minerals

MDPI

Article

Petrogenesis and Geodynamics of the Huangnihe Pluton in the Jiapigou Mining District of Northeast China: Constraints from Zircon U–Pb and Lu–Hf Isotopes

Jilong Han [1,2,3], Zhicheng Lü [1,3,*], Yanpeng Liu [4,*], Xuliang Qin [5], Xiaotian Zhang [6,7], Pengfei Huang [8], Xinwen Zhang [7], Shu Wang [7], Chuntao Zhao [7] and Jinggui Sun [7]

1 Development and Research Center, China Geological Survey, Beijing 100037, China; hanjilong@cugb.edu.cn or hanjil@126.com
2 State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China
3 Mineral Exploration Technical Guidance Center, Ministry of Natural Resources, Beijing 100037, China
4 Beijing Institute of Geology for Mineral Resources Co., Ltd., Beijing 100012, China
5 The First Geological Survey of Jilin Province, Changchun 130033, China; qinxl1988@163.com
6 State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, Nanchang 330013, China; xtzhangeology@163.com
7 College of Earth Sciences, Jilin University, Changchun 130061, China; zhangxinwen29@163.com (X.Z.); wangshu19@mails.jlu.edu.cn (S.W.); zhaoctao22@isl.ac.cn (C.Z.); sunjinggui@jlu.edu.cn (J.S.)
8 China Gold Group Jiapigou Mining Co., Ltd., Huadian 132411, China; 18629938531@163.com
* Correspondence: lzhicheng@mail.cgs.gov.cn (Z.L.); lypeng1994@126.com (Y.L.)

Abstract

The Jiapigou mining district, a world-famous gold-producing district with a capacity that greatly exceeds 180 t Au, has a mining history longer than 200 years. The large amount of Jurassic Au mineralization in this district significantly differs from that in other districts of the North China Craton (130–115 Ma). However, the deep-seated dynamic processes and mechanisms that triggered the unique Jurassic mineralization in the Jiapigou district are poorly understood. Here, we present new data on the geology, petrography, and zircon U–Pb and Lu–Hf isotopes of the typical Huangnihe pluton in the Jiapigou district to address the above issues. The results revealed the following: (1) The Huangnihe pluton comprises mainly fine-grained granite and porphyritic granite, which were emplaced at 187 ± 2 Ma (n = 13) and 166 ± 2 Ma (n = 15), respectively. (2) The Hf isotope data indicate that the two episodes of granites exhibit distinct origins: the former (εHf(t) = −1.4 to +5.3; T_{DM2} = 1784–1181 Ma) originated from juvenile lower crust, whereas the latter (εHf(t) = −14.9 to −9.7; T_{DM2} = 2987–2518 Ma) was derived from Archean crust. (3) On the basis of published geochemical data, the estimated crustal thicknesses of the Jiapigou district ca. 187 Ma, ca. 175 Ma, and ca. 166 Ma ranged from 45 to 52 km, 43 km, and 58 to 63 km, respectively. Combined with regional observations, the results of this study further reveal the following: (1) The Jurassic magmatism in the Jiapigou district can be subdivided into three episodes: 187–186 Ma, ca. 175 Ma, and 166–165 Ma. (2) The crust in the Jiapigou district gradually thickened during the Jurassic and underwent partial melting during multiple episodes of Paleo-Pacific Plate subduction, thereby generating arc-like calc-alkaline (ca. 187 Ma), adakite-like (ca. 175 Ma), and adakite magmas (ca. 166 Ma) that were emplaced to form corresponding granitoids. Moreover, syn-ore magma mixing between the ca. 175 Ma adakite-like felsic magma and mantle-derived mafic magmas was considered a crucial process in magma evolution. This process in turn promoted the enrichment of ore-forming elements within the magma system, which significantly contributed to the formation of the large Au mineralization in the Jiapigou district.

check for updates

Academic Editors: Jaime Estevão Scandolâra, Nilson Francisquini Botelho and Paola Ferreira Barbosa

Received: 11 August 2025
Revised: 18 September 2025
Accepted: 21 September 2025
Published: 25 September 2025

Citation: Han, J.; Lü, Z.; Liu, Y.; Qin, X.; Zhang, X.; Huang, P.; Zhang, X.; Wang, S.; Zhao, C.; Sun, J. Petrogenesis and Geodynamics of the Huangnihe Pluton in the Jiapigou Mining District of Northeast China: Constraints from Zircon U–Pb and Lu–Hf Isotopes. *Minerals* **2025**, *15*, 1014. https://doi.org/10.3390/min15101014

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Keywords: zircon U–Pb; Hf isotope; adakite; mesothermal gold deposits; Jiapigou; North China Craton

1. Introduction

The Jiapigou district (>>180 t Au), a representative gold-mining district at the northeastern margin of the North China Craton (NCC; Figure 1A), hosts numerous large- to medium-sized gold deposits, including the well-known Jiapigou, Erdaogou, Toudaoliuhe, and Banmiaozi deposits (Figure 1B; [1–3]). Recent studies have revealed that the gold deposits in this district are mesothermal deposits that formed in an extensional setting associated with the subduction of the Paleo-Pacific Plate and are genetically related to syn-ore intrusive rocks [3–5]. However, the giant Au mineralization in the Jiapigou district was concentrated in the Middle Jurassic (178–170 Ma; [3–5]), which is significantly different from that in other districts on the margins of the NCC (130–115 Ma, i.e., the Jiaodong, Liaodong, and Xiaoqinling districts; [6–8]). The deep-seated dynamic processes and mechanisms that triggered the unique giant mineralization in the Jiapigou district during the Middle Jurassic are poorly understood.

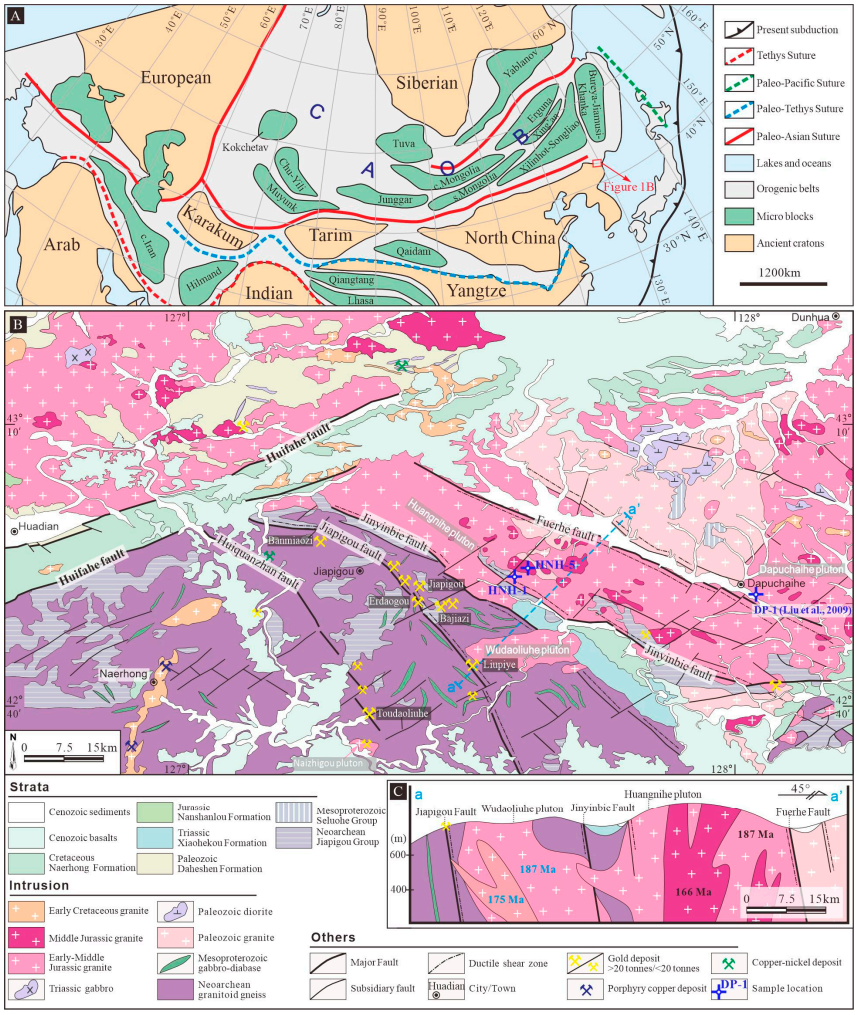

Figure 1. (**A**) Schematic tectonic map of the Eurasian continent [3] showing the location (**B**); (**B**) regional geological map of the Jiapigou district (modified after ref. [3]); and (**C**) schematic diagram (Line a–a′ (**B**)) showing the spatial relationships between the Huangnihe and Wudaoliuhe plutons and the gold deposits (modified after refs. [9,10]). The sample DP–1 in Figure 1 is cited from Ref [11]. Abbreviations: CAOB = Central Asian Orogenic Belt.

Although scholars have previously expanded upon the metallogenic background of the district on the basis of geochemical data for ore-related intrusions [3,4], studies on the complete dynamic process from pre- to post-mineralization are lacking. Our recent studies have indicated that abundant intrusions in the Jiapigou district occurred during the Phanerozoic, including pre- to post-ore intrusions (i.e., the Wudaoliuhe (186 and 175 Ma) and Huangnihe plutons; [3,12]), allowing for the identification of the chronological framework of magmatic activity and all inherent dynamic processes involved in regional Au mineralization from pre- to post-ore. We report new data on the geology, petrography, and zircon U–Pb and Lu–Hf isotopes of the typical Huangnihe pluton in the Jiapigou district to elucidate the above issues. These findings, combined with previous observations, can provide insights into the metallogenic mechanism and dynamic processes involved in this district.

2. Regional Geology and Geological Context of the Huangnihe Pluton

The NCC, which is one of the oldest cratons on Earth, is generally subdivided into the Eastern and Western Blocks, which are separated by the Trans-North China Orogen that formed during the collision between the two blocks ca. 1.9 Ga [3,6]. The basement of the NCC is dominated by Archean–Paleoproterozoic amphibolite- to granulite-facies metamorphic rocks consisting of granitoid gneiss, migmatite, amphibolite, and supracrustal rocks [7]. From the Paleozoic to the early Mesozoic, the southern and northern margins of the NCC were affected by multiple orogenic events, resulting in the formation of abundant gold deposits, which are usually clustered as gold districts, including the Xiaoqinling, Jiaodong, Jibei, and Jiapigou districts [4–8]. The Jiapigou district, located at the junction of the NCC and CAOB, experienced the formation and evolution of the NCC during the Precambrian [13], the evolution of the Paleo-Asian Ocean during the Paleozoic, and multiple subductions of the Paleo-Pacific Plate since the Late Triassic [3]. These episodes of tectonic evolution make the Jiapigou district a world-famous district characterized by tectonic–magmatic activity and large Jurassic Au mineralization (Figure 1B; [1,3,14]). Approximately 60% of the district is underlain by Paleozoic–Mesozoic granitoids, which intruded into Neoarchean granitoid gneisses and comprise mainly Huangnihe, Wudaoliuhe, Dapuchaihe, and Erdaodianzi plutons (Figure 1B; [3]). The NE-trending Huifahe fault and the NW-trending faults (i.e., the Fuerhe, Jinyinbie, Jiapigou, and Huiquanzhan faults) predominantly control the distributions of these plutons and gold deposits in the Jiapigou district (Figure 1B).

The Huangnihe pluton, situated between the Fuerhe and Jinyinbie faults, generally trends in a NW direction and is crosscut by a series of NE-trending faults (Figure 1B). Although our studies found no clear contact relationship between the Huangnihe and Wudaoliuhe plutons in the Jiapigou district [5], previous workers have proposed that the former intrudes the interior of the latter at depth (Figure 1C; [9,10]). A detailed field investigation revealed that this pluton is composed mainly of fine-grained granite and porphyritic granite (Figures 1B and 2). The fine-grained granite occurs as a batholith (Figure 2A) and has a fine-grained granitic texture and massive structure. This granite is intruded into by porphyritic granite and composed of quartz (30–35 vol.%), plagioclase (20–25 vol.%), orthoclase (30–35 vol.%), biotite (2–5 vol.%), and accessory minerals (i.e., zircon, sphene and apatite; <1 vol.%; Figure 2B). The porphyritic granite generally occurs as stocks and has a porphyritic texture and massive structure defined by 15–20 vol.% phenocrysts of perthitic orthoclase, with minor plagioclase, accessory zircon, and sphene inclusions (Figure 2C,D). The matrix (80–85 vol.%) has a fine-grained granitic texture and consists of quartz (25–30 vol.%), plagioclase (20–25 vol.%), perthitic orthoclase (15–20 vol.%), biotite (3–7 vol.%), and accessory zircon (Figure 2C).

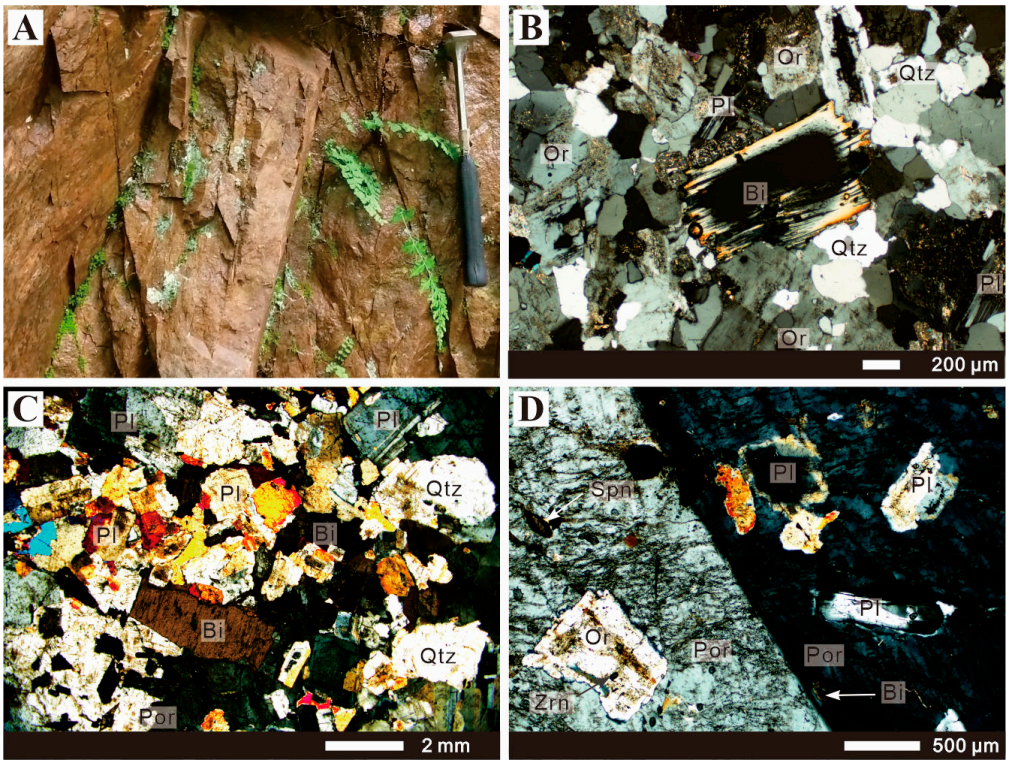

Figure 2. Fine-grained granite (HNH–1, (**A**)) and microscopic-scale petrographic characteristics of fine-grained granite (HNH–1, (**B**)) and porphyritic granite (HNH–5, (**C**,**D**)). Abbreviations: Bi—biotite; Or—orthoclase; Pl—plagioclase; Por—perthitic orthoclase; Qtz—quartz; Spn—sphene; and Zrn—zircon.

3. Results

Representative fine-grained granite (HNH–1) and porphyritic granite (HNH–5) samples (refer to Figure 1B for the sample locations) were selected for zircon U–Pb and Lu–Hf isotope analyses, which were performed at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Natural Resources, Jilin University, Changchun, China, and Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China, respectively. The analytical methods are described in detail in Supplementary File S1, and the procedures and data processing used in this study can be found in the methods described by refs. [3,4,15–18].

3.1. Zircon U–Pb Geocronology

Zircon grains are typically euhedral–subhedral and columnar, exhibit growth zoning (Figure 3A,B), and have Th/U ratios ranging from 0.32 to 1.29 (Table S1); these characteristics indicate that the zircon samples are of magmatic origin [19].

For sample HNH–1 (fine-grained granite), the zircon ages from 14 analytical spots (except for #4, which exhibits heavy Pb loss; Table S1) range from 216 to 182 Ma and fall into two distinct clusters: 216 ± 3 Ma (1 sample) and 187 ± 2 Ma (Concordia age; n = 13; Figure 3C). The youngest age of 187 ± 2 Ma (n = 13) is interpreted as the crystalline age of the fine-grained granite, whereas the older age corresponds to the crystalline age of captured zircons during magma emplacement.

For sample HNH–5 (porphyritic granite), the zircon ages from 15 analytical points (except for #12, which exhibits heavy Pb loss; Table S1) range from 174 to 160 Ma and yield a weighted mean age of 166 ± 2 Ma (n = 15; Figure 3D), which is interpreted as the crystallization age of the porphyritic granite.

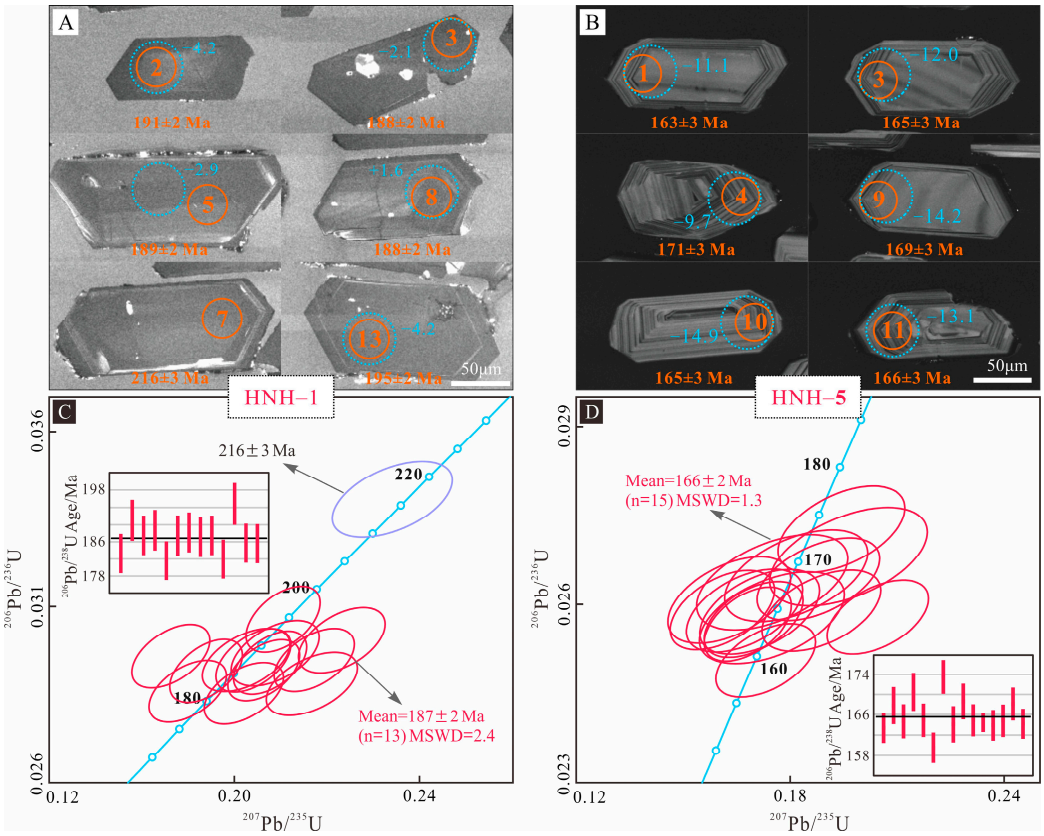

Figure 3. Representative zircon CL images (**A**,**B**) and zircon U–Pb Concordia diagrams (**C**,**D**) of the granites from the Huangnihe pluton. The U–Pb dating are denoted by orange circles and numbers, while the Lu–Hf analyses by blue circles and numbers (**A**,**B**).

3.2. Zircon Lu–Hf Data

Lu–Hf analyses were performed of the same portions of the zircon grains (refer to Figure 3 for the analysis locations). Zircons from the fine-grained granite (HNH–1) have initial $^{176}Hf/^{177}Hf$ ratios of 0.282618–0.282807, εHf(t) values of −1.4–+5.3, and T_{DM2} ages of 1784–1181 Ma (Table S2). Zircons from the porphyritic granite (HNH–5) have initial $^{176}Hf/^{177}Hf$ ratios of 0.282247–0.282396, εHf(t) values of −14.9–−9.7, and T_{DM2} ages of 2987–2518 Ma (Table S2).

4. Discussion

4.1. Chronological Framework of Mesozoic Magmatism

Previous studies have suggested that the Paleozoic–Mesozoic granitoids in this district intruded into Neoarchean granitoid gneisses and encompass largely the Huangnihe, Wudaoliuhe, Dapuchaihe, and Erdaodianzi plutons (Figure 1B; [3]). However, owing to the lack of a systematic summary of geochronological data, the multiple episodes of Phanerozoic magmatic events in this district have not been accurately constrained.

The crystalline ages of the fine-grained granite and porphyritic granite from the Huangnihe pluton obtained in this study are 187 ± 2 Ma (n = 13; Figure 3C) and 166 ± 2 Ma (n = 15; Figure 3D), respectively. These results indicate that the Huangnihe pluton is a complex pluton formed by two episodes of magmatism, similar to the nearby Wudaoliuhe (i.e., ca. 185 and 175 Ma; [12]) and Dapuchaihe plutons (i.e., ca. 166 Ma; [11]), rather than being formed in the Paleozoic, as suggested by previous studies [20].

Our U–Pb results, combined with geochronological data from the literature (Figure 4A), indicate that Phanerozoic felsic magmatism in the Jiapigou district can be divided into five main episodes: early Carboniferous (323–300 Ma), Permian (272–252 Ma), Triassic

(245–208 Ma), Early to Middle Jurassic (198–162 Ma), and Early Cretaceous (132–104 Ma) (Figure 4A; [21]). Among these episodes, Early to Middle Jurassic (198–162 Ma) magmatism can be subdivided into three sub-episodes (Figure 4B; [21]): 187–186 Ma (i.e., the Dabinghugou, Wudaoliuhe and Huangnihe plutons; [12,22]; this study), ca. 175 Ma (i.e., the Wudaoliuhe pluton and regional granitic dikes; [3,21]), and 166–165 Ma (i.e., the Dapuchaihe and Huangnihe plutons; [11]; this study). Moreover, the ca. 175 Ma granitoid is genetically related to synchronic giant gold mineralization [3,4], whereas the other two episodes of granitoids were formed before or after gold mineralization (Figure 4B).

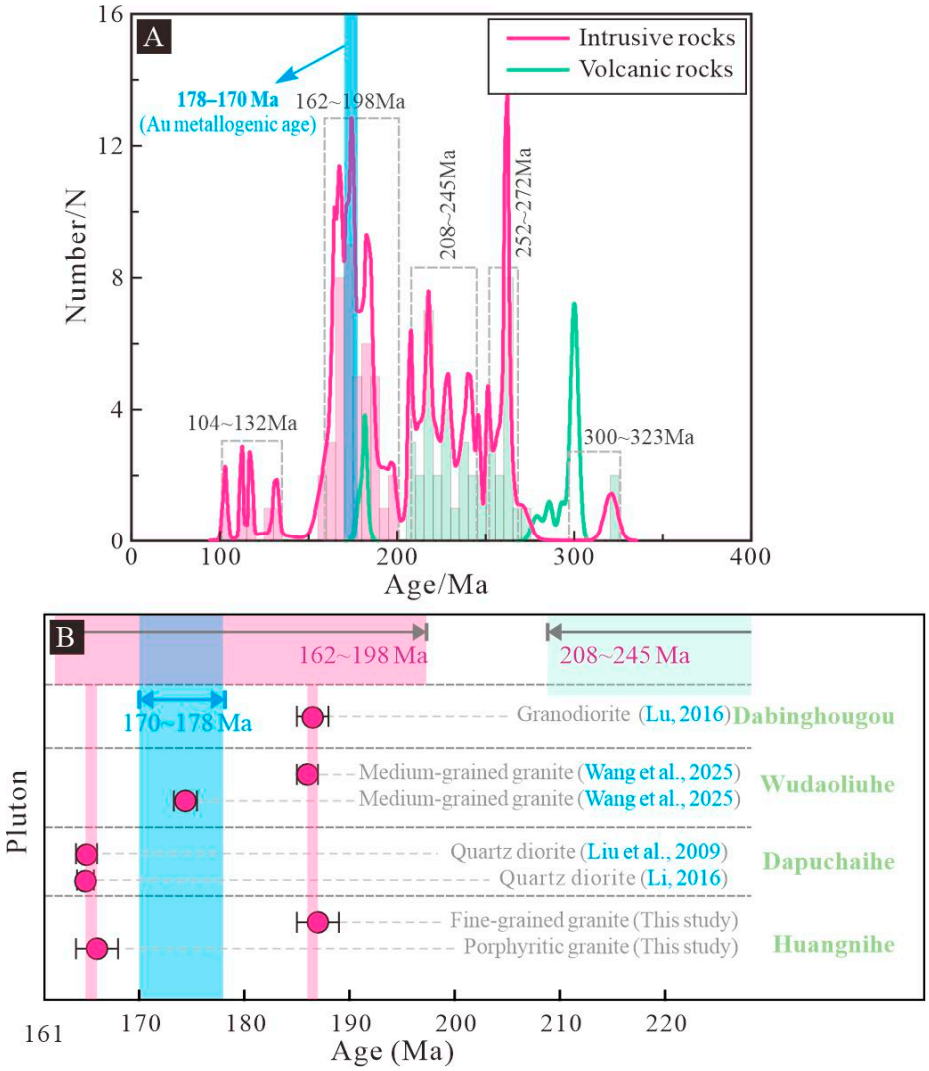

Figure 4. Chronological framework of magmatism (**A**) and summary plot of ages for the intrusions and mineralization (**B**) in the Jiapigou district. The published data of regional intrusive and volcanic rocks are from refs. [11,12,22,23].

4.2. Origin of the Huangnihe Pluton

The εHf(t) values and T_{DM2} ages of zircons from the fine-grained granite (187 ± 2 Ma) of the Huangnihe pluton ranged from −1.4 to +5.3 and 1784–1181 Ma, respectively (Table S2, Figure 5A,B), indicating that its primary magmas originated from partial melting of juvenile lower crustal material accreted during the Proterozoic. This finding is notably distinct from those of the synchronic granites of the Wudaoliuhe pluton, which originated from ancient crustal material [12].

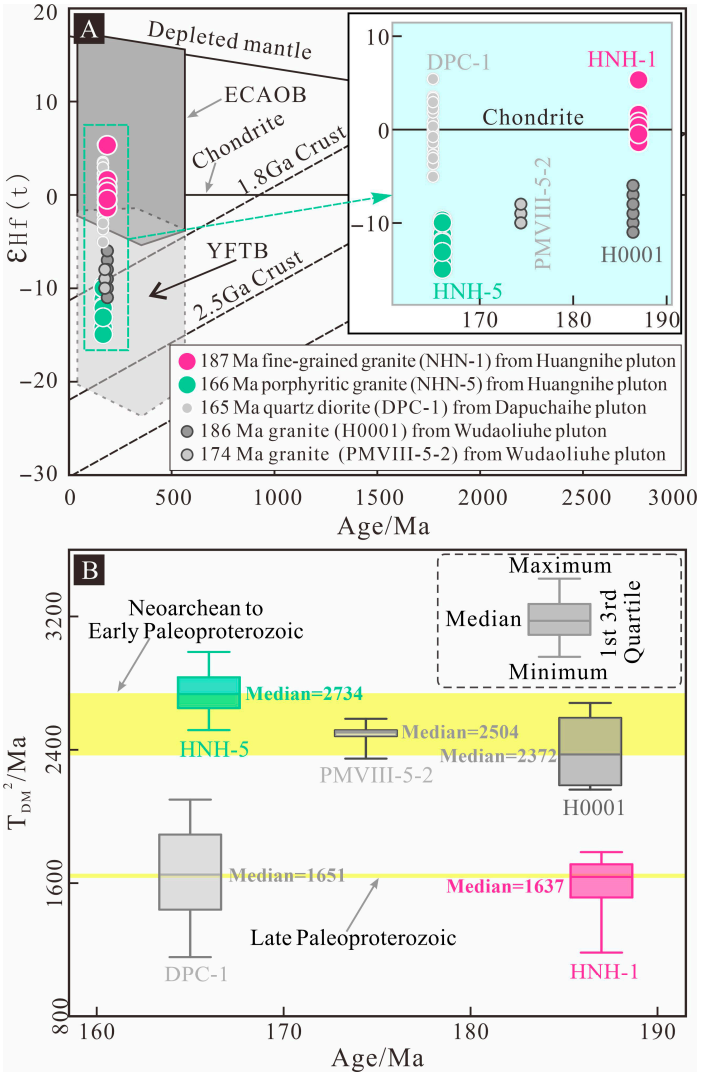

Figure 5. Plot of εHf(t) versus zircon age (**A**) and box–whisker plots of T_{DM2} age (**B**) for the Huangnihe and related plutons in the Jiapigou district. The published data for the Dapuchaihe (quartz diorite, DPC–1) and Wudaoliuhe (granites, H0001 and PMVIII–5–2) plutons are from refs. [11,12], respectively.

In contrast, the εHf(t) values and T_{DM2} ages of zircons from the porphyritic granite (166 ± 2 Ma) of the Huangnihe pluton ranged from −14.9–−9.7 and 2987–2518 Ma, respectively (Table S2, Figure 5A,B), indicating that its primary magmas originated from the partial melting of Archean crustal material. This finding is similar to those for the ca. 175 Ma granites of the Wudaoliuhe pluton and the granitic dikes in this district (Figure 5B; [3,12]) and distinct from those of the quartz diorites of the Dapuchaihe pluton [11]. Given that the porphyritic granite examined in this study matches the mineral assemblage and emplacement age of that previously reported in the same pluton (Table S3 [10,24,25]), the previously published geochemical data can serve as a useful reference for interpreting its petrogenesis. Huang [10] reported that ca. 166 Ma granites from the Huangnihe pluton have high SiO_2 and total alkali contents, high Sr/Y ratios, low Mg# values, and low $Fe_2O_3^{Total}$ contents (Table S4), indicating their affinity for thickened lower crust-derived adakite [10,26].

In summary, the two episodes of granite from the Huangnihe pluton exhibit distinct origins: the ca. 187 Ma granite originated from juvenile lower crust, whereas the ca. 166 Ma granites were derived from Archean crust and exhibit adakite affinity.

4.3. Implications for Regional Geodynamic and Gold Mineralization

Since the Late Triassic, the Jiapigou district and adjacent regions have experienced multiple episodes of Paleo-Pacific Plate subduction [3]. Under the influence of these processes, the Jiapigou district was situated in a subduction-related active continental margin setting during the Early–Middle Jurassic [3,21,27]. As noted above, three sub-episodes of granitic magmatism occurred in this district (ca. 187 Ma, 175 Ma, and 166 Ma), along with 178–175 Ma giant gold mineralization within this same interval (Rb–Sr ages of 178–175 Ma [3,4] and Re–Os ages of 177 Ma [28]). Previous studies have elaborated upon the metallogenic background of the district on the basis of geochemical data of ore-related intrusions [3,4]. However, studies on the complete dynamic process from pre- to post-mineralization are lacking. What inherent dynamic processes drove these activities? Did crust–mantle interactions facilitate gold mineralization? This research may provide several answers.

Crustal thickness variations: On the basis of global crustal thickness distribution patterns and gravity-isostatic theory, stable continental regions typically exhibit crustal thicknesses of 35–45 km, whereas continental margins exhibit crustal thicknesses of 30–35 km [29–31]. Zhang et al. (2011) [32] inferred that the crustal thickness of the eastern NCC was approximately 35 km during the Triassic, which is broadly consistent with the crustal thickness of ~37 km obtained for the study area during the Late Triassic using the LightGBM model [33]. Recently, scholars have established empirical relationships between the geochemical indices of felsic igneous rocks and crustal thickness (or Moho depth), expressed as $D_M = 27.78\ln[0.34(La/Yb)_N]$, where $(La/Yb)_N$ is the whole-rock value and D_M is the crustal thickness or Moho depth [34,35]. This empirical relationship is widely applicable for calculating crustal thickness in both island arc and collisional tectonic settings [32–35]. Here, we employ this method to calculate the crustal thickness variation trend in the Jiapigou district since the Late Triassic. In this study, whole-rock La and Yb data from the four plutons—the Wudaoliuhe, Dabinghugou, Dapuchaihe, and Huangnihe plutons—in the Jiapigou district were collected from the literature [3,10–12,22] (Table S4). The estimated crustal thicknesses of the Jiapigou district ca. 187 Ma and ca. 175 Ma ranged from 45 to 52 km and 43 km, respectively (Figure 6A), which were significantly greater than the crustal thicknesses during the Late Triassic (~37 km; [33]). These results indicate that the crust in the study area gradually thickened over time (Figure 6B) and reached its maximum thickness of 58–63 km at 166 Ma (Table S4 and Figure 6A,B), which is consistent with the petrogenesis of synchronous intrusions derived from the thickened lower crust (Section 4.2).

Regional geodynamics: Northeast Asia, including the Jiapigou district, has been influenced by the multiple episodes of subduction of the Paleo-Pacific Plate since the Late Triassic (ca. 201 Ma; [3,21,27,36]). In this subduction setting, underplated basaltic magmas trigger partial melting of the lower crust, generating felsic magmas emplaced to form ca. 187 Ma granitoids with arc-like calc-alkaline characteristics (i.e., the Wudaoliuhe and Huangnihe plutons; [12,19]; this study). Previous studies have indicated that the formation of 187 Ma granitoids may have facilitated the pre-enrichment of 175 Ma gold mineralization in the region [1,2]. With ongoing subduction and underplating, the thickening lower crust underwent partial melting, generating adakite-like magmas emplaced to form ca. 175 Ma granitoids (i.e., the Wudaoliuhe pluton and regional granitic dikes; [3,12]). The crustal thickness in this district reached a maximum of 58–63 km at 166 Ma, and partial melting occurred, forming adakitic magmas that were emplaced to form the ca. 166 Ma granitoids (i.e., the Huangnihe and Dapuchaihe plutons) ([17]; this study). Moreover, the 175 Ma ore-related intrusions are genetically related to the Au mineralization in the Jiapigou district on the basis of their temporal–spatial relationships and alterations [3–5].

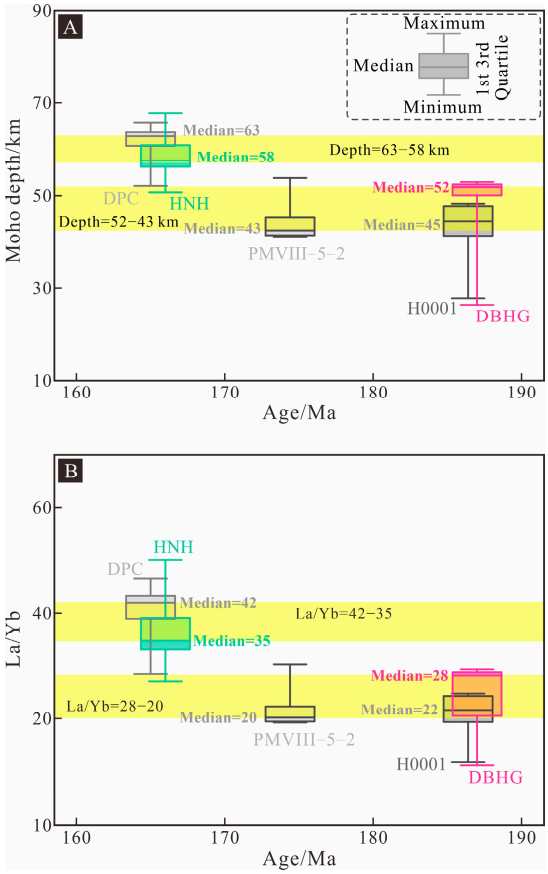

Figure 6. Box–whisker plots of Moho depth (**A**) and La/Yb (**B**) for the Huangnihe and related plutons in the Jiapigou district. The published data for the Huangnihe (granite, HNH) and Dabinghugou (granodiorite, DBHG) plutons are from refs. [10,11], while the data for the others are the same as those in Figure 5.

Implications for gold mineralization: Numerous studies have revealed that adakites are genetically related to hydrothermal Au–Cu deposits [37–39], such as porphyry deposits in southern Tibet [40] and the Philippine Archipelago [38], mesothermal gold deposits in the Chifeng–Chaoyang district at the northern margin of the NCC [41,42], and epithermal gold deposits on the continental margin of NE China [43,44]. The adakitic magmas derived from thickened crust typically contain abundant volatile components (i.e., F and Cl) and chalcophile elements (i.e., Cu, Au, and Ag) and are characterized by a high water content and a high oxidation state [40,45,46], which have contributed to the formation of hydrothermal Au–Cu deposits. As discussed above, the crust in the Jiapigou district gradually thickened during the Early–Middle Jurassic and underwent partial melting, thereby generating adakite-like (ca. 175 Ma) and/or adakite magmas (ca. 166 Ma) that were emplaced to form the ca. 175 Ma and 166 Ma granitoids (i.e., the Huangnihe–Wudaoliuhe plutons and regional granitic dikes). Moreover, Han et al. (2022) [3] reported that syn-ore magma mixing between ca. 175 Ma adakite-like felsic magma (enriched in volatile components and chalcophile elements) and mantle-derived mafic magmas (enriched in ore-forming elements, sulfur, and CO_2) was necessary for magma evolution. This mixing process further promoted the enrichment of ore-forming elements (i.e., Au and Cu), sulfur, and volatile components within the magma system, which significantly contributed to the formation of large Au mineralization in the Jiapigou district. The initial ore fluids migrated upward along the ore-controlling fault systems and precipitated in suitable positions to form gold deposits; this process was triggered by fluid boiling and fluid–rock reactions [2–5]. In

addition, adakitic rocks from 166 Ma were present in the study area, but no synchronic Au-mineralization events have been reported, which merits future comprehensive research.

In summary, due to the multiple episodes of subduction of the Paleo-Pacific Plate, the crust in the Jiapigou district gradually thickened during the Early–Middle Jurassic and underwent partial melting, generating arc-like calc-alkaline (ca. 187 Ma), adakite-like (ca. 175 Ma), and adakite magmas (ca. 166 Ma) that were emplaced to form the corresponding granitoids. Syn-ore magma mixing between ca. 175 Ma adakite-like felsic magma and mantle-derived mafic magmas was crucial for magma evolution and further promoted the enrichment of ore-forming elements within the magma system, which significantly contributed to the formation of large Au mineralization in the Jiapigou district.

5. Conclusions

(1) The Huangnihe pluton comprises mainly fine-grained granite and porphyritic granite, which were emplaced at 187 Ma and 166 Ma, respectively. Combined with published geochronological data, this study revealed that the Early–Middle Jurassic magmatism in the Jiapigou district can be subdivided into three episodes: 187–186 Ma, ca. 175 Ma, and 166–165 Ma.

(2) The geochemical and Hf isotope data indicate that the two episodes of granite from the Huangnihe pluton exhibit distinct origins: the ca. 187 Ma granite originated from juvenile lower crust, whereas the ca. 166 Ma granites were derived from Archean crust and exhibited adakite affinity.

(3) Combining regional observations, the results of this study reveal that the crust in the Jiapigou district gradually thickened during the Early–Middle Jurassic and underwent partial melting due to the multiple episodes of subduction of the Paleo-Pacific Plate, generating arc-like calc-alkaline (ca. 187 Ma), adakite-like (ca. 175 Ma), and adakite magmas (ca. 166 Ma) that were emplaced to form the corresponding granitoids. Syn-ore magma mixing between ca. 175 Ma adakite-like felsic magma and mantle-derived mafic magmas was crucial for magma evolution and promoted the enrichment of ore-forming elements within the magma system, which significantly contributed to the formation of large Au mineralization in the Jiapigou district.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min15101014/s1, Supplementary File S1: Analytical methods; Table S1: LA-ICP-MS zircon U-Pb data for the intrusions from the Huangnihe pluton; Table S2: In situ zircon Hf isotopic data for the intrusions from the Huangnihe pluton; Table S3: Comparison of the mineral assemblage, age, and geochemical composition of the porphyritic granites from the Huangnihe pluton; Table S4: Geochemical data of the intrusions in the Jiapigou district.

Author Contributions: Conceptualization, J.H. and Z.L.; methodology, J.H. and Y.L.; software, X.Z. (Xiaotian Zhang) and X.Q.; validation, X.Z. (Xinwen Zhang) and S.W.; formal analysis, X.Z. (Xiaotian Zhang); investigation, J.H., J.S., P.H. and S.W.; resources, J.H.; data curation, J.H., C.Z. and Z.L.; writing—original draft preparation, J.H.; writing—review and editing, Z.L., Y.L., J.S. and P.H.; visualization, X.Z. (Xinwen Zhang); supervision, Z.L.; project administration, J.H.; funding acquisition, J.H. and J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the National Natural Science Foundation of China (Nos. 42202068, 42302103, 42072085 and 92162323), the China Postdoctoral Science Foundation (2023M743306), the Chinese Geological Survey Programme (No. DD20221692), Deep Earth probe and Mineral Resources Exploration-National Science and Technology Major Project (No. 2025ZD1008205), and Open Research Fund Program of Key Laboratory of Metallogenic Prediction of Nonferrous Metals and Geological Environment Monitoring (Ministry of Education), Central South University (No. 2025YSJS09).

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available in the manuscript. The data in this study are unpublished and have not been submitted to any other journal for review.

Acknowledgments: We are very grateful to the 4 anonymous reviewers for their criticism and constructive comments and suggestions, which helped to significantly improve this paper.

Conflicts of Interest: The authors Yanpeng Liu and Pengfei Huang are employed by Beijing Institute of Geology for Mineral Resources Co., Ltd. and China Gold Group Jiapigou Mining Co., Ltd., respectively. All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Sun, J.G.; Xing, S.W.; Zheng, Q.D. *Geodynamic and Geochemistry of Nonferrous and Noble Metal Deposits, Northeastern China*; Jilin University Press: Changchun, China, 2006; pp. 1–128. (In Chinese)
2. Deng, J.; Yuan, W.M.; Carranza, E.J.M.; Yang, L.Q.; Wang, C.M.; Yang, L.Y.; Hao, N.N. Geochronology and thermochronometry of the Jiapigou gold belt, northeastern China: New evidence for multiple episodes of mineralization. *J. Asian Earth Sci.* **2014**, *89*, 10–27. [CrossRef]
3. Han, J.L.; Deng, J.; Zhang, Y.; Sun, J.G.; Wang, Q.F.; Zhang, Y.M.; Zhang, X.T.; Liu, Y.; Zhao, C.T.; Yang, F.; et al. Au mineralization-related magmatism in the giant Jiapigou mining district of Northeast China. *Ore Geol. Rev.* **2022**, *141*, 104638. [CrossRef]
4. Zhang, X.T.; Sun, J.G.; Han, J.L.; Feng, Y.Y. Genesis and mineralizing process of the Benqu mesothermal gold deposit in the Jiapigou ore cluster, NE China: Constraints from geology, geochronology, fluid inclusions, and whole-rock and isotope geochemistry. *Ore Geol. Rev.* **2021**, *130*, 103956. [CrossRef]
5. Han, J.L.; Lü, Z.C.; Zhao, C.T.; Zhang, X.T.; Sun, J.G.; Wang, S.; Zhang, X.W. Ore genesis of the Jurassic granite-hosted Naizhigou gold deposit in the Jiapigou District of Northeast China: Constraints from Fluid Inclusions and H–O–S Isotopes. *Minerals* **2025**, *15*, 696. [CrossRef]
6. Deng, J.; Wang, Q. Gold mineralization in China: Metallogenic provinces, deposit types and tectonic framework. *Gondwana Res.* **2016**, *36*, 219–274. [CrossRef]
7. Wang, Q.F.; Zhao, H.S.; Yang, L.; Groves, D.I.; Han, J.L.; Qiu, K.F.; Li, D.P.; Liu, Z.; Zhao, R.; Deng, J. Formation of the giant Cretaceous Jiaodong-type orogenic gold province of the North China Craton: A consequence of lithospheric multi-layer reworking. *Geosci. Front.* **2025**, *16*, 102047. [CrossRef]
8. Yu, B.; Zeng, Q.D.; Frimmel, H.E.; Wang, Y.B.; Guo, W.K.; Sun, G.T.; Zhou, T.C.; Li, J.P. Genesis of the Wulong gold deposit, northeastern North China Craton: Constraints from fluid inclusions, H–O–S–Pb isotopes, and pyrite trace element concentrations. *Ore Geol. Rev.* **2018**, *102*, 313–337. [CrossRef]
9. Liu, C.; Zhu, G.; Xie, C.L.; Zhang, S.; Li, Y.J.; Su, N.; Xiao, S.Y. Location and sinistral displacement of the eastern Liaoyuan Accretionary Belt along the Tan–Lu Fault Zone, NE China. *J. Asian Earth Sci.* **2019**, *172*, 409–422. [CrossRef]
10. Huang, Z.X. Tectonics–Fluids–Mineralization System of Jiapigou Gold Belt in the Jilin Province, China. Ph.D. Thesis, China University of Geosciences Beijing, Beijing, China, 2021; pp. 1–255. (In Chinese with English Abstract)
11. Liu, S.; Hu, R.Z.; Feng, C.X.; Feng, G.Y.; Yu, X.F.; Li, C.; Jia, D.C.; Qi, Y.Q.; Wang, T. Zircon U–Pb age, Hf isotopic compositions of Dapuchaihe adakites in eastern Jilin Province and their significance. *Acta Petrol. Sin.* **2009**, *25*, 3153–3164. (In Chinese with English Abstract)
12. Wang, S.; Sun, J.G.; Han, J.L.; Chu, X.L.; Zhang, X.T. Genesis, magmatic process and metallogenic constraints on the granitic complex in the Jiapigou gold mining district, Jilin Province: Evidence from zircon U–Pb geochronology and element and Hf isotope geochemistry. *Geol. J.* 2025, *(submitted for publication)*.
13. Yu, R.D.; Sun, J.G.; Wang, S.; Han, J.L.; Liu, Y. Neoarchean–early Paleoproterozoic crustal evolution in the Jiapigou terrane in the northeastern part of the North China Craton: Geochemistry, zircon U–Pb dating and Hf isotope constraints from the potassic granitic complex. *Precambrian Res.* **2021**, *364*, 106341. [CrossRef]
14. Han, J.L.; Sun, J.G.; Zhang, X.T.; Liu, Y.; Xu, Z.K.; Wang, S.; Xu, Z.T.; Li, X. Comparison of vein- and breccia-type Au-mineralization in the giant Jiapigou mining district of Northeast China. *Ore Geol. Rev.* **2022**, *141*, 105173. [CrossRef]
15. Song, B.; Zhang, Y.H. Introduction to the naissance of SHRIMP and its contribution to isotope geology. *J. Chin. Mass Spectrom. Soc.* **2002**, *23*, 58–62. (In Chinese with English Abstract)
16. Griffin, W.L.; Wang, X.; Jackson, S.E.; Pearson, N.J.; O'Reilly, S.Y.; Xu, X. Zircon chemistry and magma mixing, SE China: In-situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos* **2002**, *61*, 237–269. [CrossRef]
17. Anderson, T. Correction of common lead in U–Pb analyses that do not report ^{204}Pb. *Chem. Geol.* **2002**, *192*, 59–79. [CrossRef]

18. Ludwig, K.R. *User's Manual for Isoplot 3.0: A Geolocronolgical Toolkit for Microsoft Excel*; Berkeley Geochronlogical Center, Special Publication: Berkeley, CA, USA, 2003; Volume 4, pp. 1–70.
19. Wu, Y.B.; Zheng, Y.F. Genesis of zircon and its constraints on interpretation of U–Pb age. *Chin. Sci. Bull.* **2004**, *49*, 1554–1569. (In Chinese with English Abstract) [CrossRef]
20. Zhang, Y.B.; Wu, F.Y.; Zhai, M.G.; Lu, X.P. Tectonic characteristics of the Helong Block and the boundary of eastern segment of the northern margin of the North China Craton. *Sci. China Earth Sci.* **2004**, *34*, 795–806. (In Chinese)
21. Han, J.L. Metallogenesis and Geodynamic Setting of the Typical Gold Deposits in the Liuhe Area of the Huadian City, Jilin Province. Ph.D. Thesis, Jilin University, Changchun, China, 2019; pp. 1–154. (In Chinese with English Abstract)
22. Lu, Y. Petrology and Geochemistry of Early Jurassic Intrusive Rocks in the Central Jilin Province. Ph.D. Thesis, Jilin University, Changchun, China, 2016; pp. 1–68. (In Chinese with English Abstract)
23. Li, L. Research on Ore-Forming Fluids of Gold Deposits in Jiapigou-Haigou Gold Belt, Jilin Province and Deep-Seated Metallogenic Assessment. Ph.D. Thesis, Jilin Univertsity, Changchun, China, 2016; pp. 1–111. (In Chinese with English Abstract)
24. Zhang, Y.B.; Wu, F.Y.; Wilde, S.A.; Zhai, M.G.; Lu, X.P.; Sun, D.Y. Zircon U–Pb ages and tectonic implications of 'Early Paleozoic' granitoids at Yanbian, Jilin Province, northeast China. *Isl. Arc* **2004**, *13*, 484–505. [CrossRef]
25. Liu, D.Z.; Qu, S.; Wang, X.G. The basic geological features of the Huangniling rock body. *Jilin Geol.* **1994**, *13*, 41–49.
26. Defant, M.J.; Jackson, T.E.; Drummond, M.S.; de Boer, J.Z.; Bellon, H.; Feigenson, M.D.; Maury, R.C.; Stewart, R.H. The geochemistry of young volcanism throughout Western Panama and Southern Casta Rica, an overview. *J. Geol. Soc.* **1992**, *149*, 569–579. [CrossRef]
27. Xu, W.L.; Pei, F.P.; Wang, F.; Meng, E.; Ji, W.Q.; Yang, D.B.; Wang, W. Spatial–temporal relationships of Mesozoic volcanic rocks in NE China: Constraints on tectonic overprinting and transformations between multiple tectonic regimes. *J. Asian Earth Sci.* **2013**, *74*, 167–193. [CrossRef]
28. Han, J.L.; Lü, Z.C.; Zhang, X.T.; Liu, Y.; Yu, X.F.; Zhao, C.T.; Sun, J.G.; Huang, P.F.; Wang, S.; Zhang, X.W. Middle Jurassic giant Au-mineralization in the Jiapigou district of NE China: Constrains from zircon U–Pb and molybdenite Re–Os dating of the Naizhigou deposit. *Ore Geol. Rev.* 2025, *(submitted for publication)*.
29. Mooney, W.D.; Laske, G.; Masters, T.G. Crust 5.1: A global crustal model at 5° × 5°. *J. Geophys. Res.* **1998**, *103*, 727–747. [CrossRef]
30. McQuarrie, N.; Chase, C.G. Raising the Colorado Plateau. *Geology* **2000**, *28*, 91–94. [CrossRef]
31. Platt, J.P. From orogenic hinterlands to Mediterranean-style back-arc basins: A comparative analysis. *J. Geol. Soc.* **2007**, *164*, 297–311. [CrossRef]
32. Zhang, C.H.; Li, C.M.; Deng, H.L.; Liu, Y.; Liu, L.; Wei, B.; Li, H.B.; Liu, Z. Mesozoic contraction deformation in the Yanshan and northern Taihang mountains and its implications to the destruction of the North China Craton. *Sci. China Earth Sci.* **2011**, *54*, 798–822. [CrossRef]
33. Xue, J.X.; Cai, K.D.; Zhang, Z.J.; Wang, K. Timing and style of final closure of the Paleo-Asian Ocean: Perspectives from the Big Geodata Analysis and machine learning model. *J. Geophys. Res. Solid Earth* **2025**, *130*, e2024JB029877. [CrossRef]
34. Hu, F.Y.; Ducea, M.N.; Liu, S.W.; Chapman, J.B. Quantifying crustal thickness in continental collisional belts: Global perspective and a geologic application. *Sci. Rep.* **2017**, *7*, 7058. [CrossRef]
35. Profeta, L.; Ducea, M.N.; Chapman, J.B.; Paterson, S.R.; Gonzales, S.M.H.; Kirsch, M.; Petrescu, L.; DeCelles, P.G. Quantifying crustal thickness over time in magmatic arcs. *Sci. Rep.* **2015**, *5*, 17786. [CrossRef] [PubMed]
36. Wu, F.Y.; Sun, D.Y.; Ge, W.C.; Zhang, Y.B.; Grant, M.L.; Wilde, S.A.; Jahn, B.M. Geochronology of the Phanerozoic granitoids in northeastern China. *J. Asian Earth Sci.* **2011**, *41*, 1–30. [CrossRef]
37. Thieblemont, D.; Stein, G.; Lescuyer, J.L. Gisements epithermaux et porphyrigues: La connexion adakite. *Earth Planet. Sci.* **1997**, *325*, 103–109.
38. Zhang, Y.; Tian, J.; Hollings, P.; Gong, L.; Alburo, I.; Berador, A.E.; Francisco, D.G. Mesozoic porphyry Cu–Au mineralization and associated adakite-like magmatism in the Philippines: Insights from the giant Atlas deposit. *Miner. Depos.* **2019**, *55*, 881–900. [CrossRef]
39. Zhang, L.Y.; Li, S.C.; Zhao, Q.Y. A review of research on adakites. *Int. Geol. Rev.* **2021**, *63*, 47–64. [CrossRef]
40. Li, J.X.; Qin, K.Z.; Li, G.M.; Xiao, B.; Chen, L.; Zhao, J.X. Post-collisional ore-bearing adakitic porphyries from Gangdese porphyry copper belt, southern Tibet: Melting of thickened juvenile arc lower crust. *Lithos* **2011**, *126*, 265–277. [CrossRef]
41. Fu, L.B.; Wei, J.H.; Kusky, T.M.; Chen, H.Y.; Tan, J.; Li, Y.J.; Shi, W.J.; Chen, C.; Zhao, S.Q. The Cretaceous Duimiangou adakite-like intrusion from the Chifeng region, northern North China Craton: Crustal contamination of basaltic magma in an intracontinental extensional environment. *Lithos* **2012**, *134–135*, 273–288. [CrossRef]
42. Liu, L.; Gu, X.X.; Zhang, Y.M.; Ouyang, X.; Wang, L.Z.; Gao, L.Y. Genesis of the Jinchanggouliang gold deposit, Chifeng, China: Constraints from fluid inclusions and isotopic geochemistry. *Ore Geol. Rev.* **2019**, *115*, 103180. [CrossRef]
43. Sun, J.G.; Liu, Y.; Xu, Z.K.; Xu, Z.T.; Chu, X.L.; Gu, A.L. Large-scale epithermal mineralization of late Mesozoic and the constraints of deep geological processes on mineralization in the continental margin of NE China. *J. Jilin Univ. (EarthScience Ed.)* **2023**, *53*, 651–692. (In Chinese with English Abstract)

44. Qiao, S.L.; Ma, X.H. Geochronological and geochemical constraints on age and origin of granodiorite of Nongping Au-Cu porphyry deposit in Jilin Province, China. *Miner. Depos.* **2018**, *37*, 387–402. (In Chinese with English Abstract)
45. Cooke, D.R.; Hollings, P.; Walsh, J.L. Giant porphyry deposits: Characteristics, distribution, and tectonic controls. *Econ. Geol.* **2005**, *100*, 801–818. [CrossRef]
46. Sillitoe, R.H. Porphyry copper systems. *Econ. Geol.* **2010**, *105*, 3–41. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.