaoning Province, Northeast China and their implications. *Acta Micropalaeontologica Sin.* **2016**, *33*, 261–271. (In Chinese with English Abstract)
84. Kozhevnikov, V.M.; Ruzhentsev, S.V.; Dergunov, A.B.; Filippova, I.B.; Tomurtogoo, O.; Arvisbaatar, N.; Bayasgalan, T. The South Siberia—Central Mongolia transect. *Tectonophysics* **1993**, *225*, 361–378.
85. Zorin, Y.A. Geodynamics of the western part of the Mongolia-Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia. *Tectonophysics* **1999**, *306*, 33–56. [CrossRef]
86. Mo, S.G.; Han, M.L.; Li, J.Y. Compositions and orogenic processes of Mongolia-Okhotsk Orogen. *J. Shandong Univ. Sci. Technol.* **2005**, *24*, 50–52, 64. (In Chinese with English Abstract)
87. Kravchinsky, V.A.; Cogné, J.P.; Harbert, W.P.; Kuzmin, M.I. Evolution of the Mongol-Okhotsk Ocean as constrained by new palaeomagnetic data from the Mongol-Okhotsk suture zone, Siberia. *Geophys. J. Int.* **2002**, *148*, 34–57. [CrossRef]
88. Sorokin, A.A.; Sorokin, A.P.; Ponomarchuk, V.A.; Travin, A.V. The age and geochemistry of volcanic rocks on the eastern flank of the Umlekan-Ogodzha volcanoplutonic belt (Amur region). *Russ. Geol. Geophys.* **2010**, *51*, 369–379. [CrossRef]
89. Wang, C.Y.; Wang, D.B.; Qu, J.J. Chronology and geochemistry of rhyolites in Manketou'ebo Formation from Keyihe area,north-central Greater Xing'an Range. *J. Heilongjiang Univ. Sci. Technol.* **2017**, *27*, 46–50. (In Chinese with English Abstract)
90. Gao, L.F.; He, Z.H.; Sui, Z.M.; Lu, K.J.; Liu, F.Y. Chronology and geochemistry of volcanic rocks from Manketouebo Formation in the Suolun area, central Da Hinggan Mountains and their tectonic implications. *Geol. Bull. China* **2018**, *37*, 881–894. (In Chinese with English Abstract)
91. Liu, K.; Wu, T.T.; Liu, J.L.; Bao, Q.Z.; Du, S.Y. Geochronology and geochemistry of volcanic rocks in Manketou'ebo Formation of Tulihe area, northern Da Hinggan Mountains. *Geol. China* **2018**, *45*, 367–376. (In Chinese with English Abstract)
92. Guo, J.G.; Zhang, Y.J.; Zhang, C.; Li, W.; Wang, Y.; Wang, Q.Z.; Guo, J. Formation age and geochemical characteristics of volcanic rocks in Manketou'ebo Formation in Kundu area of Ar Horqin Banner, Inner Mongolia. *Geol. Bull. China* **2018**, *37*, 1652–1661. (In Chinese with English Abstract)
93. Jia, B.; Wei, L.Y.; Wu, H.H.; Zhang, Z.; Tang, W.D.; Liu, T.H.; Chai, C.H.; Meng, W.Y. Chronology, geochemistry and geological significance of volcanic rocks of the Manketouebo Formation in Horqin Right-Front Banner area, Inner Mongolia. *Acta Petrol. Et Mineral.* **2021**, *40*, 859–873. (In Chinese with English Abstract)
94. Si, Q.L.; Cui, T.R.; Tang, Z.; Li, W.; Wu, X.W.; Jiang, B.; Li, L.C. Chronology, geochemistry and petrogenesis of the volcanic rocks in Manitu Formation in Chaihe Area, Central Great Xing'an Range. *J. Jilin Univ. Earth Sci. Ed.* **2015**, *45*, 389–403. (In Chinese with English Abstract)
95. Zhang, X.; Zhen, S.U.; Gao, Y. Zircon U–Pb geochronology and geochemistry of the early Cretaceous volcanic rocks from the Manitu Formation in the Hongol Area, Northeastern Inner Mongolia. *Acta Geol. Sin. Engl. Ed.* **2017**, *91*, 1286–1304. [CrossRef]
96. Tao, C.Z.; Li, Z.M.; Wang, D.Q.; Shen, X.; Zhang, Y.J.; Li, B. La-icp-ms zircon U-Pb dating and geochemistry of the volcanic rocks from manitu formation in Ulanhot region of southern Daxinganling. *Geol. Resour.* **2015**, *24*, 102–109. (In Chinese with English Abstract)
97. Wang, C.Y.; Sun, D.Y.; Tian, L.H.; Bu, J.; Shang, Y.H. Latest zircon u-pb age of the baiyingaolao formation volcanic rocks in the keyihe area of north-central da hinggan mountains. *Acta Geol. Sin.* **2018**, *92*, 360–361. [CrossRef]
98. Yin, Y.K.; Gao, Y.F.; Wang, P.J.; Qu, X.J.; Liu, H.B. Discovery of Triassic volcanic-sedimentary strata in the basement of Songliao Basin. *Sci. Bull.* **2019**, *64*, 644–646. [CrossRef]
99. Liu, H.B.; Wang, P.J.; Gao, Y.F.; Hou, H.S.; Yin, Y.K.; Li, H.H.; Feng, Y.H. New data from ICDP borehole SK2 and its constraint on the beginning of the Lower Cretaceous Shahezi Formation in the Songliao Basin, NE China. *Sci. Bull.* **2020**, *66*, 411–413. [CrossRef]
100. Gao, R.Q.; Xiao, D.M. *New Progress in Oil and Gas Exploration in Songliao and Its Peripheral Basins*; Petroleum Industry Press: Beijing, China, 1995; pp. 13–15. (In Chinese with English Abstract)
101. Zhu, D.F.; Ren, Y.G.; Wu, H.Y.; Wu, G.Y.; Wan, C.B.; Wu, X.M. A preliminary study on the buried Permian and Jurassic in the Northern Songliao Basin. *Chin. J. Geol.* **2007**, *42*, 690–708, 778. (In Chinese with English Abstract)
102. Qu, X.J.; Wang, P.J.; Gao, Y.F.; Wan, X.Q. Chronostratigraphy of Huoshiling Formation in the Songliao Basin, NE China. *Earth Sci. Front.* **2014**, *21*, 234–250. (In Chinese with English Abstract)
103. Qu, X.J.; Wang, P.J.; Yao, R.S.; Gao, Y.F.; Bai, B. Stratigraphical sequence and regional correlation of Huoshiling Formation in southern Songliao Basin. *J. Cent. South Univ.* **2014**, *45*, 2716–2727. (In Chinese with English Abstract)
104. Wang, P.J.; Liu, W.Z.; Wang, S.X.; Song, W.H. 40Ar/39Ar and K/Ar dating on the volcanic rocks in the Songliao basin, NE China: Constraints on stratigraphy and basin dynamics. *Int. J. Earth Sci.* **2002**, *91*, 331–340. [CrossRef]

105. Lin, M.Q.; Li, J.G. Palynological assemblages from the Tuchengzi and Dabeigou formations in the Luanping Basin at Sanchazi Section, Northern Hebei Province and their implications. *Acta Palaeontol. Sin.* **2021**, *60*, 263–280. (In Chinese with English Abstract)
106. Sun, G.; Sha, J.G.; Wang, Y.G.; Yuan, F.S.; Xiong, X.Z.; Piao, T.Y. Jurassic-Cretaceous Boundary of Dong'anzhen, Raohe, Heilongjiang with a new knowledge of Buchia. *Acta Palaeontol. Sin.* **1989**, *28*, 579–590. (In Chinese with English Abstract)
107. Sun, G.; Zhen, S.L.; Sun, X.K.; He, C.Q.; Piao, T.Y.; Shang, Y.K.; Zhang, C.B.; Yu, Z.Z.; Zhao, Y.H. Recent advance in the research of the strata near the Jurassic-Cretaceous boundary in eastern Heilongjiang. *J. Stratigr.* **1992**, *16*, 49–54, 83. (In Chinese with English Abstract)
108. Sun, X.K.; He, C.Q. Dinoflagellates from upper Jurassic dongrong formation of Suibin, Heilongjiang. *Acta Palaeontol. Sin.* **1992**, *31*, 190–205, 267.
109. He, C.Q.; Zhu, Y.H. Dinoflagellate assemblage from the uppermost part of the Dongrong formation with discussion on Jurassic-Cretaceous boundary in Suibin area, Northeastern Heilongjiang province, Ne China. *Acta Palaeontol. Sin.* **2003**, *42*, 328–345. (In Chinese with English Abstract)