

Late Paleozoic–Early Mesozoic Tectonic Evolution of the Zongwulong Shan-Qinghai Nanshan Tectonic Belt in the Northern Qaidam Continent, Northern Tibet

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ABSTRACT: The Zongwulong Shan-Qinghai Nanshan tectonic belt of the northern Tibetan Plateau experienced a protracted tectonic history, including the openings and closures of the Proto- and Paleo-Tethyan Oceans. Although the tectonic belt has been extensively studied, details regarding the tectonic processes involved in its development remain controversial. To better constrain the tectonic processes of this tectonic belt, we conducted detailed field geological mapping, zircon U-Pb geochronology, and whole-rock geochemical and Sr-Nd isotopic analyses. Our results show that intrusive rocks in the tectonic belt crystallized in ca. 292–233 Ma, perhaps in an arc/subduction setting. Geochemical and Sr-Nd isotopic data suggest that Early Permian–Late Triassic ultramafic-intermediate intrusions were sourced from the enriched mantle, whereas intermediate-acidic rocks were sourced from mixed crust-mantle. We present the tectonic model that involves: (1) Early Devonian–Early Permian intracontinental extension occurred in the northern margin of the Qaidam continent (ca. 416–292 Ma); (2) Early Permian–Late Triassic northward subduction of the Paleo-Tethyan Ocean resulted in arc magmatism (ca. 292–233 Ma); and (3) subsequent Late Triassic intracontinental extension (ca. 233–215 Ma). Our results suggest that the Late Paleozoic–Early Mesozoic development of the Zongwulong Shan-Qinghai Nanshan was related to the opening, subduction, and slab retreat of the Paleo-Tethyan Ocean, which has key implications for the tectonic evolution of the northern Tibetan Plateau.

KEY WORDS: Paleo-Tethyan Ocean, northern Tibetan Plateau, Late Paleozoic–Early Mesozoic magmatism, Zongwulong Shan-Qinghai Nanshan tectonic belt, subduction-collision, tectonics.

0 INTRODUCTION

The Zongwulong Shan-Qinghai Nanshan tectonic belt is located along the northern margin of the Qaidam Basin in the northern Tibetan Plateau, at the junction of the Qinling, Qilian, and Kunlun orogens. The tectonic belt extends between the Altyn Mountains in the west (Guo et al., 2009) to the area of Gonghe County in the Qinghai Nanshan (Chen et al., 2019). The southern and northern boundaries of the tectonic belt are the Oulongbuluke Block and South Qilian Orogen, respectively (Qin et al., 2018; Guo et al., 2009; Xin et al., 2006; Figure 1). The Zongwulong Shan-Qinghai Nanshan is a composite tec-

tonic belt that has undergone a protracted history including the openings and closures of the Proto- and Paleo-Tethyan Oceans (Fu et al., 2021). Constraining its tectonic development is critical to improving our understanding of the geologic evolution of the northern Tibetan Plateau.

Although the Zongwulong Shan-Qinghai Nanshan tectonic belt has been extensively studied (e.g., Zhao et al., 2022; Zhang et al., 2019, 2017a, b, c; Guo et al., 2009; Qiang, 2008), details of its tectonic evolution remain uncertain and controversial, which has led to an inadequate understanding of the role the southern Paleo-Tethyan Ocean had in influencing regional tectonics. There are two views on the tectonic evolution of the Zongwulong Shan-Qinghai Nanshan tectonic belt based on its rock assemblages (e.g., ophiolites, basement metamorphic rocks, and magmatic arc rocks), the timing of the ocean basin opening and closure, and subduction polarity. One viewpoint is that the early Carboniferous Zongwulong tectonic belt was a rift filled with flysch deposits.

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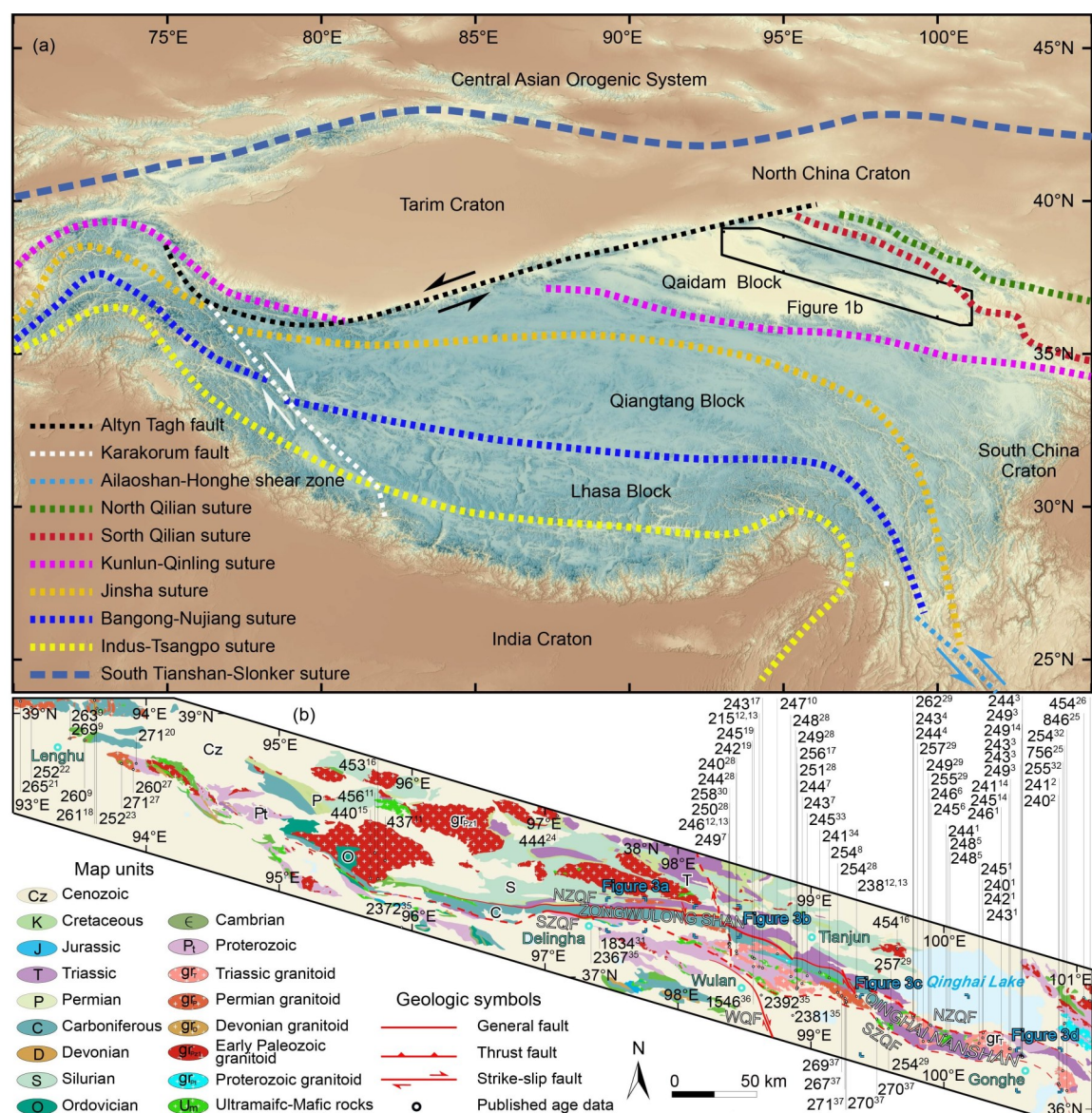


Figure 1. (a) Map of the Tibetan Plateau showing major tectonic divisions and boundaries of the Tethyan orogenic system, modified Li et al. (2024), Hapoff et al. (2020), Wu C et al. (2019), Yin and Harrison (2000), and Yin and Nie (1996). The location of Figure 1b is shown. (b) Geological map of the Zongwulong Shan-Qinghai Nanshan region. The map is compiled from Li et al. (2024), Pan et al. (2004), CGS (1999), and this study. The locations of Figures 3a–3d are shown. Abbreviations: NZQF. North Zongwulong Shan-Qinghai Nanshan fault; SZQF. South Zongwulong Shan-Qinghai Nanshan fault; WQF. Wenquan strike-slip fault. Data are compiled from: 1. Zhang (2017); 2. Zhang et al. (2017a); 3. Zhang et al. (2017b); 4. Zhang et al. (2017c); 5. Zhang et al. (2019); 6. Wang et al. (2019); 7. Peng et al. (2016); 8. Wang and Zhou (2016); 9. Gao et al. (2019); 10. Wang et al. (2017); 11. Zhu et al. (2016); 12. Guo et al. (2009); 13. Qiang (2008); 14. Li et al. (2018); 15. Lu et al. (2007); 16. Qin et al. (2018); 17. Zhang et al. (2022); 18. Jia et al. (2017); 19. Yue et al. (2021); 20. Zhuang et al. (2020); 21. Dong et al. (2014); 22. Dong et al. (2015); 23. Hu et al. (2016); 24. Zhang et al. (2018); 25. Yong et al. (2008); 26. Liu (2019); 27. Wu et al. (2009); 28. Wu C L et al. (2019); 29. Zou et al. (2023); 30. Chen et al. (2012); 31. Liao et al. (2014); 32. Zou et al. (2022); 33. Ding et al. (2022); 34. Pan et al. (2021); 35. Gong et al. (2012); 36. Lyu et al. (2021); 37. Zeng et al. (2018).

By the end of the Early Carboniferous, the northern and southern rift margins experienced contraction and tectonic inversion, followed by rifting during Permian–Triassic. The relatively modest depth of the rift basin suggests limited extension, which may explain why an ocean basin did not develop (Li et al., 2024; Li and Nie, 1985). Another viewpoint suggests that the Zongwulong tectonic belt developed a minor ocean basin, namely the Zongwulong Ocean (e.g., Zou et al., 2023, 2022; Zhao et al., 2022;

Zhang et al., 2019, 2017a, b, c; Wang and Zhou, 2016; Guo et al., 2009, 2007; Qiang, 2008). Several models have been proposed for the development of the Zongwulong Ocean: (1) southward subduction model (e.g., Wang and Zhou, 2016; Guo et al., 2009; Qiang, 2008), which can be further divided into the subduction-collision model (e.g., Qiang, 2008; Figure 2a) and subduction-oblique subduction model (Peng et al., 2016; Figure 2b); (2) northward subduction model of the Qaidam–West Qinling

Block (Sun et al., 2004), which involves the Qinghai Nanshan granite belt being the result of the subduction and collision of the West Qinling Block along the North Qaidam–Shangdan suture towards the Qilian Block (Figure 2c); and (3) the model involving Late Paleozoic–Early Mesozoic magmatism (e.g., Zou et al., 2023, 2022; Ding et al., 2022; Zhang J P et al., 2022; Pan et al., 2021; Yue et al., 2021; Zhuang et al., 2020; Gao et al., 2019; Wang M et al., 2019; Wu C L et al., 2019, 2009; Zhang Y M et al., 2019, 2017a, b, c; Li et al., 2018; Zeng et al., 2018; Jia et al., 2017; Wang Y S et al., 2017; Hu et al., 2016; Peng et al., 2016; Wang and Zhou, 2016; Dong et al., 2015, 2014; Chen et al., 2012; Guo et al., 2009; Qiang, 2008; Figure 1b) derived from the northward subduction of the Paleo-Tethyan Ocean in the eastern Kunlun region (e.g., Wu C et al., 2022, 2019, 2016; Zhang et al., 2022; Yue et al., 2021; Chen et al., 2019; Li et al., 2018; Wang et al., 2017; Cheng, 2015). The different tectonic models predict the spatial and temporal distribution of the magmatic rocks and the petrogenesis and geochemical characteristics of related magmatic rocks, such as the southward subduction needs the occurrence of arc-related magmatic rocks in the northern Qaidam continent. To differentiate between these models and explore the tectonic evolution of the Zongwulong Shan–Qinghai Nanshan tectonic belt, we integrated previous constraints with new field geological mapping, geochemistry, and geochronology in the region.

1 GEOLOGICAL SETTING

The Zongwulong Shan–Qinghai Nanshan tectonic belt is between the northern margin of the Qaidam continent and the southern margin of the South Qilian Block, which records the tectonic processes of the Paleo-Tethys Ocean (Li et al., 2024; Wu et al., 2023; Figure 1). Metamorphic basement rocks of the Paleoproterozoic Dakendaban Group (labeled Pt1) are exposed near Delingha City and Wulan County in the South Zongwulong Shan. The Dakendaban Group mainly consists of mica schist, gneiss, marble, quartzite, and amphibolite,

all with zircon U–Pb ages of ca. 2.4–1.8 Ga (Liao et al., 2014; Gong et al., 2012). These ages suggest that the Dakendaban Group may correlate with the basement rocks of the Tarim Craton (Gong et al., 2012). Few granites of the Dakendaban Group yield a ca. 1.5 Ga zircon U–Pb age (Lyu et al., 2021; Figure 1b). Neoproterozoic metasedimentary strata (labeled Pt₃) of the Zongwulong Shan–Qinghai Nanshan tectonic belt include meta-sandstone, carbonaceous slate, and phyllite exposed north of the NZQF and mica ± garnet quartz schist, marble, quartz gneiss, and plagioclase amphibolite south of the SZQF. Meta-sandstone, phyllite, carbonaceous slate, and thin marble are exposed in the core of the Zongwulong Shan area between the SZQF and NZQF (Li et al., 2024). The Qinghai Nanshan area is mainly composed of meta-sandstone and gneiss (Figure 1b).

Sedimentary rocks of the Zongwulong Shan–Qinghai Nanshan tectonic belt consist of the Carboniferous Zongwulongshan Group, Permian strata, and Quaternary deposits (Li et al., 2024; QBGR, 1978, 1976a; Figure 1b). The core of the tectonic belt contains Neoproterozoic metamorphic basement rocks and Permian granitoid intrusions (Li et al., 2024; Figures 1b, 3a, and 3b). The Zongwulongshan Group includes basalt, andesite, limestone, dolomite, phyllite, tuff, and slate. Permian strata are > 2 km thick and consist of sandstone, shale, conglomerate, and limestone (Li et al., 2024; QBGR, 1978, 1976a). The Zongwulongshan Group in Tianjun County of Qinghai Province is characterized by (ultra-) mafic rocks (e.g., basalt) and siliceous rocks. Basalt and diabase porphyry of the Zongwulongshan Group yield Rb–Sr isochron ages of 331 ± 88 and 318 ± 3 Ma, respectively. The Zongwulongshan Group is commonly considered an ophiolite suite formed in a relatively small ocean basin during Early Carboniferous intracontinental rifting (Wang, 2014; Wang et al., 2001). However, subsequent alteration of the ophiolite suite may have disturbed the Rb–Sr system and as such, the isochron ages may not reflect the timing of magmatism (Chen et al., 2020; Li, 2008). Li (2008) performed zircon U–Pb dating using a sensitive

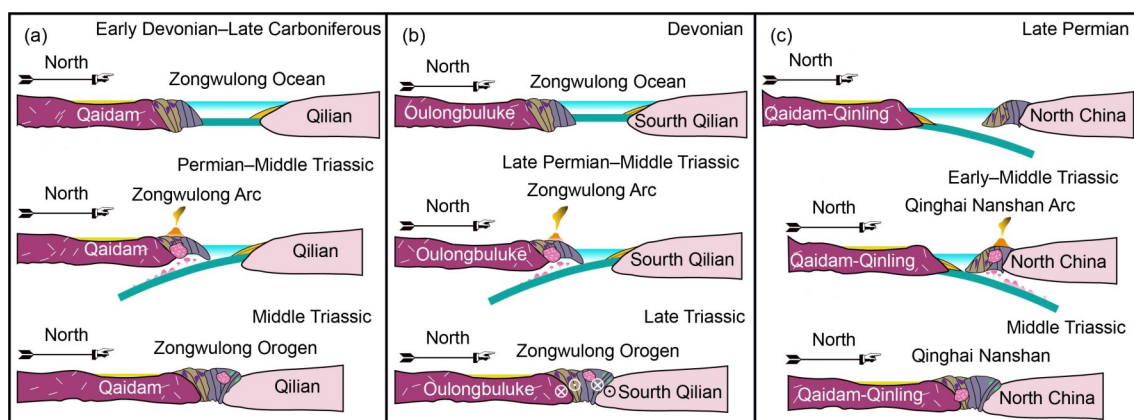


Figure 2. Existing tectonic models for the evolution of the Zongwulong Shan–Qinghai Nanshan. (a) Southward subduction and direct collision of the Zongwulong Ocean (e.g., Qiang, 2008); (b) southward subduction and oblique collision of the Zongwulong Ocean (Peng et al., 2016); (c) northward subduction and collision of the Qaidam–West Qinling Block (Sun et al., 2004).

high-resolution ion microprobe to obtain a weighted average age of ca. 233 Ma for gabbro of the ophiolite suite, although few zircon grains were analyzed. Zircon grains of diabase and granite of the ophiolite suite yield weighted average ages of ca. 509 and ca. 445 Ma, respectively, which are interpreted to represent the crystallization timing of some ophiolitic rocks in the Tianjun Nanshan. These ophiolitic rocks are thought to have formed in a back-arc basin (Fu et al., 2021), the crystallization ages of which are consistent with those of serpentinites of the Tethyan tectonic domain in the region (Fu et al., 2021, 2018; Song et al., 2019, 2013; Yan et al., 2019; Xia et al., 2016; Xiao et al., 2009). The ophiolitic rocks may also have been produced during the northward subduction of the Paleo-Tethyan Ocean, with their current spatial distribution being controlled by Cenozoic tectonics (Wu et al., 2023). Thus, disagreement remains regarding the petrogenesis of the ophiolite suite. Quaternary strata include alluvium, colluvium, and flood deposits (Figures 1b, 3a, and 3b).

The Qinghai Nanshan area is mainly composed of Neoproterozoic, Carboniferous, Permian, Triassic, and Quaternary strata (Figure 1b). Neoproterozoic strata consist of meta-sandstone, schist, and gneiss. Carboniferous strata include meta-sandstone interlayered with other metasedimentary rocks. Permian strata are meta-limestone, meta-conglomerate, and slate. Triassic strata consist of is mainly composed of slate, marble, meta-sandstone, and meta-conglomerate. Quaternary strata are alluvium, lacustrine deposits, and glacial tillite (Li et al., 2024; Zhang et al., 2019, 2017a, b, c; QBGR, 1976b, 1969a, b; Figures 1b, 3c, and 3d).

The northern margin of Qaidam continent in the Tibetan Plateau experienced multiple magmatic episodes from the Paleoproterozoic – Early Mesozoic, including Late Paleozoic–Early Mesozoic magmatism in the Zongwulong Shan-Qinghai Nanshan tectonic belt (e.g., Zou et al., 2023, 2022; Ding et al., 2022; Zhang J P et al., 2022; Pan et al., 2021; Yue et al., 2021; Zhuang et al., 2020; Gao et al., 2019; Wang M et al., 2019; Wu C L et al., 2019, 2009; Zhang Y M et al., 2019, 2017a, b, c; Li et al., 2018; Zeng et al., 2018; Jia et al., 2017; Wang Y S et al., 2017; Hu et al., 2016; Peng et al., 2016; Wang and Zhou, 2016; Chen et al., 2015, 2012; Dong et al., 2015, 2014; Guo et al., 2009; Qiang, 2008). Magmatism is mainly recorded in the eastern portion of the Zongwulong Shan-Qinghai Nanshan tectonic belt, including Wulan County and Qinghai Nanshan. Smaller distributions of magmatic rocks occur in the northwest and surrounding Delingha City in the tectonic belt. Magmatic rocks consist of granites, granodiorites, diorites, minor gabbro, gabbroic diorite, and pyroxenite (Zhang et al., 2019, 2017a, b, c; QBGR, 1976b, 1969a, b; Figures 1b and 3). These rocks are interpreted to be related to the subduction and subsequent collision of the Paleo-Tethyan Ocean and the northern Eastern Kunlun-Qaidam continent (e.g., Wu C et al., 2022, 2019, 2016; Zhang et al., 2022; Yue et al., 2021; Chen et al., 2019; Wu C L et al., 2019; Li et al., 2018;

Wang et al., 2017; Cheng, 2015). Some scholars alternatively regard the magmatic rocks to be products of the southward subduction of the Zongwulong Ocean (e.g., Zou et al., 2023, 2022; Zhao et al., 2022; Zhang et al., 2019, 2017a, b, c; Wang and Zhou, 2016; Guo et al., 2009, 2007; Qiang, 2008). Thus, the tectonic setting of the Late Paleozoic–Early Mesozoic magmatism remains controversial.

The northwest-striking Zongwulong Shan-Qinghai Nanshan is a tectonic belt bounded by the North Zongwulong Shan-Qinghai Nanshan thrust fault (NZQF) in the northeast and South Zongwulong Shan-Qinghai Nanshan thrust fault (SZQF) in the southwest (Figures 1b and 3). Major faults and lithologies of the tectonic belt are described below. Aside from the NZQF and SZQF, the tectonic belt hosts the Wenquan strike-slip fault (WQF). The NZQF and the SZQF may extend northwestward along the northern and southern slopes of the Zongwulong Shan, respectively, to the Altyn fault. To the southeast, these faults extend along the southern slope of the Qinghai Nanshan and Qinghai Lake, possibly terminating in the Longyangxia Reservoir of Gonghe County (Wu et al., 2023; Chen et al., 2019; Guo et al., 2007). The NZQF is a south-dipping thrust fault, whereas the SZQF is a north-dipping thrust fault. Xu et al. (2001) reported a north-dipping lithospheric-scale thrust fault south of the Qinghai Nanshan from tomographic cross-sections of the northern Tibetan Plateau. This thrust fault may be the extension of the SZQF to the east. The WQF strikes through the Zongwulong Shan-Qinghai Nanshan tectonic belt to the northwest within the eastern part of Wulan County (Chen et al., 2019; Figure 1b).

2 FIELD OBSERVATION

We observed that the Zongwulong Shan tectonic belt predominantly contains Neoproterozoic, Carboniferous, Permian, Triassic, and Quaternary strata. Carboniferous strata form a broad, east-west-trending anticline situated between the SZQF and the NZQF (Figure 1b). Our major field observations include:

(1) The SZQF is a north-dipping thrust fault with a hanging wall composed of upper Carboniferous meta-carbonate and overlying Permian sandstone, shale, conglomerate, and limestone. The footwall of the SZQF consists of Neoproterozoic basement metamorphic rocks. Some Paleoproterozoic basement rocks are exposed and intruded by Silurian granite (Figures 3 and 4a). Multiple north-striking thrust faults occur south of the SZQF (Figure 3) and may represent branched thrusts (Li et al., 2024). Here, both older-over-younger and younger-over-older relationships along the SZQF, indicating the fault experienced multiple-slip histories. A previous study on the activities of the SZQF suggests the nature of tectonic inversion of initial rift-margin normal fault during the convergence of the Zongwulong-Qinghai Nanshan rift (Li et al., 2024).

(2) The NZQF is a south-dipping thrust fault with Lower Carboniferous marble and phyllite and overlying

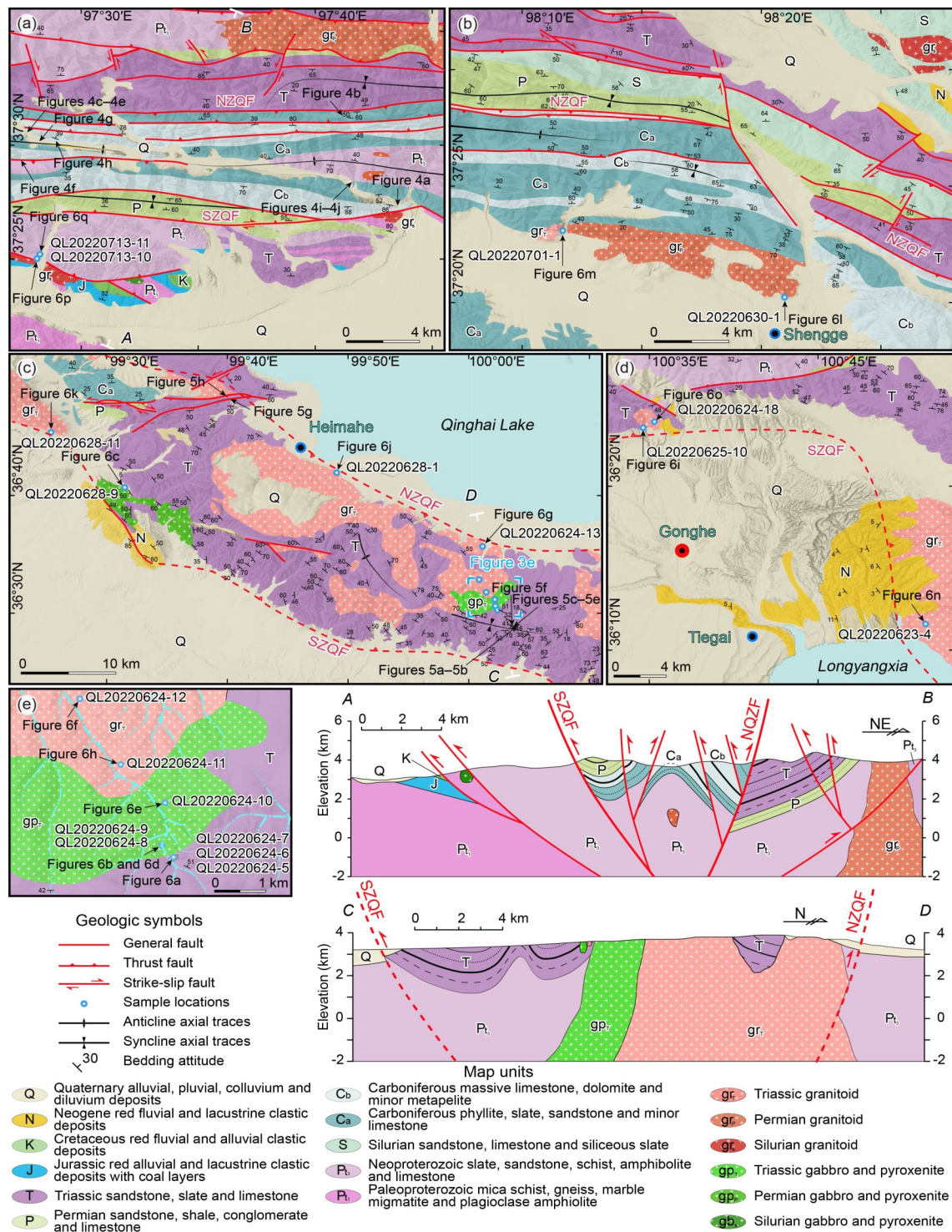


Figure 3. Geological map and cross sections of the Zongwulong Shan–Qinghai Nanshan. The map is compiled from previous studies (Li et al., 2024; QBGR, 1978, 1976a, b, 1969a, b), satellite-image analysis (e.g., Google Earth), and this study. The locations of field photographs in Figures 4–6 are also shown. Abbreviations: NZQF, North Zongwulong Shan–Qinghai Nanshan fault; SZQF, South Zongwulong Shan–Qinghai Nanshan fault.

Upper Carboniferous meta-carbonate. The footwall of the NZQF consists of Permian sandstone, shale, conglomerate, and limestone and overlying Triassic sandstone and limestone (Figures 3 and 4b). Triassic strata are folded and imbricated by thrusts, perhaps due to slip along the NZQF to the south (Figure 3).

(3) Neoproterozoic, Permian, Carboniferous, and Quaternary strata are exposed between the SZQF and NZQF. Carboniferous strata form the main unit and consist of an upper limestone sequence and a lower sequence consisting of marble and phyllite. Carboniferous strata are folded into a broad anticline (Figures 3 and 4c–



Figure 4. Representative field photographs of the Zongwulong Shan region. Note that the formats of planar structure attitudes are dip direction and dip angle.

4h) with parasitic folds mostly within lower sequence phyllite (Figures 4i and 4j).

The Qinghai Nanshan tectonic belt contains Neoproterozoic, Carboniferous, Permian, Triassic, and Quaternary strata (Figures 3c and 3d) possibly between the SZQF and NZQF (Wu et al., 2023; Chen et al., 2019). Our major field observations include:

(1) Triassic strata, including slate and marble, are the most widespread unit in the Qinghai Nanshan tecton-

ic belt. These strata form northwest-trending, macroscopic, and parasitic folds, which may be related to contraction throughout the Qinghai Nanshan tectonic belt (Figures 5a–5f).

(2) A few faults are exposed in the Qinghai Nanshan tectonic belt. Those mapped include southeast-dipping thrust faults that cut Triassic limestone in the northwest and juxtapose Triassic granite and limestone (Figures 3, 5g, and 5h).

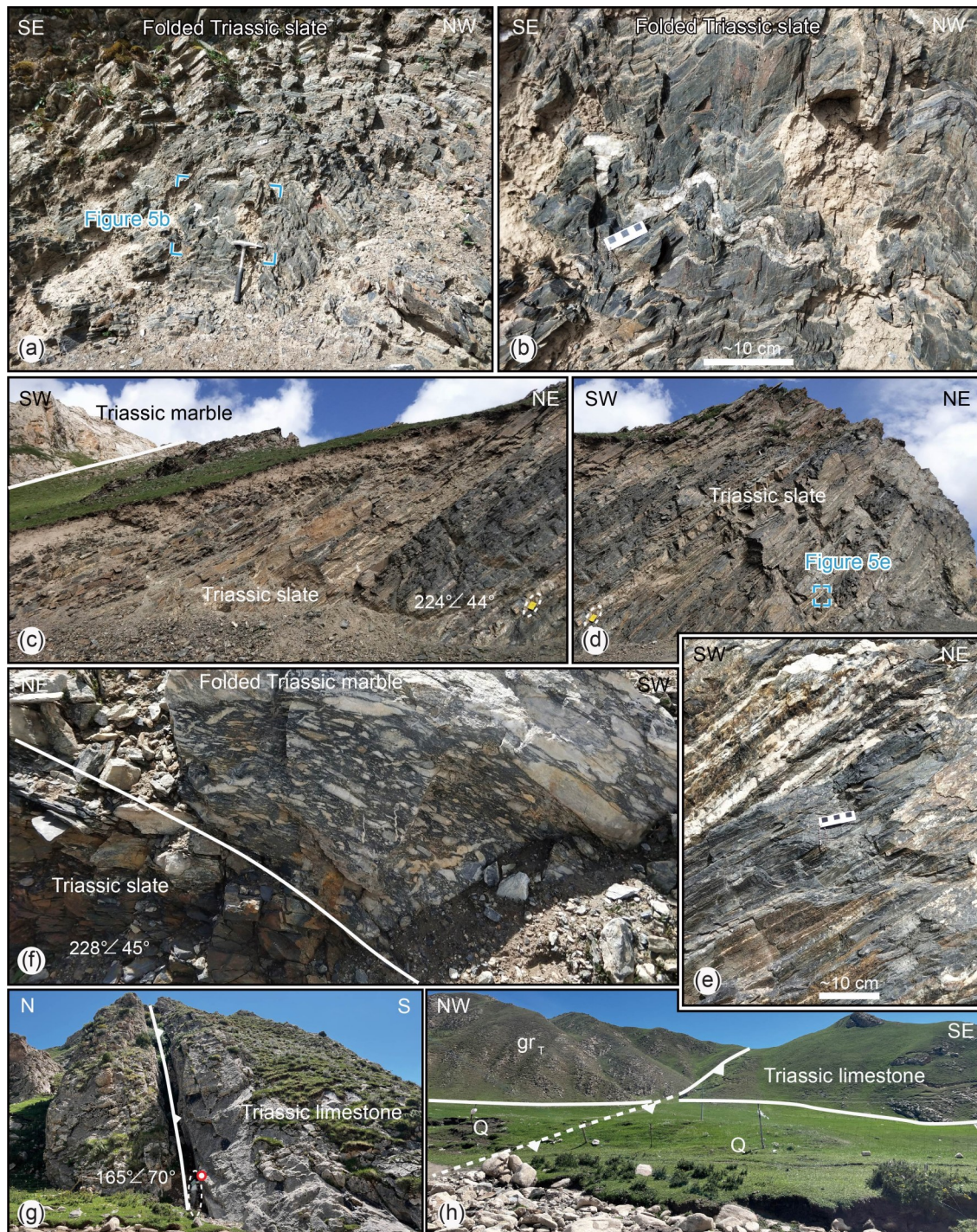


Figure 5. Representative field photographs of the Qinghai Nanshan region. Note that the formats of planar structure attitudes are dip direction and dip angle.

3 SAMPLE DESCRIPTION AND PETROGRAPHY

We performed U–Pb zircon geochronology and geochemical analyses of five (ultra-)mafic rock samples, three intermediate-mafic rock samples, nine granitoid samples, and two leucogranite vein samples from the Zongwulong Shan–Qinghai Nanshan. Sample locations are listed in Table 1 and shown in Figure 3.

3.1 (Ultra-)Mafic Rocks

Five ultramafic-mafic rock samples (QL20220624-5,

QL20220624-6, QL20220624-8, QL20220624-9, and QL20220628-9) were collected from the Qinghai Nanshan (Figures 3c and 3e).

The olivine pyroxenite sample (QL20220624-5) is dark gray, slightly weathered, and contains idiomorphic granular texture and massive structure (Figure 6a). The olivine pyroxenite contains olivine (~20%–30%), pyroxene (~60%–70%), and minor carbonate and metallic minerals (~10%–20%) (Figure 7a).

Two gabbro samples (QL20220624-6 and

Table 1 Summary of sample locations in the Zongwulong Shan-Qinghai Nanshan region

Sample No.	Rock type	Latitude (N)	Longitude (E)	Elevation(m)	Interpreted age (Ma)	MSWD	n	Method
QL20220623-4	Granodiorite	36°11'38.72"	100°51'17.11"	2 715	238 ± 4	1.60	20 out of 25	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220624-5	Olivine pyroxenite	36°30'14.88"	100°02'31.31"	3 827	N.D.	N.D.	N.D.	Major and trace elements
QL20220624-6	Gabbro	36°30'14.88"	100°02'31.31"	3 827	N.D.	N.D.	N.D.	Major and trace elements
QL20220624-7	Granite	36°30'14.88"	100°02'31.31"	3 827	248 ± 2	1.60	9 out of 25	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220624-8	Olivine gabbro	36°30'28.96"	100°02'17.83"	3 725	N.D.	N.D.	N.D.	Major and trace elements
QL20220624-9	Gabbro	36°30'28.96"	100°02'17.83"	3 725	241 ± 1	1.60	17 out of 25	Major and trace elements/zircon U-Pb
QL20220624-10	Gabbroic diorite	36°31'09.24"	100°02'20.56"	3 662	N.D.	N.D.	N.D.	Major and trace elements/Sr-Nd isotope
QL20220624-11	Monzogranite	36°31'45.39"	100°01'38.39"	3 602	237 ± 2	1.90	15 out of 25	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220624-12	Gabbroic diorite	36°32'46.71"	100°01'02.82"	3 509	N.D.	N.D.	N.D.	Major and trace elements/Sr-Nd isotope
QL20220624-13	Gabbroic diorite	36°35'37.91"	100°01'18.20"	3 347	236 ± 2	1.90	23 out of 25	Major and trace elements/zircon U-Pb
QL20220624-18	Granodiorite	36°24'08.90"	100°35'31.13"	3 427	N.D.	N.D.	N.D.	Major and trace elements/Sr-Nd isotope
QL20220625-10	Monzogranite	36°23'33.42"	100°34'50.93"	3 222	233 ± 3	2.00	13 out of 25	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220628-1	Monzogranite	36°41'51.99"	99°49'14.82"	3 230	236 ± 2	0.88	25 out of 25	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220628-9	Amphibole gabbro	36°40'40.03"	99°31'35.00"	3 613	253 ± 3	0.91	21 out of 25	Major and trace elements/zircon U-Pb
QL20220628-11	Monzogranite	36°45'17.44"	99°25'35.78"	3 614	246 ± 1	1.80	18 out of 25	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220630-1	Monzogranite	37°20'10.04"	98°21'15.38"	3 509	292 ± 9	1.80	9 out of 30	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220701-1	Monzogranite	37°23'02.97"	98°11'51.86"	3 602	238 ± 2	1.90	16 out of 25	Major and trace elements/zircon U-Pb/Sr-Nd isotope
QL20220713-10	Leucogranite dike	37°25'14.86"	97°28'15.27"	3 402	271 ± 6*	2.00	30 out of 36	Major and trace elements/Sr-Nd isotope
QL20220713-11	Leucogranite dike	37°25'15.6"	97°28'15.63"	3 413	271 ± 7*	2.00	31 out of 36	Major and trace elements/Sr-Nd isotope

MSWD, mean square of weighted deviates; n, number of selective zircon grains for weighted mean age; N.D., no data; *, age data from Li et al. (2024).

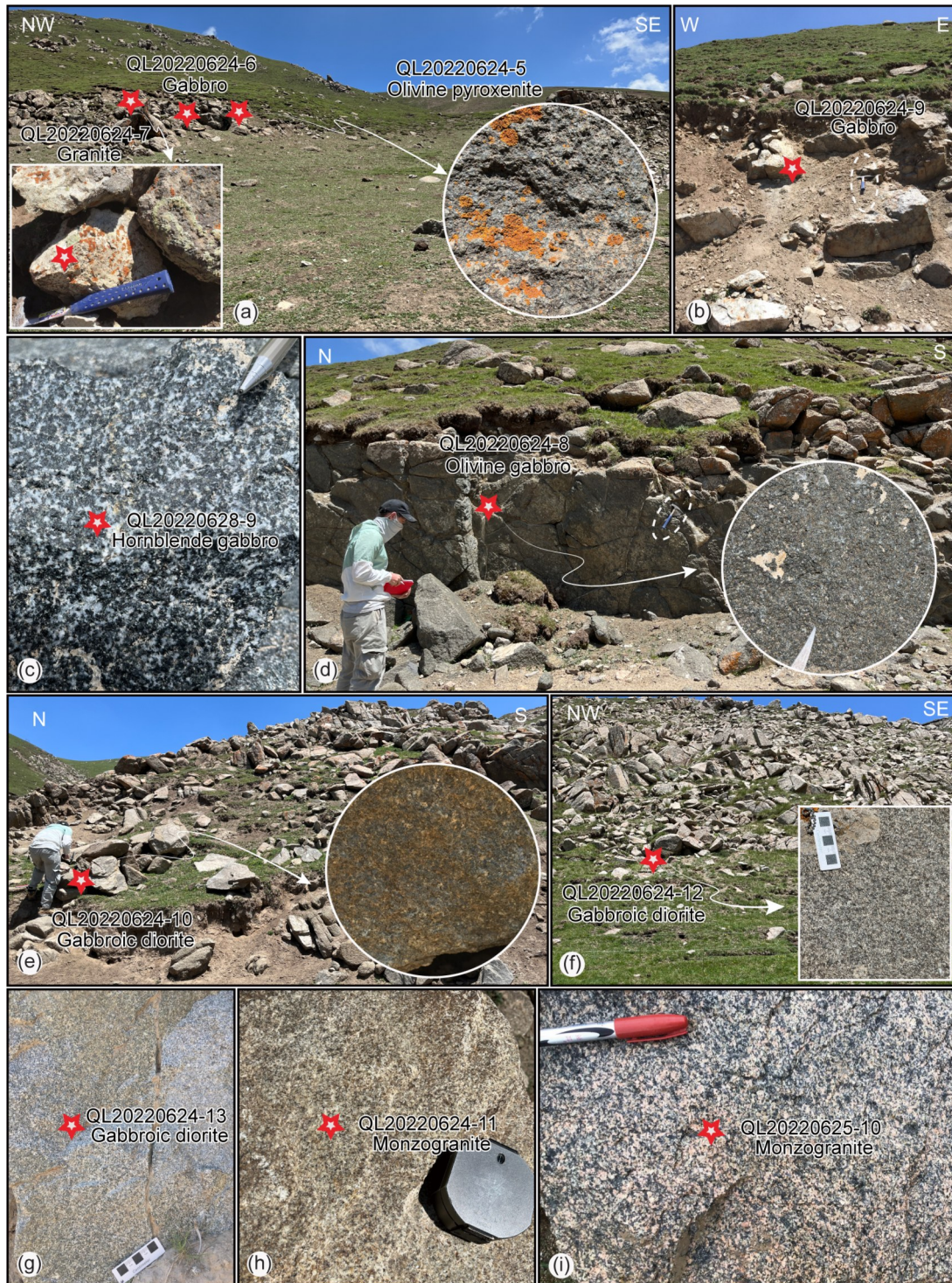


Figure 6. Photographs sampled outcrops in the Zongwulong Shan–Qinghai Nanshan region.

QL20220624-9) are dark gray, slightly weathered, and contain holocrystalline texture and massive structure (Figures 6a and 6b). The gabbro samples consist mainly of plagioclase (~40%–50%), pyroxene (~30%–40%), and other minerals (~10%–20%) (Figures 7b and 7d).

The amphibole gabbro (QL20220628-9) is black, slightly weathered, and contains holocrystalline texture and massive structure (Figure 6c). The amphibole gabbro consists mainly of amphibole (~10%–15%), plagioclase (~40%–50%), pyroxene (~30%–40%), and other minerals (~5%–10%) (Figure 7e).

The olivine gabbro (QL20220624-8) is dark gray, slightly weathered, and contains holocrystalline texture and massive structure (Figure 6d). The olivine gabbro contains olivine (~10%–20%), plagioclase (~40%–50%), pyroxene (~20%–30%), and other minerals (~10%–20%) (Figure 7c).

The gabbroic diorite (QL20220624-10 and -12) is dark gray, slightly weathered, and contains holocrystalline texture and massive structure (Figure 6e). The gabbroic diorite contains plagioclase (~40%–50%), pyroxene (~30%–40%), and other minerals (~10%–20%) (Figure 7f).

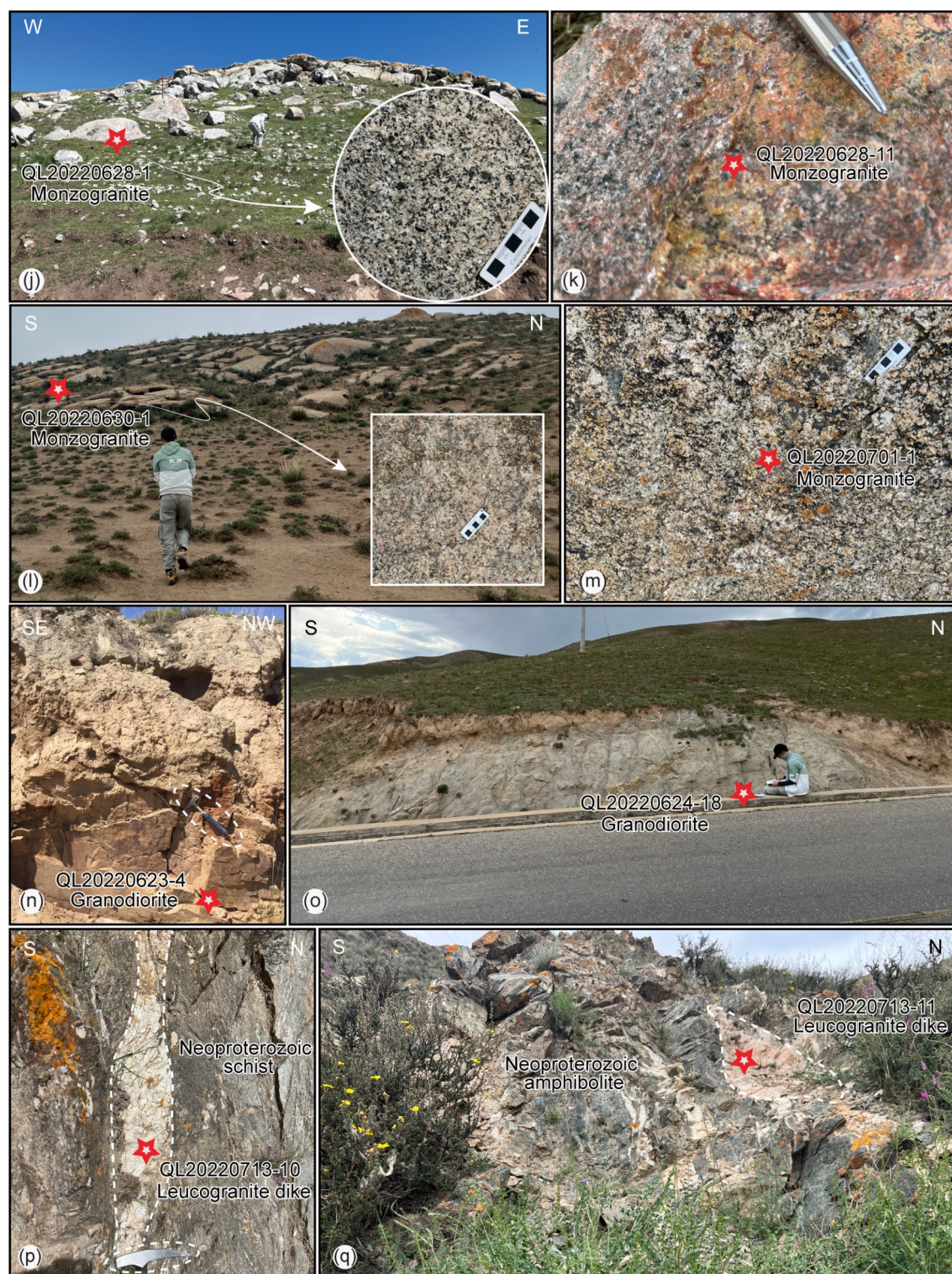


Figure 6. Continued.

3.2 Mafic-Intermediate Rocks

Three gabbroic diorite rock samples (QL20220624-10, QL20220624-12, and QL20220624-13) were collected from the Qinghai Nanshan (Figures 3d and 3e). These samples are dark gray, slightly weathered, and display holocrystalline texture and massive structure (Figures 6e–6g). The samples mainly contain plagioclase (~50%–60%), pyroxene (~10%–20%), amphibole (~10%–

20%), and other minerals (~10%–20%) (Figures 7f–7h).

3.3 Intermediate-Felsic Rocks

Seven granitoid samples were collected from the Qinghai Nanshan (Figures 3c–3e). Two granitoid rock samples were collected from the Zongwulong Shan (Figure 3b).

Six monzogranite samples (QL20220624-11,

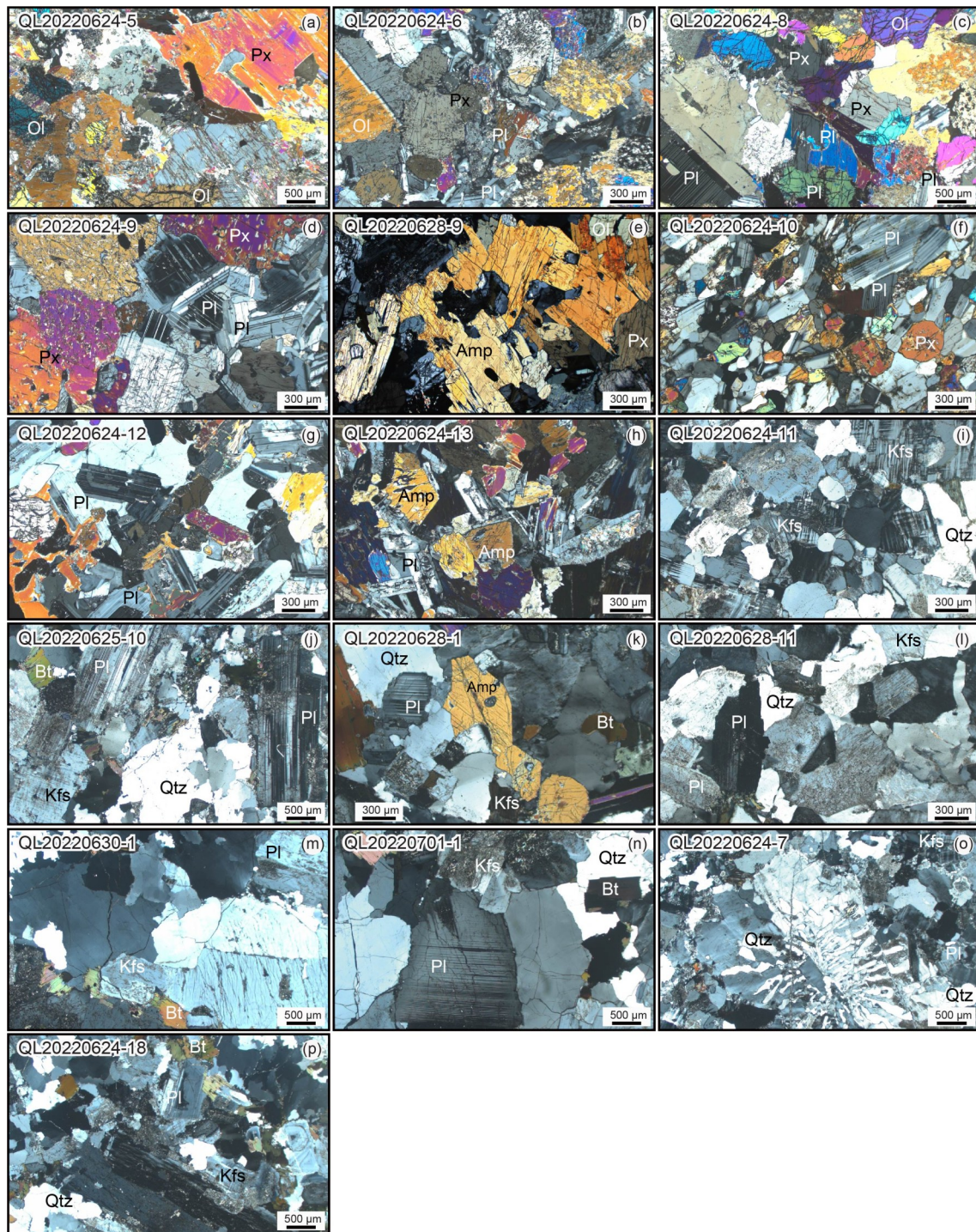


Figure 7. Photomicrographs in cross-polarized light of samples collected in this study. Abbreviations: Qtz, quartz; Pl, plagioclase; Kfs, K-feldspar; Bt, biotite; Cpx, clinopyroxene; Amp, amphibole; Px, pyroxene; Ol, olivine.

QL20220625-10, QL20220628-1, QL20220628-11, QL20220630-1, and QL20220701-1) are grey-auburn, slightly weathered, and display holocrystalline texture and massive structure (Figures 6h–6m). The monzogranite samples consist mainly of quartz (~30%–40%), K-feldspar (~20%–30%), plagioclase (~20%–30%), biotite (~5%–10%), and other minerals (~5%–10%) (Figures 7i and 7n).

One granite sample (QL20220624-7) is gray-white,

slightly weathered, and contains holocrystalline texture and massive structure (Figure 6a). The granite sample contains quartz (~40%–50%), K-feldspar (~20%–30%), biotite (~5%–10%), and other minerals (~15%–20%) (Figure 7o). Sample QL20220624-7 was collected adjacent to sample QL20220624-5 and QL20220624-6.

Two granodiorite samples (QL20220623-4 and QL20220624-18) are grey-ochre, slightly weathered, and display holocrystalline texture and massive structure (Fig-

ures 6n and 6o). These granodiorite samples (QL20220623-4 and QL20220624-18) consist mainly of plagioclase (~40%–50%), K-feldspar (~10%–20%), quartz (~20%–30%), biotite (~5%–10%), and other minerals (~5%–10%) (Figure 7p). Sample QL20220624-18 was collected adjacent to sample QL20220625-10.

3.4 Leucogranite Dikes

Two leucogranite dike samples (QL20220713-10 and QL20220713-11) were collected from the Zongwulong Shan (Figure 3a). These leucogranite dike samples are white-pinkish, slightly weathered, and contain holocrystalline texture and massive structure. The leucogranite dikes were mapped intruding Neoproterozoic schist and amphibolite (Figures 6p and 6q).

4 ANALYTICAL METHODS AND RESULTS

4.1 U-Pb Zircon Geochronology

Zircon grains analyzed for their crystallization ages were initially separated by traditional methods, such as crushing, sieving, and magnetic and density separations, and mounted in epoxy with standard grains. Cathodoluminescence images of zircons were collected using a scanning electron microscope to evaluate zonation. Zircon grains were then analyzed using an Agilent 7500a inductively coupled plasma-mass spectrometer (ICP-MS) with a 193-nm laser-ablation system at the Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing. Common Pb corrections were performed following the method of Andersen (2002). We analyzed 25–30 zircon grains from each igneous rock sample and reported $^{206}\text{Pb}/^{238}\text{U}$ ages for zircon ages younger than 1 000 Ma. Isoplot was used to generate concordia plots and calculate weighted mean ages (Ludwig, 2003). Reported weighted mean ages and concordia plot errors are 2σ and at the 95% confidence level (Figure 8). Weighted mean ages are interpreted to reflect the crystallization age of the sample. Details of geochronologic data are presented in Table S1.

Zircon grains separated from the igneous samples are colorless and euhedral to subhedral (Figure 8). The zircon grains have long-axis diameters between ~100–200 μm and are equiaxial, short columnar, or long columnar. The edges of most zircon grains are straight and broken. CL images of most zircon grains are bright with clear internal texture and clear oscillatory zoning. Analyzed Th/U ratios range from 0.17 to 3.17 (Table S1), indicating that the measured grains are primarily of magmatic origin.

A total of 280 zircon grains analyzed from eleven mafic-felsic magmatic samples yield U-Pb ages spanning ca. 206–353 Ma (Figure 8). Most zircon grain analyses are concordant or nearly concordant, clustering as single-age populations. To eliminate the effects of radiation damage, Pb loss, and analytical error, we use ages that belong to the same Gaussian distribution for calculating weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages. We interpret that the

weighted mean ages to represent the crystallization ages of the sampled rocks.

Twenty-five zircon grains analyzed from granodiorite sample QL20220623-4 yield U-Pb ages between ca. 206 and ca. 292 Ma. The weighted mean age of twenty concordant analyses is 238 ± 4 Ma (MSWD = 1.6) (Figure 8a), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from granite sample QL20220624-7 yield U-Pb ages between ca. 231 and ca. 266 Ma. The weighted mean age of nine concordant analyses is 248 ± 2 Ma (MSWD = 1.6) (Figure 8b), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from gabbro sample QL20220624-9 yield U-Pb ages between ca. 230 and ca. 252 Ma. The weighted mean age of seventeen concordant analyses is 241 ± 1 Ma (MSWD = 1.6) (Figure 8c), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from monzogranite sample QL20220624-11 yield U-Pb ages between ca. 213 and ca. 251 Ma. The weighted mean age of fifteen concordant analyses is 237 ± 2 Ma (MSWD = 1.9) (Figure 8d), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from gabbroic diorite sample QL20220624-13 yield U-Pb ages between ca. 230 and ca. 249 Ma. The weighted mean age of twenty-three concordant analyses is 236 ± 2 Ma (MSWD = 1.9) (Figure 8e), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from monzogranite sample QL20220625-10 yield U-Pb ages between ca. 211 and ca. 265 Ma. The weighted mean age of thirteen concordant analyses is 233 ± 3 Ma (MSWD = 2.0) (Figure 8f), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from monzogranite sample QL20220628-1 yield U-Pb ages between ca. 230 and ca. 242 Ma. The weighted mean age of twenty-five concordant analyses is 236 ± 2 Ma (MSWD = 0.88) (Figure 8g), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from amphibole gabbro sample QL20220628-9 yield U-Pb ages between ca. 241 and ca. 265 Ma. The weighted mean age of twenty-one concordant analyses is 253 ± 3 Ma (MSWD = 0.91) (Figure 8h), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from monzogranite sample QL20220628-11 yield U-Pb ages between ca. 235 and ca. 253 Ma. The weighted mean age of eighteen concordant analyses is 246 ± 1 Ma (MSWD = 1.8) (Figure 8i), which represents the crystallization age of this sample. Thirty zircon grains analyzed from monzogranite sample QL20220630-1 yield U-Pb ages between ca. 209 and ca. 535 Ma. The weighted mean age of nine concordant analyses is 292 ± 9 Ma (MSWD = 1.8) (Figure 8j), which represents the crystallization age of this sample. Twenty-five zircon grains analyzed from monzogranite sample QL20220701-1 yield U-Pb ages between ca. 216 and ca. 246 Ma. The weighted mean age of sixteen concordant analyses is 238 ± 2 Ma (MSWD = 1.9) (Figure 8k), which represents the crystallization age of this sample.

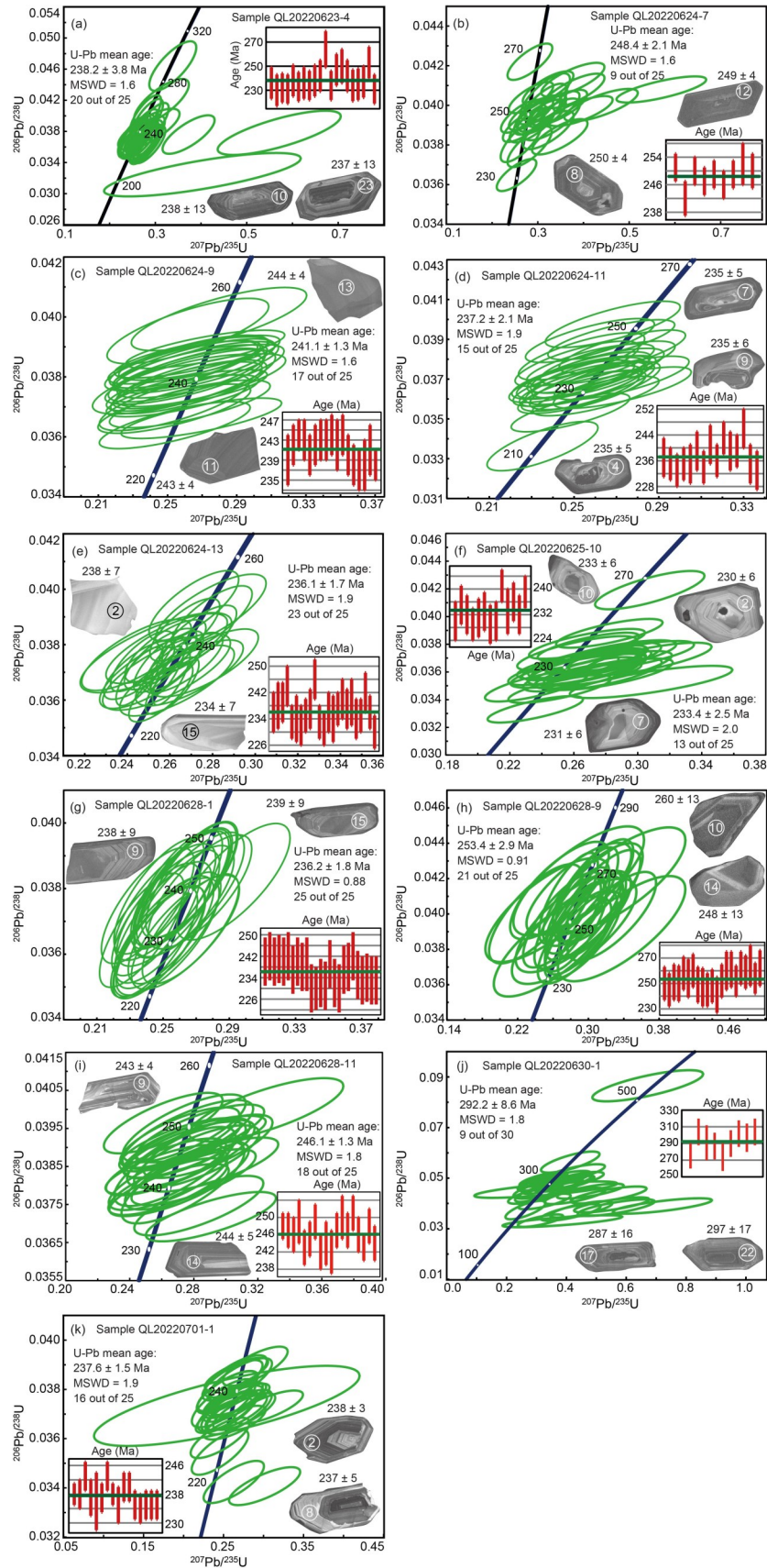


Figure 8. U-Pb concordia diagrams showing results of single-shot zircon analyses and representative zircon cathodoluminescence (CL) images for each sample. Error ellipses are 2σ . Circles represent $\sim 30\ \mu\text{m}$ analyzed spots for U-Pb dating. The numbers in the circles represent the analytical sampling numbers. The insets represent the results of weighted mean ages of dated samples. Abbreviations: MSWD, mean square of weighted deviates.

4.2 Whole-Rock and Sr-Nd Isotope Geochemistry

Samples were analyzed for whole-rock major oxide, trace element, and Sr-Nd isotope geochemistry at the Wuhan Sample Solution Analytical Technology Co., Ltd. Prior to analysis, weathered surfaces of rock samples were removed. Residual samples were crushed and ground into powder (> 200 mesh). Major element compositions were determined using a ZSX Primus II wavelength dispersive X-ray fluorescence spectrometer. Trace element compositions were measured using an Agilent 7700e ICP-MS. Sr-Nd isotopes were analyzed using a Neptune Plus multi-collector ICP-MS. Analytical results of standard samples BCR-2 and RGM-2 include: $^{143}\text{Nd}/^{144}\text{Nd} = 0.512\,638 \pm 0.000\,015$ (2σ) and $^{87}\text{Sr}/^{86}\text{Sr} = 0.705\,012 \pm 0.000\,02$ (2σ), and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512\,803 \pm 0.000\,01$ (2σ) and $^{87}\text{Sr}/^{86}\text{Sr} = 0.704\,184 \pm 0.000\,01$ (2σ), respectively. Detailed analytical procedures are described in Li et al. (2012) and Liu Y S et al. (2004). Whole-rock geochemical and Sr-Nd isotopic data are presented in Table S2 and Table S3.

Nineteen igneous rock samples from the Zongwulong Shan-Qinghai Nanshan were collected for whole-rock, major oxide, and trace element geochemistry. These samples include five ultramafic-mafic rock samples, three mafic-intermediate rock samples, nine intermediate-acidic rock samples, and two leucogranite dike samples. Geochemistry results are shown in Table S2.

Nine granitoid samples (i. e., QL20220623-4, QL20220624-7, QL20220624-11, QL20220624-18, QL20220625-10, QL20220628-1, QL20220628-11, QL20220630-1, and QL20220701-1) have felsic compositions ($\text{SiO}_2 = 64.98\text{ wt.}\% - 76.00\text{ wt.}\%$) spanning the granodiorite to granite fields on the $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ versus SiO_2 discriminant diagram (Middlemost, 1994; Irvine and Baragar, 1971; Figure 9a). These samples fall within the (high-K) calc-alkaline field on the K_2O versus SiO_2 discriminant diagram (Le Maitre, 1989; Figure 9b) and metaluminous field on the A/NK versus A/CNK diagram (Maniar and Piccoli, 1989; Figure 9c). Most samples plot within the I- and S-type granite fields on the Nb versus $10\,000 \times \text{Ga}/\text{Al}$ diagram (Whalen et al., 1987; Figure 9d). These samples display relatively flat ($\text{La}/\text{Yb} = 7 - 40$) rare earth element patterns and are characterized by negative Ba, Nb, P, and Ti anomalies on trace-element diagrams (Sun and McDonough, 1989; Figures 9e and 9f). Two granitoid samples (i.e., QL20220630-1 and QL20220701-1) display no Eu anomalies, whereas the remaining seven samples show negative Eu anomalies on the chondrite-normalized rare earth element diagram (Sun and McDonough, 1989; Figure 9f).

Five (ultra-)mafic rock samples have low-silica compositions ($\text{SiO}_2 = 46.1\text{ wt.}\% - 50.78\text{ wt.}\%$) and fall within the gabbro field (i. e., sample QL20220624-5, QL20220624-8, QL20220624-9, and QL20220628-9). These five samples plot between gabbro and gabbroic diorite on the $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ versus SiO_2 discriminant diagram (Middlemost, 1994; Irvine and Baragar, 1971; Figure 9a). Sample QL20220624-6 falls within the transition

between gabbro and gabbroic diorite (Figure 9a). The samples are mostly calc-alkaline except for one sample (QL20220624-9) that is tholeiitic on the K_2O versus SiO_2 discriminant diagram (Le Maitre, 1989; Figure 9b). Primitive mantle-normalized trace element patterns of the five samples show enrichment in large-ion lithophile elements (LILEs, i.e., K, Rb, Sr, and Pb) and depletion in high field strength elements (HFSEs, i.e., Nb, Ta, P, and Ti). Sample primitive mantle-normalized trace element patterns are similar to those shown on primitive mantle-normalized, multi-element spider diagrams (Sun and McDonough, 1989; Figure 9g). Four (ultra-)mafic rock samples (QL20220624-5, QL20220624-6, QL20220624-8, and QL20220628-9) have negative Eu anomalies on chondrite-normalized rare earth element diagrams (Sun and McDonough, 1989; Figure 9h).

Three mafic-intermediate rock samples have felsic compositions ($\text{SiO}_2 = 51.08\text{ wt.}\% - 53.10\text{ wt.}\%$), falling within the gabbroic diorite compositional field (i.e., sample QL20220624-10 and QL20220624-13) on the $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ versus SiO_2 discriminant diagram (Middlemost, 1994; Irvine and Baragar, 1971; Figure 9a). Sample QL20220624-12 plot between gabbro and gabbroic diorite (Figure 9a). Three samples are calc-alkaline on the K_2O versus SiO_2 discriminant diagram (Le Maitre, 1989; Figure 9b). Primitive mantle-normalized trace element patterns of the three samples show enrichment in LILEs (i.e., K, Rb, and Pb), but depletion in HFSEs (i.e., Nb, Ta, P, and Ti). Sample primitive mantle-normalized trace element patterns are similar to those shown in primitive mantle-normalized, multi-element spider diagrams (Sun and McDonough, 1989; Figure 9g). Sample QL20220624-13 displays a negative Eu anomaly on the chondrite-normalized rare earth element diagram (Sun and McDonough, 1989; Figure 9h).

Two leucogranite dike samples (QL20220713-10 and QL20220713-11) have felsic compositions ($\text{SiO}_2 = 66.10\text{ wt.}\% - 74.63\text{ wt.}\%$) and fall within the granite (QL20220713-10) and granodiorite (QL20220713-11) fields on the $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ versus SiO_2 discriminant diagram (Middlemost, 1994; Figure 9a). The two samples are metaluminous on the A/NK versus A/CNK diagram (Maniar and Piccoli, 1989; Figure 9c). Sample QL20220713-10 is sub-alkaline and calc-alkaline, whereas sample QL20220713-11 is alkaline and shoshonitic on the $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ versus SiO_2 discriminant diagram and K_2O versus SiO_2 discriminant diagram (Middlemost, 1994; Le Maitre, 1989; Irvine and Baragar, 1971; Figures 9a and 9b). The two samples do not fall within the normal fields on the Nb versus $10\,000 \times \text{Ga}/\text{Al}$ diagram (Whalen et al., 1987; Figure 9d), primitive mantle-normalized, multi-element spider diagram, and chondrite-normalized rare earth element diagram (Sun and McDonough, 1989; Figures 9i and 9j). These compositions may be due to the influence of wall rocks or later geological processes during their intrusion of Neoproterozoic metamorphic rocks.

The Sr-Nd isotopic data of the two gabbroic diorite samples, two leucogranite dike samples, and nine granit-

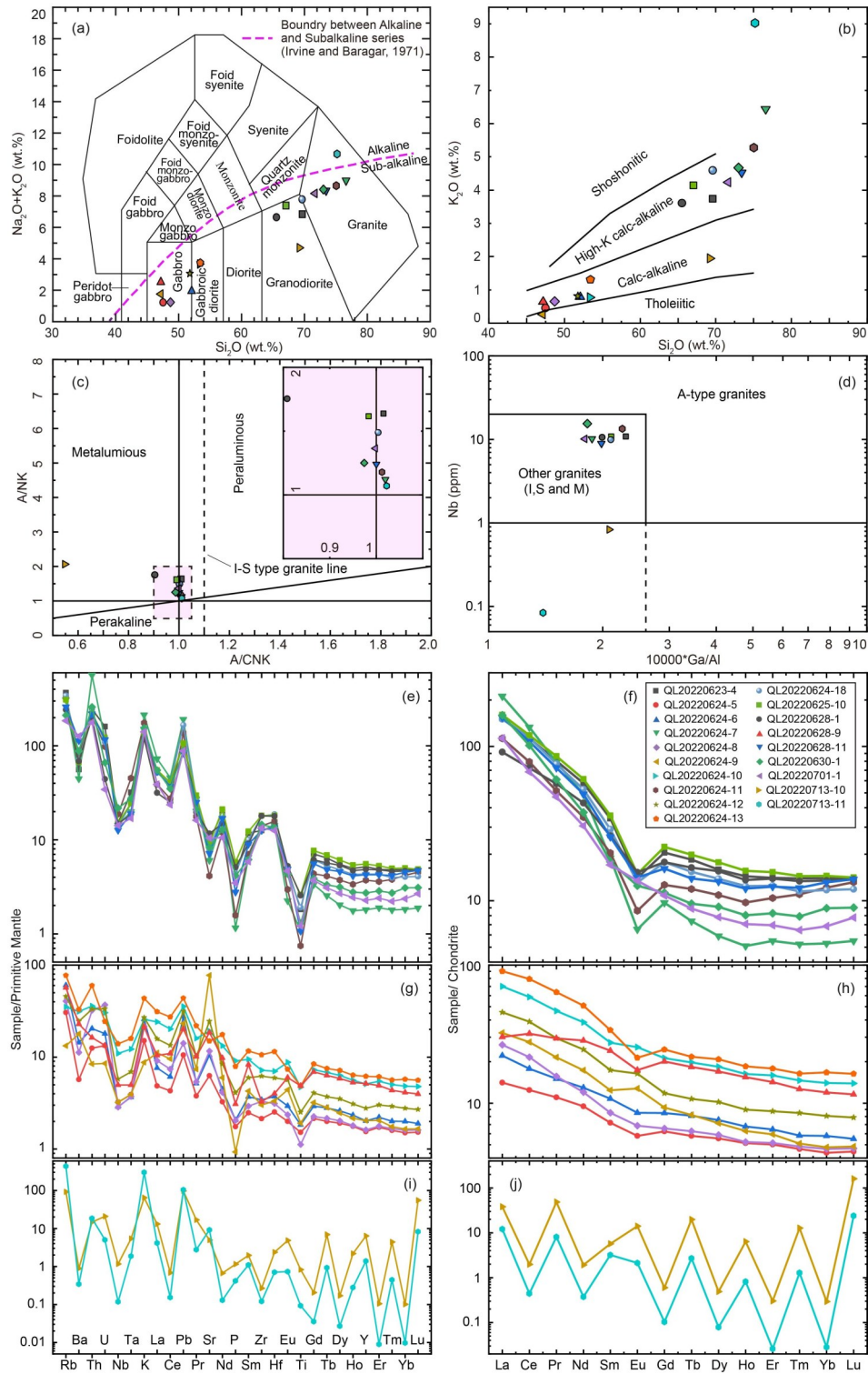


Figure 9. Geochemical results of samples from the Zongwulong Shan–Qinghai Nanshan. (a) $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 diagram. Normalization values are from Irvine and Baragar (1971) and Middlemost (1994). (b) K_2O versus SiO_2 diagram. Normalization values are from Le Maitre (1989). (c) A/NK versus A/CNK diagram. Normalization values are from Maniar and Piccoli (1989). Abbreviations: A, Al_2O_3 content; NK, $\text{Na}_2\text{O} + \text{K}_2\text{O}$ content; CNK, $\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}$ content. (d) Nb versus $10\,000 \times \text{Ga/Al}$ diagram. Normalization values are from Whalen et al. (1987). (e)–(f) Trace-element diagrams for granitoids: (e) primitive mantle-normalized, multi-element spider diagrams; (f) Chondrite-normalized rare earth element patterns. Normalization values are from Sun and McDonough (1989). (g)–(h) Trace-element diagrams for (ultra-)mafic and mafic-intermediate samples: (g) primitive mantle-normalized, multi-element spider diagrams; (h) chondrite-normalized rare earth element patterns. Normalization values are from Sun and McDonough (1989). (i)–(j) Trace-element diagrams for leucogranite dikes: (i) primitive mantle-normalized, multi-element spider diagrams; (j) chondrite-normalized rare earth element patterns. Normalization values are from Sun and McDonough (1989).

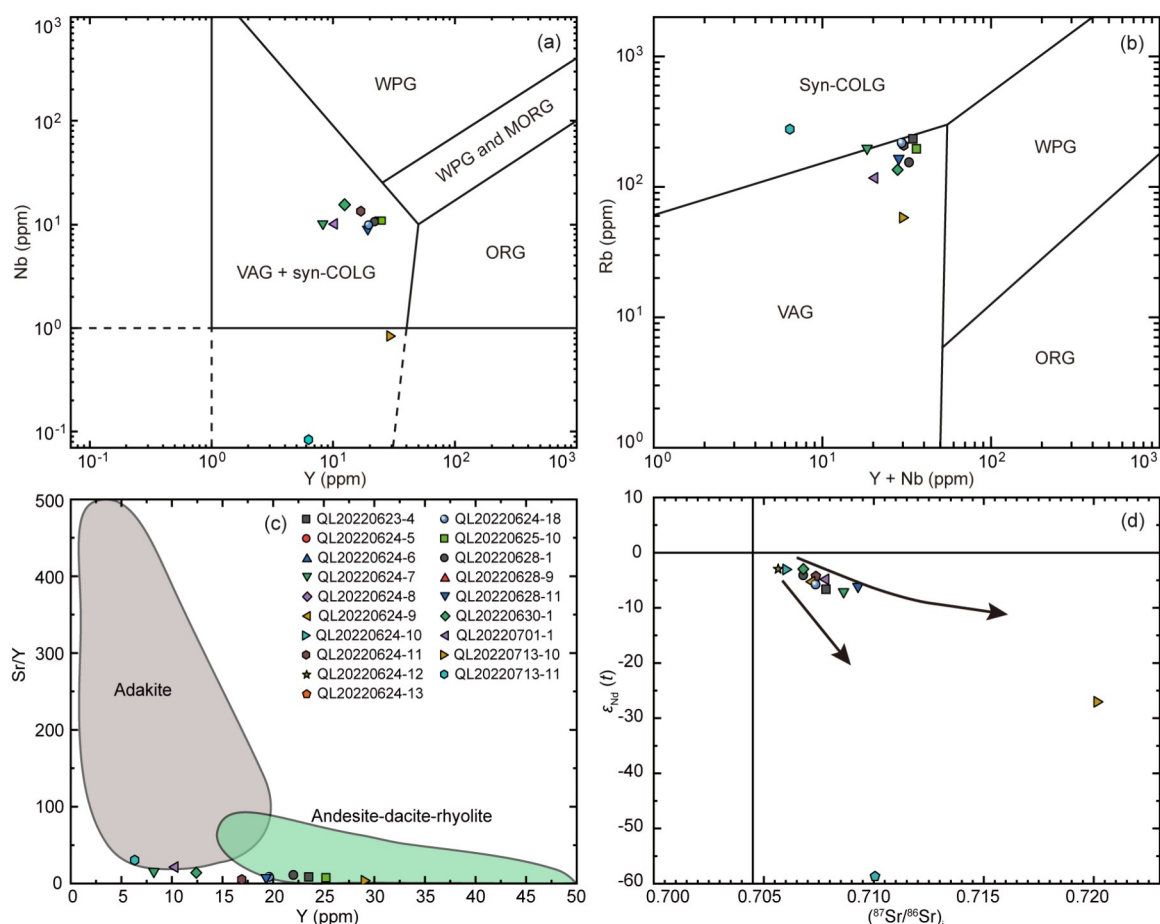


Figure 10. (a) and (b) plutonic rock discrimination diagrams. Normalization values are from Pearce et al. (1984). (c) Sr/Y versus Y diagram of Defant and Drummond (1990); (d) $\epsilon_{\text{Nd}}(t)$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram. CHUR, Chondritic uniform reservoir.

oid samples are shown in Table S3. Except for the two leucogranite dike samples (QL20220713-10 and QL20220713-11), Sr-Nd isotopic results fall within normal ranges. The remaining eleven samples yield $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values of 0.705 655–0.709 281 and $(^{143}\text{Nd}/^{144}\text{Nd})_i$ values of 0.511 954 775–0.512 179 153. The remaining eleven samples have $\epsilon_{\text{Nd}}(t)$ values of -7.1 to -2.98 and model ages of ca. 1.58–1.06 Ga (Table S3; Figure 10).

5 DISCUSSION

5.1 Late Paleozoic–Early Mesozoic Magmatism in the Zongwulong Shan-Qinghai Nanshan Tectonic Belt

Based on new and existing geochemistry of the Late Paleozoic–Early Mesozoic intrusive rocks in the Zongwulong Shan-Qinghai Nanshan belt (Table S2 and Table S4), we present the following findings regarding their petrogenesis and magma evolution.

(1) In Harker diagrams, major oxides including Al_2O_3 , MgO, TFe_2O_3 , CaO, Na_2O , and K_2O have relatively high proportions (Figure 11). Al_2O_3 , MgO, TFe_2O_3 , and CaO are negatively correlated with SiO_2 (Figures 11b, 11c, 11e, and 11f), whereas Na_2O , K_2O , and SiO_2 are positively correlated with SiO_2 (Figures 11g, 11h, and 11i). Such correlations may reflect the fractional crystallization of olivine, pyroxene, amphibole, mica, feldspar, and quartz

and the evolution from Late Paleozoic–Early Mesozoic (ultra-)mafic to intermediate to felsic compositions of the magma evolution.

(2) SiO_2 compositions of 45 wt.%–52 wt.% correspond with increases in Al_2O_3 and steep decreases in MgO. This may reflect olivine crystals consuming MgO and TFe_2O_3 instead of Al_2O_3 and pyroxene crystals consuming MgO, CaO, and minor amounts of TFe_2O_3 and Al_2O_3 (Figures 11b, 11c, 11e, and 11f). However, in the same samples with SiO_2 of 45 wt.%–52 wt.%, Na_2O and K_2O do not participate in the reaction and their proportions increase likely due to partial melting (Figures 11g, 11h, and 11i). SiO_2 compositions of 52 wt.%–77 wt.% correspond with decreases in TFe_2O_3 , CaO, and MgO. These decreases in high-silica samples may be related to the crystallization of pyroxene, amphibole, mica, and quartz (Figures 11c, 11e, and 11f). The horizontal ordinate of SiO_2 shows an inflection point at ~52 wt.%, where Al_2O_3 transitions from increasing to decreasing proportions (Figure 11b). This may reflect crystallization of plagioclase, which is supported by negative Eu anomalies of Late Paleozoic–Early Mesozoic magmatic samples (Li et al., 2022; Figures 9f and 9h).

(3) SiO_2 compositions of 45 wt.%–77 wt.% correspond with changes in major elements from being rich in Fe and Mg and poor in Si and Na + K to being poor in Fe

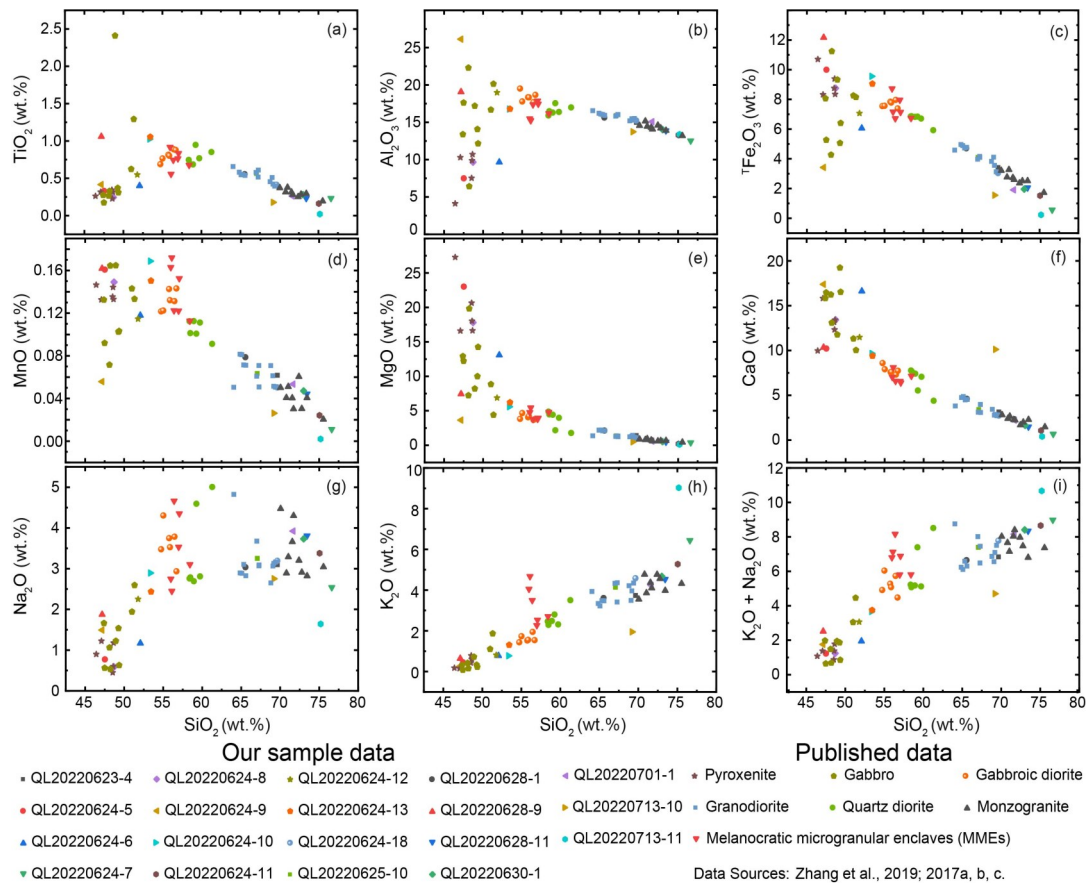


Figure 11. Harker diagrams showing the variations of major elements. This major element data and previous major element data are listed in Table S2 and Table S4, respectively.

and Mg and rich in Si and Na + K (Figure 11). These changes likely indicate the evolution from (ultra-)mafic to felsic magmas. The overall trends of the Harker diagram are controlled by essential and subordinate mineral elements, whereas minor changes may be related to the addition or reduction of accessory mineral elements (Figure 11).

(4) SiO_2 compositions of 57 wt.% and 67 wt.% are irregular in Harker diagrams (Figures 11g, 11h, and 11i), which may suggest that rising magma mixed at the crust-mantle boundary. The melanocratic micro-granular enclaves in the Late Paleozoic–Early Mesozoic intermediate acidic rocks of the Eastern Kunlun and the Zongwulong Shan–Qinghai Nanshan tectonic belt (e.g., Wang et al., 2019; Chen G C et al., 2018; Zhang Y M et al., 2017a, b, c; Gao et al., 2015; Xia et al., 2014; Chen X H et al., 2012; Zhang J Y et al., 2012; Liu C D et al., 2004) share this characteristic and support a mixed magma source (Peng et al., 2016).

5.2 Timing and Tectonic Setting of Intrusive Rocks

Previous studies have shown that the Zongwulong Shan–Qinghai Nanshan tectonic belt experienced magmatic activity during the Late Paleozoic–Early Mesozoic (e.g., Zou et al., 2023, 2022; Ding et al., 2022; Pan et al., 2021; Yue et al., 2021; Zhuang et al., 2020; Gao et al., 2019; Wang M et al., 2019; Wu C L et al., 2019, 2009;

Zhang et al., 2019, 2017a, b, c; Li et al., 2018; Zeng et al., 2018; Jia et al., 2017; Wang Y S et al., 2017; Hu et al., 2016; Peng et al., 2016; Wang and Zhou, 2016; Dong et al., 2015, 2014; Chen et al., 2012; Guo et al., 2009; Qiang, 2008; Figure 1b). We determined ca. 292–233 Ma crystallization ages for (ultra-)mafic to intermediate-acidic rocks in the Zongwulong Shan–Qinghai Nanshan, which provides further evidence of magmatism during this time (Figure 8).

Nine granitoid samples plot mostly within the I- and S-type granite fields (Whalen et al., 1987; Figure 9d), which are commonly associated with arc magmatism and/or crustal anatexis (Li et al., 2022). These samples also plot within the volcanic arc field on the granite classification diagram (Pearce et al., 1984; Figures 10a and 10b) and outside the adakite field on the Sr/Y versus Y (ppm) diagram (Defant and Drummond, 1990; Figure 10c). The nine samples display relatively flat ($\text{La}/\text{Yb} = 7\text{--}40$) rare earth element patterns and are characterized by negative Ba, Nb, P, and Ti anomalies (Sun and McDonough, 1989; Figures 9e and 9f), indicative of an arc/subduction setting for the original melt (Li et al., 2022).

Two leucogranite dike samples (QL20220713-10 and QL20220713-11) plot outside the boundaries of the Nb (ppm) versus Y (ppm) granite classification diagram (Pearce et al., 1984; Figure 10a), which may be due to the influence of wall rocks and/or later geological pro-

cesses during intrusion of Neoproterozoic metamorphic rocks. Sample QL20220713-10 falls within the volcanic arc field, whereas sample QL20220713-11 plots within the syn-collision granite on the Rb (ppm) versus Y + Nb (ppm) granite classification diagram (Pearce et al., 1984; Figure 10b). Sample QL20220713-10 falls within the andesite-dacite-rhyolite compositional field, whereas sample QL20220713-11 plots near the adakite field on the Sr/Y versus Y(ppm) diagram (Defant and Drummond, 1990; Figure 10c). Sample QL20220713-11 may have been generated in a partial-remelting crust setting, which was induced by the compression of north-dipping subduction of the Paleo-Tethys oceanic slab in the south (Wu et al., 2022, 2016). In contrast, sample QL20220713-10 may reflect later subduction. The $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values of the nine granitoid samples and two gabbroic diorite samples are 0.706–0.709 (Table S3), potentially reflecting a subduction-related magmatic arc setting.

The nine granitoid samples and two gabbroic diorite samples have negative $\epsilon_{\text{Nd}}(t)$ values of -7.1 to -2.98 and plot within the fourth quadrant of the $\epsilon_{\text{Nd}}(t)$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram (Figure 10d). These results indicate either a crust, enriched mantle (Han et al., 2003), or mixed crust-mantle source (Gao et al., 2015). The (ultra-)mafic and mafic-intermediate rock samples are enriched in LREEs and display a flat HREE pattern without Ce anomalies, similar to the enriched mid-ocean ridge basalt pattern on the chondrite-normalized rare earth element diagram (Sun and McDonough, 1989; Figure 9h). This suggests that the (ultra-)mafic and mafic-intermediate rocks originated from the enriched mantle. The melanocratic micro-granular enclaves in granodiorite of the Qinghai Nanshan (e.g., Wang et al., 2019; Zhang et al., 2017a, b, c) indicate that the source of the intermediate-acidic rocks was mixed crust-mantle (Peng et al., 2016).

In summary, the ca. 292–233 Ma (ultra)mafic magmatic rocks display the imprints of the enriched mantle, and those intermediate-felsic magmatic rocks display the features of subduction-related arc magmatic rocks. The distribution of Late Paleozoic–Early Mesozoic magmatic rocks in the Zongwulong Shan-Qinghai Nanshan is broad and across the tectonic belt. These rocks in a broader region are characterized by a trend of southward younging, which is interpreted as the result of the southward roll-back of the Paleo-Tethys oceanic slab (Wu et al., 2022, 2016). The above observations limit our understanding for the Late Paleozoic–Early Mesozoic tectonic model, and the north-dipping subduction of the Paleo-Tethys oceanic slab is a suitable scenario.

5.3 Tectonic Connection between the Eastern Kunlun Orogen and Zongwulong Shan-Qinghai Nanshan Tectonic Belt

The northern Tibetan Plateau hosted the expansion, subduction, and collision of the Paleo-Tethyan Ocean (Wu et al., 2023). We interpret that the tectonic evolutions of the Zongwulong Shan-Qinghai Nanshan region along the northern edge of Qaidam continent and East-

ern Kunlun region were related, such that the Late Paleozoic–Early Mesozoic arc magmatism in the Zongwulong Shan-Qinghai Nanshan was a product of northward Paleo-Tethyan oceanic subduction in the Eastern Kunlun region (e.g., Wu C et al., 2022, 2019, 2016; Zhang et al., 2022; Yue et al., 2021; Chen et al., 2019; Li et al., 2018; Wang et al., 2017; Cheng, 2015). Evidence for this interpretation includes: (1) Late Paleozoic–Early Mesozoic magmatism is well documented in both the Zongwulong Shan-Qinghai Nanshan tectonic belt (e.g., Zou et al., 2023, 2022; Ding et al., 2022; Zhang J P et al., 2022; Pan et al., 2021; Yue et al., 2021; Zhuang et al., 2020; Gao et al., 2019; Wang M et al., 2019; Wu C L et al., 2019, 2009; Zhang Y M et al., 2019, 2017a, b, c; Li et al., 2018; Zeng et al., 2018; Jia et al., 2017; Wang Y S et al., 2017; Hu et al., 2016; Peng et al., 2016; Wang and Zhou, 2016; Dong et al., 2015, 2014; Huang et al., 2014; Chen et al., 2012; Qiang, 2008; Gehrels et al., 2003) and Eastern Kunlun region (e.g., Wu C et al., 2022, 2019, 2016; Xiong et al., 2016, 2014; Ding et al., 2014; Liu B et al., 2014; Xia et al., 2014; Dai et al., 2013; Li et al., 2013; Chen et al., 2012; Zhang et al., 2012; Liu Y J et al., 2005; Liu C D et al., 2004; Harris et al., 1988). In addition, the northwest-southeast-trending Zongwulong Shan-Qinghai Nanshan tectonic belt and the east-west-trending eastern Kunlun tectonic belt are proximal and have similar orientations. (2) Both the Zongwulong Shan-Qinghai Nanshan and Eastern Kunlun tectonic belts contain similar rock assemblages, including melanocratic micro-granular enclaves within Late Paleozoic–Early Mesozoic intermediate-acidic rock bodies (e.g., Wang et al., 2019; Chen et al., 2018; Zhang et al., 2017a, b, c; Gao et al., 2015; Xia et al., 2014; Chen et al., 2012; Zhang et al., 2012; Liu C D et al., 2004). (3) The T_{DM} of the Xiangride intermediate acidic rocks (ca. 242–240 Ma) in the Eastern Kunlun region are ca. 1.62–1.14 Ga, with $\epsilon_{\text{Nd}}(t)$ values of -7.15 to -1.59 (Wang et al., 2008; Chen et al., 2007). The T_{DM} of the Kaerqueka granodiorite (ca. 234 Ma) in the Eastern Kunlun region are ca. 1.33–1.25 Ga, with $\epsilon_{\text{Nd}}(t)$ values of -5.3 to -4.2 (Gao et al., 2015). Similarly, the T_{DM} of mafic-intermediate and intermediate-acidic rocks (ca. 248–233 Ma) in the Zongwulong Shan-Qinghai Nanshan tectonic belt are ca. 1.58–1.06 Ga, with $\epsilon_{\text{Nd}}(t)$ values of -7.1 to -2.98 (Table S3). This agreement in whole-rock Sr-Nd isotope data for the Eastern Kunlun and the Zongwulong Shan-Qinghai Nanshan tectonic belts suggest contemporaneous, Late Paleozoic–Early Mesozoic magmatism.

5.4 Late Paleozoic–Early Mesozoic Tectonic Evolution

Based on new and existing results, we present a new model for the Late Paleozoic–Early Mesozoic tectonic evolution of the Zongwulong Shan-Qinghai Nanshan in the northern Tibetan Plateau (Figure 12).

(1) During the Late Paleozoic, Devonian sedimentary rocks were widely deposited from the northern margin of the Qaidam continent to the eastern Kunlun region (Mu et al., 2018). Several igneous bodies formed at this

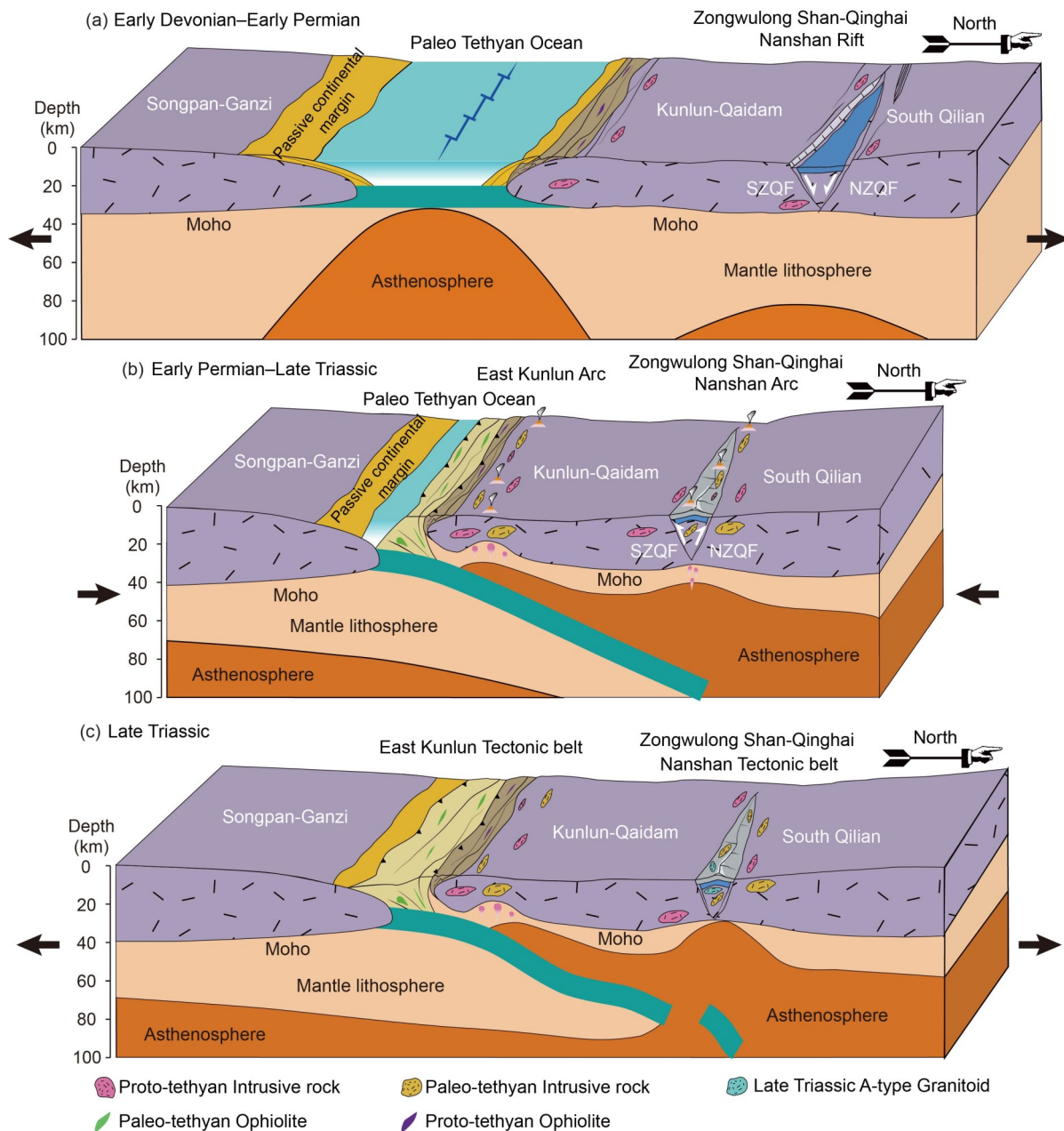


Figure 12. Model for the Late Paleozoic–Early Mesozoic tectonic evolution of the Zongwulong Shan–Qinghai Nanshan region.

time, including the Chahannuo hornblende gabbro (ca. 416 Ma) in Wulan County (Peng et al., 2016), Lalongwa mafic rocks (ca. 394 Ma) of the Kuhai-Saishitang belt (Sun et al., 2004), gabbro veins (ca. 357 Ma) within the Daken Daban Group of the Zongwulong Shan (Zhuang et al., 2019), Haerguole and Deerni ophiolite (ca. 333 and ca. 308 Ma, respectively) (Liu et al., 2011; Yang et al., 2004) in the Buqingshan area (Yang et al., 2004). Chen (2014) interpreted that Early Devonian deposition of sedimentary rocks of the Maoniushan Group indicates the onset of the next tectonic cycle in the Eastern Kunlun region.

We interpret that the present-day area from the northern Qaidam continent to the Eastern Kunlun region experienced intracontinental extension from the Early Devonian–Early Permian, marking the opening of the Paleo-

Tethyan Ocean. The eastern Kunlun region fully developed into the Paleo-Tethyan Ocean. In contrast, the Zongwulong Shan–Qinghai Nanshan region formed small rifts in the Early Devonian (Guo et al., 2009; Qiang, 2008), and a larger, mature rift during the Early Carboniferous, during which Carboniferous strata were deposited (Peng et al., 2018). The main sources of the Carboniferous strata were Neoproterozoic granite gneiss in the Yuka-Shaliuhe (ultra-)high-pressure metamorphic belt and late Early Paleozoic granite in the Tanjianshan ophiolite-volcanic arc belt (Peng et al., 2020). The Zongwulong rift may have been the northern branch of the Paleo-Tethyan Ocean (Li et al., 2024; Li and Nie, 1985; Figure 12a).

(2) As the Paleo-Tethyan Ocean subducted northward during the Late Paleozoic – Early Mesozoic, the Zongwulong Shan–Qinghai Nanshan area spanning the

northern Qaidam continent and eastern Kunlun region experienced widespread arc magmatism (Wu et al., 2023; Figure 12b). The timing of magmatism related to Paleo-Tethyan oceanic subduction along the northern Qaidam continent (Figures 1b and 3) is constrained to ca. 292–233 Ma (Figure 12b). Evidence includes zircon U-Pb crystallization ages and magmatic arc geochemistry of Early Permian monzogranite (ca. 292 Ma; sample QL20220630-1) and Late Triassic monzogranite (ca. 233 Ma; sample QL20220625-10) in the Zongwulong Shan-Qinghai Nanshan area. The Late Triassic monzogranite in the same area may have been generated during a later stage of Paleo-Tethyan oceanic subduction.

Slab dehydration of the subducting Paleo-Tethyan oceanic lithosphere resulted in partial melting in the mantle wedge and the petrogenesis of mafic magma. As the mafic magma rose, it underwent fractional crystallization with decreasing temperature. Some mafic magma crystallized olivine, pyroxene, and mafic plagioclase forming (ultra-)mafic and mafic-intermediate compositions such as those of the pyroxenite (ca. 248 Ma) (Zhang et al., 2019), gabbro (ca. 253–241 Ma), and gabbroic diorite (ca. 236 Ma) sampled in this study. The mafic magma stalled at the crust-mantle boundary, where it melted lower crust to form more felsic compositions, such as those of the granite (ca. 248 Ma), granodiorite (ca. 238 Ma), and monzogranite (ca. 292–233 Ma) sampled in this study. Underplated, mantle-derived magma and the felsic mixed, resulting in the petrogenesis of melanocratic micro-granular enclaves observed in granodiorite of the Qinghai Nanshan (e.g., Wang et al., 2019; Zhang et al., 2017a, b, c).

(3) During the Triassic, the Erlangdong A-type granite (ca. 215 Ma) (Guo et al., 2009; Qiang, 2008) and Guanjiarji A-type granite (ca. 230 Ma) (Peng et al., 2016) were generated in the Zongwulong Shan-Qinghai Nanshan region. The A-type granite is interpreted to have been generated during extension that followed subduction (Eby, 1992, 1990; Turner et al., 1992; Whalen et al., 1987). The occurrence of A-type granite in the Zongwulong Shan-Qinghai Nanshan indicates the Triassic slab retreat of the northward subducted Paleo-Tethyan oceanic lithosphere, during which the regional tectonic stress field shifted from compression to extension (Wu et al., 2023, 2016; Figure 12c).

6 CONCLUSIONS

Our field observations and analytical results improve our understanding of the Late Paleozoic–Early Mesozoic tectonic evolution of the Zongwulong Shan-Qinghai Nanshan along the northern margin of the Tibetan Plateau. The following key findings are drawn from this study.

(1) Intrusive rocks crystallized ca. 292–233 Ma, perhaps in a subduction arc-related setting. These results provide additional evidence of Permian–Triassic magmatism in the Zongwulong Shan-Qinghai Nanshan.

(2) Geochemical and Sr-Nd isotopic data suggest that Early Permian–Late Triassic ultramafic-mafic and

mafic-intermediate intrusions in the Zongwulong Shan-Qinghai Nanshan were sourced from enriched mantle. In contrast, intermediate-acidic rocks in the region may have been sourced from mixed crust-mantle.

(3) We present a new Late Paleozoic–Early Mesozoic tectonic model that involves three major stages: (i) Early Devonian–Early Permian intracontinental extension along the northern Qaidam continent was expressed as Early Carboniferous–Early Permian (ca. 416–292 Ma) rifting in the Zongwulong Shan-Qinghai Nanshan area. (ii) Early Permian–Late Triassic (ca. 292–233 Ma) northward subduction of the Paleo-Tethyan Ocean caused arc magmatism in the Zongwulong Shan-Qinghai Nanshan area. (iii) Arc magmatism was followed by Late Triassic (ca. 233–215 Ma) intracontinental extension in the Zongwulong Shan-Qinghai Nanshan area.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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