Supplementary Materials

for

The largest and longest-lived low-$\delta^{18}O$ magmatic event on Earth

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Supplementary Text S1. Geological setting

Th South China consists of the Yangtze Block in the northwest and the Cathaysian Block in the southeast, which amalgamated along the Sibao/Jiangnan Orogen during the Neoproterozoic. The western margin of the Yangtze Block is one of the most extensively developed regions of Meso–Neoproterozoic magmatic and sedimentary rocks in South China, and is an important area for investigating magmatism, crustal evolution, and surface fluid–lithosphere interaction during the breakup of Rodinia. Several Neoproterozoic low-$\delta^{18}O$ felsic intrusions occur along this margin, providing key materials for evaluating the spatiotemporal distribution and petrogenesis of low-$\delta^{18}O$ magmatism in South China (Figure S1).

Neoproterozoic strata and volcano-sedimentary successions are well developed in the study area, including the Suxiong Formation, Yanbian Group, Ebian Group, Huangshuihe Group, Bikou Group, Sinian strata, and other volcano-sedimentary sequences. The regional stratigraphy is characterized by a wide range of formation ages, incomplete exposure, and scattered distribution. Exposed units include Neoarchean–Paleoproterozoic metamorphic complexes, as well as Sinian, Devonian, Permian, Triassic, Cretaceous, Jurassic, and Quaternary strata. The Neoarchean–Paleoproterozoic units are mainly metamorphic rocks, whereas the Sinian, Devonian, and Permian units are dominated by marine sedimentary and volcanic rocks that have commonly undergone varying degrees of deformation and metamorphism. Triassic and Cretaceous intrusive rocks are widely distributed and range from mafic and intermediate to felsic and alkaline compositions, with felsic rocks being the most abundant.

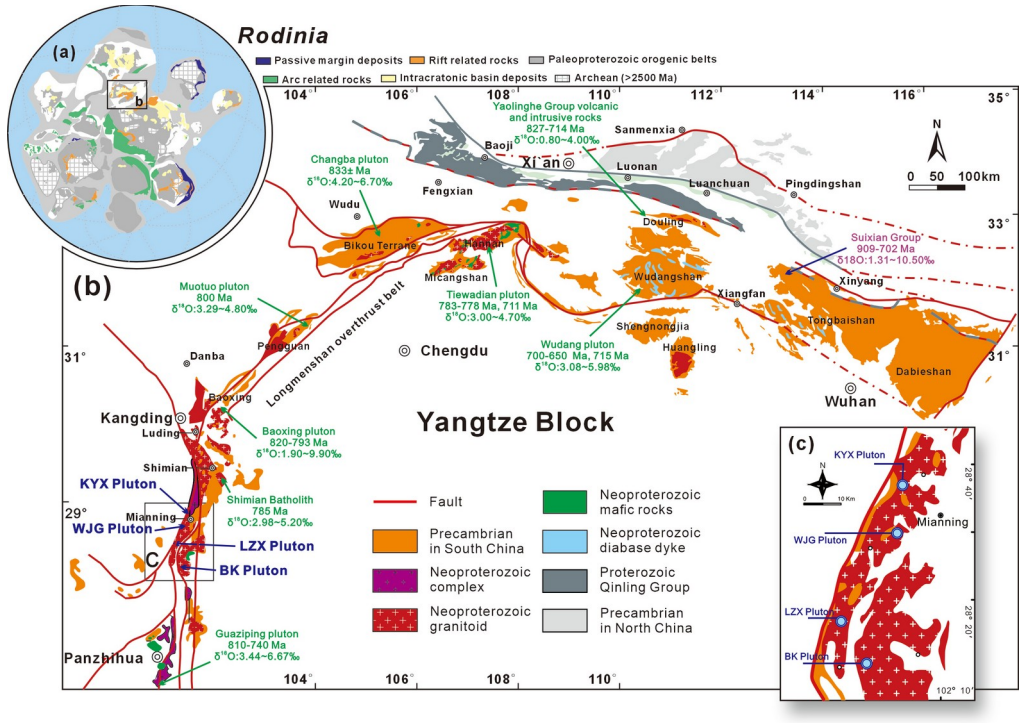

Figure S1. Regional geological setting of the northern and western margins of the Yangtze Block and locations of the studied plutons. (a) Reconstruction of the Rodinia supercontinent showing the tectonic position of the Yangtze Block; (b) simplified geological map of the northern and western margins of the Yangtze Block, showing the distribution of Neoproterozoic magmatic rocks, Precambrian units, major faults and tectonic belts; (c) enlarged geological map of the study area showing the locations of the BK, LZX, WJG and KYX plutons.

Neoproterozoic magmatic rocks are widely distributed along the western margin of the Yangtze Block, mainly along the nearly N–S-trending Anninghe Fault zone and adjacent areas. Their emplacement ages are chiefly concentrated at ca. 860–740 Ma. These magmatic rocks are predominantly felsic, with minor associated mafic to intermediate intrusion. Their near N–S distribution is closely related to the Kangdian Rift system and the Anninghe Fault system, reflecting intense magmatic activity under an extensional tectonic setting along the western margin of South China during the Neoproterozoic. The Mianning pluton is located in the northern part of the Kangdian Rift system, bounded or controlled by the nearly N–S-trending Jinghe Fault to the west and adjacent to the Anninghe Fault to the east, with an exposed area of approximately 700 km^2. It intrudes the Neoproterozoic Suxiong bimodal volcanic succession, is overlain by Upper Sinian sedimentary rocks, and is locally cut by Permian basalts and later dikes or intrusive bodies. The marginal parts of the Mianning pluton are mainly composed of alkali-feldspar granite, plagioclase granite, and minor syenite. Sparse xenoliths and relatively abundant dikes occur in the area, including quartz veins, diabase dikes, and minor granitic pegmatite and fine-grained granitic dikes.

Supplementary Text S2. Sample localities and sample descriptions

Four representative plutons from the Mianning–Xichang area were investigated in this study: KYX, WJG, LZX, and BK. These plutons are spatially close to the Anninghe Fault system and are distributed along a nearly N–S-trending belt on the western margin of the Yangtze Block (Figure S1). The LZX pluton was sampled at Longzixiang, Mianning County, with coordinates of 102°04′34.19″E and 28°19′29.08″N, and is composed of granite. The BK pluton was sampled at Bakou, Mianning City, with coordinates of 102°08′49.10″E and 28°18′44.81″N, and is also composed of

granite. The KYX pluton was sampled at Kaiyuanxiang. Xichang City, with coordinates of 102°06′37.32″E and 27°52′39.45″N, and consists of quartz syenite. The WJG pluton was sampled at Wangjiagou, Xichang City, with coordinates of 102°07′13.09″E and 27°45′44.27″N, and is composed of granite.

The four plutons are generally light-colored and granitoid in appearance. The LZX granite is greyish white to light grey, massive, and locally cut by joints and fractures. It is mainly composed of quartz and feldspar, with quartz accounting for approximately 30–40 vol.%, feldspar for 50–60 vol.%, and mafic minerals generally less than 10 vol.%. The KYX quartz syenite is greyish white to light grey and medium- to coarse-grained, with locally uneven distribution of light and dark minerals. It is dominated by feldspar, accounting for approximately 65–75 vol.%, with quartz accounting for 10–20 vol.% and mafic minerals for 5–10 vol.%. The WJG granite is greyish white to light grey, medium- to fine-grained to medium-grained, and relatively homogeneous. It consists mainly of quartz and feldspar, with quartz accounting for approximately 30–35 vol.%, feldspar for 55–65 vol.%, and mafic minerals for 5–10 vol.%. The BK granite is light greyish white and medium- to fine-grained to medium-grained, with abundant felsic minerals and only minor mafic minerals. It contains approximately 35–40 vol.% quartz, 55–60 vol.% feldspar, and generally less than 5 vol.% mafic minerals.

Figure S2. Field photographs, hand specimens, and representative rock textures of the studied plutons in the Mianning–Xichang area. (a) KYX quartz syenite; (b) WJG granite; (c) LZX pluton sample; (d) BK granite.

Overall, the LZX, WJG, and BK samples are granites mainly composed of quartz, K-feldspar, plagioclase, and minor biotite and/or hornblende, whereas the KYX sample is a quartz syenite characterized by abundant feldspar and relatively low quartz contents. Some feldspar, biotite, and hornblende grains show weak alteration, including sericitization, chloritization, and clay mineral replacement. The samples are generally well preserved, although local effects of late fractures, low-temperature fluid activity, and surface weathering are present.

Supplementary Text S3. Whole-rock geochemical results

Whole-rock major- and trace-element compositions of the KYX, WJG, LZX, and BK samples are listed in Table S7. The four sample groups show distinct lithological and geochemical characteristics.

The KYX samples are quartz syenites and are characterized by high SiO_2 contents of 72.98–74.29 wt.% and high total alkali contents, with $Na_2O + K_2O$ = 8.74–9.04 wt.%. Their low CaO, MgO, and P_2O_5 contents are consistent with a highly evolved felsic to alkaline composition. Trace-element data show strong enrichment in Rb, Zr, Nb, Hf, Th, and U, together with very low Sr contents, indicating a highly differentiated felsic magma.

The WJG samples are granites with SiO_2 contents of 68.50–69.38 wt.% and moderate total alkali contents of 6.50–6.74 wt.%. Compared with KYX, they contain higher CaO and Sr–Ba contents but lower Zr–Nb–Hf contents, suggesting a less evolved granitic composition. Their relatively uniform major-element compositions also indicate limited lithological variation within the sampled WJG granite.

The LZX samples are intermediate rocks, with lower SiO_2 contents of 48.75–53.10 wt.% and relatively high Fe–Mg–Ca contents. They are also characterized by high Sr and V contents and low Rb, Nb, Th, and U contents. These features distinguish LZX from the felsic KYX, WJG, and BK samples and support its classification as an intermediate igneous rock.

The BK samples are felsic rocks with high SiO_2 contents of 73.98–77.00 wt.% and relatively high total alkali contents of 7.69–10.85 wt.%. Their low Fe–Mg–Ca contents, low Sr contents, and generally low mafic-compatible element contents are consistent with highly evolved felsic rocks. Compared with KYX, the BK samples have lower Zr–Nb–Hf contents and lower total REE abundances.

Overall, the whole-rock geochemical data support the lithological classification of the four sample groups: KYX as quartz syenite, WJG and BK as felsic granitoids, and LZX as intermediate igneous rocks. KYX and BK represent more evolved felsic compositions, WJG represents a relatively less evolved granite, and LZX records a more mafic to intermediate component within the sampled plutonic suite.

Supplementary Text S4. LA–ICP–MS zircon U–Pb results

LA–ICP–MS zircon U–Pb analytical results for the LZX, WJG, KYX, and BK samples are listed in Table S4. Most analyzed zircons have relatively high Th/U ratios, generally greater than 0.4, indicating a magmatic origin.

The LZX sample yields a coherent Neoproterozoic zircon age population. Most analyses are concordant and give $^{206}Pb/^{238}U$ ages of ca. 747–752 Ma, defining a weighted mean $^{206}Pb/^{238}U$ age of ca. 748 Ma. This age is interpreted as the crystallization age of the LZX pluton.

The WJG sample also shows a concentrated Neoproterozoic age population. Most concordant analyses yield $^{206}Pb/^{238}U$ ages of ca. 710–722 Ma, with one discordant analysis excluded. These data define a weighted mean $^{206}Pb/^{238}U$ age of ca. 719 Ma, representing the crystallization age of the WJG granite.

The KYX sample is dominated by concordant Neoproterozoic zircon ages of ca. 688–699 Ma. Two much younger analyses at ca. 270–273 Ma are excluded from the main age population. The remaining Neoproterozoic analyses define a weighted mean $^{206}Pb/^{238}U$ age of ca. 692 Ma, which is interpreted as the crystallization age of the KYX quartz syenite.

The BK sample records a more scattered Neoproterozoic zircon age distribution. Most analyses yield $^{206}Pb/^{238}U$ ages between ca. 775 and 833 Ma, whereas several analyses are discordant or younger. This dispersed age pattern suggests a more complex zircon record, possibly involving inherited, mixed, or disturbed zircon domains. The main Neoproterozoic age population indicates that the BK felsic rocks are related to early Neoproterozoic magmatism.

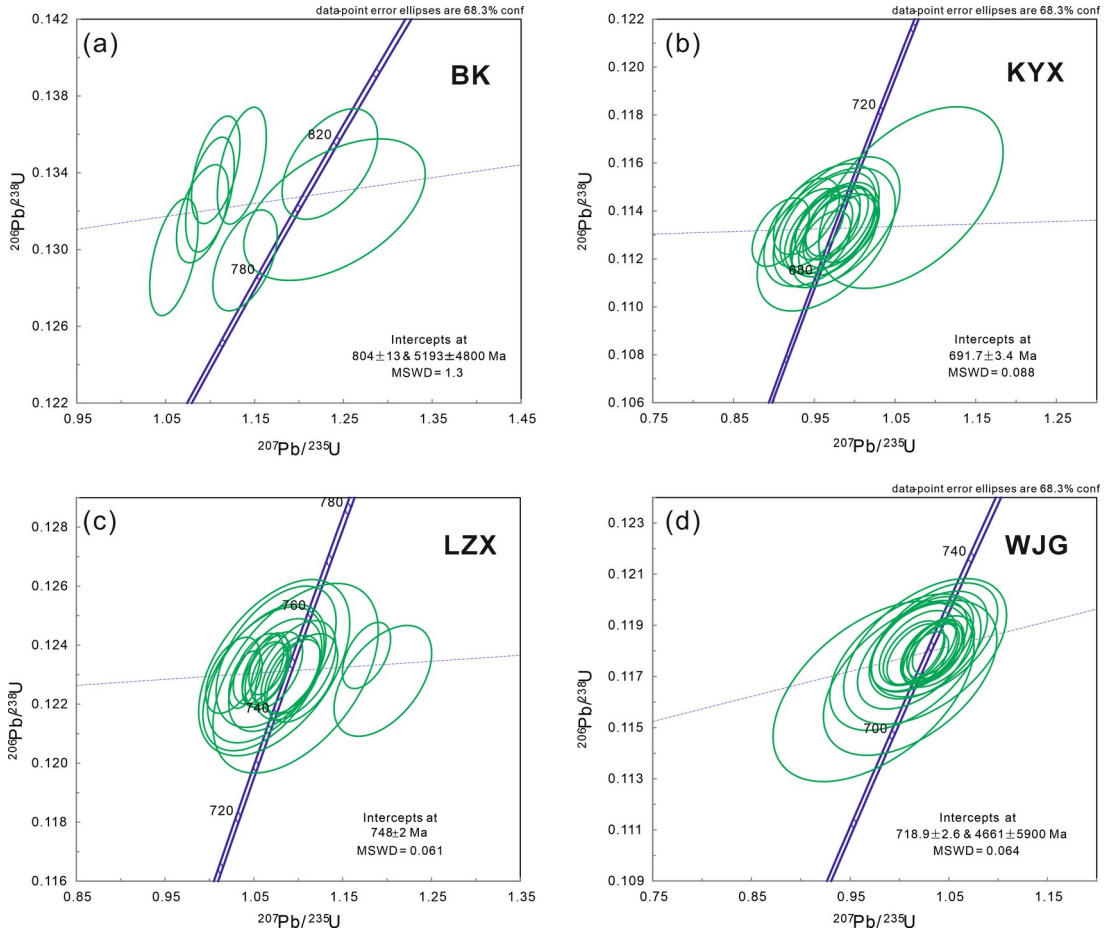

Figure S3. Zircon U–Pb concordia diagrams showing crystallization ages of the BK, KYX, LZX, and WJG plutons.

Overall, the zircon U–Pb data indicate that the studied plutons record prolonged Neoproterozoic magmatism along the western margin of the Yangtze Block. The reliable crystallization ages are ca. 748 Ma for LZX, ca. 719 Ma for WJG, and ca. 692 Ma for KYX, whereas BK preserves an older and more scattered Neoproterozoic zircon age population.

Supplementary Text S5. Zircon Lu-Hf isotope and O isotope analysis

Zircon Lu–Hf and oxygen isotope analytical results for the LZX, WJG, KYX, and BK samples are listed in Table S5. The analyzed zircons show variable Hf isotopic compositions and $\delta^{18}O$ values among the four sample groups.

The LZX zircons yield relatively low $^{176}Lu/^{177}Hf$ ratios of 0.00121–0.00326 and initial $^{176}Hf/^{177}Hf$ ratios of 0.282340–0.282509. Their εHf(t) values are positive, ranging from +1.0 to +6.8, with TDM1 and TDM2 model ages of 1.04–1.30 Ga and 1.21–1.58 Ga, respectively. The $\delta^{18}O$ values of LZX zircons range from 3.74‰ to 5.80‰, with most analyses lower than typical mantle zircon values, indicating a distinct low-$\delta^{18}O$ zircon population.

The WJG zircons have $^{176}Lu/^{177}Hf$ ratios of 0.00063–0.00174 and initial $^{176}Hf/^{177}Hf$ ratios of 0.282289–0.282449. Their εHf(t) values range from −1.2 to +4.3, suggesting slightly variable but mainly positive Hf isotopic compositions. The corresponding TDM1 and TDM2 model ages are 1.12–1.34 Ga and 1.36–1.71 Ga, respectively. The $\delta^{18}O$ values of WJG zircons are relatively concentrated, ranging from 4.46‰ to 5.26‰.

Figure S4. Cathodoluminescence images of representative zircons from the LZX, KYX, BK, and WJG plutons, showing in situ U–Pb dating, Lu–Hf isotope and O isotope analytical spots. The blue circle represents the location of Lu–Hf isotope analysis, the red circle represents the location of U–Pb dating, and the yellow circle represents the location of O isotope analysis. The values below each zircon indicate the U–Pb age, εHf(t) value and $\delta^{18}O$ value. Scale bars are 100 μm.

The KYX zircons show the largest isotopic variation among the samples analyzed. Excluding two younger analyses, the main Neoproterozoic zircon population has $^{176}Lu/^{177}Hf$ ratios of 0.00061–0.00198 and initial $^{176}Hf/^{177}Hf$ ratios of 0.282285–0.282515. Their εHf(t) values range from −2.4 to +6.1, and the TDM1 and TDM2 model ages are 1.03–1.36 Ga and 1.23–1.75 Ga, respectively. The $\delta^{18}O$ values vary widely from 0.84‰ to 8.34‰, indicating a heterogeneous oxygen isotope composition within the KYX zircon population. Two younger analyses yield ages of ca. 269–293 Ma and have markedly positive εHf(t) values of approximately +11.4 to +11.5, with younger Hf model ages.

The BK zircons are characterized by low $^{176}Lu/^{177}Hf$ ratios of 0.00017–0.00162 for the main Neoproterozoic population. Their initial $^{176}Hf/^{177}Hf$ ratios range from 0.282373 to 0.282547, and εHf(t) values are consistently positive, ranging from +2.4 to +9.2. The TDM1 and TDM2 model ages are 0.98–1.22 Ga and 1.10–1.50 Ga, respectively. The $\delta^{18}O$ values of BK zircons range from 4.00‰ to 5.25‰. Two older analyses at ca. 1020 Ma and 1250 Ma have higher εHf(t) values of +12.4 to +13.5 and $\delta^{18}O$ values of 4.46‰–4.71‰.

Supplementary Text S6. Abbreviations used in Figure 2

A, Amazonia; **Ant**, Antarctica; **AUS**, Australia; **NC**, North China; **P**, Paranapanema; **SF**, São Francisco Craton; **ANS**, Arabian–Nubian Shield; **SC**, South China; **SM**, Sahara Metacraton; **WAC**, West African Craton.