Tibetan Plateau insights into >1100°C crustal melting in the Quaternary

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ABSTRACT

Partial melting during high- to ultrahigh-temperature (UHT) metamorphism facilitates crustal differentiation, element transfer, and the evolution of topography in orogens, however the mechanisms that drive heating of Earth's crust remain controversial. In this contribution, we provide new evidence from ~2.3 Ma dacites in the Tibetan Plateau, the youngest known UHT metamorphic event. Our results show that these dacites were mainly generated by fluid-absent melting of metasedimentary rocks and minor mafic rocks at peak temperatures of 1100–1150 °C and pressures of 0.8–0.9 Gpa. The dacites represent mixtures of UHT melts and granulite residues and are geochemically similar to A-type granites with extremely high heat production values (5.33–5.99 μW m^{-3}). Compared with the geological and geophysical observations, numerical modelling indicates that the key factor determining the thermal evolution of Tibet is the thickness of the radioactive layer. Orogens dominated by rocks of felsic composition, like Tibet, could easily reach UHT conditions within a short period of time (20–40 million years) after crustal thickening by radioactive heating, without the need for an additional tectonic mechanism.

INTRODUCTION

Chemically evolved, silica-rich continental crust is a key feature of Earth (e.g., Rudnick, 1995). Partial melting during high-temperature metamorphism has played a dominant role in crustal differentiation, reworking, and element transfer throughout Earth history (Brown 2013; Cipar et al., 2020). Although, this substantial crustal melting plays a key role in the orogenic transition from linear mountain ranges to flat plateaus (Zhang et al., 2022), the primary mechanism that drives heating of Earth's crust remains enigmatic.

The identification of Ultra-high-temperature (UHT) metamorphism (>900°C with pressures of 0.7–1.3 Gpa; Harley & Motoyoshi, 2000; Brown, 2006) has extended our understanding of crustal evolution to very high thermal regimes. Hence, the UHT crustal record is generally accepted as the key to solving the mystery of Earth's crustal heating (Clark et al., 2011), although the driving tectonic mechanism remains controversial. Competing models have been proposed to account for extreme crustal temperatures, including the involvement of continental back-arcs (e.g., Brown 2006), long-lived mountain plateaus with high contents of heat-producing elements (Clark et al., 2011), post-thickening lithospheric extension (Cipar et al., 2020), and mantle plume impingement (Santosh et al., 2008).

Our understanding of the primary mechanism that generates UHT conditions is hindered by the uncertainties regarding tectonic setting. Furthermore, since most UHT records are from Neoarchean–Cambrian granulite rocks (e.g., Brown 2006), some key information is commonly erased by long-term modification during their exhumation or later tectonism. However, in this paper we present new data (Figs. 1A-C) from the youngest known UHT melts and their residual granulite enclaves from the central Tibetan Plateau. This data provides an important information on the processes by which the continental crust of Tibet becomes extremely hot.

GEOLOGICAL SETTING

The Tibetan Plateau is the highest and largest orogenic plateau on Earth, and it has evolved from collision between India and Eurasia since *ca.* 60 Ma (e.g., Hu et al., 2015). The Qiangtang block (QB) lies in the central Tibetan Plateau and is divided into southern and northern Qiangtang (SQB and NQB) by the Paleo-Tethys Ocean suture zone (Fig. 1A) (Zhang et al., 2014). Cenozoic volcanic rocks occur widely in the QB and were erupted mainly in the Eocene–Oligocene (Wang et al., 2008, 2012). Geophysical data indicate that the present NQB probably has the highest thermal state of the entire plateau (Fig. 1A), and this is consistent with the occurrence of granulite xenoliths in the Dongyue Lake area (Hacker et al. 2000). The host lavas of these xenoliths have recently reclassified as dacites based on preliminary major- and trace-element analyses (Wang et al., 2016). The present study focuses on these dacites and enclaves from the Dongyue Lake area of the NQB, and confirms that they are UHT melts containing granulite residues.

PETROGRAPHY

The NQB dacites contain phenocrysts of plagioclase (Pl), K-feldspar (Ksp), and quartz (Qtz) in a cryptocrystalline–glassy groundmass. They record 10–20 vol.% entrainment of restite from the source, including phenocryst-like peritectic minerals (Figs. S1A-E) and millimeter-scale granulite enclaves (Fig. S1F). The restites have consistent compositions that are similar to those of typical UHT pelitic granulites, including high-F phlogopite (Phl; F = 4.4–5.5 wt.%), aluminous orthopyroxene (Opx_{Al}; Al_2O_3 = 7.2–9.0 wt.%), spinel (Sp), Ksp, ilmenite (Ilm), and minor titanomagnetite (Tim) (Table S1). They also contain minor high-F pargasite (Prg; F = ~1.8 wt.%; Table S1), orthopyroxene (Opx) and clinopyroxene (Cpx), minerals typical of UHT mafic granulites (e.g., Tsunogae et al., 2003). Although most high-F Phl and Prg in the dacites are euhedral–subhedral and almost indistinguishable from phenocrysts in texture, their compositions are similar to those of crystals in the UHT granulite enclaves of this study (Table S1) and those worldwide (e.g., the Napier Complex in East Antarctica; Motoyoshi and Hensen, 2001; Tsunogae et al., 2003). This confirms that they are entrained peritectic minerals of metamorphic origin.

A granulite enclave from sample 5123-2 is heterogeneous at the millimeter scale and can be divided into melanocratic domains of Opx_{Al} + Sp + Ksp + Ilm and leucocratic domains of Pl + Ksp + Phl ± Qtz (Figs. 2 and S1). Phl occurs locally as a relict mineral which has partially broken down to Opx_{Al} + Sp ± Ilm (Figs. S1G, H). Opx_{Al} occurs in aggregates and has a maximum Al_2O_3 content of 8.3–9.0 wt.%. Ksp has X_{an} (Ca/ (Ca + Na + K)) values of 0.03–0.05. A P–T pseudosection was calculated and contoured with isopleths of $Al^{IV}(Opx_{Al})$ and X_{An}(Ksp) for relevant assemblages (Fig. 2A). Al in Opx_{Al} is widely used as a geothermometer for UHT metamorphism due to its low diffusion rate (Kelsey, 2008). The observed Opx_{Al} + Sp + Ilm + Ksp assemblage (Figs. 2B, C), which has the highest Al^{IV} value of 0.20–0.21, is predicted to be stable at 1100°C–1150°C and pressures of 0.8–0.9 Gpa (Fig. 2A), representing peak conditions. Some Opx_{Al} which occurs as individual minerals in the matrix with relatively low Al^{IV} values of 0.17–0.20 (Table S1), is a prograde metamorphic mineral. The observed minerals and enclaves are thus residual materials formed during a series of UHT metamorphic reactions below or at peak conditions.

GEOCHRONOLOGY AND ISOTOPIC COMPOSITIONS

Dacite samples 5123-2 and 5124-2 yielded weighted-mean whole-rock $^{40}Ar/^{39}Ar$ ages of 2.95 ± 0.73 Ma and 3.16 ± 0.59 Ma, respectively, and sample 5126-1 yielded a weighted-mean phlogopite $^{40}Ar/^{39}Ar$ age of 2.20 ± 0.15 Ma (Figs. 1C, S2; Table S2). In addition, three dacite samples (5123-2, 5126-1, and 5133) were selected for zircon U–Pb dating by secondary-ion mass spectrometry. Most of the zircon grains show concentric oscillatory zoning in cathodoluminescence images (Fig. S2), and have high Th/U ratios (0.62–3.54), indicating a magmatic origin (Hoskin and Schaltegger, 2000). Results of 37 analyses were identical within analytical uncertainty, yielding a weighted-mean age of 2.29 ± 0.08 Ma (Fig. 1B; Table S3). This is interpreted as the crystallization age of these dacites, consistent with the zircon U–Pb age range of the three individual samples of 2.36 ± 0.11 Ma to 2.23 ± 0.10 Ma (Fig. S2).

The dacites have near-identical Pb isotopic compositions ($^{206}Pb/^{204}Pb$, 18.80–18.89; $^{207}Pb/^{204}Pb$, 15.73–15.80; $^{208}Pb/^{204}Pb$, 39.29–39.47; Table S4), similar to those of marine sediments and granulite xenoliths in QB Cenozoic volcanic rocks (Figs. 3A, B). *In situ* zircon Hf–O isotopic analyses of three dacite samples yielded variable $\varepsilon_{Hf}(t)$ values of +0.6 to –25.9 and $\delta^{18}O$ values of 6.1–8.0 (Table S5), broadly similar to those of S-type granites (Fig. 3C).

DISCUSSION

Insights from the youngest known example of UHT crustal reworking

In contrast to the prolonged cooling of HT–UHT granulite terrains (e.g., Wang et al., 2020), the cooling of granulite enclaves in volcanic rocks may be rapid (minutes to months; Cesare, 2008). It follows that the phlogopite $^{40}Ar/^{39}Ar$ cooling age of *ca.* 2.2 Ma should reflect (or be close to) the timing of UHT metamorphism, which is consistent with the metamorphic ages (~2.5–3.4 Ma) obtained in previous study (Hacker et al., 2000). Combined with the mineralogical observations and the same metamorphic and magmatic ages, the dacites and their entrainment of granulite residues are products of the same UHT metamorphism/partial melting event beneath the NQB.

The dacites thus represent the youngest (2.3 Ma) and hottest (>1100°C) crustal melting recorded to date, providing new insights into crustal reworking under extreme conditions: (1) This study provides a clear modern tectonic setting, in a collisional orogen with thickened crust, in which UHT conditions can be generated. (2) Mineralogical evidence indicates that UHT crustal felsic magma is a mixture of melt with a peritectic assemblage of entrained and residual granulite enclaves. The residues are mainly composed of UHT pelitic granulites and a small amount of mafic granulites (Fig. S1), indicating that the NQB dacites were generated by partial melting of metasedimentary rocks and minor mafic rocks. This is consistent with their zircon Hf–O and whole-rock Pb isotopic compositions (Figs. 3A-C). (3) The substitution of F for OH in the nominally hydrous minerals (Phl and Prg) of the present study implies that UHT partial melting occurs under extreme H_2O-poor conditions. (4) The UHT crustal magmas are geochemically characterized by both high 10000Ga/Al ratios and zircon saturation temperatures (946–973 ºC) in conjunction low Sr/Y values (Fig. S3) (Wang et al., 2016), similar to typical "A-type" granites. They also have extremely high heat-production values of 5.33–5.99 μW m^{-3} (Fig. 3D). Hence UHT partial melting and melt migration may thus enhance the transfer of radioactive elements from the deep crust to the upper crust.

How does orogenic crust get extremely hot?

UHT metamorphism is not usually associated with mantle-derived magmas (e.g., Clark et al., 2011). This is consistent with the scarcity of Quaternary mafic–ultramafic magmatism in the NQB. In a large collisional orogen, radioactive heat production in thickening crust (Clark et al., 2011) in combination with thinning lithosphere (Cipar et al., 2020; Wang et al., 2020) may play a key role in generating UHT conditions.

The Tibetan Plateau is a young active orogen and most of its evolutionary controls are known or well defined. Geophysical data indicate that the NQB has thick (~70 km) continental crust and a thin (~150 km) lithosphere (Gao et al., 2013; Tunini et al., 2016). The occurrence of Eocene (47–38 Ma) eclogitic crust-derived adakitic rocks indicates that the NQB crust has been thickened since *ca.* 47 Ma (Wang et al., 2008), likely reaching its near-present thickness during the Eocene (e.g., Wang et al., 2014). Therefore, the NQB has attained UHT conditions (>1100°C) relatively rapidly over a period of < 45 million years (Myr) after crustal thickening, much shorter than previous estimates of ~120 Myr (Clark et al., 2011). Furthermore, low erosion rates of <0.05 mm yr^{-1} since *ca.* 45 Ma have been estimated for central Tibet (Rohrmann et al., 2012). Based on these considerations, we used a 1-dimensional thermal model to reproduce the development of UHT conditions in the NQB according to two alternative end-member crustal models (Figs. 4A, B).

The "classic" Alps-type crustal model involves a 20-km-thick radioactive felsic upper layer and a 15-km-thick lower non-radioactive mafic layer, which doubles in thickness at 47 Ma by homogenous deformation (Fig. 4A). To replicate the extreme temperature of the NQB requires an extremely high radioactive heat production (>4.0 μW m^{-3}) (Fig. 4C). The calculated heat-production of Devonian–Eocene felsic rocks from NQB is 1.66–2.96 μW m^{-3} (Fig. 3D), averaging 2.54 μW m^{-3} (Table S6), much lower than theoretical requirements. Hence this model does not fit with geological observations in

Tibet.

The Tibet-type crustal model (Fig. 4B) indicates that the NQB could have a more silica-rich lower crust, corresponding to a much thicker (≥ 60 km) radioactive layer in the thickened crust. In this model the UHT conditions of NQB can be reproduced with a normal heat production of ~2.5 μW m^{-3} (Fig. 4D). In addition, the thermal evolution of the NQB crust based on this model is consistent with the metamorphic evolution of the NQB as inferred from crustal xenoliths (Fig. 4E) (Zhang et al., 2022). Furthermore, recent geophysical data indicate that the thick Tibetan crust lacks a mafic lower layer and is predominantly felsic in composition (Wang et al., 2021). Therefore, a more felsic and radioactive lower crust is likely to be a primary requirement for the development of UHT conditions during continental collision.

The composition of the lower crust remains controversial but recent studies demonstrate that at least some of lower crust need not be mafic and the bulk continental crust may be more silica rich than generally thought (Hacker et al., 2011; Wang et al., 2021). During sediment subduction, subduction erosion, and continent subduction, the original lower crust of the upper plate could be reworked into more felsic crust by relamination (Hacker et al., 2011). Qiangtang and other Tibetan blocks have undergone long-term subduction of the oceanic lithosphere and multi-stage continental collision because of subduction and closure of the intervening Tethyan oceans (e.g., Zhang et al., 2014). Therefore, felsic rocks could form much of the Tibetan lower crust, which is consistent with geophysical observations (Wang et al., 2021) and our numerical modelling (Fig. 4).

Modelling with both a thin lithosphere thickness of 150 km and normal lithosphere (190 km) was undertaken to assess the effect of lithospheric thinning on thermal evolution (Tunini et al., 2016; Molnar et al., 1993). The results of this modelling are shown in Fig. 4C, D and significantly, the difference in heating between the two cases was not as marked as expected, indicating that lithospheric thinning has very little influence.

IMPLICATIONS

Insights this young UHT terrane in the Tibetan Plateau confirm that the orogen is an important tectonic setting in which UHT conditions can develop. If an orogen has a Tibet-type crust with predominantly felsic rocks, then its entire middle–lower crust can reach UHT conditions within 20–40 Myr after crustal thickening via radioactive heating (Fig. 4E). These high temperatures can develop without the need for anomalously high heat production or lithospheric thinning. HT-UHT conditions will trigger substantial partial melting, crustal weakening, and crustal flow, leading to the transformation of linear mountain ranges to flat plateaus (Zhang et al., 2022). In contrast, orogens with Alps-type crust (more mafic lower crust) have difficulty attaining high temperatures unless prolonged (>120 Myr) radioactive heating occurs at very low erosion rates (Clark et al., 2011). This observation explains the varying thermal state, metamorphism and topographic features in different orogens throughout Earth history.

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FIGURE CAPTIONS

Figure 1. (A) Geological sketch map of Tibet showing major blocks, Cenozoic magmatic rocks, and geothermal state (i.e., depth of the 1250°C isotherms; Deng et al., 2016). NQB, northern Qiangtang Block; SQB, southern Qiangtang Block; IYZS, Indus–Yarlung Zangbo Suture; BNS, Bangong–Nujiang Suture; JS, Jinsha Suture; LSS, Longmu Co-Shuanghu Suture; AKMS, Anymaqen–Kunlun–Muztagh Suture. (B) Zircon U–Pb data of dacites. (C) $^{40}Ar/^{39}Ar$ age spectra of phlogopite.

Figure 2. (A) P–T pseudosection for the UHT granulite. (B) Photomicrograph (plane-polarized light) of UHT granulite and host dacite and (C) back-scattered electron image. L, melt; Opx_{Al}, aluminous orthopyroxene; Sp, spinel; Ksp, K-feldspar; Grt, garnet; Sa, sapphirine; Ilm, ilmenite; Pl, plagioclase; Cd, cordierite.

Figure. 3 (A) $^{206}Pb/^{204}Pb$–$^{208}Pb/^{204}Pb$ diagram. (B) $^{206}Pb/^{204}Pb$–$^{207}Pb/^{204}Pb$ diagram. (C) εHf(t)–$\delta^{18}O$ diagram (t = 2.3 Ma). (D) The calculated heat-production of Devonian–Quaternary felsic rocks from NQB (Table S6). Data of granulite xenoliths in the QB are after Lai and Qin (2008). The field for Hf–O isotopic compositions of S-type granites is after Kemp et al. (2007). The mean value of heat production in global granitic crust is from Artemieva et al. (2017). NHRL: Northern Hemisphere Reference Line. EM1 and EM2: enriched mantle end-members (Zindler & Hart, 1986).

Figure. 4 1D thermal model of UHT conditions in the QB. (A) Alps-type and (B) Tibet-type crustal models. (C) Modelled geothermal gradient at 2.3 Ma based on Alps-type crustal model, with varying rates of heat production (A_{rad}) for felsic crust. (D) Modelled geothermal gradient at 2.3 Ma based on a normal heat production of 2.5 μW m^{-3}, with varying thickness of felsic crust. (E) P–T evolution of the QB based on Tibet-type crustal model from initial crustal thickening at 47 Ma to the present. Modelling generally follows the code of Clark et al. (2011). A latent heat of melting (320 kJ kg^{-1}) was included in all modelling.

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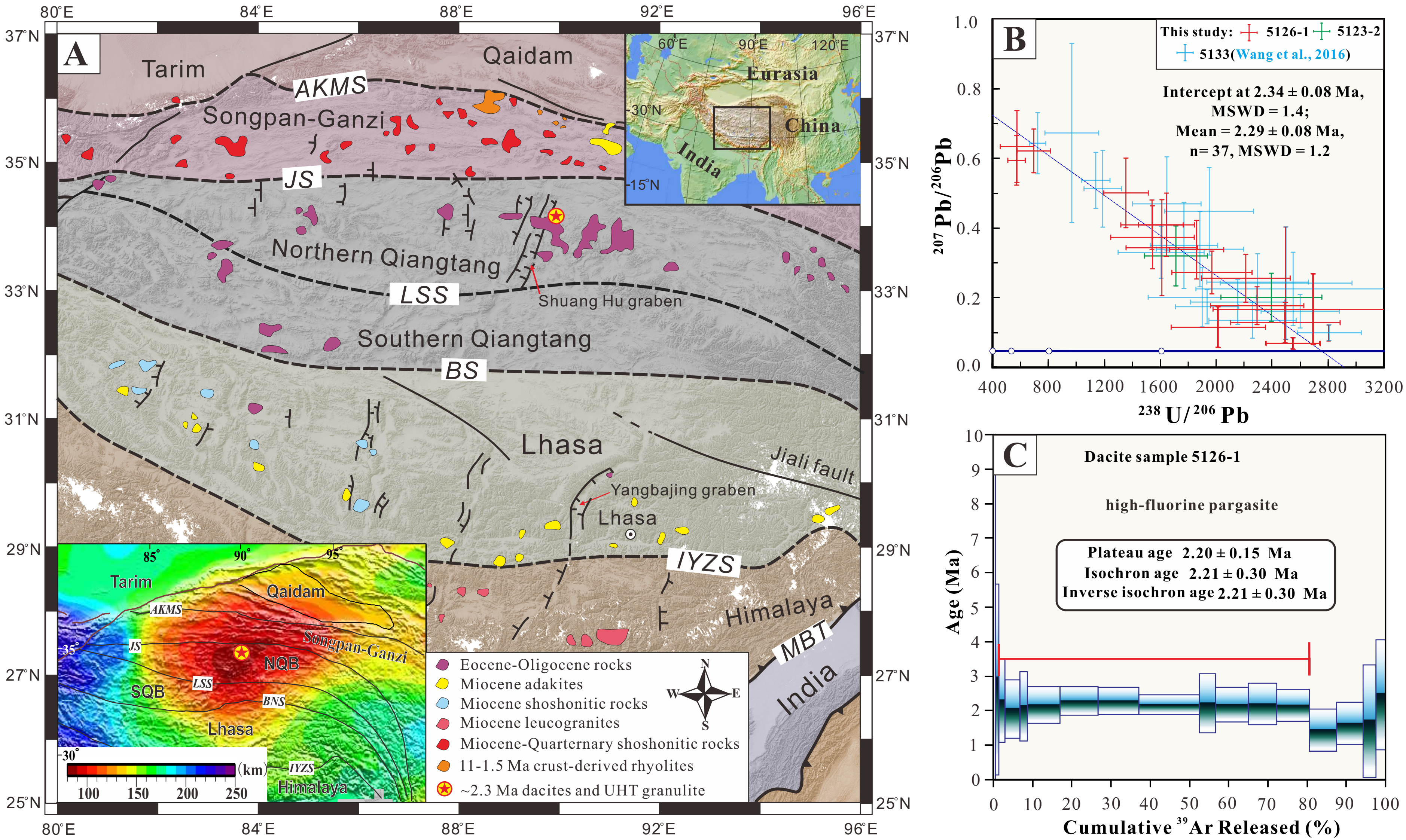
Figure 1



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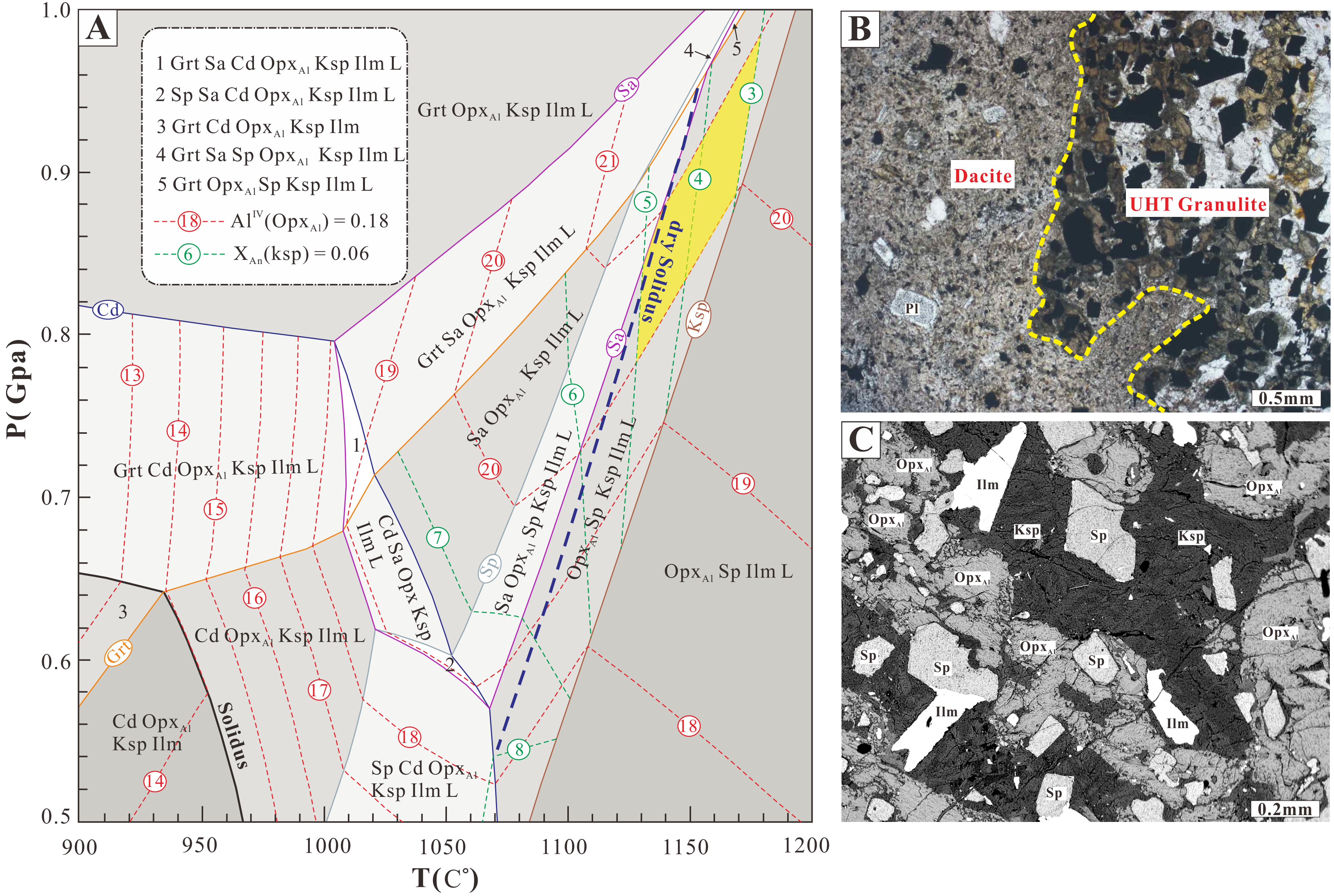
Jiali fault
Yangbajing graben
Lhasa
IYZS
Himalaya
MBT
India
Eurasia
China
India
NQB
SQB
Lhasa
Himalaya
(km)
Eocene-Oligocene rocks
Miocene adakites
Miocene shoshonitic rocks
Miocene leucogranites
Miocene-Quarternary shoshonitic rocks
11-1.5 Ma crust-derived rhyolites
~2.3 Ma dacites and UHT granulite
B
This study: 5126-1 5123-2
5133(Wang et al., 2016)
Intercept at 2.34 ± 0.08 Ma,
MSWD = 1.4;
Mean = 2.29 ± 0.08 Ma,
n= 37, MSWD = 1.2
207Pb/206Pb
238U/206Pb
C
Dacite sample 5126-1
high-fluorine pargasite
Plateau age 2.20 ± 0.15 Ma
Isochron age 2.21 ± 0.30 Ma
Inverse isochron age 2.21 ± 0.30 Ma
Age (Ma)
Cumulative 39Ar Released (%)

Figure 2



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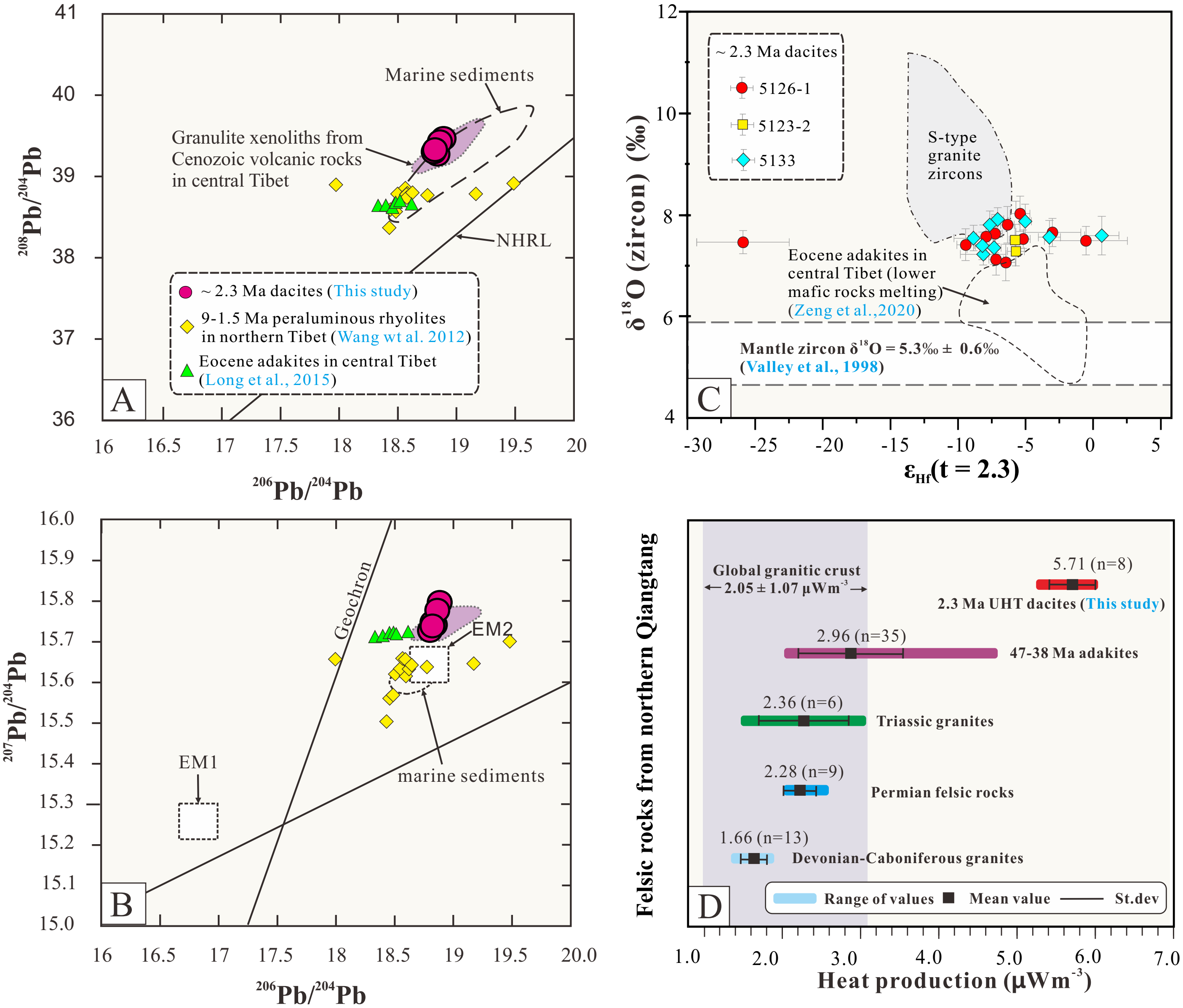
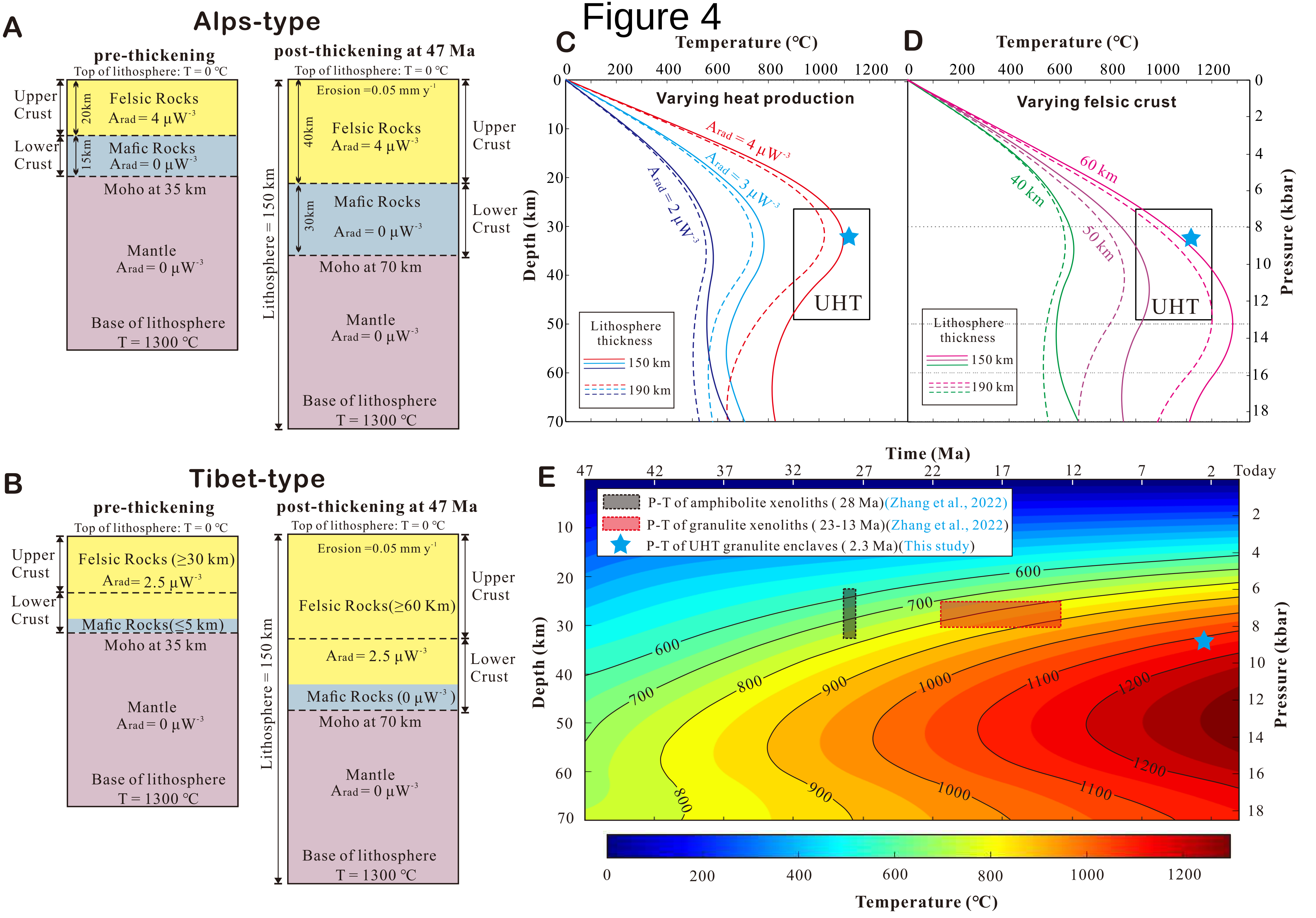
2 Sp Sa Cd Opx_{Al} Ksp Ilm L
3 Grt Cd Opx_{Al} Ksp Ilm
4 Grt Sa Sp Opx_{Al} Ksp Ilm L
5 Grt Opx_{Al} Sp Ksp Ilm L
18 $Al^{IV}(Opx_{Al}) = 0.18$
6 $X_{An}(ksp) = 0.06$
Grt Opx_{Al} Ksp Ilm L
Grt Sa Opx_{Al} Ksp Ilm L
Sa Opx_{Al} Ksp Ilm L
Grt Cd Opx_{Al} Ksp Ilm L
Cd Sa Opx Ksp Ilm L
Sa Opx_{Al} Sp Ksp Ilm L
Opx_{Al} Sp Ksp Ilm L
Opx_{Al} Sp Ilm L
Cd Opx_{Al} Ksp Ilm L
Cd Opx_{Al} Ksp Ilm
Sp Cd Opx_{Al} Ksp Ilm L
dry Solidus
Solidus
P(Gpa)
T(C°)
B
Dacite
UHT Granulite
Pl
0.5mm
C
Opx_{Al}
Ilm
Ksp
Sp
0.2mm

Figure 3



A
Marine sediments
Granulite xenoliths from Cenozoic volcanic rocks in central Tibet
NHRL
~ 2.3 Ma dacites (This study)
9-1.5 Ma peraluminous rhyolites in northern Tibet (Wang wt al. 2012)
Eocene adakites in central Tibet (Long et al., 2015)
$^{208}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
B
Geochron
EM2
EM1
marine sediments
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
C
~ 2.3 Ma dacites
5126-1
5123-2
5133
S-type granite zircons
Eocene adakites in central Tibet (lower mafic rocks melting) (Zeng et al.,2020)
Mantle zircon $\delta^{18}O$ = 5.3‰ ± 0.6‰ (Valley et al., 1998)
$\delta^{18}O$ (zircon) (‰)
ε_{Hf}(t = 2.3)
D
Global granitic crust 2.05 ± 1.07 μWm^{-3}
5.71 (n=8)
2.3 Ma UHT dacites (This study)
2.96 (n=35)
47-38 Ma adakites
2.36 (n=6)
Triassic granites
2.28 (n=9)
Permian felsic rocks
1.66 (n=13)
Devonian-Caboniferous granites
Range of values
Mean value
St.dev
Felsic rocks from northern Qiangtang
Heat production (μWm^{-3})

Figure 4


A
Alps-type
pre-thickening
Top of lithosphere: T = 0 ℃
Upper Crust
Lower Crust
20km
15km
Felsic Rocks
Arad = 4 μW-3
Mafic Rocks
Arad = 0 μW-3
Moho at 35 km
Mantle
Arad = 0 μW-3
Base of lithosphere
T = 1300 ℃
post-thickening at 47 Ma
Top of lithosphere: T = 0 ℃
Erosion =0.05 mm y-1
40km
30km
Lithosphere = 150 km
Felsic Rocks
Arad = 4 μW-3
Mafic Rocks
Arad = 0 μW-3
Upper Crust
Lower Crust
Moho at 70 km
Mantle
Arad = 0 μW-3
Base of lithosphere
T = 1300 ℃
B
Tibet-type
pre-thickening
Top of lithosphere: T = 0 ℃
Upper Crust
Lower Crust
Felsic Rocks (≥30 km)
Arad= 2.5 μW-3
Mafic Rocks(≤5 km)
Moho at 35 km
Mantle
Arad = 0 μW-3
Base of lithosphere
T = 1300 ℃
post-thickening at 47 Ma
Top of lithosphere: T = 0 ℃
Erosion =0.05 mm y-1
Felsic Rocks(≥60 Km)
Arad = 2.5 μW-3
Mafic Rocks (0 μW-3)
Upper Crust
Lower Crust
Lithosphere = 150 km
Moho at 70 km
Mantle
Arad = 0 μW-3
Base of lithosphere
T = 1300 ℃
C
Temperature (℃)
Varying heat production
Depth (km)
Arad = 4 μW-3
Arad = 3 μW-3
Arad = 2 μW-3
UHT
Lithosphere thickness
150 km
190 km
D
Temperature (℃)
Varying felsic crust
60 km
40 km
50 km
UHT
Lithosphere thickness
150 km
190 km
Pressure (kbar)
E
Time (Ma)
47 42 37 32 27 22 17 12 7 2 Today
P-T of amphibolite xenoliths (28 Ma)(Zhang et al., 2022)
P-T of granulite xenoliths (23-13 Ma)(Zhang et al., 2022)
P-T of UHT granulite enclaves (2.3 Ma)(This study)
Depth (km)
Pressure (kbar)
Temperature (℃)