

Granitic magmatism related to early Paleozoic continental collision in North Qinling

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Zircon U-Pb dating of early Paleozoic granitoids in North Qinling yields three age peaks of ~500, ~452 and ~420 Ma. They can be temporally correlated with high-pressure to ultrahigh-pressure metamorphism at ca. 500 Ma, retrograde granulite-facies metamorphisms at ca. 450 Ma and amphibolite-facies metamorphism at ca. 420 Ma, respectively. The first episode of granitic magmatism is considered to have resulted from continental collision, whereas the second and third episodes of magmatism are attributed to crustal uplifting. Combined with the regional geological setting and new results from high-pressure and ultrahigh-pressure metamorphic rocks, the ca. 500 Ma magmatism is interpreted as the result of partial melting of sedimentary rocks in accretionary wedge between the south Qinling microcontinent and the north Qinling belt including the southern margin of the North China Craton. The ca. 450 Ma intensive magmatism is ascribed to dehydration melting of deeply subducted continental crust at thickened conditions in response to slab breakoff, and the final magmatism in ca. 420 Ma is interpreted as the product of partial melting during the tectonic transition from contraction to extension.

U-Pb dating, granitoids, high-pressure to ultrahigh-pressure, tectonic evolution, North Qinling

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The Qinling orogen is located between the North China Block (NCB) and South China Block (SCB), and is linked with the Tongbai-Dabie orogens to the east and the Qilian-Kunlun orogens to the west. It serves as an important part of the Central Orogenic Belt of China. Since the 1980s, many geologists have been involved in the study of the tectonic evolution of the Qinling orogen, and numerous results have been obtained. The Qinling orogen is regarded as a composite orogen that experienced multiple tectonic development. The final collision between the NCB and SCB occurred in the early Mesozoic along the Mianlue suture zone [1–3], shaping its present tectonic framework (Figure 1) that is comprised of the north Qinling belt (NQB, included the

southern margin of the NCB), south Qinling belt (SQB) and the northern margin of the SCB separated by the Shangdan suture zone (SDSZ) and Mianlue suture zone (MLSZ), respectively. However, the early tectonic evolution of the Qinling orogen is poorly constrained, such as the timing of subduction of Paleozoic oceanic crust and subsequent collisional process for the closure of Paleotethys. Advances have been made in the understanding of time-space distribution and the nature of HP-UHP metamorphism in the NQB [4–15] after two-decade consistent studies, demonstrating that the early Paleozoic HP-UHP metamorphism was the consequence of northward continental deep-subduction along the SDSZ [16]. The new results concerning the early Paleozoic HP-UHP metamorphism shed some new light on the process and age of subduction of the oceanic crust as

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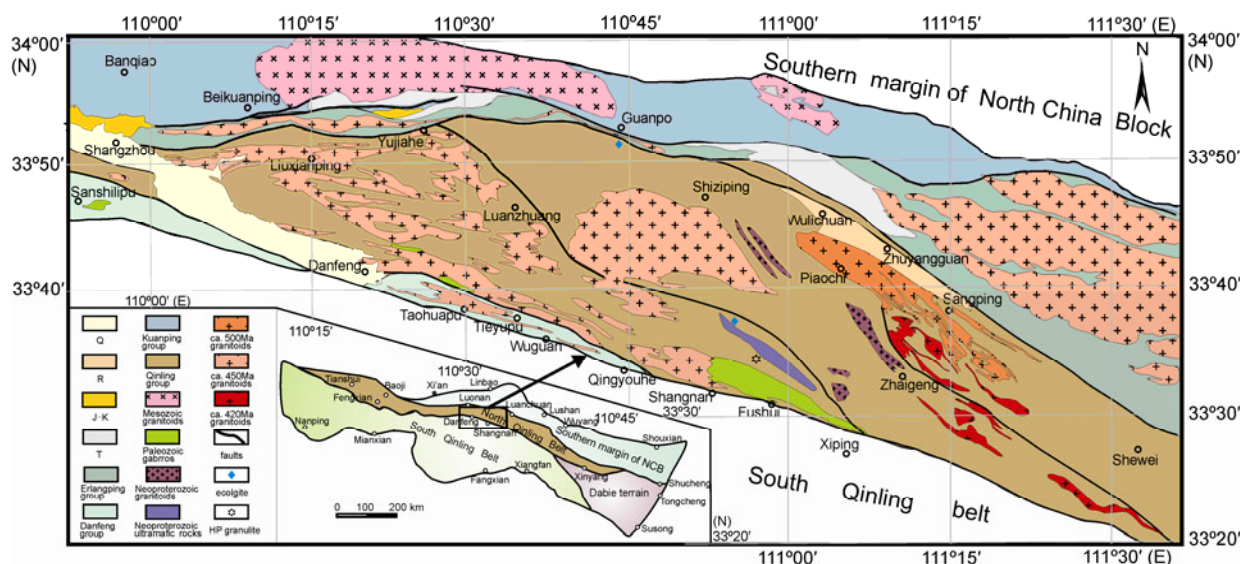


Figure 1 Sketch geological map of the Shangzhou-Danfeng areas in NQB.

well as amalgamation among continental blocks during the early Paleozoic in the Qinling orogen.

The oceanic/continental subduction and continental collision could result in HP-UHP metamorphism, and the subducted slab may be exhumed due to its detachment in subduction channel and slab breakoff in the transitional zone between ocean and crust [17,18]. Granitic magmatism in the subducting, collisional and post-collisional processes would occur owing to dehydration and thermal change of subducted and exhumed slabs in progressive and retrogressive metamorphism [19,20]. As a result, different tectonic stage and origin of granitoids in continental orogen can be used to constrain the processes and closing time of oceanic basins, continental collision and exhumation. We thus carried out a comprehensive study of some granitoid plutons adjacent to HP-UHP rocks in the NQB. We also make a discussion about possible relationship of early Paleozoic collision and subsequent granitic magmatism in the NQB in consideration of some new results of HP-UHP metamorphism, and try to reconstruct early Paleozoic tectonic history in the Qinling orogen.

1 Geological setting

The NQB, bounded on the north by the Luonan-Luanchuan fault and on the south by the SDSZ, consists of four units, the Kuanping, Erlangping, Qinling and Danfeng groups from north to south, extending more than one thousand kilometers from east to west. The Kuanping Group displays an association of greenschists, mica-quartz schists and quartz-rich marbles, and yields young concordant detrital zircon ages of 550–450 Ma from meta-sandstones, confirming that they were formed in a period from the late Neoproterozoic to the early Paleozoic [21]. To the south of the Kuanping group occurs the Erlangping Group, which is

dominated by greenschist- to amphibolite-facies backarc-basin volcanics associated with some sedimentary rocks. The Erlangping Group is intruded by 490–480 Ma granitoids [22], suggesting that it should have been formed before 490 Ma. The Qinling Group occurs as lenticular bodies scattering in the middle of the NQB, and consists mainly of biotite-plagioclase and garnet-sillimanite gneisses, mica-quartz schists, graphite marbles and minor amphibolites. Detrital zircons from the Qinling Group gives ages from 1500 to 1900 Ma [21,23] and gneissic granitoids are dated at 950 Ma [24]. These facts indicate that their protoliths were formed in the early Neoproterozoic. The Danfeng Group crops out in the southern NQB, and is composed of arc volcanic-sedimentary rocks that underwent greenschist to low amphibolite facies metamorphism and is intruded by the 517–430 Ma gabbroic intrusion [25]. Their youngest concordant detrital zircon age is 827 Ma, suggesting that the Danfeng Group was deposited after 827 Ma [21], most possibly during 827–517 Ma. It is also striking that there exist many early Paleozoic granitoid plutons [26] and anatectic veins in the NQB. A number of HP-UHP rocks have been identified in the boundary areas between the Shaanxi and Henan provinces, with the metamorphic peak ages of ca. 500 Ma [16]. All the data imply that the NQB should be an important tectonic belt formed from the Neoproterozoic to early Paleozoic.

2 Early Paleozoic granitoid intrusions in the NQB

Early Paleozoic granitic plutons in NQB widely occur in the areas of Danfeng County in Shaanxi Province and Xixia County in Henan Province (Figure 1). The granitoids can be subdivided into three types according to their field features.

(1) Gneissic granitoid plutons. The Piaochi pluton or

batholith is a proxy of this type, which intrudes into the Qinling Group, and crops out in an area north of Piaochi village in Xixia County of Henan Province. This pluton experienced strong deformation with its gneissic structure parallel to regional foliation. It consists of medium- to coarse-grained monzogranites with mineral assemblage of K-feldspar (~35%), plagioclase (~30%), quartz (~25%), biotite (~15%) and minor hornblende (~3%). The pluton yields a formation age of 496.1 ± 4.2 Ma, consistent with the age of 495 ± 6 Ma obtained by Wang et al. [26]. Furthermore, two anatectic granitic veins in the Qinling Group to the southern Piaochi village of Xixia County and Yongyu of Danfen County of Shaanxi Province gives weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 501.2 ± 4.2 Ma and 501.4 ± 8.1 Ma, respectively, which are interpreted as formation ages similar to the ages of 500 Ma [27] and 497 ± 12 Ma [24] from granitic veins in the NQB. They are texturally and compositionally similar to gneissic batholith, implying that both were formed in the same magmatic event. The gneissic granitoids and anatectic veins obviously represent an earliest event of magmatism caused by the crustal partial melting and granitic intrusion in the NQB during early Paleozoic.

(2) Granitic plutons with weak gneissic structures. These granitic plutons are widely present in the Qinling, Erlangping and Danfeng groups. Some plutons, such as the Liuxianping, Kuanping, Zaoyuan, Huichizi, Shangnan and Sikeshe plutons, show weak gneissic to massive structures and medium- to coarse-grained textures. They are composed mainly of monzogranites, granodiorites and some biotite-granites with mineral assemblages of K-feldspars (25%–40%), plagioclases (30%–35%), quartz (25%–30%), amphibolite (8%–15%), biotites (5%–10%) and minor opaque oxides. The Liuxianping pluton is dated at 456.1 ± 1.9 Ma, the Kuanping pluton at 452.8 ± 2.0 Ma, and the Zaoyuan pluton at 456.1 ± 1.9 Ma, the Huichizi plutons at 445.6 ± 6.1 Ma, and the Sikeshe pluton at 464.1 ± 4.6 – 468.5 ± 4.1 Ma, respectively [22]. In addition, garnet-bearing mica-granitic plutons, like the Huangbaicha and Shangmashi plutons, intrude into the northern part of the Qinling Group, with their ages varying from 447.8 ± 2.5 Ma to 445.7 ± 5.3 Ma. They have mineral assemblages of K-feldspars (~40%), plagioclases (~20%), quartz (~30%), muscovites (~8%) and minor biotites (~5%) and garnet (~5%). Furthermore, coeval Ziyu gabbroic pluton intruded into the Danfeng meta-volcanic-sedimentary sequence. This gabbroic pluton obtained the formation age of 432.2 ± 2.3 Ma. The Lajimiao and Sifangtai gabbroic plutons intruding the Danfeng Group also yield the forming ages of 422 ± 7 Ma and 460 ± 29 Ma [28,29]. Together with Lajimiao and Sifangtai gabbroic plutons, the Ziyu gabbroic pluton was representative of early Paleozoic basic magmatism. Thus, the crust-derived and mantle-derived magmas occurred around 450 Ma, indicating a strong thermo-tectonic magmatic event during early Paleozoic.

(3) Undeformed massive leucogranite plutons. They ap-

pear as undeformed smaller granitic bodies or veins intruding the Piaochi pluton and Qinling Group, and consist chiefly of medium-grained muscovite granites. Their mineral assemblages are K-feldspar (~40%), plagioclase (~20%), quartz (~30%), muscovite (~8%) and minor garnet (~5%). The Anjiping pluton yields a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 416.7 ± 1.8 Ma, and a granitic vein in the Piaochi pluton gives a similar age of 411.7 ± 3.7 Ma. These ages are interpreted as forming ages and imply the latest granitic magmatism event during early Paleozoic.

3 Granitic magmatism in response to tectonic events

Previous studies on the NQB tectonics proposed that the Qinling oceanic crust began northward subduction in early Paleozoic, and the NQB then developed as an active continental margin characterized by development of a trench-arc-basin system. The oceanic crust was consumed around the middle Paleozoic, with remnant sea basins persisting into the Carboniferous [1,3,30,31]. Supported by new data of high-quality geochronology and results, it is suggested that the subduction of the Qinling oceanic crust might have started as early as 600 Ma, and lasted until 520 Ma [21]. Several episodes of arc-continental collision might have taken place in the process of early Paleozoic convergence between the NCB and SCB. The Qinling oceanic crust was completely consumed along the SDSZ in the Devonian [1,13,25,32,33]. The HP-UHP metamorphism with the peak age of 500 Ma and two-phase retrogressive metamorphism of 450 Ma granulite- and 420 Ma amphibolite-facies, were distinguished in the NQB. The HP-UHP rocks are interpreted as the products of deep continental subduction, whereas two separate uplift events might be responsible for the two-phase retrogressive metamorphism [14–16]. Obviously, the three stages of granitic magmatism with the ages of 500, 450 and 420 Ma (Figure 2) are consistent with

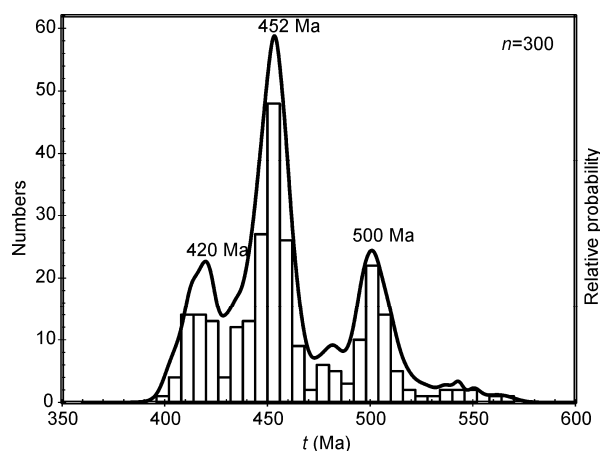


Figure 2 Histogram of zircon U-Pb ages for the granitoids in NQB.

the HP-UHP peak metamorphism and the two-phase retrogressive metamorphism, and their occurrences might be attributed to closure of Qinling ocean basin, the collision between NCB and SQB, and the related thermotectonic magma events.

The first-stage (~500 Ma) granitic magmatism was contemporaneous with the ca. 500 Ma HP-UHP metamorphism [16]. Considering that the granitic pluton and coeval anatectic veins were strongly deformed, the granitic magmatism might have resulted from crustal partial melting under the compressive environment. The plutons are geochemically similar to S-type granitoids with high contents of SiO_2 (71.01%–71.62%), $\text{K}_2\text{O}+\text{Na}_2\text{O}$ (8.14%–8.43%), Al_2O_3 (15.41%–15.73%) and low CaO (1.56%–1.91%), MgO (0.48%–0.73%; $\text{Mg}^\# = 43.19\text{--}48.01$). Their A/CNK values range from 1.05 to 1.09, indicating peraluminous and calc-alkaline series. They are characterized by high LREE and LILE, moderate negative Eu anomalies, poor HFSE and depletion of Nb, Ta, Sr, Ti and P. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are very high, ranging from 0.72123 to 0.72710. They, however, have very low $\varepsilon_{\text{Nd}}(t)$ of -10.6 to -9.3 (Figure 3). The two-stage model ages (T_{DM2}) of the Piaochi monzogranite are from 1.82 to 2.15 Ga. The Piaochi pluton and anatectic veins have negative zircon $\varepsilon_{\text{Hf}}(t)$ values -27.54 to -6.21 for the Piaochi pluton and -17.05 to -0.53 for the anatectic veins (Figure 3). The T_{DM2} ranges from 1.59 to 2.66 Ga for the Piaochi pluton and from 1.25 to 2.14 Ga, respectively. In addition, there occur many inherited zircons in the Piaochi pluton and anatectic veins with age range from 2.5 to 0.60 Ga. All isotopic compositions mentioned above suggest that they are predominantly derived from Mesoproterozoic crust, similar to the Qinling paragneisses. Interestingly, the inherited zircons with the ages from 850 to 650 Ma are not present in paragneisses of the Qinling Group, although the inherited zircons of 2.5–1.0 Ga is coherent with Paleo-Mesoproterozoic peak of detrital zircons from the Qinling Group [21]. The 850–650 Ma ages were recently reported in the SQB and the northern margin of the SCB [34–37], implying that they came partially from the SQB basement besides paragneisses from the Qinling

Group. It is likely that the plutons originated mainly from partial melting of clastic rocks from the NQB, with some addition of the SQB materials due to the northward subduction of the SQB beneath the NQB including the southern margin of the NCB around 500 Ma. The above data can thus account for the simultaneousness of granitic magmatism the HP-UHP metamorphism in the NQB.

The second-stage (~450 Ma) granitic magmatism extensively intrude into different units of the NQB, and occurred simultaneously with granulite retrogressive metamorphism as a result of the first-phase uplifting [16]. The granitic plutons are fairly deformed and composed mainly of I-type granodiorites, monzogranites and minor garnet-bearing mica granites. Monzogranite and granodiorite have variable SiO_2 ($\text{SiO}_2=64.31\text{--}75.32\%$), high $\text{K}_2\text{O}+\text{Na}_2\text{O}$ (6.01%–10.45%), Al_2O_3 (13.67%–17.87%; $\text{A/CNK}=1.01\text{--}1.17$) and high Na_2O ($\text{Na}_2\text{O}/\text{K}_2\text{O}=0.48\text{--}3.89$), low FeO^T (0.34%–3.88%) and MgO (0.09%–1.39%; $\text{Mg}^\# = 25.69\text{--}52.17$). They are obviously calc-alkaline to high-K calc-alkaline and peraluminous, characterized by low to moderate fractionation of LREE and HREE and moderate negative to positive Eu anomalies ($\text{Eu}/\text{Eu}^*=0.48\text{--}1.47$). They are also enriched in LILEs and depleted in HFSEs with pronounced negative spikes of Nb, Ta, Ti and P. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are moderate to high, ranging from 0.70237 to 0.70972. The $\varepsilon_{\text{Nd}}(t)$ values vary from -6.26 to 0.21 (Figure 3) and T_{DM2} from 1.17 to 1.20 Ga, respectively. The zircon $\varepsilon_{\text{Hf}}(t)$ values are from -11.7 to 8.6 (Figure 3) and T_{DM2} ages from 0.84 to 2.56 Ga, suggesting a mixed source from mantle and crust materials, which is similar to those of first-stage granitoids. The coeval gabbros display a constant SiO_2 (48.16%–48.66%), low K_2O (0.22%–0.27%) and high Na_2O (2.29%–2.81%), FeO^T (6.53%–7.60%) and MgO (9.12%–9.74%). Geochemically, the gabbros have an affinity of mantle-derived magma in subduction zones, showing a flat REE pattern, relative enrichment of LILEs and evidently positive Pb anomaly and depletion of Nb and Ta. They have low $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios of 0.70353 to 0.70434 and positive $\varepsilon_{\text{Nd}}(t)$ values of 3.98 to 4.10. The zircon $\varepsilon_{\text{Hf}}(t)$ values are variable from -23.7 to 9.6 (Figure 3), indicating the

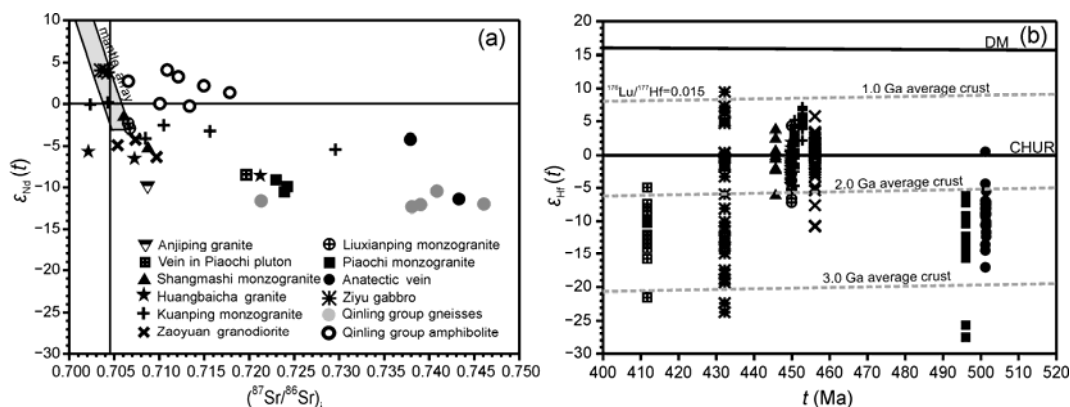


Figure 3 Plot of Sr–Nd isotopes (a) and $\varepsilon_{\text{Hf}}(t)$ values corrected to the crystallization ages of zircon (b) for the granitoids in NQB.

decoupling between Nd isotope of whole rock and zircon Hf isotopic composition. Generally, this kind of decoupling is interpreted in two ways: (1) depleted mantle-derived magma was highly contaminated by crustal materials when it rose from mantle wedge above subduction zone, triggered by slab break-off; and (2) metasomatism within mantle-wedge above subduction zone resulted from aqueous fluids derived from subducted crust [17]. In this case, fluids usually contain ancient detrital zircons, and the metasomatized peridotites are juvenal lithospheric mantle. Thus, mafic magmas generated as a result of partial melting of mantle that experienced crust-mantle reaction in subduction channel tends to be relatively depleted in Sr and Nd isotopic composition of whole rock and displays variations of depletion and enrichment of zircon Hf compositions. The Ziyu gabbros have negative to positive zircon $\varepsilon_{\text{Hf}}(t)$ values, and consistent Si_2O , and no evident increase in LREE and LILEs, indicating that they were derived from partial melting of mantle source that have undergone crust-mantle reaction in subduction channel. Compared with the monzogranites and granitoids, the garnet-bearing granites have relatively high SiO_2 (70.03%–76.75%), $\text{K}_2\text{O}+\text{Na}_2\text{O}$ (7.42%–8.85%), FeO^{T} (0.34%–3.05%) and low MgO (0.04%–1.50%; $\text{Mg\#}=20.57\text{--}51.98$). The Al_2O_3 values are from 12.86% to 15.53%. Thus, they are calcic-alkalic and metaluminous with A/CNK values from 0.99 to 1.16. They are geochemically characterized by moderate fractionation between LREE and HREE with strong to moderate Eu anomalies ($\text{Eu}/\text{Eu}^*=0.12\text{--}0.79$) and enrichment of Rb, depletion of Th, Ba, Sr and Ti, thereby displaying the characteristics of S-type granitoids. They show moderate initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from 0.70605 to 0.70855 and negative $\varepsilon_{\text{Nd}}(t)$ values from -4.99 to -1.22 (Figure 3). The two-stage model ages (T_{DM2}) vary from 1.59 to 1.29 Ga. The zircon $\varepsilon_{\text{Hf}}(t)$ values are from -6.2 to 5.0 (Figure 3), and T_{DM2} from 1.01 to 1.54 Ga, indicating that they were the products of the partial melting of Mesoproterozoic sedimentary rocks. In addition, the Liuxianping pluton shares geochemical features with those of adakite rocks, characterized by strong fractionation between LREE and HREE, slightly Eu anomaly and high Sr, low Y and high Sr/Y ratios. These facts indicate that they were generated in thickened crust in a post-collisional setting. This tectonothermal event likely resulted in intrusions of the magma derived from partial melting of the crust at different depths due to the crustal uplifting and of the mantle-derived magma as a result of subducted slab break-off. Some local crust-derived magma was mixed with juvenile mantle-derived magma.

The third-stage (~420 Ma) granitic plutons are coeval with retrogressive metamorphism of amphibolite facies due to second uplifting. These plutons appear as small stocks/or veins and intrude into the Qinling Group. They are mostly undeformed massive leucogranite with high SiO_2 (73.96%–74.22%), $\text{K}_2\text{O}+\text{Na}_2\text{O}$ (8.70%–9.0%), Al_2O_3 ($\text{Al}_2\text{O}_3=14.01\%\text{--}14.43\%$; A/CNK=1.07–1.17) and FeO^{T} (0.39%–

1.21%), low MgO (0.10%–0.15%; $\text{Mg\#}=21.72\text{--}36.08$), and thus belong to the peraluminous high-K calc-alkaline to shoshonitic series. Geochemically, they are characterized by the low to moderate fractionation between LREE and HREE with strongly negative Eu anomaly ($\text{Eu}/\text{Eu}^*=0.13\text{--}0.37$) and depletion of Nb, Ta, Sr, P and Ti, showing typical features of highly differentiation granitoids. They possess high radioactive isotope with the $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios of 0.70882 to 0.72047, $\varepsilon_{\text{Nd}}(t)$ values of -17.70 to -7.65 (Figure 3). The T_{DM2} varies from 1.97 to 1.78 Ga. Zircon $\varepsilon_{\text{Hf}}(t)$ values are from -21.1 to -5.1 (Figure 3), T_{DM2} from 1.46 to 2.29 Ga, suggesting that they were formed mainly by the partial melting of the Mesoproterozoic crustal materials. On account of strong differentiation and high K contents, the leucogranite resulted likely from high differentiation of crust-derived magma in an extensional setting.

4 Concluding remarks

Our study demonstrates three-stages of granitic magmatism in NQB that are genetically related to the ca. 500 Ma deep continental-subduction, ca. 450 Ma crustal thickening and uplifting due to continent-continent collision, and subsequent crustal uplifting in ca. 420 Ma, respectively. The ca. 500 Ma granitoids are the products of S-type magma generated as a result of the partial melting of sedimentary rocks of an accretion wedge between the SQB and NQB including the southern margin of the NCB during the continental collision. The ca. 450 Ma granitic magmatism resulted from the partial melting of the crust due to dehydration of deep-subducted continental materials. The crustal thickening and slab break-off during the subduction and convergence might have played an important role in the upwelling and partial melting of mantle wedge materials. It was then followed by the intrusion of mantle-derived basic magma owing to partial melting of crustal materials, and widespread occurrence of monzogranites and granodiorites in the NQB. Contractual tectonism led to shortening and dehydration of supracrustal rocks. The partial melting of supracrustal pelitic rocks then produced highly differentiated leucogranite, indicating that the NQB had switched to a stable or extensional tectonic setting around 420 Ma.

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