Involvement of the Northeastern Margin of South China Block in Rodinia Supercontinent Evolution: A Case Study of Neoproterozoic Granitic Gneiss in Rizhao Area, Shandong Province

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Abstract: The South China Plate is an important part of the Rodinia supercontinent in the Neoproterozoic. The Rizhao area, located on the northeastern margin of the South China Plate, records multiple periods of magmatism, among which Neoproterozoic granitic gneiss is of great significance to the tectonic evolution of the South China Block. In this study, systematic petrology, geochemistry, isotopic chronology, and zircon Hf isotopic analyses were carried out on gneisses samples of biotite alkali feldspar granitic and biotite monzogranitic compositions in the Rizhao area. Geochemical analyses suggest that these granitic rocks belong to the sub-alkaline series and have high potassium contents. They are enriched in large-ion lithophile elements K, Rb, and Ba; depleted in high field strength elements P, Nb, and Ti; enriched in light rare earth elements and moderately depleted in heavy rare earth elements; and have weak to moderate negative Eu anomalies and weak negative Ce anomalies. These rocks are post-orogenic A-type granites. LA-MC-ICP-MS U-Pb dating of zircons from two biotite alkali-feldspar granitic gneiss samples yielded weighted mean ages of 785 ± 8 Ma (MSWD = 3.0) and 784 ± 6 Ma (MSWD = 1.5), respectively, and a biotite monzogranitic gneiss sample yielded a weighted mean age of 789 ± 6 Ma (MSWD = 2.3). Lu-Hf isotopic analyses on zircon grains from the two types of Neoproterozoic-aged gneisses sampled yielded εHf(t) values ranging from −19.3 to −8.8 and from −26.3 to −10.4, respectively, and the corresponding two-stage Hf model age ranges are 2848–3776 Ma and 2983–3682 Ma, respectively. These granites are the product of Neoproterozoic magmatic activity and are mainly derived from the partial melting of Archean continental crust. Combining the geochemical characteristics and zircon U-Pb-Lu-Hf isotopic analyses, these A-type granitic gneisses appear to have formed in an intracontinental rift extension environment during the initial break-up of the Rodinia supercontinent, as part of the supercontinent break-up process at the northeastern margin of the South China Block.

Keywords: Neoproterozoic; granitic gneiss; geochemistry; Zircon U-Pb; Lu-Hf isotopes

1. Introduction

The Rodinia supercontinent was first proposed by McMenamin and McMenamin [1], and Hoffman [2] improved and developed the SWEAT hypothesis. The splicing of ancient cratons formed the Rodinia supercontinent during the formation of the Grenville orogenic belt around 1.10 Ga [3–6]. After the concept of the supercontinent was proposed, its formation and evolution process attracted widespread attention from geologists. The supercontinent existed for ca. 1050–650 Ma and experienced convergence in the late Mesoproterozoic (1.3–1.0 Ga Grenville period) and rifting in the early-middle Neoproterozoic [7].
Some researchers have also proposed that mantle plume activity caused supercontinent rifting [8].

The South China Block is an essential part of the Rodinia supercontinent. In the process of supercontinent reconstruction, there are the following views on the location of the South China Block: (1) located in the core of the Rodinia supercontinent between Australia and Laurentia [5,6,9]; (2) located at the edge of the supercontinent, northeast of the Indian plate [10,11]. Different views on the location of the South China Block within the Rodinia supercontinent have led to the following views on the tectonic background of ca. 860–750 Ma igneous rocks around the block: (1) they are of mantle plume origin and formed in a tensional environment related to mantle plumes [8,9,12]; (2) they are of island arc origin and formed in a compressional environment [13]; (3) they formed in a tensional environment derived from the extensional collapse of the Yangtze–Cathaysia post-orogenic lithosphere [14].

The Rizhao area in Shandong Province is located to the east of the Tanlu Fault on the northeastern margin of the South China Block and belongs to the Qinling–Dabie–Sulu Orogenic Belt [6,9,15] (Figure 1). The Neoproterozoic granitic gneisses in the area have not been reported on before, but their key role in the reconstruction of the South China Block makes their study particularly important. Based on the systematic field investigation, petrology, geochemistry, isotope chronology, and Hf isotope analyses were carried out to determine the formation age and petrogenesis of the Neoproterozoic granitic gneisses in the Rizhao area, and to discuss the characteristics of the magma source area and its tectonic significance.

Figure 1. Geological map of the Rizhao area of the South China Block. (a) The inset modified from [15] shows the location of the South China Block. (b) Tectonic sketch map of the Rizhao and adjacent areas, modified from [16]. Abbreviations: UHP = ultra-high-pressure; HP = high-pressure.

2. Geological Setting and Petrographic Characteristics

The Sulu Orogenic Belt is located on the northeastern margin of the South China Block [6,9]. The belt consists mainly of granitic gneiss (>80% of the area), with a small
amount of podded or layered eclogites [15]. The Rizhao area of Shandong Province is located in the east-central part of the Sulu Orogenic Belt, adjacent to the Yellow Sea (Figure 2).

Figure 2. Simplified geological map of the Rizhao area.

The exposed strata in the study area mainly include the Paleoproterozoic Jingshan Group, the Cretaceous Laiyang Group, the Cretaceous Qingshan Group, and the Quaternary sequences (Figure 2). The Paleoproterozoic Jingshan Group consists mainly of biotite metamorphic granulite, biotite schist, and two-mica schist, with minor garnet fibrolite biotite schist, dolomitic hornblende granulite, plagioclase amphibolite, diopside, and diorite marble. The Cretaceous Laiyang Group consists mainly of clastic sequences with medium-fine-grained feldspar sandstone and medium-thick-layered volcaniclastic components. The Cretaceous Qingshan Group consists mainly of volcanic rocks, including basalt, trachyandesite, andesitic agglomerate breccia, tuff breccia agglomerate, rhyolitic breccia, and brecciated tuff. The Quaternary sequences include Pleistocene-Holocene residual slope deposits and a mixture of Holocene alluvial, marine, and aeolian deposits.

Regional faults include the NE-trending Haoguanzhuang Fault, the Xiangdi-Gaogezihuang Fault, and the Rizhao-Jiaonan Fault (Figure 2). Magmatic rocks are distributed over a wide area and include many rock types of Paleoproterozoic, Mesoproterozoic, Neoproterozoic, and Mesozoic age, of which Neoproterozoic magmatic rocks are the most common. Paleoproterozoic rocks mainly include the Xishuikuang fine-grained meta-gabbro. Mesoproterozoic rocks include the Yandunshan medium-fine-grained meta-pyroxene hornblende rock and the Laohuangshan...
medium-fine-grained metagabbro. The Neoproterozoic units include various metamorphic granite intrusions of the Tieshan, Yuejishan, and Rongcheng super-units, and the lithologies are mainly the alkali feldspar granitic gneiss and monzogranitic gneiss with different component of biotite. The Mesozoic magmatic rocks include the Triassic Liulinzhuan super-unit, the Jurassic Linglong super-unit, and the Cretaceous Buliu, Weideshan, and Dalaoshan super-units. Lithologies include monzogranite, syenite, hornblende granite, and quartz syenite.

The Neoproterozoic gneiss units investigated in this study (Figures 2 and 3) are mainly biotite alkali feldspar granitic gneisses (e.g., sample numbers of RZ07, RZ08, RZ16, and RZ30) and biotite monzogranitic gneisses (e.g., sample numbers of RZ04 and RZ47). The biotite alkali feldspar granitic gneisses are generally light red–brown in color and have a massive structure (Figure 3a,d). They are porphyroclastic and contain alkali feldspar and plagioclase phenocrysts that are generally between 0.8 and 8.0 mm in size (Figure 3a–f). Alkali feldspar (~15% of the intrusion) is euhedral to subhedral in platelike forms and is dominated by K-feldspar. Some are altered to kaolinite, sericite, and carbonate. Plagioclase (~3–5% of the intrusion) is mainly subhedral in platelike forms, and some have been altered to sericite and kaolinite. These phenocrysts are hosted by fine-grained groundmass (generally 0.1–0.8 mm) or aphyric groundmass containing ~45 vol% K-feldspar, ~10 vol% plagioclase, ~25 vol% quartz, ~3%–5% vol% biotite and minor muscovite, and showing gneissose structure. Minor accessory minerals (~2 vol%) include zircon, apatite, and sphene. Some K-feldspar and plagioclase grains are also altered to sericite and kaolinite. Quartz grains are anhedral, and their aggregates are generally banded. Biotite and muscovite are scaly and are generally intergrown with micrographic quartz grains in banded aggregates.

Figure 3. Field photographs and photomicrographs of the Rizhao granitic gneisses: (a–c) porphyritic biotite alkali feldspar granitic gneiss; (d–f) porphyritic biotite alkali feldspar granitic gneiss; (g–i) porphyritic biotite monzogranitic gneiss; (j–l) medium-fine-grained biotite monzogranitic gneiss. Abbreviations: Qtz = quartz; Bt = biotite; Pl = plagioclase; Kfs = K-feldspar; Amp = amphibolite.

The biotite monzogranitic gneisses are brown–gray in color, with palimpsest porphyroclastic or subhedral granular texture and gneissose structure (Figure 3f–l). For the porphyroclastic gneisses, the phenocrysts (~10% of the intrusion) are dominated by K-feldspar and minor plagioclase with sizes of 0.5–5 mm (Figure 3g). These phenocrysts are hosted by fine-grained or aphyric groundmass (generally <0.2 mm) containing ~30
vol% K-feldspar, ~30 vol% plagioclase, ~20 vol% quartz, and ~10 vol% biotite (Figure 3h,i). The subhedral granular gneisses (Figure 3j–l) are composed of 25–35 vol% K-feldspar, 20–30 vol% plagioclase, ~25 vol% quartz, 5–10 vol% biotite, and ~2 vol% accessory minerals, which include zircon, magnetite, apatite, and sphene. Some K-feldspar and plagioclase grains are also altered to sericite and kaolinite. Quartz grains are anhedral, and their aggregates are generally banded. Biotite and muscovite are scaly and are generally intergrown with micrographic quartz grains in banded aggregates.

3. Sampling and Analytical Methods

Based on the systematic field investigation of the Neoproterozoic units, representative samples were selected for whole-rock geochemical, LA-ICP-MS zircon U-Pb, Lu-Hf, and trace element analyses. The sampling locations are shown in Figure 2. Sample RZ04 is porphyritic biotite monzogranitic gneiss, collected from the drillcore ZK7-7 at a depth of 60.5 m; RZ07 is fine-grained biotite alkali feldspar granitic gneiss, collected from the drillcore ZK10-1 at a depth of 59.7 m; RZ08 is medium-fine-grained biotite alkali feldspar granitic gneiss, collected from the drillcore ZK0-6 at a depth of 49.5 m; RZ16 is fine-grained biotite monzogranitic gneiss, collected from the drillcore ZK-2-1 at a depth of 50 m; RZ30 is porphyritic biotite alkali feldspar granitic gneiss, collected from the drillcore ZK-6-4 at a depth of 53 m; and RZ47 is medium-fine-grained biotite monzogranitic gneiss collected from the surface. Thin-section polishing and mineral separation were undertaken at the Hebei Institute of the Regional Geological Survey Langfang City, Hebei Province, China. Mineral concentrates were prepared using a combination of heavy liquid, magnetic separation, and handpicking techniques, and were analyzed using X-ray diffraction to ensure they were >99% pure.

3.1. Whole-Rock Major- and Trace-Element Analyses

The whole-rock major- and trace-element compositions were analyzed at the Hebei Institute of the Regional Geological Survey, Langfang City, Hebei Province, China. The major element analysis was based on GB/T14506.28-2010, and the analytical instrument used was an Axios max X-ray fluorescence spectrometer (Axios, Arlington, VA, USA). The H$_2$O$^-$ and H$_2$O$^+$ analysis was based on GB/T14506.2-2010, and the calcination vector, H$_2$O$^-$, and H$_2$O$^+$ analysis instrument was a P124S electronic analytical balance. The FeO content analysis was based on GB/T14506.14-2010 using a 50-mL burette. The rare earth and trace element analysis was based on GB/T 14506.30-2010, and the analytical instrument was an ICAPQ inductively coupled plasma mass spectrometer. The laboratory temperature was 18–27 °C, and the relative humidity was 25%–50%.

3.2. Zircon U–Pb, Trace Element, and Lu–Hf Isotopic Analyses

Prior to analysis, the zircons were mounted in epoxy and polished to approximately half their thickness to reveal their interiors. All of the zircons were imaged using reflected and transmitted light and cathodoluminescence (CL) with an Electron Microprobe to determine internal structures and to select spots for zircon U-Pb analysis at the Hebei Institute of the Regional Geological Survey, Langfang City, Hebei Province, China. Zircon sample pretreatment and analyses were carried out at the Beijing Zhongke Mining Research Testing Technology Co., Ltd., Beijing, China. Zircon U-Pb isotope and trace element analyses were conducted using the laser ablation multi-receiver inductively coupled plasma mass spectrometer (LA-ICP-MS; Agilent 7500, Agilent, Tokyo, Japan). The laser wavelength was 193 nm, the laser energy density was 13–14 J/cm$^2$, and the frequency was 8–10 Hz. The ablation protocol employed a spot diameter of 35 μm at a 6 Hz repetition rate for 40 s for zircon. Helium was used as the carrier gas to transport aerosol ICP-MS efficiently. The external standard sample for calibration was Plešovice (age 337 ± 0.37 Ma) [17]. The results of the analysis were calculated using ICP-MS DataCal 10.2 software. See [18] for detailed instrument operation.
The zircon Lu-Hf isotope analysis was performed using a New Wave-213 nm ArF-excimer laser-ablation system linked to a Neptune multiple-collector inductively coupled plasma mass spectrometer (NEPTUNE plus, Thermo Fisher Scientific, Waltham, MA, USA) at the Beijing Zhongke Kuangyan GeoAnalysis Co. Ltd., Beijing, China. The laboratory temperature was 18–22 °C, and the relative humidity was <65%. The ablation protocol employed a spot diameter of 55 µm at a 10 Hz repetition rate and a fluence of 7–8 J/cm² for zircon. Helium was used as a carrier gas to enhance the efficiency of the transport ablated material to the Neptune Plus (MC-ICPMS). The standard lead calibration used the ComPbCorr#3.17 calibration program [19] (In the calculation of the mantle model age of Hf, the present value of 176Hf/177Hf of the depleted mantle is 0.28325, and 176Lu/177Hf is 0.0384 [20]). The crustal model age is calculated using the average crustal 176Lu/177Hf = 0.015 [21].

4. Results
4.1. Whole-Rock Major- and Trace-Element Concentrations

Whole-rock major- and trace-element compositions of six granite gneiss samples are listed in Table S1. These rocks are characterized by 64.78–72.24 wt.% SiO₂, 3.62–5.29 wt.% Na₂O, 2.53–5.32 wt.% K₂O, 0.27–1.15 wt.% MgO, 1.03–3.72 wt.% CaO, 13.05–15.31 wt.% Al₂O₃, and 0.15–0.53 wt.% TiO₂, respectively. The total-alkali-silica (TAS) diagram (Figure 4a) shows the samples plot in the granite and quartz monzonite fields, with sub-alkaline characteristics. These rocks have high K₂O/SiO₂ ratios and belong to the high-potassium calc-alkaline series (Figure 4b).

![Figure 4.](image-url) (a) Total-alkali-silica (TAS) diagram [22]; (b) K₂O–SiO₂ diagram ([23] for the Rizhao granitic gneisses).

The rare earth contents of the Rizhao granitic gneiss samples are relatively low, with a ΣREE content range of 165.18–309.46 ppm. Chondrite-normalized REE patterns of the Rizhao granitic gneiss samples are relatively uniform. They are enriched in light rare earth elements, moderately depleted in heavy rare earth elements, and show moderate fractionation between light and heavy rare earth elements (Figure 5a). They show moderate to weak negative Eu anomaly with δEu values of 0.37–0.94 and show weak negative Ce anomaly with δCe values of 0.81–0.94. Except for sample RZ47, the (La/Yb)N values of the granites are greater than 10 (12.24–51.23). The N-MORB-normalized trace element patterns (Figure 5b) show that they are enriched in large-ion lithophile elements K, Rb, and Ba and depleted in high-field-strength elements P, Nb (except for sample RZ47) and Ti.
Figure 5. (a) Chondrite-normalized REE and (b) N-MORB-normalized trace element patterns of the Rizhao granitic gneisses (normalizing factors are from [24]; N-MORB compositions are from [24]).

4.2. Zircon U–Pb Ages and Trace Element Contents

Zircons of three granitic gneiss samples, including RZ07 and RZ30 of biotite alkali feldspar granitic gneiss and RZ47 of biotite monzogranitic gneiss, have been selected for CL image, LA-MC-ICP-MS U-Pb analysis, and simultaneous trace element analysis. The majority of the zircons from these granitic gneiss samples are light to dark gray in color, are transparent, and have aspect ratios that range from 1:1 to 3:1 (Figure 6). They appear long prismatic and euhedral morphology with oscillatory zoning discernible during CL imaging (Figure 6), which is a distinctive feature of crystallization from a felsic magma [25–27]. A small number of zircons contain inherited cores, but all analyses targeted zircon rims, avoiding these cores. The trace element analysis and isotopic dating were also conducted on crack and inclusion free regions. The results of the trace element analysis and U-Pb dating are presented in Tables S2 and S3, respectively.

Zircons from the sample RZ07 (porphyritic biotite alkali feldspar granitic gneiss; Figure 3a) have Pb contents of 26.54–150.25 ppm, Th contents of 122.83–634.01 ppm, U contents of 80.63–578.00 ppm, and Th/U ratios of 0.87–1.98. Trace element analysis also shows that these zircons have low La contents of <1.39, low $\Sigma$REE contents of 917.7–4850.9 ppm, low LREE contents of 36.6–243.8 ppm, high (Sm/La)$_N$ ratios of 4.8–3046.9, and high (Ce/Ce*)$_N$ ratios of 23.3–1105.7. The analysis of 18 zircons yielded $^{206}$Pb/$^{238}$U dates between c. 807 and 753 Ma, all of which are concordant and yield a $^{206}$Pb/$^{238}$U weighted mean age of 785 ± 8 Ma, MSWD = 3.0 (2 sigma) (Figure 6b).

Zircons from the sample RZ30 (porphyritic biotite alkali feldspar granitic gneiss; Figure 3d) have Pb contents of 10.34–37.58 ppm, Th contents of 28.80–153.34 ppm, U contents of 34.70–180.90 ppm, and Th/U ratios of 0.27–1.36. Trace element analysis also shows that these zircons have low La contents with most <0.07, low $\Sigma$REE contents of 404.8–1487.9 ppm, low LREE contents of 10.0–65.6 ppm, high (Sm/La)$_N$ ratios of 89.4–7334.0, and high (Ce/Ce*)$_N$ ratios of 71.3–810.3. The analysis of 13 zircons yielded $^{206}$Pb/$^{238}$U dates between c. 798 and 767 Ma, all of which are concordant and yield a $^{206}$Pb/$^{238}$U weighted mean age of 784 ± 6 Ma, MSWD = 1.5 (2 sigma) (Figure 6d).

Zircons from the sample RZ47 (medium-fine-grained biotite monzogranitic gneiss; Figure 3j) have Pb contents of 6.05–40.40 ppm, Th contents of 28.74–163.12 ppm, U contents of 21.36–287.86 ppm, and Th/U ratios of 0.25–1.87. Trace element analysis also shows that these zircons have low La contents with most <0.19 (except for two analysis spots), low $\Sigma$REE contents of 483.4–2103.9 ppm, low LREE contents of 7.6–216.9 ppm, high (Sm/La)$_N$ ratios with most >175.1, and high (Ce/Ce*)$_N$ ratios of 33.9–323.2 (except for two analysis spots). The analysis of 29 zircons yielded $^{206}$Pb/$^{238}$U dates between c. 834 and 754 Ma, all of which are concordant and yield a $^{206}$Pb/$^{238}$U weighted mean age of 789 ± 6 Ma, MSWD = 2.3 (2 sigma) (Figure 6d).
4.3. Zircon Lu-Hf Isotopes

All the zircons in this study have low $^{176}\text{Lu}/^{177}\text{Hf}$ ratios, indicating low radiogenic Hf accumulation. Therefore, the initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratio can represent the Hf isotope composition at the time of formation [28]. The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and $\varepsilon_{\text{Hf}}(t)$ values

Figure 6. Zircon cathodoluminescence (CL) images and U–Pb concordia diagrams of the Rizhao granitic gneisses: (a,b) RZ07, (c,d) RZ30, and (e,f) RZ47.
were calculated based on the U-Pb isotopic ages for each zircon. The two-stage model age ($T_{\text{DMC}}$) was calculated based on the depleted mantle source [20]. The results are shown in Table S4.

The zircons from the sample RZ07 present εHf(0) values of −35.9 to −32.1, and εHf(t) values of −19.3 to −15.6 (Figure 7). The single-stage model ages ($T_{\text{DM}}$) range from 1999 Ma to 2137 Ma, and the two-stage model ages ($T_{\text{DMC}}$) range from 3458 Ma to 3776 Ma. The zircons from the sample RZ30 present εHf(0) values of −30.0 to −25.4, and εHf(t) values of −13.3 to −8.8 (Figure 7). The single-stage model ages ($T_{\text{DM}}$) range from 1717 Ma to 1887 Ma, and the two-stage model ages ($T_{\text{DMC}}$) range from 2848 Ma to 3236 Ma. The zircons from the sample RZ47 present εHf(0) values of −35.2 to −26.8, and εHf(t) values of −18.3 to −10.4 (Figure 7). The single-stage model ages ($T_{\text{DM}}$) range from 1776 Ma to 2066 Ma, and the two-stage model ages ($T_{\text{DMC}}$) range from 2983 Ma to 3682 Ma.

Figure 7. Plots of zircon εHf(t) values versus U-Pb ages of the Rizhao granitic gneisses (a,b), and (a) is modified after [29].

5. Discussion

5.1. Genetic Discrimination of Zircon

The zircons of the Rizhao granitic gneisses are mostly light to dark gray in color and transparent with aspect ratios ranging from 1:1 to 3:1, and appear prismatic and euhedral with oscillatory zoning visible on cathodoluminescence imaging (Figure 6), consistent with the zircons of igneous origin [25–27]. The Th/U ratios in igneous zircons from various rocks is generally close to 0.5, whereas zircons grown under metamorphic conditions have much lower Th/U ratios of ≪0.01 [30–32]. Zircon trace element analyses show that the Th/U ratios of RZ07, RZ30, and RZ47 vary from 1.03 to 2.22 (mean = 1.47), 0.28 to 1.40 (mean = 0.83), and 0.28 to 2.02 (mean = 1.10), suggesting an igneous origin similar to some post-collisional granites [32] and clearly different from a metamorphic origin (Figure 8a). Relatively higher Th contents relative to U contents could result from a higher magma temperature, due to the sensitivity of zircon Th/U ratios to temperature variations [32–34].

In this study, the zircon saturation temperatures ($T_{\text{Zr}}$) for the biotite alkali feldspar granitic gneisses RZ07 and the biotite monzogranitic gneisses RZ47 calculated by using the Ti-in-zircon thermometer proposed by [35] are 646.6 °C to 871.1 °C (mean = 739.3 °C), and 623.1 °C to 768.4 °C (mean = 717.5 °C), respectively. It is consistent with the Th/U ratio analysis results (Figure 8a) that zircons from the biotite alkali feldspar granitic gneiss of RZ07 have a relatively large average Th/U ratio of 1.47 compared to 1.10 for zircons from the biotite monzogranitic gneiss of RZ47. The high zircon saturation temperature value of 871.1 °C in this study is similar to those of typical peralkaline A-type granite (average
value 883 °C), but significantly higher than those of typical I-type (average value 781 °C) and S-type (average value 764 °C) granites [36].

On the other hand, zircons from felsic rocks generally have Th/U ratios <1.0 [32,37–40], and a relatively high Th/U ratio of >1.0 in zircon is more likely to be associated with a rift environment rather than an arc-related environment, such as the North American Midcontinent Rift in western Lake Superior [41]. A typical feature of such granites, even in zircon with normal Th/U, is the presence of large amorphous melt inclusions, as in the zircon CL images of RZ07-04, RZ07-23, RZ30-12, RZ47-02, RZ47-10, and RZ47-23 (Figure 6). Additionally, high Th/U ratios are characteristic of zircon crystallized from evolved mafic rocks, such as gabbro pegmatite [42,43], but this zircon should not exhibit oscillatory zoning and is distinctly different from the zircons in this study. Zircon from rift-related rocks also tends to show strong development of primary crystal faces, whereas that from arc-related rocks tends to have well-developed secondary faces [44]. These features are probably the result of rapid crystallization from a high-temperature magma, as noted by [44], because rift-related magmas are formed by decompression melting at relatively high temperatures, whereas arc-related magmas are formed at minimum melting temperatures of the hydrated mantle [36,41]. This is consistent with our further discussion of tectonic settings in Section 5.3 below.

In addition, these zircons were characterized by low total rare earth element ($\sum$REE) concentrations of 404.8–4850.9 ppm, low LREE concentrations of 7.6–243.8 ppm, extremely low (La/Yb)$_N$ ratios with most <0.0001, high (Sm/La)$_N$ ratios with an average of 761.5, and significantly positive Ce anomalies (Ce/Ce*)$_N$ values with most >23.3 (mean = 219.4), indicating a typical igneous origin and clear different from hydrothermal zircons (Figure 8b–d) [30–32]. Therefore, the zircons of the Rizhao granitic gneisses used in this study are of magmatic origin.

5.2. Diagenetic Age and Characteristics of the Magma Source

The zircon U-Pa dating of the representative Rizhao granitic gneisses shows that the biotite alkali-feldspar granitic gneisses were emplaced at c. 785 to 784 Ma and the biotite monzogranitic gneiss was emplaced at c. 789 Ma (Figure 6). All of these ages are consistent within geological error, suggesting that they were formed in the Neoproterozoic.

The geochemical characteristics and the aluminum-rich minerals (cordierite, muscovite, garnet) and alkaline ferromagnesian minerals in rocks are adequate markers for distinguishing I-, S-, and A-type granites [29,45]. Petrographic observations by naked eye and microscope indicate the presence of large amounts of primary biotite and small amounts of primary muscovite and hornblende in the Rizhao granitic gneisses. This is different from either typical I- or S-Type granites [45–47]. Whole-rock major- and trace-element analyses on the Rizhao granitic gneisses indicated that they are enriched in Si, Fe and alkaline and depleted in Mg, enriched in light rare earth elements, moderately depleted in heavy rare earth elements, and show moderate fractionation between light and heavy rare earth elements, resembling characteristics of typical A-type granites [48]. The 10,000 Ga/Al ratios of the Rizhao granitic gneisses range from 2.01 to 2.58, with an average of 2.33, which is close to the lower limit of 2.6 for A-type granites and higher than the average values of I- and S-type granites [49,50]. Previous studies have also shown that elements such as P, Th, Ba, and Rb can distinguish highly differentiated I-type and S-type granites [45,46]. The P$_2$O$_5$ content of I-type granites generally decreases with the increase of SiO$_2$. This is particularly evident when SiO$_2$ exceeds 75%, with the majority exhibiting a P$_2$O$_5$ content of less than 0.05%. In contrast, the P$_2$O$_5$ content of S-type granites is seen to either increase or remain unaltered with the increase of SiO$_2$ content [47]. The granitic gneisses analyzed in this study all have low P$_2$O$_5$ contents of 0.05%–0.17% and decrease slightly with increasing SiO$_2$ content (64.78–72.24 wt.%), exhibiting significant differences from typical S- or I-type granites. In the Na$_2$O + K$_2$O versus 10,000 Ga/Al discrimination diagram (Figure 9a), three samples plot within the A-type granite range and can be distinguished from fractionated I- and S-type granites [50]. A relative enrichment
of Al and depletion of Na and K could result from the weathering and/or hydrothermal alteration of feldspar into Al-rich minerals such as kaolinite (Figure 3). Therefore, we propose that the Rizhao granitic gneisses belong to A-type granite.

Figure 8. Discrimination plots for magmatic, metamorphic, and hydrothermal zircon according to [30,51]. (a) zircon Th–U plot; (b) zircon LREE–REE plot; (c) zircon (Sm/La)N–La plot; (d) zircon (Ce/Ce*)N–(Sm/La)N plot.

The A-type granite was subsequently classified into two subtypes, designated A1 and A2, based on their distinct provenance and formation environment. The A1 granites are of mantle-derived origin, whereas the A2 granites are of crustal or island-arc magma [48]. In the TiO$_2$–SiO$_2$ discrimination diagram (Figure 9b), most of these sample spots fall into the rift-related granites range. In the Nb–Y–3Ga and Nb–Y–Ce triangular discrimination diagrams (Figure 9c,d), most granitic gneiss samples plot within the A2 region, indicating an affinity with island-arc magma origin [48]. In the Y + Nb versus Rb and Y versus Nb discrimination diagrams (Figure 10), most granitic gneiss samples plot within the post-collision granite region, indicating they formed at a post-collision tectonic background [52]. This indicates that the northeastern margin of the South China Block during the Neoproterozoic period was characterized by an active continental margin environment related to subduction, in accordance with previous studies on the breakup of the Rodinia supercontinent [5–9].
Figure 9. Genetic discrimination diagrams for the Rizhao granitic gneisses according to [48,50,52]. (a) Na$_2$O + K$_2$O–10,000 Ga/Al discrimination diagram; (b) TiO$_2$–SiO$_2$ discrimination diagram; (c) Nb–Y–3Ga triangular discrimination diagram; (d) Nb–Y–Ce triangular discrimination diagram. Abbreviation: RRG = rift-related granites; CEUG = continental uplift-related granites; A1 = A1-type granites; A2 = A2-type granites.

Figure 10. Tectonic discrimination diagrams [52] for the Rizhao granitic gneisses. (a) Rb–Y+Nb diagram; (b) Nb–Y discrimination diagram. Abbreviation: Syn-COLG = syn-collision granite; VAG = volcanic arc granite; WPG = within plate granite; ORG = ocean ridge granite; Post-COLG = post-collision granite.
The \( f_{\text{Lu/Hf}} \) values of the granites range from \(-0.98\) to \(-0.93\), much lower than the average value \(-0.72\) in the continental crust [53]. The \( \varepsilon_{\text{Hf}}(t) \) values of zircons from these granitic gneisses range from \(-19.3\) to \(-8.8\), indicating that the magma source was mainly Paleoproterozoic or Archean crust. Previous studies have shown that the content and ratio of Sr and Y in granite are closely related to the residual phase of its magma source [54]. Among HREEs, Yb is most affected by crystallization of garnet, while Dy and Ho are most affected by crystallization of amphibole [55]. Nb and Ta preferentially enter amphibole and rutile during partial melting, and Ti enters rutile [56]. It has been previously hypothesized that when the garnet content within the residual phase of the magma source area reaches 10%, the granitic magma formed by partial melting will exhibit adakite characteristics [57]. In this study, the \( Y/Yb \) ratios of the Rizhao granitic gneisses range from 8.08 to 10.96, with a mean value of approximately 10. The granite does not exhibit the characteristics of adakite, suggesting that the residual minerals in the magma source were predominantly amphibole [58], lacking garnet. The negative Eu anomaly is consistent with this hypothesis, as it suggests the presence of plagioclase in the magma source area.

5.3. Tectonic Settings

The Sulu Orogenic Belt is located on the northeastern margin of the South China Block [6,9], which has undergone complex tectonic–magmatic evolution since Neoproterozoic [59–61]. The position of the South China Block (Figure 1a) in the Rodinia supercontinent and the tectonic background of Neoproterozoic magma formation have constituted a central topic of geological debate in recent decades. In the process of supercontinent reconstruction, there are the following views on the location of the South China Block: (1) Located in the core of the Rodinia supercontinent between Australia and Laurentia, it formed in a tensional environment related to a mantle plume [5,6,8,9]; (2) Located at the edge of the supercontinent, northeast of the Indian plate, it formed in a compressional environment related to the island arc around the Yangtze continental margin [10,11,13]; (3) Located at the edge of the supercontinent, it formed in a plate-rift tensional environment derived from the extension and collapse of the Yangtze–Cathaysia post-orogenic lithosphere [14]. The main ideas and evidence for these tree models, as well as the links and insights to the present study, are described below.

(1) Island arc-related model:

Some researchers proposed that the geochemistry of the granite gneiss at the western margin of the Yangtze Plate at 860–760 Ma has island arc characteristics [13]. Combined with the magmatic rocks with island arc geochemical characteristics at the same period in the southeastern margin of the Yangtze Plate, an island arc model was established and compared with India [13,42]. The island arc model suggests that there was an oceanic subduction zone for an extended period (950–735 Ma) on the western margin of the Yangtze Block (Figure 1a), and the rift basin in the South China Block is a back-arc expansion [13,62,63]. The Hannan–Wangjiangshan pluton on the Yangtze Plate’s northern margin was initially considered as arc magmatic rocks [15]. Based on systematic petrological, mineralogical, and geochemical analyses, other researchers proposed that the rocks formed in the mantle and inherited the Zr and Hf depletion characteristics of island-arc basalts due to the accumulation of crystals [64]. The tectonic strain within of the Yanbian Group is generally northward, which is inconsistent with the subduction direction of the island arc model. In this study, the zircon Hf isotope analyses on the Rizhao granitic gneisses present distinctly negative \( \varepsilon_{\text{Hf}}(t) \) values of \(-19.3\) to \(-8.8\) (Figure 7). The two-stage model age (\( T_{\text{DM}^-} \)) analysis results indicate that the magma mainly derived from the Archean continental crust, with a small proportion of juvenile Paleoproterozoic continental crust. This is different from island arc granites, which have a lot of mantle-derived materials [10,11,13]. Therefore, the Neoproterozoic granitic gneisses in Rizhao area were not the product of the island arc in a compressional environment.
(2) Mantle plume model:

The mantle plume model suggests that the Jiangnan orogenic belt mainly formed at 1000–960 Ma, coeval with the global Grenville orogeny \cite{8,12,65}, and South China is located in the center of the Rodinia supercontinent. Bimodal magmatic activity at 830–795 Ma and 780–745 Ma developed within the Rodinia supercontinent and throughout South China, as well as unroofing and continental rift sedimentation with a thickness of approximately 1000 km. The mantle plume model is based on the correlation of dykes in northern Guangxi (~828 Ma) \cite{9} with the Gairdner dyke group in Australia (827 \pm 6 Ma) \cite{66}. The Gairdner mafic dyke group in Australia is thought to have formed in an intraplate environment associated with the coeval South China mantle plume that caused the breakup of the Rodinia supercontinent \cite{67}. It is believed that the South China Craton was located between Australia and Laurentia, southeast of the Australian block, with the Yangtze block close to Australia and the Cathaysian block close to Laurentia, located in the core of the Rodinia supercontinent \cite{5,6,9}.

Previous studies suggest the Taohong and Xiqiu plutons in the southeastern margin of the Yangtze Plate formed at ~913 Ma and ~905 Ma, respectively \cite{48}. Li et al. \cite{7} further concluded that South China is located between the two ancient continents of Gondwana and Laurentia. The Sibao Movement led to the final amalgamation of the Cathaysia and Yangtze Plates at ~0.9 Ga (Figure 1a) to form a uniform South China Block, completing the final aggregation of the two ancient continents of Gondwana and Laurentia. This amalgamation time is consistent with the Neoproterozoic orogenic belt of the Eastern Ghats of India and the Rayner Province of Eastern Antarctica of ca. 990–900 Ma, resulting in the final amalgamation of the Rodinia supercontinent at 900 Ma \cite{12}. Following the formation of the Rodinia supercontinent, rifting commenced as a consequence of mantle plume activities. The most significant mantle plume activity is believed to have occurred at approximately 825 Ma, as evidenced by a series of magmatic events recorded in the South China, the Australian, and the Indian Blocks \cite{8,9}. However, the results of these geochronological studies do not agree with the age of the Rizhao granitic gneisses in the present study, and there is a lack of evidence for mantle plume genesis in this area, such as the coeval basic dyke swarms, so it is difficult to link the Neoproterozoic granitic gneisses in the Rizhao area to the mantle plume model.

(3) Plate rift model:

Based on zircon age and Hf-O isotope analysis of Neoproterozoic volcanic rocks in the Jiangnan orogenic belt on the southeastern margin of the Yangtze and the Panxi and Kangding areas on the western margin of the Yangtze Plate, a plate rift model was proposed \cite{14}. This model suggests that subduction of the oceanic crust around the Yangtze at 1.3–1.1 Ga led to the development of large-scale island arc magmatic rocks and the accretion of new crust. It can be reasonably deduced that the arc–continent collision and the subsequent syn-collision on a large scale should have caused the remelting of numerous island-arc-related magmatic rocks. The collision at 830–800 Ma caused the collapse of the thickened orogenic belt.

For example, on the western margin of the Yangtze Plate, the zircon U-Pb ages of the Mianning A-type granite, the Xitianba A-type granite, and the Leidashu A-type granite concentrate at 768–783 Ma \cite{68}, ~801 Ma \cite{69}, and ~750 Ma \cite{69}, respectively. The gravel sedimentary record of the Kangdian Rift on the western margin of the Yangtze Block corresponds well to that of the Neoproterozoic Rift on the southeastern margin of the Yangtze Block \cite{70} and the Adelaide Rift in Australia \cite{71}. The zircon U-Pb ages of tuff in the lower Lvliang Formation, alkaline basalt in the Suxiong Formation, and alkaline basalt at the bottom of the Chengjiang Formation are 819 \pm 9 Ma \cite{72}, 800–810 Ma \cite{5,73,74}, and 804 \pm 6 Ma \cite{75}, indicating that the Kangdian Rift began to develop at ~800 Ma. Basic dike swarms of ca. 760–790 Ma are also widely developed in the Kangdian Rift, further indicating that rifting was widely developed during this period \cite{76,77}. The Emeishan diabase dyke on the western margin of the Yangtze Plate was emplaced at ~814 Ma and was
deemed to have formed in a rift environment [16]. Furthermore, coeval basaltic and bimodal basaltic magmatism activities of approximately 830–800 Ma have been documented in the surrounding region [78,79].

On the southern margin of the Yangtze Plate, zircon U-Pb dating indicates that the bimodal Shangshu basalt formed at ~790 Ma [80]. Zircon SHRIMP U-Pb dating results from an evolved member of andesitic composition in the Yiyang komatiitic basalt is 823 ± 6 Ma [81]. Rift-related mafic–ultramafic rocks are also developed in northern Guangxi on the southern margin of the Yangtze Plate, and zircon U-Pb dating results suggest that they formed at ca. 825–841 Ma [9,82]. Bimodal spilite is developed in northern Guangxi, with zircon U-Pb ages of ~765 Ma [67]. Therefore, subduction of the oceanic crust and emplacement of island arc magma on the southern and western margins of the Yangtze Plate should have ended by ~1100 Ma, followed by a long period of arc–continent collision and orogenic collapse magmatism until at least ~790 Ma or even later.

The above results show that numerous Neoproterozoic bimodal magmatic assemblages, basic dyke swarms, and A-type granites were widely developed around and/or inside the South China Block. The Rizhao area in the Sulu Orogenic Belt is located on the northeastern margin of the South China Block. LA-MC-ICP-MS zircon U-Pb analyses suggest that the Rizhao granitic gneisses mainly formed at ca. 788–784 Ma. During this period, the South China block was subject to the influence of the mantle plume, situated within an extensional tectonic environment. This resulted in the occurrence of intraplate rifting events [8,12,65]. However, for the Rizhao area on the northeastern margin of the South China Block, it may be thousands of kilometers from the suspected center of the mantle plume if we refer to the present-day geography [8,9]. In addition, there is a lack of evidence for mantle plume genesis in the Rizhao area, such as the coeval basic dyke swarms, so it is difficult to directly link the Neoproterozoic granitic gneisses in the Rizhao area to the mantle plume-induced rifting of the overlying crust. Zircon Lu-Hf isotopic analyses of the Rizhao granitic gneisses reveal negative $\varepsilon_{\text{Hf}}(t)$ values of −19.3 to −8.8 (Figure 7), which are distinct from those observed in island arc granites with a significant mantle-derived component and positive $\varepsilon_{\text{Hf}}(t)$ values [10,11,13]. The two-stage model age ($T_{DM}^{C}$) analysis results further indicate that the granitic magma mainly derived from the Archean continental crust. This is different from island arc granites in a compressional environment, which have a lot of mantle-derived materials [10,11,13]. The TiO$_2$–SiO$_2$ discrimination diagram for the granites (Figure 9b) shows that the Rizhao granitic gneisses (788–784 Ma) lie near the boundary on the field for rift granites. In the Y + Nb versus Rb and Y versus Nb discrimination diagrams (Figure 10), most granitic gneiss samples plot within the post-collision granite region, indicating they formed at a post-collision tectonic background [52]. As discussed in Section 5.1, zircons from the Rizhao granitic gneisses display comparable features with those from a rift environment, with relatively high Th/U ratios (Table S2; Figure 8a), clear oscillatory zoning (Figure 6), large amorphous melt inclusions (Figure 6), and a relatively high zircon saturation temperature (Table S2).

Therefore, we conclude that the Neoproterozoic granitic gneisses in the Rizhao area formed at the beginning stage of an intracontinental rift extension environment (Figure 11), which is a tectonic response of the Rodinia supercontinent related to the formation of a distant mantle plume in the central part of South China [8,9]. Subduction of the oceanic crust and emplacement of island arc magma on the northeastern margins of the Yangtze Plate could have also ended by ~1100 Ma, followed by a long period of arc–continent collision and orogenic collapse magmatism until ~790 Ma. After ~790 Ma, the Sulu Orogenic Belt was in an intracontinental rift extension environment on the Yangtze Plate’s northeastern margin.
6. Conclusions

(1) The Neoproterozoic granitic gneisses in the Rizhao area formed at ~790 Ma. They are sub-alkaline series rocks with high potassium characteristics. They are also enriched in light rare earth elements, moderately depleted in heavy rare earth elements, and exhibit moderate fractionation between the two. Additionally, they display weak to moderate negative Eu anomalies and weak negative Ce anomalies. They belong to A-type granites. The mineral assemblage in the magma source area was amphibole + plagioclase.

(2) Zircons from the Rizhao granitic gneisses present clear oscillatory zoning, large amorphous melt inclusions, a relatively high zircon saturation temperature, relatively high Th/U ratios, and negative $\epsilon_{\text{Hf}}(t)$ values. The two-stage model ages ($T_{DM}^{C}$) suggest that the partial melting of a mixture of Archean crustal materials and a small amount of Paleoproterozoic juvenile continental crust components formed the granite.

(3) The Rizhao granitic gneisses formed in an intraplate rifting environment on the Rodinia supercontinent.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min14080807/s1, Table S1: Major element (wt.%) and trace element (ppm) compositions of the Rizhao granitic gneisses; Table S2: Zircon trace element (ppm) composition of the Rizhao granitic gneisses; Table S3: Zircon U-Pb data of the Rizhao granitic gneisses; Table S4: Zircon Lu-Hf isotopic analysis results of the Rizhao granitic gneisses.

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