# Supplementary information

## $CO_2$ emissions due to melt-carbonate interactions triggered the Miocene Climatic Optimum

Shuaiqi Liu[1, 2]; Guibin Zhang[1]*; Lifei Zhang[1]; A. Alexander G. Webb[3]; Kohen W. Bauer[4]; N. Ryan McKenzie[5]; Hongcheng Guo[6]

[1]The Key Laboratory of Orogenic Belts and Crustal Evolution, MOE, School of Earth and Space Sciences, Peking University, Beijing 100871, China

[2]Key Laboratory of Metallogenic Prediction of Nonferrous Metals and Geological Environment Monitoring, MOE, School of Geosciences and Info-Physics, Central South University, Changsha 410083, China

[3]Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

[4]Ocean Networks Canada, University of Victoria, Victoria, British Columbia, Canada.

[5]Department of Earth Sciences and Laboratory for Space Research, University of Hong Kong, Hong Kong, China

[6]Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA 1801, United States

*Corresponding author: gbzhang@pku.edu.cn

## This Supplementary Information includes:

- Supplementary text
- Supplementary Figures 1−13
- Supplementary Data 1−8

## Supplementary Text

### Geological Background

The Himalaya is divided into the Tethyan Himalayan (THS), Greater Himalayan (GHS), Lesser Himalayan (LHS), and Sub-Himalayan (SHS) sequences from north to south. These units are bounded by the South Tibetan Detachment System (STDS), Main Central Thrust (MCT), and Main Boundary Thrust (MBT), respectively (Supplementary Fig. 1a)[1]. The GHS represents the high-grade metamorphic core within these units and is sandwiched by two low−grade metamorphosed units, THS and LHS. The GHS mainly consists of upper amphibolite- to granulite-facies pelitic migmatites, orthogneisses, and calc-silicate rocks with abundant emplaced leucogranites[1].

The east Everest region in south Tibet, central Himalaya was characterized by high-pressure eclogite and overprinted UHT metamorphism (Supplementary Fig. 1b). The peak $P-T$ conditions of the eclogite were estimated at ~20 kbar and 730−770 °C; the UHT metamorphism occurs at 6−11 kbar, 900−970 °C[2]. The gneisses in this area display strong migmatization and interact with many layered leucosomes[3]. The exposed litho-tectonic units in this area include the THS, GHS, and the Ama Drime Massif (ADM)[2]. The GHS in this area is mainly composed of pelitic migmatites, granitic migmatites, and calc-silicates with minor granulitized eclogites occurring as massive lenses or dikes[2, 4]. The ADM presents as an extensional dome bounded by the Ama Drime detachment (ADD) and Nyönno Ri detachment (NRD) on its two sides[5]. Rocks in this area are mainly orthogneisses, pelitic migmatites, leucogranites, and eclogites[6]. This study focuses on a skarn-like reaction zone and marble from the Thongmön area outside of the ADM (Fig. 1a-d). The reaction zone can be subdivided into three parts (garnet−epidote−amphibole zones). The sample location is close to the granulitized eclogite where the leucosome pockets were wrapped in the eclogite lenses.

### Petrography and mineral chemistry

The reaction zone was separated into garnet, epidote, and amphibole zones (Fig. 1a-d). The garnet zones consist of quartz (40 vol.%), garnet (20 vol.%), diopside (10 vol.%), calcite (10 vol.%), zoisite (5 vol.%), anorthite (5 vol.%), and minor epidote, titanite, and Na-rich plagioclase (<5 vol.%) (Supplementary Figs 2a–c, 3a–c, and 4a–b). The garnet porphyroblasts exhibit core−rim zonation, with compositions of $Grs_{51-81}Alm_{0.1-19}Prp_{0.1-2}Sps_{0.5-2}Adr_{0-46}$ (Supplementary Fig. 11a–b). The garnet cores contain sparse inclusions of quartz, diopside, epidote, and titanite, and the rims are intergrown with zoisite, anorthite, and Na-rich plagioclase inclusions (Supplementary Figs 3a–b and 4a–b). The rare earth element (REE) patterns of the garnet cores and rims have flat heavy REE patterns [$(Dy/Yb)_N$ = 0.63−1.81] and slightly negative Eu anomalies (Eu/Eu* = 0.52−0.92) (Supplementary Fig. 11c–d). The garnet rims have higher Adr, light REE, Th, U, Zr, and Hf contents, and lower Grs, Alm, and Prp contents than the cores (Supplementary Fig. 11).

Diopside consists of two types, based on color ($Dio^{I}$ = white; $Dio^{II}$ = light green).

$Dio^{I}$ (Al = 0.004−0.06 a.p.f.u. and Ca = 1.02−1.05 a.p.f.u.) has lower Al and higher Ca contents than $Dio^{II}$ (Al = 0.08−0.19 a.p.f.u. and Ca = 0.93−1.05 a.p.f.u.) (Supplementary Data 1). The anorthite has a compositional range of $An_{97–98}Or_{2–3}$. Zoisite occurs in polymineralic inclusions with anorthite and Na-rich plagioclase in the garnet rims and has undetectable $Fe^{3+}$ (Supplementary Fig. 3a–c). Calcite in the garnet zones exhibits oscillatory zoning in cold cathodoluminescence images (Supplementary Fig. 4j–k). These calcite grains have CaO = 52.8−55.5 wt.% and $CO_2$ = 44.2−46.9 wt.%, enrichments in light REEs and depletions in heavy REEs, and $^{87}Sr/^{86}Sr$ = 0.714901−0.716807 (Supplementary Fig. 13a-d).

The epidote zones consist of quartz (40 vol.%), epidote (30 vol.%), diopside (20 vol.%), anorthite (5 vol.%), and minor titanite, Na-rich plagioclase, calcite, and magnetite (<5 vol.%) (Supplementary Figs 2d–g and 3d). Epidote is anhedral–subhedral with Ps contents [$Fe^{3+}/(Fe^{3+} + Al)$] of 0.20−0.27. Diopside (Al = 0.13−0.15 a.p.f.u. and Ca = 0.93−0.96 a.p.f.u.) in contact with epidote contains inclusions of quartz and titanite, and is surrounded by magnetite (Supplementary Fig. 2g and Data 1). Sodium-rich plagioclase has a cuspate shape, resembling a melt film (Supplementary Fig. 2k).

The amphibole zones consist of quartz (40 vol.%), anorthite (25 vol.%), amphibole (15 vol.%), Na-rich plagioclase (10 vol.%), epidote (2 vol.%), and minor K-feldspar, phlogopite, titanite, and opaque minerals (e.g., magnetite, pyrite, and chalcopyrite) (Supplementary Figs 2h–i and 4e–i). Amphibole is classified as ferroedenite and exhibits chloritization (Supplementary Data 1). Epidote occurs as anhedral crystals between anorthite and amphibole, and has Ps = 0.23−0.27. Sodium-rich plagioclase is interstitial between amphibole and anorthite (Supplementary Figs 2k, 3e−i, and 4c−d). The anorthite and K-feldspar have compositions of $An_{85–87}Ab_{13–15}$ and $Or_{94}Ab_{6}$, respectively (Supplementary Data 1). The patchy leucosome in the amphibole zones mainly consist of anorthite, Na-rich plagioclase, and quartz (Supplementary Fig. 2k).

The nearby marble occurs as meter- to decimeter-wide black veins in outcrops and consists mainly of calcite (>85 vol.%), wollastonite (~5 vol.%), graphite (~5 vol.%), and minor diopside and quartz (<5 vol.%) (Fig. 1 a-c and Supplementary Fig. 2l). The calcite comprises two types, based on grain size ($Cc^1$ = 250−500 μm and $Cc^2$ < 100 μm) (Supplementary Fig. 2l). Both types of calcite have light REE enriched patterns, positive Eu anomalies, and similar Mn–Sr contents and $^{87}Sr/^{86}Sr$ ratios (0.722788−0.724011), but the $Cc^1$ occurs as aggregates with wollastonite and has higher REE and Y contents than $Cc^2$ (Supplementary Fig. 13).

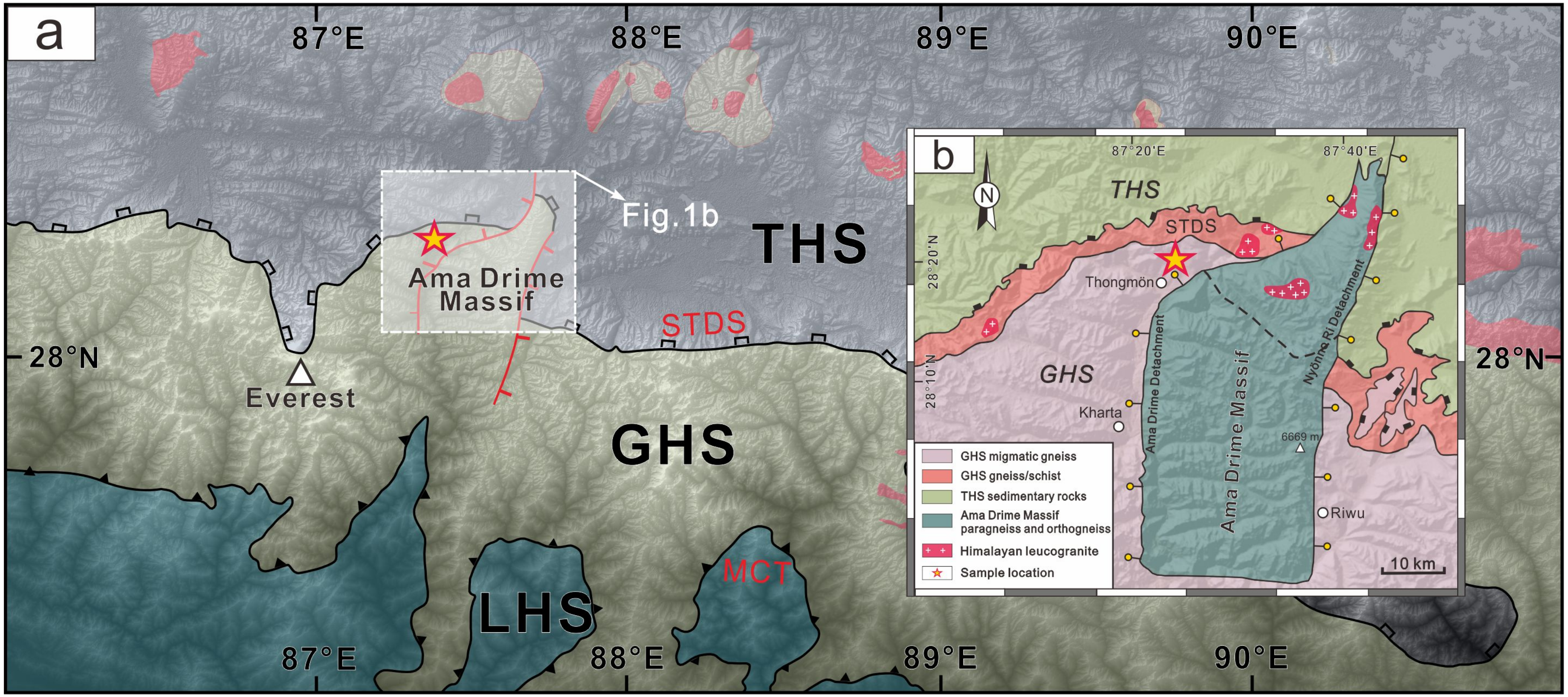
## $P-T$ estimates

To determine the crustal conditions of the reactions and $CO_2$ release, we explored the temperature and pressures at which metamorphism occurred. The temperature was estimated based on the Ti-in-zircon[7], Zr-in-titanite[8], and Ti-in-amphibole[9] thermometers. The Ti-in-zircon thermometer yielded a maximum temperature of 731°C for the garnet zones, 723°C for the amphibole selvages, and 685°C for the epidote selvages (Supplementary Fig. 10a). Titanite from the amphibole selvages has Zr =

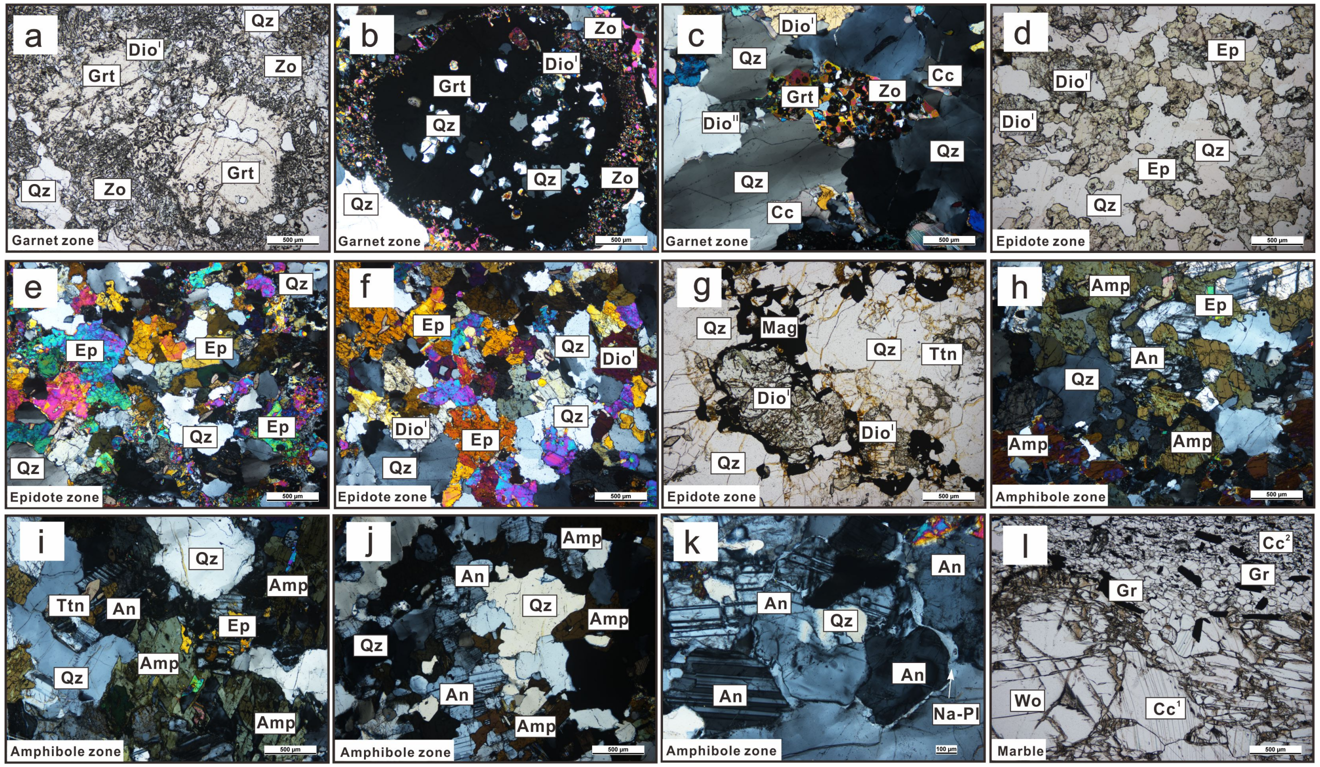
210−695 μg/g and yielded a temperature range of 726−793°C. The Ti-in-amphibole thermometer yielded a temperature range of 753−828°C (Supplementary Fig. 10a). These thermometers yielded a temperature range of 685−828°C (Supplementary Fig. 10a).

The near-monomineralic mineral assemblages made it difficult to estimate the pressure. We evaluated the pressure based on Al coordination in clinopyroxene, as high $Al^{VI}$ contents are favored in a low-temperature and high-pressure environment[10]. To test this method, omphacite and clinopyroxene inclusions in garnet and clinopyroxene symplectites from a central Himalayan eclogite[4], and diopside in magmatic skarns[11] were also examined. Omphacite is stable above 15 kbar and is characterized by the highest $Al^{VI}$ contents[4]. The Cpx symplectites have intermediate $Al^{VI}$ contents and were formed at 1.2−1.4 GPa. The diopside in the skarns has low $Al^{VI}$ contents and was formed at <100 MPa and ~850°C[11]. Diopside from the garnet zones has slightly higher $Al^{VI}$ contents than the Cpx symplectites, indicating it was formed at 1.2−1.4 GPa (Supplementary Fig. 10b). As such, the melt−carbonate interactions occurred under *P*–*T* conditions of 1.2−1.4 GPa and 685−828°C.

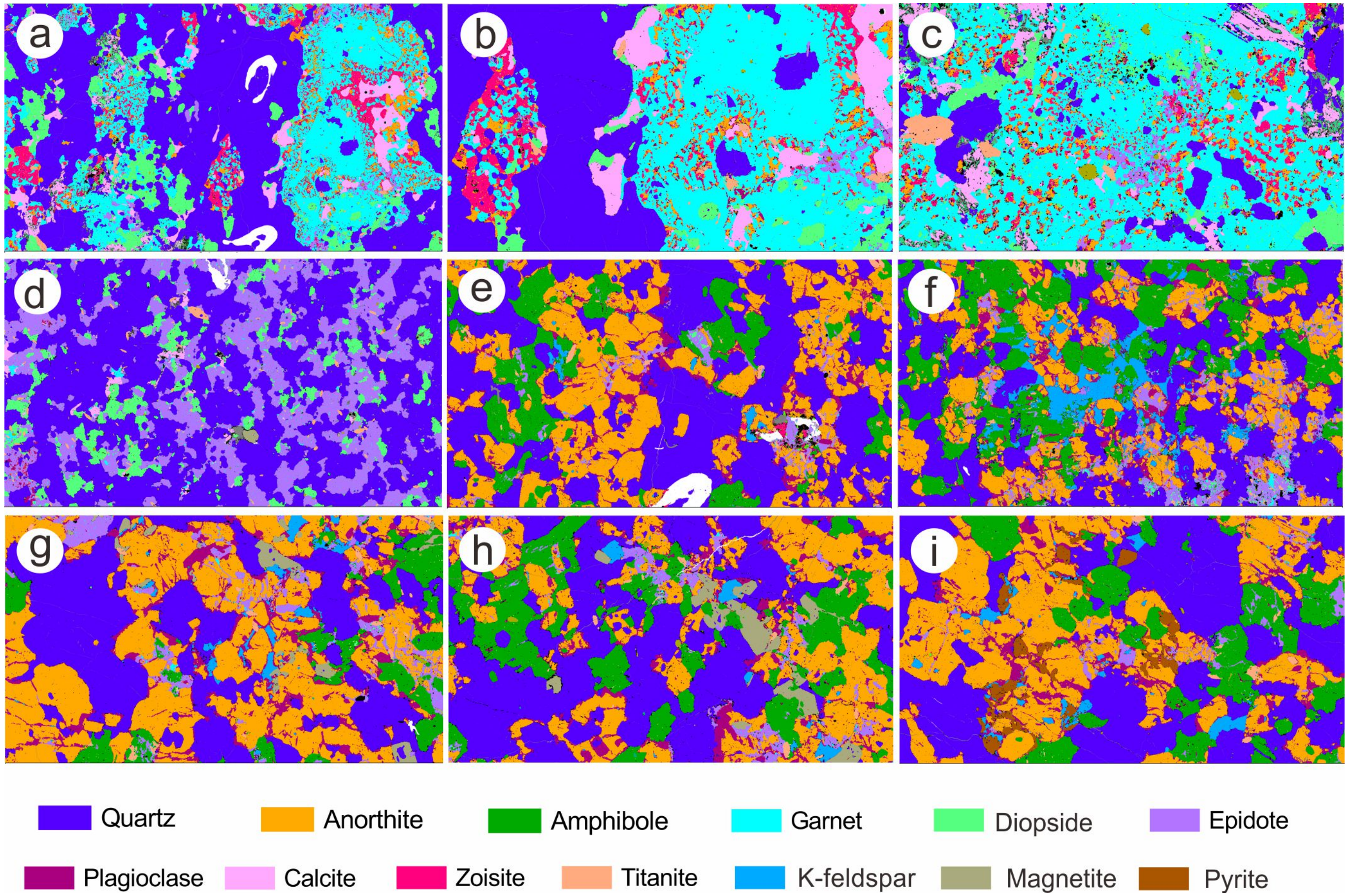
## Supplementary Figures



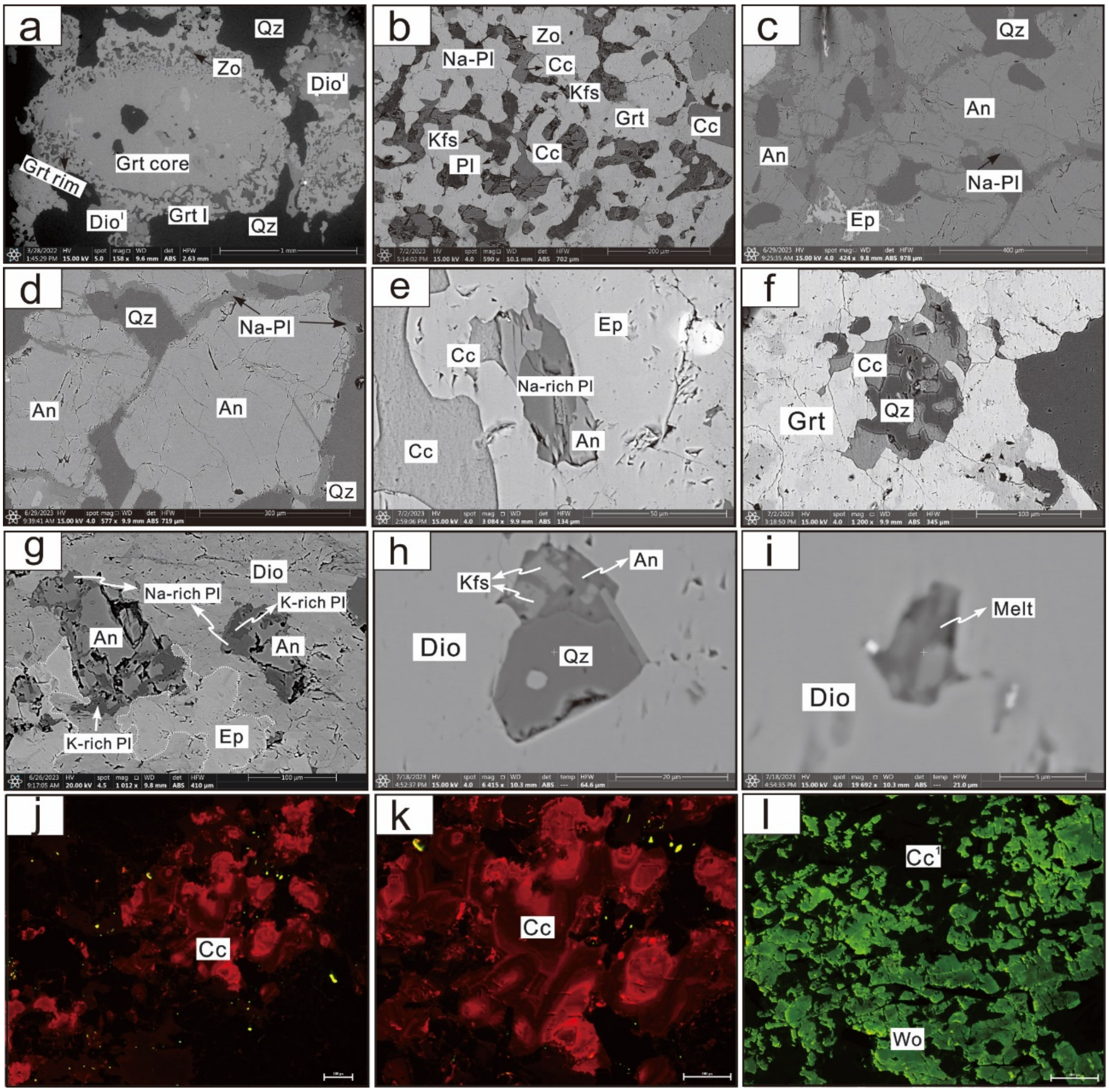

**Supplementary Figure 1 a.** Geological sketch map of the Himalayan orogen (modified from ref[12]); **b.** Simplified geological map of the Ama Drime Massif in the east Everest area (modified from ref[2]).



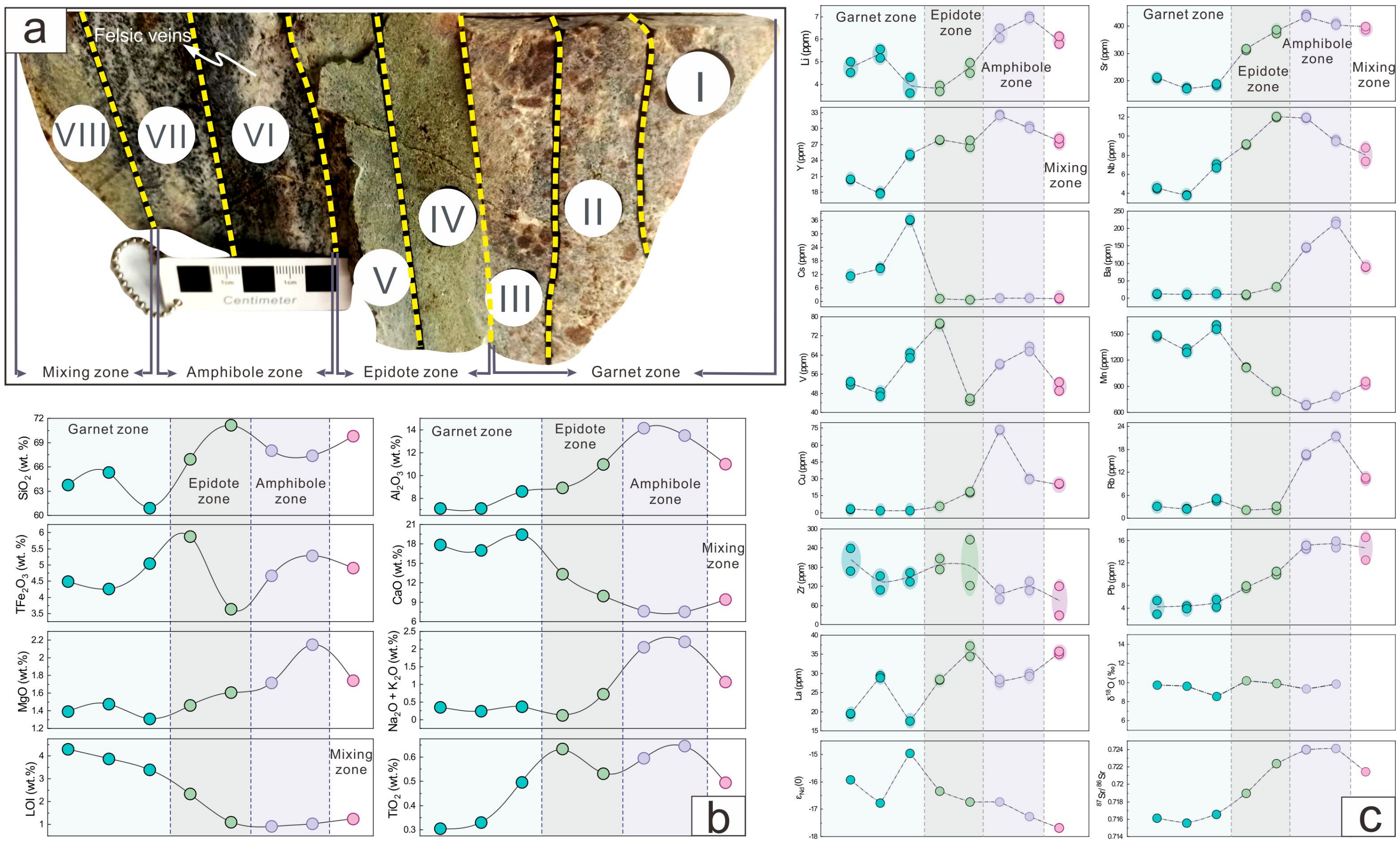

**Supplementary Figure 2** Photomicrographs of the reaction zones from melt−carbonate interaction from the Ama Drime Massif, central Himalaya. **a-b.** Garnets display obvious core−rim zonation in the garnet zones, the garnet cores are clean with large quartz, and diopside inclusions while the rims are intertwined with abundant irregular zoisite and anorthite inclusions; **c.** Aggregates of garnet and zoisite from the garnet zones; **d-f.** Mineral assemblages of the epidote zones, consisting of epidote, diopside, and quartz; **g.** Magnetite occurs as coronas along the boundary of diopside; **h-i.** The amphibole zones consisting of amphibole, plagioclase, quartz, and minor epidote; **j.** The felsic leucosomes in the amphibole zones, mainly consisting of plagioclase, quartz, and minor amphibole; **k.** The Na-rich plagioclase occurs as cuspate shapes along the boundary of the anorthite; **l.** The mineral assemblages of the marble, mainly consisting of calcite, wollastonite, and graphite, two types of calcite grains were recognized and the type I ($Cc^1$) has larger grain sizes than the type II ($Cc^2$).



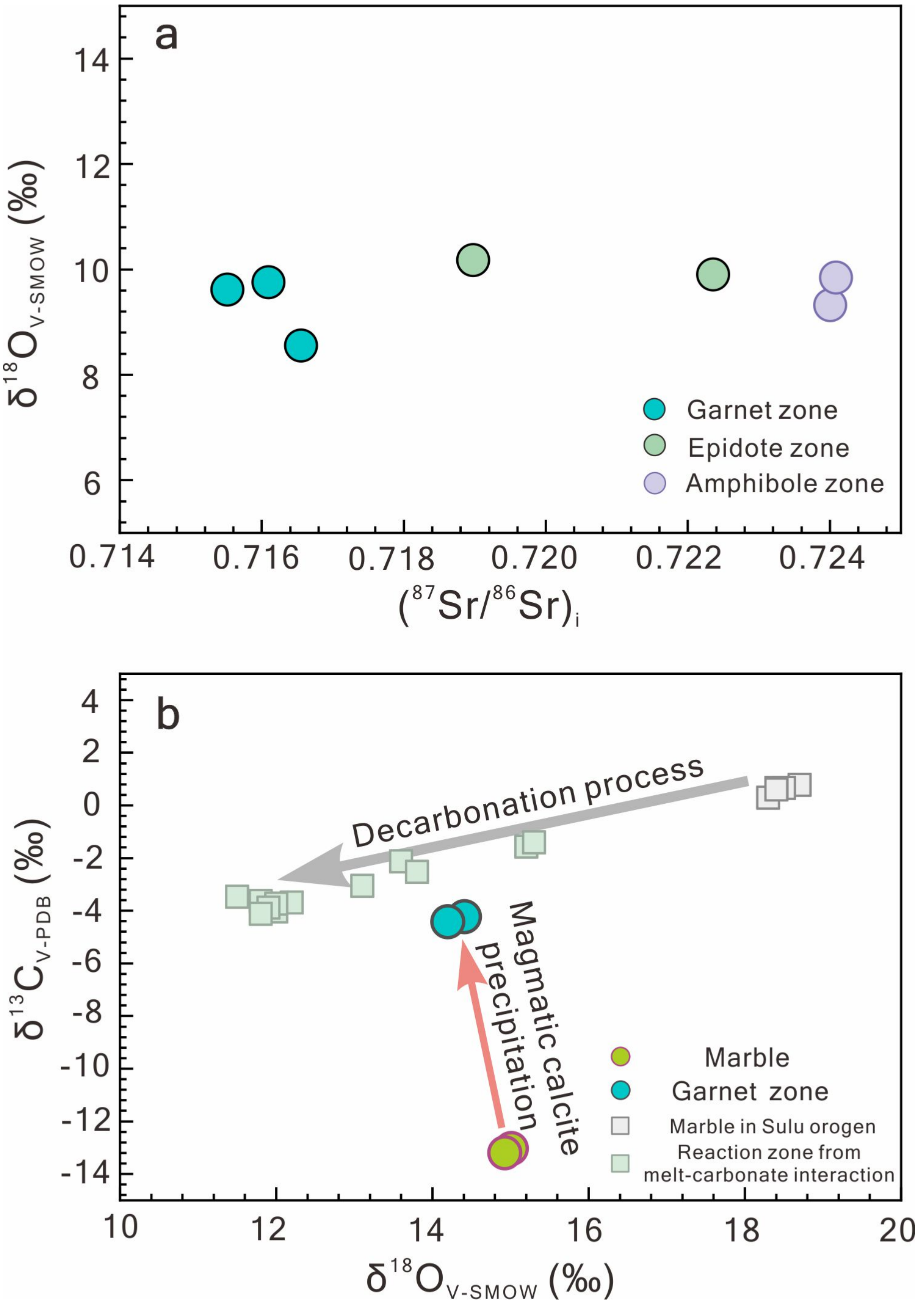

**Supplementary Figure 3** TIMA phase mapping of the thin sections showing the texture and mineral assemblages. **a-c.** Garnet zones; **d.** Epidote zones; **e-i.** Amphibole zones.



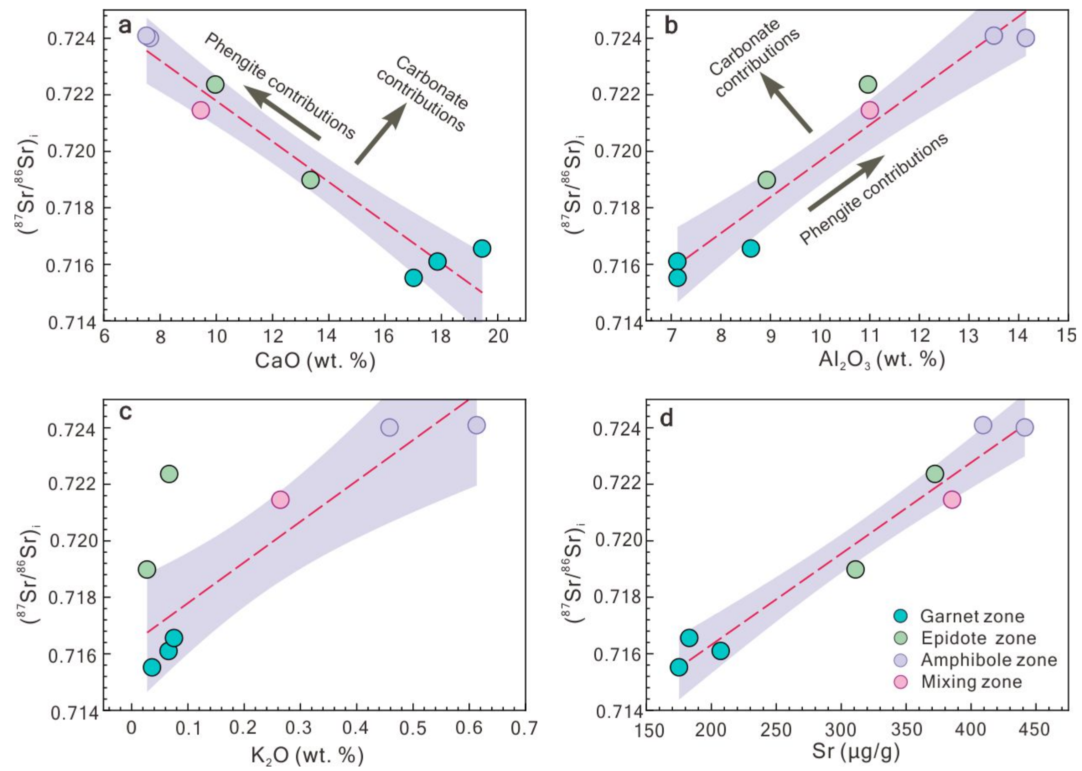

**Supplementary Figure 4** Back-scattered images and cold cathodoluminescence images of the reaction zones and marble. **a.** Garnet showing core-rim zonations in the garnet zones, the garnet cores are clean with Qz, Dio, and Ttn inclusions while the garnet rims are filled with Zo and An inclusions; **b.** Multi-phase inclusions (MIs) in the garnet rims; **c-d.** Na-rich plagioclase occurs as cuspate shape or veinlets along the boundary of the anorthite in the amphibole zones; **e.** MIs in epidote consisting mainly of Cc−Na-rich Pl−An; **f.** Cc−Qz inclusions in garnet; **g.** MIs in diopside consisting of An−Na-rich Pl−K-rich Pl; **h-i.** MIs (Kfs−Qz−An) and melt inclusions in diopside; **j-k.** Cold cathodoluminescence images of calcite showing red oscillatory zoning in the garnet zones; **l.** Wollastonite and calcite grains under cold cathodoluminescence from the marble.



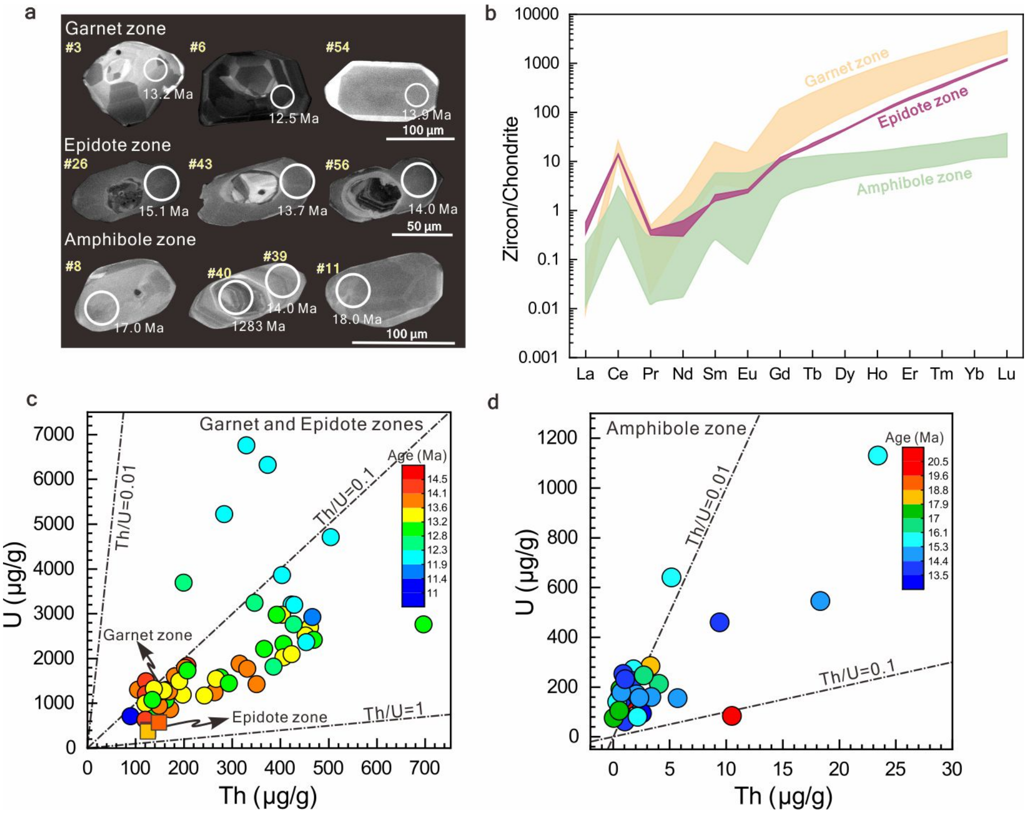

**Supplementary Figure 5** A melt−marble reaction profile and geochemical variations along the profile. **a.** The hand specimen of the reaction zones from melt−carbonate interaction, the reaction zone can be separated into the amphibole, epidote, and garnet zones, centimeter felsic veins occur in the amphibole zone; **b.** The major elemental profiles along the reaction zone; **c.** Trace elemental and isotopic compositional profiles along the reaction zone.



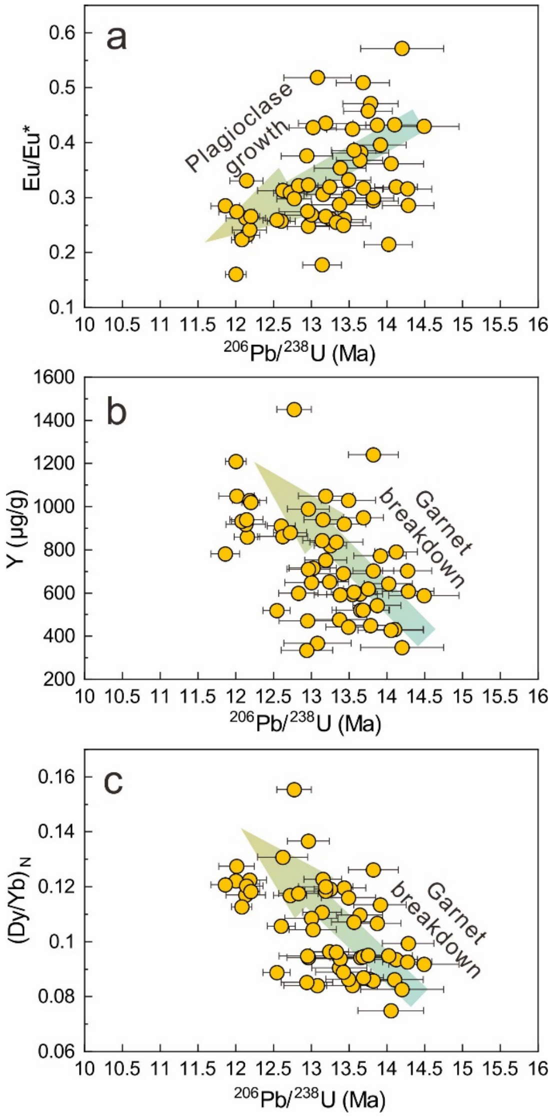

**Supplementary Figure 6** The Sr−O−C isotopic compositions of the calc-silicate zones and marble. **a.** Plot of $(^{87}Sr/^{86}Sr)_i$ versus $\delta^{18}O_{V\text{-}SMOW}$ (‰) for the reaction zones; **b.** Carbonate C−O isotopic compositions from the garnet zones and marble, C−O isotopic data of the marble, calc-silicates, and calcite-bearing leucosome from the Sulu orogen[13] are plotted for comparison.



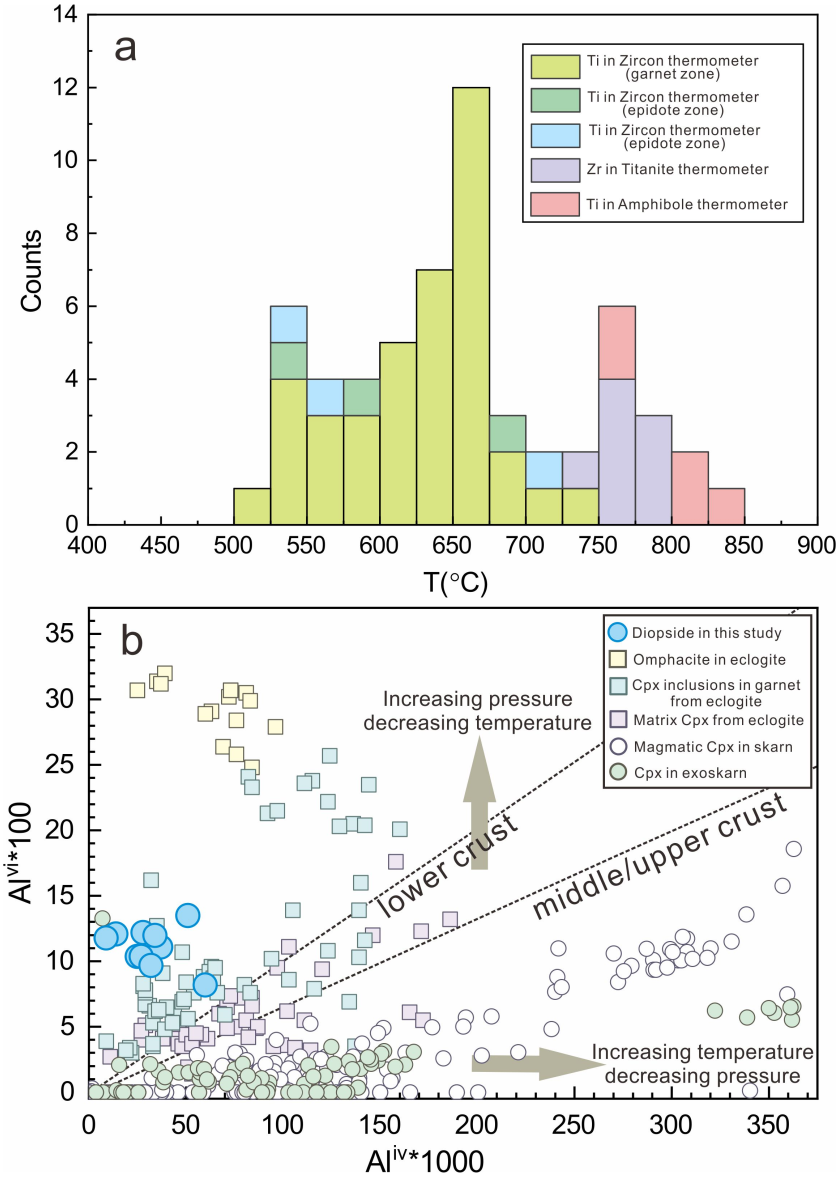

**Supplementary Figure 7** Plots of whole-rock ($^{87}$Sr/$^{86}$Sr)$_i$ versus **a.** CaO; **b.** $Al_2O_3$; **c.** $K_2O$; and **d.** Sr contents for the reaction zones.



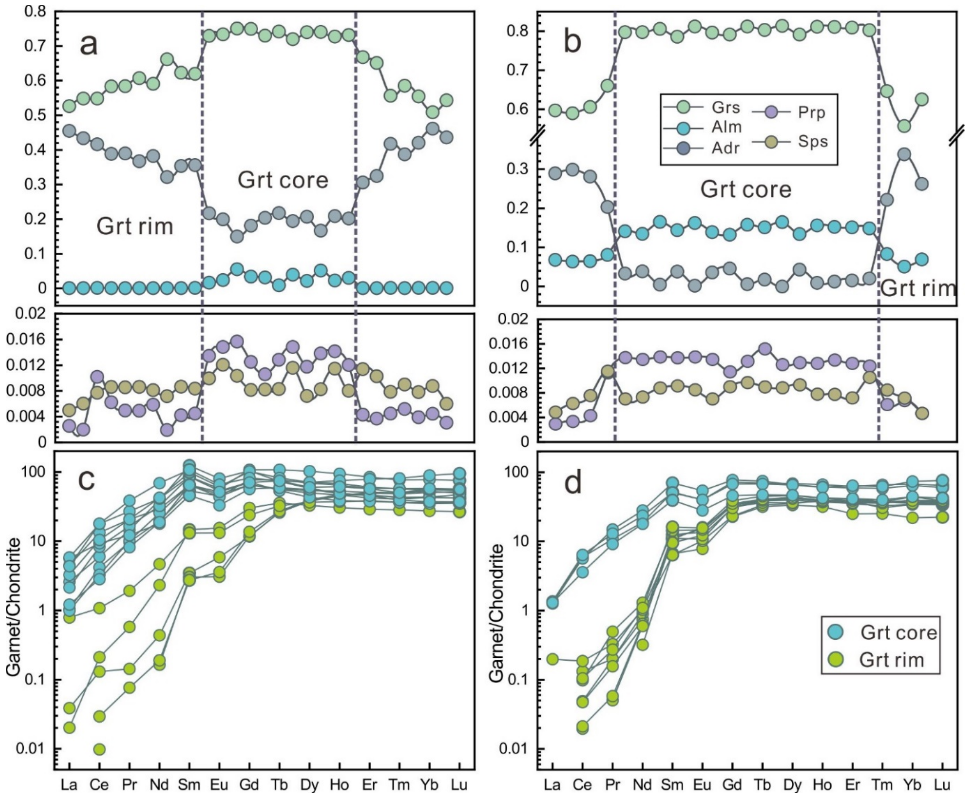

**Supplementary Figure 8** Timing of melt−carbonate interaction from zircon U−Pb dating in different calc-silicate reaction zones. **a.** Cathodoluminescence images of the zircons; **b.** Chondrite-normalized REE patterns of the zircons; **c–d.** Zircon ages and Th, U contents. Ages in garnet zone cluster at 14.5−11.9 Ma, 15.1−13.7 Ma for the epidote zone, and 20.3−13.2 Ma for the amphibole zone.



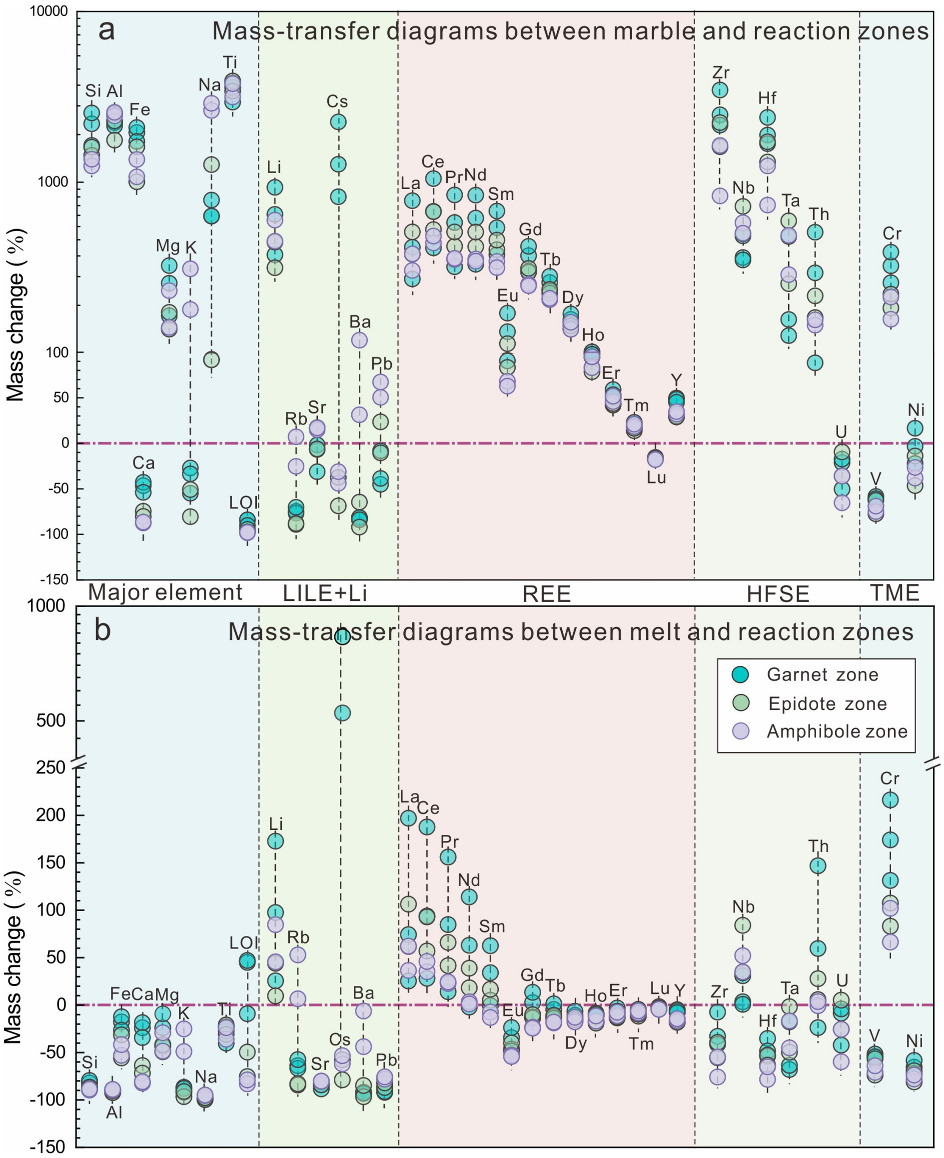

**Supplementary Figure 9** Diagrams of Eu/Eu*, Y, and $(Dy/Yb)_N$ versus ages **(a−c)** of zircons from the garnet zones.



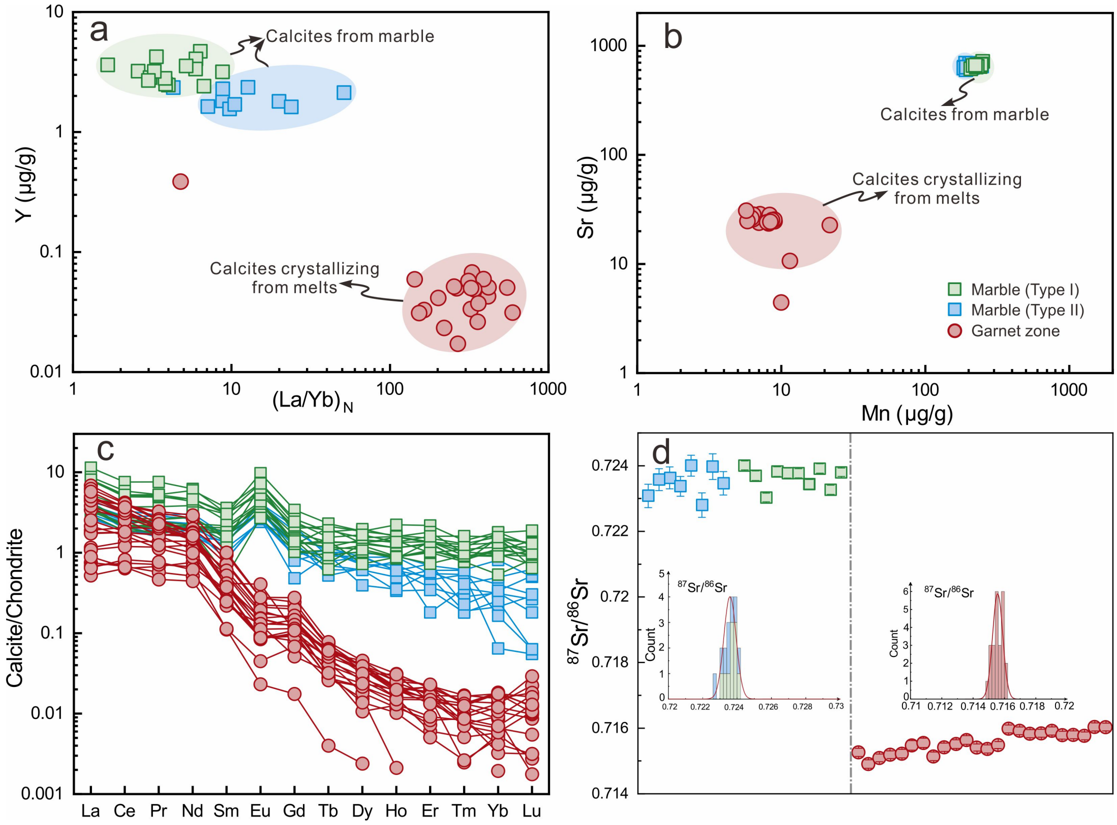

**Supplementary Figure 10** Pressure and temperature conditions for melt−marble interaction. **a.** The temperature of melt−carbonate interaction calculated from different thermometers; **b.** Plot of $Al^{iv}$ * 1000 vs $Al^{vi}$ * 100 for diopside from reaction zones, Omphacite, clinopyroxene inclusions in garnet, and clinopyroxene symplecitite from the eclogite[2] and clinopyroxene from the magmatic skarns[11] are plotted for comparison.




**Supplementary Figure 11** Garnet major-element profiles (**a−b**) and chondrite-normalized REE patterns **(c−d)** from the garnet zones.




**Supplementary Figure 12** Mass-transfer diagram during melt–carbonate interaction. **a.** The mass losses and gains of different groups of elements for the reaction zones relative to the composition of the marble; **b.** The mass losses and gains of different groups of elements for the reaction zones relative to the composition of the eclogite-derived partial melts; Ytterbium (Yb) was chosen as the most immobile element. A positive deviation from the 0 % reference line indicates mass gain of a certain element, whereas a negative deviation indicates the mass loss.




**Supplementary Figure 13** Calcite geochemistry from the marble and garnet zones. **a.** Plot of $(La/Yb)_N$ vs. Y; **b.** Plot of Mn vs. Sr; **c**. Chondrite-normalized REE patterns for calcite; **d.** The strontium isotopic variations of calcite from the garnet zones and marble.

## References


1. Yin, A. Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. *Earth-Sci. Rev.* **79**, 163-164 (2006).
2. Wang, J. M. *et al.* First evidence of eclogites overprinted by ultrahigh temperature metamorphism in Everest East, Himalaya: Implications for collisional tectonics on early Earth. *Earth Planet. Sci. Lett.* **558**, (2021).
3. Li, Q. *et al.* Metamorphic PT path, U-Pb zircon dating and tectonic implications of High-pressure Pelitic Granulites from the Kharta region, Southern Tibet, China. *Gondwana Res.* **104**, 23-38 (2022).
4. Li, Q. *et al.* Petrology and zircon U–Pb dating of well-preserved eclogites from the Thongmön area in central Himalaya and their tectonic implications. *J. Metamorph. Geol.* **37**, 203-226 (2019).
5. Jessup, M. J. *et al.* Orogen-parallel extension and exhumation enhanced by denudation in the trans-Himalayan Arun River gorge, Ama Drime Massif, Tibet-Nepal. *Geology* **36**, 587-590 (2008).
6. Cottle, J. M. *et al.* Geochronology of granulitized eclogite from the Ama Drime Massif: Implications for the tectonic evolution of the South Tibetan Himalaya. *Tectonics* **28**, (2009).
7. Ferry, J. M. & Watson, E. B. New thermodynamic models and revised calibrations for the Ti-in-zircon and Zr-in-rutile thermometers. *Contrib. Mineral. Petrol.* **154**, 429-437 (2007).
8. Hayden, L. A. *et al.* A thermobarometer for sphene (titanite). *Contrib. Mineral. Petrol.* **155**, 529-540 (2008).
9. Liao, Y. *et al.* Titanium in calcium amphibole: Behavior and thermometry. *Am. Miner.* **106**, 180-191 (2021).
10. Yarger, J. L. *et al.* Al coordination changes in high-pressure aluminosilicate liquids. *Science* **270**, 1964-1967 (1995).
11. Whitley, S. *et al.* Magmatic and Metasomatic Effects of Magma–Carbonate Interaction Recorded in Calc-silicate Xenoliths from Merapi Volcano (Indonesia). *J. Petrol.* **61**, (2020).
12. Wu, C. G. *et al.* Tectonothermal transition from continental collision to post-collision: Insights from eclogites overprinted in the ultrahigh-temperature granulite facies (Yadong region, central Himalaya). *J. Metamorph. Geol.* **40**, 955-981 (2022).
13. Guo, S. *et al.* Formation of carbon-bearing silicate melts by melt-metacarbonate interaction at convergent plate margins. *Earth Planet. Sci. Lett.* **597**, 117816 (2022).

**Supplementary Data 1** Mineral major compositions of the studied calc-silicate zones.

| Mineral | Garnet zones | | | | | | Garnet zones | | | | | | Garnet zones | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Grt rim | | | Grt core | | | Grt rim | | | Grt core | | | Dio I | | |
| | Max | Min | Average | Max | Min | Average | Max | Min | Average | Max | Min | Average | Max | Min | Average |
| $SiO_2$ | 38.9 | 37.2 | 38.3 | 39.7 | 37.6 | 38.7 | 40.8 | 39.3 | 40.2 | 41.7 | 40.5 | 41.0 | 54.3 | 50.1 | 52.4 |
| $TiO_2$ | 0.56 | 0.35 | 0.43 | 0.45 | 0.25 | 0.36 | 0.57 | 0.40 | 0.48 | 0.50 | 0.23 | 0.37 | 0.15 | 0.00 | 0.07 |
| $Al_2O_3$ | 15.7 | 11.6 | 13.5 | 20.0 | 16.7 | 19.0 | 13.7 | 11.6 | 12.6 | 18.7 | 17.9 | 18.4 | 4.28 | 1.74 | 2.97 |
| $Fe_2O_3$ | 16.4 | 11.3 | 14.1 | 9.09 | 6.05 | 7.92 | 11.0 | 6.67 | 8.73 | 1.69 | 0.00 | 0.78 | 6.12 | 0.00 | 0.93 |
| FeO | 0.15 | 0.10 | 0.13 | 3.20 | 0.57 | 1.82 | 5.46 | 3.87 | 4.76 | 8.22 | 6.82 | 7.54 | 11.7 | 5.93 | 10.2 |
| MnO | 0.78 | 0.44 | 0.63 | 0.69 | 0.42 | 0.55 | 0.73 | 0.32 | 0.49 | 0.53 | 0.35 | 0.42 | 0.56 | 0.27 | 0.37 |
| MgO | 0.47 | 0.08 | 0.20 | 0.50 | 0.36 | 0.44 | 0.41 | 0.12 | 0.22 | 0.43 | 0.33 | 0.38 | 11.6 | 9.02 | 9.72 |
| CaO | 37.1 | 35.4 | 35.9 | 34.6 | 32.9 | 33.8 | 33.7 | 33.0 | 33.3 | 32.3 | 31.3 | 31.7 | 25.9 | 23.8 | 24.4 |
| $Na_2O$ | 0.05 | 0.00 | 0.02 | 0.05 | 0.00 | 0.03 | 0.03 | 0.00 | 0.01 | 0.04 | 0.00 | 0.01 | 0.20 | 0.10 | 0.15 |
| $K_2O$ | 0.03 | 0.00 | 0.01 | 0.03 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Totals | 104.1 | 102.0 | 103.2 | 103.2 | 99.6 | 101.9 | 100.5 | 99.1 | 99.9 | 101.3 | 100.0 | 100.6 | 102.9 | 99.3 | 101.2 |
| Oxygens | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 6 | 6 | 6 |
| Si | 2.98 | 2.90 | 2.94 | 3.01 | 2.85 | 2.91 | 3.16 | 3.10 | 3.14 | 3.16 | 3.10 | 3.13 | 2.01 | 1.88 | 1.95 |
| Ti | 0.03 | 0.02 | 0.02 | 0.03 | 0.01 | 0.02 | 0.03 | 0.02 | 0.03 | 0.03 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 |
| Al | 1.40 | 1.06 | 1.22 | 1.79 | 1.52 | 1.69 | 1.25 | 1.08 | 1.16 | 1.68 | 1.60 | 1.65 | 0.19 | 0.08 | 0.13 |
| $Fe^{3+}$ | 0.96 | 0.64 | 0.81 | 0.52 | 0.34 | 0.45 | 0.66 | 0.39 | 0.51 | 0.10 | 0.00 | 0.04 | 0.17 | 0.00 | 0.03 |
| $Fe^{2+}$ | 0.01 | 0.01 | 0.01 | 0.20 | 0.04 | 0.11 | 0.35 | 0.26 | 0.31 | 0.53 | 0.44 | 0.48 | 0.37 | 0.18 | 0.32 |
| Mn | 0.05 | 0.03 | 0.04 | 0.04 | 0.03 | 0.03 | 0.05 | 0.02 | 0.03 | 0.03 | 0.02 | 0.03 | 0.02 | 0.01 | 0.01 |
| Mg | 0.05 | 0.01 | 0.02 | 0.06 | 0.04 | 0.05 | 0.05 | 0.01 | 0.03 | 0.05 | 0.04 | 0.04 | 0.63 | 0.51 | 0.54 |
| Ca | 3.04 | 2.89 | 2.95 | 2.83 | 2.67 | 2.73 | 2.82 | 2.75 | 2.79 | 2.63 | 2.56 | 2.59 | 1.05 | 0.95 | 0.98 |
| Na | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| K | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sum | 8.06 | 8.00 | 8.02 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 4.00 | 3.95 | 3.97 |
| Prp | 0.01 | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.02 | 0.01 | 0.01 | | | |
| Grs | 0.67 | 0.51 | 0.59 | 0.75 | 0.72 | 0.74 | 0.66 | 0.56 | 0.61 | 0.81 | 0.79 | 0.80 | | | |
| Alm | 0.00 | 0.00 | 0.00 | 0.06 | 0.01 | 0.03 | 0.08 | 0.05 | 0.07 | 0.17 | 0.13 | 0.15 | | | |
| Sps | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | | | |
| Adr | 0.46 | 0.31 | 0.39 | 0.22 | 0.15 | 0.20 | 0.34 | 0.20 | 0.27 | 0.05 | 0.00 | 0.02 | | | |

| Mineral | Garnet zones | | | Garnet zones | | | Garnet zones | | | Garnet zones | | | Epidote zones | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dio II | | | Zo | | | An | | | Cc | | | Dio I | | |
| | Max | Min | Average | Max | Min | Average | Max | Min | Average | Max | Min | Average | Max | Min | Average |
| $SiO_2$ | 55.6 | 52.0 | 54.1 | 45.9 | 43.4 | 45.0 | 44.4 | 44.1 | 44.2 | 0.03 | 0.00 | 0.01 | 53.6 | 52.1 | 52.8 |
| $TiO_2$ | 0.04 | 0.00 | 0.01 | 0.06 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.07 | 0.00 | 0.01 | 0.14 | 0.02 | 0.07 |
| $Al_2O_3$ | 1.44 | 0.09 | 0.40 | 29.5 | 24.8 | 27.7 | 36.4 | 35.9 | 36.1 | 0.02 | 0.00 | 0.01 | 3.33 | 2.92 | 3.11 |
| $Fe_2O_3$ | 3.74 | 1.04 | 2.43 | 0.11 | 0.00 | 0.01 | 0.49 | 0.32 | 0.42 | | | | 0.00 | 0.00 | 0.00 |
| FeO | 9.81 | 3.43 | 6.29 | 0.39 | 0.09 | 0.19 | 0.00 | 0.00 | 0.00 | 0.07 | 0.02 | 0.04 | 12.0 | 11.8 | 11.9 |
| MnO | 0.65 | 0.20 | 0.44 | 0.03 | 0.00 | 0.01 | 0.02 | 0.00 | 0.01 | 0.06 | 0.02 | 0.04 | 0.51 | 0.49 | 0.50 |
| MgO | 15.6 | 9.97 | 13.1 | 0.08 | 0.00 | 0.04 | 0.02 | 0.00 | 0.01 | 0.05 | 0.01 | 0.03 | 9.36 | 8.87 | 9.04 |
| CaO | 27.2 | 26.1 | 26.7 | 22.6 | 19.2 | 20.2 | 21.3 | 21.2 | 21.2 | 55.5 | 52.8 | 54.8 | 23.7 | 23.5 | 23.6 |
| $Na_2O$ | 0.14 | 0.05 | 0.09 | 2.33 | 1.55 | 1.98 | 0.28 | 0.25 | 0.27 | 0.02 | 0.00 | 0.01 | 0.16 | 0.13 | 0.15 |
| $K_2O$ | 0.04 | 0.00 | 0.01 | 0.19 | 0.09 | 0.14 | 0.04 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 |
| Totals | 104.2 | 102.1 | 103.3 | 97.7 | 91.4 | 95.2 | 102.4 | 102.3 | 102.3 | 55.8 | 53.1 | 54.9 | 101.9 | 100.6 | 101.2 |
| Oxygens | 6 | 6 | 6 | 12.5 | 12.5 | 12.5 | 8 | 8 | 8 | | | | 6 | 6 | 6 |
| Si | 1.98 | 1.92 | 1.96 | 3.56 | 3.29 | 3.45 | 2.02 | 2.00 | 2.01 | | | | 1.99 | 1.96 | 1.97 |
| Ti | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | | | | 0.00 | 0.00 | 0.00 |
| Al | 0.06 | 0.00 | 0.02 | 2.63 | 2.34 | 2.51 | 1.95 | 1.93 | 1.94 | | | | 0.15 | 0.13 | 0.14 |
| $Fe^{3+}$ | 0.10 | 0.03 | 0.07 | 0.01 | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | | | | 0.00 | 0.00 | 0.00 |
| $Fe^{2+}$ | 0.30 | 0.10 | 0.19 | 0.03 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | | | | 0.37 | 0.37 | 0.37 |
| Mn | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | | | | 0.02 | 0.02 | 0.02 |
| Mg | 0.83 | 0.55 | 0.71 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | | | | 0.52 | 0.49 | 0.50 |
| Ca | 1.05 | 1.02 | 1.04 | 1.83 | 1.58 | 1.66 | 1.04 | 1.03 | 1.03 | | | | 0.96 | 0.93 | 0.94 |
| Na | 0.01 | 0.00 | 0.01 | 0.34 | 0.23 | 0.29 | 0.03 | 0.02 | 0.02 | | | | 0.01 | 0.01 | 0.01 |
| K | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | | | | 0.00 | 0.00 | 0.00 |
| Sum | 4.00 | 4.00 | 4.00 | 8.02 | 7.91 | 7.95 | 5.03 | 5.02 | 5.02 | | | | 3.97 | 3.95 | 3.96 |
| An | | | | | | | 0.98 | 0.98 | 0.98 | | | | | | |
| Ab | | | | | | | 0.02 | 0.12 | 0.14 | | | | | | |
| Or | | | | | | | 0.00 | 0.00 | 0.00 | | | | | | |

| Mineral | Epidote zones | | | | Amphibole zones | | | Amphibole zones | | Amphibole zones | | | Amphibole zones | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ep | | | | Amp | | | Ep | | An | | | Kfs | | |
| | Average | Max | Min | Average | Max | Min | Average | Max | Min | Max | Min | Average | Max | Min | Average |
| $SiO_2$ | 40.2 | 41.3 | 39.5 | 40.1 | 44.8 | 42.7 | 43.8 | 40.4 | 40.0 | 49.1 | 48.7 | 48.9 | 66.9 | 64.8 | 65.9 |
| $TiO_2$ | 0.15 | 0.12 | 0.00 | 0.05 | 1.95 | 1.33 | 1.62 | 0.16 | 0.14 | 0.03 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 |
| $Al_2O_3$ | 22.4 | 24.1 | 22.3 | 22.8 | 11.3 | 9.86 | 10.7 | 22.5 | 22.4 | 32.1 | 31.7 | 31.9 | 17.1 | 15.8 | 16.4 |
| $Fe_2O_3$ | 11.8 | 13.0 | 8.66 | 10.6 | 0.73 | 0.00 | 0.30 | 13.1 | 10.4 | 0.43 | 0.29 | 0.36 | 2.16 | 0.04 | 1.10 |
| FeO | 0.86 | 2.74 | 0.12 | 1.29 | 17.9 | 17.4 | 17.7 | 1.58 | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| MnO | 0.21 | 0.19 | 0.01 | 0.11 | 0.47 | 0.40 | 0.42 | 0.21 | 0.20 | 0.02 | 0.00 | 0.01 | 0.03 | 0.01 | 0.02 |
| MgO | 0.04 | 0.05 | 0.02 | 0.03 | 8.75 | 8.18 | 8.51 | 0.04 | 0.03 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| CaO | 22.6 | 23.1 | 22.9 | 23.0 | 11.4 | 11.2 | 11.4 | 22.7 | 22.5 | 16.9 | 16.8 | 16.9 | 0.02 | 0.00 | 0.01 |
| $Na_2O$ | 0.03 | 0.02 | 0.00 | 0.01 | 1.35 | 1.11 | 1.23 | 0.05 | 0.01 | 1.56 | 1.31 | 1.44 | 0.59 | 0.59 | 0.59 |
| $K_2O$ | 0.01 | 0.01 | 0.00 | 0.00 | 1.73 | 1.41 | 1.61 | 0.01 | 0.00 | 0.06 | 0.04 | 0.05 | 14.80 | 14.20 | 14.50 |
| Totals | 97.1 | 98.7 | 96.6 | 97.2 | 98.3 | 96.5 | 97.2 | 97.2 | 97.0 | 99.7 | 99.5 | 99.6 | 98.9 | 98.2 | 98.6 |
| Oxygens | 12.5 | 12.5 | 12.5 | 12.5 | 23 | 23 | 23 | 12.5 | 12.5 | 8 | 8 | 8 | 8 | 8 | 8 |
| Si | 3.17 | 3.24 | 3.13 | 3.16 | 6.79 | 6.53 | 6.64 | 3.19 | 3.15 | 2.25 | 2.24 | 2.25 | 3.12 | 3.01 | 3.06 |
| Ti | 0.01 | 0.01 | 0.00 | 0.00 | 0.22 | 0.15 | 0.19 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Al | 2.08 | 2.23 | 2.07 | 2.12 | 2.02 | 1.76 | 1.92 | 2.09 | 2.07 | 1.74 | 1.71 | 1.73 | 0.94 | 0.87 | 0.90 |
| $Fe^{3+}$ | 0.70 | 0.77 | 0.51 | 0.63 | 0.08 | 0.00 | 0.04 | 0.77 | 0.62 | 0.02 | 0.01 | 0.01 | 0.08 | 0.00 | 0.04 |
| $Fe^{2+}$ | 0.06 | 0.18 | 0.01 | 0.08 | 2.27 | 2.22 | 2.24 | 0.10 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mn | 0.01 | 0.01 | 0.00 | 0.01 | 0.06 | 0.05 | 0.05 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mg | 0.00 | 0.01 | 0.00 | 0.00 | 1.97 | 1.87 | 1.93 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ca | 1.91 | 1.95 | 1.92 | 1.94 | 1.86 | 1.84 | 1.85 | 1.92 | 1.90 | 0.84 | 0.83 | 0.83 | 0.00 | 0.00 | 0.00 |
| Na | 0.00 | 0.00 | 0.00 | 0.00 | 0.40 | 0.33 | 0.36 | 0.01 | 0.00 | 0.14 | 0.12 | 0.13 | 0.05 | 0.05 | 0.05 |
| K | 0.00 | 0.00 | 0.00 | 0.00 | 0.34 | 0.27 | 0.31 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.88 | 0.84 | 0.86 |
| Sum | 7.94 | 7.97 | 7.93 | 7.96 | 15.61 | 15.48 | 15.54 | 7.95 | 7.93 | 4.95 | 4.95 | 4.95 | 4.93 | 4.92 | 4.92 |
| An | | | | | | | | | | 0.87 | 0.85 | 0.00 | 0.00 | 0.98 | 0.98 |
| Ab | | | | | | | | | | 0.14 | 0.14 | 0.06 | 0.06 | 0.02 | 0.12 |
| Or | | | | | | | | | | 0.94 | 0.94 | 0.94 | 0.94 | 0.00 | 0.00 |

**Supplementary Data 2** Mineral trace element compositions of the studied calc-silicate zones.

| Mineral | Garnet zones | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Grt rim | | | Grt core | | | Grt rim | | | Grt core | | |
| | Max | Min | Average | Max | Min | Average | Max | Min | Average | Max | Min | Average |
| Ti | 2790 | 1590 | 2323 | 2150 | 1860 | 1992 | 2810 | 1770 | 2395 | 2290 | 1810 | 2067 |
| Mn | 5950 | 3810 | 4743 | 6060 | 4610 | 5418 | 5900 | 3030 | 4426 | 5790 | 4160 | 4704 |
| Rb | 54.7 | 0.10 | 11.6 | 3.90 | 0.04 | 1.97 | 0.39 | 0.00 | 0.15 | 0.28 | 0.00 | 0.04 |
| Sr | 96.0 | 0.47 | 23.8 | 24.4 | 0.00 | 5.37 | 86.0 | 0.42 | 25.7 | 0.25 | 0.00 | 0.12 |
| Y | 146 | 61.5 | 93.14 | 72.8 | 51.8 | 64.96 | 198 | 73.5 | 137 | 69.8 | 51.9 | 62 |
| Zr | 118.1 | 40.3 | 71.02 | 9.1 | 5.92 | 7.158 | 200 | 41.4 | 114 | 20.6 | 5.85 | 8.11 |
| Nb | 1.07 | 0.029 | 0.2179 | 0.167 | 0.095 | 0.1344 | 0.198 | 0.01 | 0.05 | 0.19 | 0.042 | 0.13 |
| La | 1.38 | 0.24 | 0.75 | 0.19 | 0.00 | 0.04 | 3.50 | 0.05 | 0.62 | 0.05 | 0.00 | 0.01 |
| Ce | 11.0 | 1.73 | 5.73 | 0.66 | 0.01 | 0.18 | 8.30 | 0.86 | 3.08 | 0.11 | 0.00 | 0.04 |
| Pr | 3.66 | 0.78 | 1.69 | 0.18 | 0.00 | 0.05 | 1.88 | 0.36 | 0.97 | 0.05 | 0.00 | 0.02 |
| Nd | 32.3 | 8.41 | 15.7 | 2.18 | 0.08 | 0.73 | 16.7 | 5.09 | 9.58 | 0.61 | 0.15 | 0.38 |
| Sm | 19.0 | 7.01 | 12.2 | 2.25 | 0.42 | 1.13 | 11.5 | 6.02 | 8.30 | 2.47 | 0.98 | 1.68 |
| Eu | 4.67 | 1.92 | 3.13 | 0.90 | 0.18 | 0.48 | 3.15 | 1.63 | 2.50 | 0.93 | 0.45 | 0.75 |
| Gd | 22.1 | 11.7 | 16.5 | 6.23 | 2.40 | 3.76 | 20.6 | 9.44 | 16.4 | 8.00 | 4.68 | 6.42 |
| Tb | 4.02 | 2.02 | 2.68 | 1.34 | 0.97 | 1.11 | 4.51 | 1.76 | 3.38 | 1.68 | 1.19 | 1.43 |
| Dy | 26.1 | 11.0 | 16.2 | 10.1 | 8.34 | 9.43 | 35.2 | 11.8 | 23.7 | 11.7 | 8.50 | 10.22 |
| Ho | 5.34 | 2.18 | 3.39 | 2.67 | 1.74 | 2.34 | 7.66 | 2.40 | 5.00 | 2.38 | 1.80 | 2.16 |
| Er | 14.0 | 6.27 | 9.30 | 8.36 | 4.79 | 7.10 | 22.1 | 6.88 | 13.63 | 6.95 | 4.16 | 6.05 |
| Tm | 2.08 | 0.92 | 1.36 | 1.24 | 0.72 | 1.04 | 2.83 | 1.02 | 1.83 | 0.96 | 0.65 | 0.88 |
| Yb | 15.2 | 5.94 | 9.33 | 9.42 | 4.67 | 7.25 | 17.40 | 7.56 | 12.26 | 7.50 | 3.73 | 6.11 |
| Lu | 2.41 | 0.90 | 1.40 | 1.38 | 0.68 | 1.07 | 2.16 | 1.07 | 1.67 | 0.99 | 0.57 | 0.89 |
| Hf | 4.58 | 1.50 | 2.64 | 0.47 | 0.29 | 0.36 | 8.04 | 1.20 | 4.67 | 0.91 | 0.41 | 0.49 |
| Ta | 0.07 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Pb | 1.93 | 0.01 | 0.61 | 0.45 | 0.09 | 0.27 | 2.09 | 0.04 | 0.56 | 0.01 | 0.00 | 0.01 |
| Th | 0.57 | 0.17 | 0.38 | 0.10 | 0.00 | 0.02 | 0.34 | 0.06 | 0.17 | 0.04 | 0.00 | 0.01 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U | 2.99 | 1.27 | 1.95 | 0.32 | 0.04 | 0.14 | 3.72 | 0.58 | 2.47 | 0.85 | 0.07 | 0.26 |
| REE | 143 | 72.4 | 99.3 | 37.9 | 32.9 | 35.7 | 148 | 61.3 | 103 | 43.9 | 26.9 | 37.0 |
| Eu/Eu* | 0.76 | 0.60 | 0.68 | 0.92 | 0.52 | 0.70 | 0.75 | 0.58 | 0.66 | 0.87 | 0.58 | 0.71 |
| (Dy/Yb)N | 1.51 | 0.80 | 1.19 | 1.20 | 0.69 | 0.91 | 1.81 | 0.89 | 1.28 | 1.53 | 1.04 | 1.14 |

| Mineral | Amphibole zones | | | | | | Garnet zones | | | Marble | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Amp | | | Sph | | | Cc | | | Cc-II | | | Cc-I | | |
| | Max | Min | Average | Max | Min | Average | Max | Min | Average | Max | Min | Average | Max | Min | Average |
| Ti | 209000 | 5610 | 23869 | 233000 | 194000 | 214143 | 5.30 | 0.00 | 0.24 | 4.80 | 2.20 | 3.50 | 0.00 | 0.00 | 0.00 |
| Mn | 4780 | 1320 | 3945 | 1590 | 1248 | 1393 | 21.7 | 5.71 | 8.47 | 246 | 185 | 201 | 250 | 207 | 232 |
| Rb | 30.5 | 10.1 | 20.2 | 21.9 | 12.8 | 17.7 | 0.00 | 0.00 | 0.00 | 0.41 | 0.00 | 0.10 | 0.56 | 0.00 | 0.04 |
| Sr | 102 | 46.2 | 82.3 | 55.8 | 42.4 | 48.0 | 30.9 | 4.44 | 24.3 | 694 | 604 | 650 | 720 | 616 | 662 |
| Y | 9280 | 66.9 | 755 | 9590 | 4480 | 8216 | 0.39 | 0.00 | 0.06 | 2.36 | 1.56 | 1.93 | 4.71 | 2.41 | 3.26 |
| Zr | 574 | 22.6 | 82.7 | 695 | 347 | 521 | 0.19 | 0.00 | 0.01 | 0.08 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Nb | 1184 | 13.2 | 105 | 1550 | 836 | 1194 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| La | 1071 | 11.8 | 101 | 1147 | 551 | 828 | 1.63 | 0.12 | 0.69 | 1.01 | 0.63 | 0.82 | 2.71 | 0.69 | 1.29 |
| Ce | 3730 | 40.8 | 339 | 3730 | 1850 | 2766 | 2.57 | 0.39 | 1.35 | 2.05 | 1.15 | 1.44 | 4.62 | 1.14 | 2.16 |
| Pr | 477 | 6.63 | 44.5 | 477 | 257 | 367 | 0.31 | 0.04 | 0.16 | 0.28 | 0.15 | 0.20 | 0.72 | 0.16 | 0.33 |
| Nd | 2180 | 34.1 | 205 | 2180 | 1150 | 1674 | 1.37 | 0.21 | 0.64 | 1.43 | 0.74 | 1.01 | 2.90 | 0.86 | 1.56 |
| Sm | 651 | 9.60 | 59.4 | 682 | 348 | 531 | 0.15 | 0.02 | 0.07 | 0.26 | 0.13 | 0.20 | 0.55 | 0.08 | 0.33 |
| Eu | 166 | 1.74 | 14.0 | 179 | 89 | 148 | 0.02 | 0.00 | 0.01 | 0.24 | 0.14 | 0.19 | 0.57 | 0.16 | 0.30 |
| Gd | 911 | 11.6 | 79.4 | 959 | 477 | 764 | 0.06 | 0.00 | 0.03 | 0.43 | 0.10 | 0.25 | 0.70 | 0.21 | 0.37 |
| Tb | 194 | 1.82 | 16.3 | 204 | 105 | 168 | 0.01 | 0.00 | 0.00 | 0.04 | 0.02 | 0.03 | 0.09 | 0.02 | 0.05 |
| Dy | 1318 | 11.6 | 110 | 1400 | 711 | 1186 | 0.07 | 0.00 | 0.01 | 0.25 | 0.10 | 0.19 | 0.50 | 0.18 | 0.35 |
| Ho | 309 | 2.57 | 25.5 | 317 | 157 | 274 | 0.01 | 0.00 | 0.00 | 0.05 | 0.02 | 0.04 | 0.13 | 0.05 | 0.07 |
| Er | 1018 | 7.05 | 82.4 | 1060 | 530 | 921 | 0.04 | 0.00 | 0.00 | 0.12 | 0.03 | 0.08 | 0.36 | 0.12 | 0.22 |
| Tm | 175 | 1.06 | 13.9 | 181 | 89.4 | 160 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.01 | 0.04 | 0.02 | 0.03 |
| Yb | 1188 | 7.51 | 94.9 | 1260 | 613 | 1115 | 0.05 | 0.00 | 0.00 | 0.14 | 0.01 | 0.06 | 0.31 | 0.09 | 0.21 |
| Lu | 142 | 1.15 | 11.72 | 148 | 69.9 | 130 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.01 | 0.05 | 0.02 | 0.03 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hf | 63.8 | 1.74 | 7.20 | 74.6 | 36.5 | 58.1 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ta | 99.6 | 0.38 | 8.17 | 168 | 74.9 | 104 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pb | 18.7 | 6.84 | 14.60 | 7.77 | 5.78 | 6.91 | 0.18 | 0.05 | 0.14 | 0.55 | 0.01 | 0.15 | 0.51 | 0.02 | 0.19 |
| Th | 847 | 0.24 | 61.1 | 847 | 363 | 599 | 0.09 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| U | 499 | 0.14 | 36.0 | 594 | 285 | 477 | 0.01 | 0.00 | 0.00 | 0.65 | 0.01 | 0.18 | 0.00 | 0.00 | 0.00 |
| REE | 13530 | 153 | 1197 | 13530 | 7057 | 11034 | 5.40 | 0.91 | 2.96 | 6.17 | 3.52 | 4.51 | 14.1 | 4.34 | 7.30 |
| Eu/Eu* | 0.66 | 0.43 | 0.50 | 0.78 | 0.66 | 0.71 | 1.94 | 0.47 | 0.66 | 4.14 | 1.89 | 2.74 | 4.15 | 2.07 | 2.73 |
| (Dy/Yb)N | 1.38 | 0.74 | 1.04 | 0.78 | 0.63 | 0.72 | 7.91 | 0.97 | 3.61 | 10.95 | 0.80 | 3.25 | 1.93 | 0.68 | 1.15 |

**Supplementary Data 3** Whole-rock major- and trace element compositions of the studied calc-silicate zones and marble.

| Samples | Garnet zones | | | Epidote zones | | Amphibolite zones | | Mixing zones | Marble | |
|---|---|---|---|---|---|---|---|---|---|---|
| | TM-21-11.1 | TM-21-11.2 | TM-21-11.3 | TM-21-11.4 | TM-21-11.5 | TM-21-11.6 | TM-21-11.7 | TM-21-11.8 | MD-21-10 | MD-21-11 |
| Major elements (wt.%) | | | | | | | | | | |
| $SiO_2$ | 63.8 | 65.3 | 60.9 | 66.9 | 71.2 | 68.0 | 67.4 | 69.8 | 4.30 | 1.83 |
| $Al_2O_3$ | 7.13 | 7.13 | 8.61 | 8.93 | 11.0 | 14.1 | 13.5 | 11.0 | 0.47 | 0.66 |
| $TFe_2O_3$ | 4.49 | 4.26 | 5.05 | 5.88 | 3.64 | 4.67 | 5.29 | 4.91 | 0.34 | 0.23 |
| CaO | 17.9 | 17.0 | 19.4 | 13.4 | 9.97 | 7.65 | 7.52 | 9.45 | 51.8 | 51.7 |
| MgO | 1.39 | 1.48 | 1.31 | 1.46 | 1.61 | 1.72 | 2.15 | 1.74 | 0.61 | 2.94 |
| $K_2O$ | 0.07 | 0.04 | 0.08 | 0.03 | 0.07 | 0.46 | 0.61 | 0.26 | 0.14 | 0.14 |
| $Na_2O$ | 0.28 | 0.21 | 0.30 | 0.10 | 0.66 | 1.59 | 1.59 | 0.80 | 0.05 | 0.01 |
| MnO | 0.20 | 0.18 | 0.22 | 0.16 | 0.12 | 0.10 | 0.12 | 0.14 | 0.04 | 0.00 |
| $TiO_2$ | 0.31 | 0.33 | 0.50 | 0.63 | 0.53 | 0.60 | 0.65 | 0.49 | 0.02 | 0.03 |
| $P_2O_5$ | 0.10 | 0.10 | 0.07 | 0.09 | 0.09 | 0.09 | 0.10 | 0.11 | 0.05 | 0.08 |
| LOI | 4.30 | 3.88 | 3.40 | 2.35 | 1.10 | 0.92 | 1.04 | 1.24 | 42.1 | 42.3 |
| Total | 99.9 | 99.9 | 99.9 | 99.9 | 99.9 | 100.0 | 100.0 | 100.0 | 99.9 | 100.0 |

| Samples | TM-21-11.1 | | TM-21-11.2 | | TM-21-11.3 | | TM-21-11.4 | | TM-21-11.5 | | TM-21-11.6 | | TM-21-11.7 | | TM-21-11.8 | | MD-21-10 | | MD-21-11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trace elements (μg/g) | | | | | | | | | | | | | | | | | | | |
| Li | 4.52 | 4.99 | 5.55 | 5.18 | 3.62 | 4.31 | 3.94 | 3.68 | 4.96 | 4.49 | 6.06 | 6.49 | 7.01 | 6.91 | 5.78 | 6.13 | 0.56 | 0.94 | 2.18 |
| Be | 1.01 | 1.14 | 0.98 | 0.93 | 1.01 | 1.06 | 1.28 | 1.14 | 2.49 | 2.72 | 2.83 | 3.00 | 2.96 | 3.32 | 1.70 | 2.06 | 0.35 | 0.91 | 0.20 |
| B | 11.7 | 7.31 | 3.93 | 5.04 | 27.5 | 8.83 | 3.68 | 12.9 | 41.7 | 8.74 | 4.02 | 5.45 | 4.04 | 27.3 | 4.61 | 10.7 | 3.59 | 100.0 | 36.9 |
| Sc | 7.75 | 7.90 | 7.50 | 7.37 | 8.12 | 8.20 | 9.02 | 9.41 | 8.67 | 9.38 | 10.7 | 10.8 | 14.0 | 13.6 | 10.5 | 10.7 | 0.73 | 5.61 | 0.77 |
| Ti | 2618 | 2664 | 2488 | 2364 | 3315 | 3225 | 3669 | 3702 | 3727 | 3863 | 3544 | 3575 | 3553 | 3465 | 3141 | 2952 | 896 | 933 | 1183 |
| V | 51.5 | 53.0 | 48.7 | 46.8 | 64.9 | 62.9 | 76.9 | 77.3 | 44.7 | 46.0 | 59.8 | 60.3 | 67.6 | 65.6 | 52.8 | 49.1 | 85.4 | 203 | 6.63 |
| Cr | 39.7 | 40.3 | 40.7 | 38.9 | 42.2 | 39.5 | 41.7 | 41.5 | 45.3 | 45.5 | 43.9 | 44.3 | 48.5 | 47.8 | 44.1 | 31.1 | 7.23 | 14.5 | 6.42 |
| Mn | 1470 | 1491 | 1334 | 1291 | 1607 | 1554 | 1119 | 1118 | 844 | 841 | 680 | 689 | 785 | 788 | 916 | 956 | 323 | 603 | 100 |
| Co | 5.41 | 5.49 | 5.68 | 5.50 | 5.59 | 5.49 | 6.04 | 6.00 | 4.81 | 4.86 | 10.5 | 10.3 | 8.98 | 9.01 | 6.83 | 7.26 | 1.01 | 1.04 | 0.36 |
| Ni | 14.6 | 14.9 | 15.6 | 15.3 | 14.8 | 14.3 | 20.4 | 20.6 | 12.1 | 12.6 | 17.0 | 16.8 | 18.4 | 17.8 | 21.9 | 22.8 | 19.2 | 23.4 | 2.02 |
| Cu | 2.45 | 3.12 | 1.78 | 1.87 | 1.75 | 1.60 | 5.44 | 5.61 | 17.5 | 18.4 | 73.1 | 73.8 | 30.0 | 29.6 | 25.3 | 25.9 | 2.80 | 6.45 | 2.86 |
| Zn | 174 | 126 | 111 | 100 | 168 | 115 | 144 | 168 | 106 | 197 | 127 | 145 | 146 | 172 | 124 | 204 | 187 | 160 | 270 |
| Ga | 13.3 | 13.4 | 13.6 | 13.4 | 13.7 | 13.8 | 15.3 | 15.4 | 16.0 | 16.7 | 18.5 | 18.6 | 18.3 | 18.3 | 16.1 | 17.0 | 1.11 | 2.62 | 1.00 |
| As | 3.34 | 3.69 | 2.95 | 2.90 | 2.98 | 2.74 | 4.03 | 6.36 | 3.89 | 4.09 | 5.37 | 5.36 | 4.09 | 4.25 | 4.28 | 4.31 | 1.36 | 2.42 | 2.20 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Se | 21.3 | 24.1 | 24.3 | 22.4 | 20.2 | 20.8 | 25.2 | 27.5 | 26.6 | 28.8 | 27.9 | 28.6 | 23.8 | 22.6 | 26.0 | 25.9 | 3.37 | 6.49 | 1.62 |
| Rb | 3.06 | 3.12 | 2.51 | 2.47 | 4.54 | 5.09 | 2.10 | 2.11 | 2.18 | 3.05 | 16.4 | 16.6 | 21.5 | 21.4 | 10.2 | 10.7 | 5.66 | 18.8 | 12.5 |
| Sr | 207 | 211 | 175 | 170 | 183 | 188 | 311 | 316 | 372 | 385 | 442 | 434 | 409 | 404 | 385 | 398 | 523 | 327 | 911 |
| Y | 20.4 | 20.5 | 18.0 | 17.7 | 24.9 | 25.1 | 27.8 | 27.9 | 26.4 | 27.7 | 32.7 | 32.4 | 30.5 | 30.0 | 27.2 | 28.1 | 3.50 | 21.1 | 2.28 |
| Zr | 168 | 239 | 108 | 153 | 134 | 163 | 173 | 207 | 122 | 266 | 79.9 | 110 | 136 | 107 | 120 | 29.6 | 2.68 | 7.31 | 5.03 |
| Nb | 4.44 | 4.60 | 3.85 | 3.79 | 7.09 | 6.65 | 9.04 | 9.17 | 11.9 | 12.0 | 11.9 | 11.9 | 9.62 | 9.45 | 8.77 | 7.34 | 0.65 | 1.49 | 0.38 |
| Mo | 0.13 | 0.15 | 0.08 | 0.15 | 0.25 | 0.19 | 0.29 | 0.30 | 0.35 | 0.33 | 0.25 | 0.24 | 0.21 | 0.20 | 0.24 | 0.20 | 1.53 | 2.66 | 0.19 |
| Sn | 7.55 | 7.87 | 6.02 | 5.93 | 8.05 | 7.93 | 11.5 | 11.7 | 7.61 | 7.85 | 7.03 | 7.02 | 8.49 | 8.35 | 7.08 | 6.67 | 0.34 | 1.15 | 0.57 |
| Cs | 11.1 | 11.2 | 14.8 | 14.6 | 35.8 | 36.1 | 1.19 | 1.21 | 0.57 | 0.59 | 1.23 | 1.26 | 1.38 | 1.38 | 1.20 | 1.25 | 0.41 | 1.87 | 1.66 |
| Ba | 11.3 | 12.4 | 9.9 | 10.7 | 12.3 | 13.0 | 7.67 | 10.16 | 32.5 | 33.1 | 145 | 146 | 220 | 213 | 88.6 | 90.4 | 109.9 | 94.1 | 50.4 |
| La | 19.4 | 19.5 | 29.4 | 28.8 | 17.6 | 17.5 | 28.2 | 28.5 | 34.6 | 37.2 | 27.6 | 28.5 | 29.9 | 29.2 | 35.1 | 35.8 | 3.55 | 5.82 | 1.97 |
| Ce | 46.2 | 46.9 | 61.1 | 58.7 | 38.6 | 38.2 | 58.8 | 59.6 | 69.4 | 74.1 | 58.7 | 59.0 | 57.8 | 57.1 | 71.1 | 72.9 | 5.17 | 9.25 | 3.40 |
| Pr | 5.24 | 5.33 | 6.45 | 6.16 | 4.07 | 4.04 | 6.30 | 6.34 | 7.09 | 7.60 | 6.34 | 6.28 | 5.85 | 5.70 | 7.29 | 7.43 | 0.69 | 1.19 | 0.43 |
| Nd | 21.6 | 22.0 | 25.3 | 24.0 | 16.4 | 16.7 | 24.6 | 25.3 | 27.8 | 29.0 | 25.0 | 25.1 | 22.3 | 22.0 | 27.9 | 28.3 | 3.70 | 4.68 | 1.86 |
| Sm | 4.65 | 4.75 | 5.02 | 4.75 | 4.35 | 4.46 | 5.72 | 5.78 | 6.09 | 6.34 | 5.85 | 5.83 | 5.00 | 4.91 | 5.54 | 5.64 | 0.49 | 1.12 | 0.33 |
| Eu | 0.78 | 0.79 | 0.81 | 0.79 | 0.80 | 0.80 | 0.96 | 0.96 | 1.08 | 1.15 | 1.02 | 1.03 | 0.90 | 0.88 | 0.93 | 0.95 | 0.38 | 0.52 | 0.07 |
| Gd | 4.02 | 4.09 | 3.95 | 3.76 | 4.30 | 4.32 | 5.31 | 5.41 | 5.29 | 5.59 | 5.46 | 5.45 | 4.91 | 4.85 | 5.01 | 5.09 | 0.47 | 1.32 | 0.33 |
| Tb | 0.58 | 0.60 | 0.55 | 0.52 | 0.67 | 0.68 | 0.82 | 0.84 | 0.82 | 0.85 | 0.90 | 0.90 | 0.83 | 0.81 | 0.77 | 0.79 | 0.06 | 0.25 | 0.05 |
| Dy | 3.40 | 3.54 | 3.17 | 3.07 | 4.18 | 4.27 | 4.94 | 5.04 | 4.86 | 5.06 | 5.71 | 5.77 | 5.51 | 5.33 | 4.83 | 4.91 | 0.45 | 2.05 | 0.31 |
| Ho | 0.66 | 0.68 | 0.61 | 0.60 | 0.85 | 0.85 | 0.95 | 0.97 | 0.94 | 0.97 | 1.13 | 1.13 | 1.10 | 1.09 | 0.96 | 0.97 | 0.08 | 0.53 | 0.06 |
| Er | 1.91 | 2.03 | 1.80 | 1.73 | 2.46 | 2.46 | 2.84 | 2.94 | 2.75 | 2.92 | 3.38 | 3.38 | 3.21 | 3.22 | 2.81 | 2.90 | 0.26 | 1.98 | 0.19 |
| Tm | 0.27 | 0.29 | 0.25 | 0.25 | 0.35 | 0.36 | 0.42 | 0.43 | 0.41 | 0.43 | 0.50 | 0.50 | 0.47 | 0.47 | 0.42 | 0.41 | 0.03 | 0.36 | 0.03 |
| Yb | 1.88 | 1.97 | 1.67 | 1.66 | 2.36 | 2.39 | 2.95 | 3.06 | 2.82 | 2.94 | 3.41 | 3.40 | 3.11 | 3.10 | 2.83 | 2.84 | 0.23 | 2.91 | 0.16 |
| Lu | 0.27 | 0.28 | 0.24 | 0.24 | 0.34 | 0.36 | 0.43 | 0.45 | 0.41 | 0.43 | 0.49 | 0.49 | 0.45 | 0.45 | 0.40 | 0.41 | 0.03 | 0.51 | 0.02 |
| Hf | 3.47 | 4.98 | 2.46 | 3.35 | 3.12 | 3.67 | 3.98 | 4.77 | 2.96 | 5.80 | 2.11 | 2.59 | 3.10 | 2.56 | 2.75 | 1.03 | 0.08 | 0.22 | 0.13 |
| Ta | 0.29 | 0.41 | 0.29 | 0.31 | 0.93 | 0.55 | 0.71 | 0.71 | 1.33 | 1.11 | 1.36 | 1.41 | 0.82 | 0.83 | 0.82 | 0.52 | 0.04 | 0.20 | 0.05 |
| Pb | 2.93 | 5.34 | 4.35 | 3.91 | 4.12 | 5.50 | 7.49 | 7.90 | 9.89 | 10.5 | 14.6 | 15.1 | 14.8 | 15.8 | 12.5 | 16.5 | 3.30 | 8.25 | 7.97 |
| Th | 12.4 | 12.6 | 17.1 | 16.7 | 7.48 | 7.78 | 12.9 | 13.7 | 15.0 | 18.0 | 14.1 | 14.4 | 13.4 | 13.5 | 14.1 | 14.1 | 0.78 | 4.89 | 0.63 |
| U | 2.94 | 3.16 | 2.74 | 2.72 | 2.34 | 2.38 | 3.76 | 3.93 | 5.08 | 5.45 | 4.35 | 4.42 | 2.15 | 2.03 | 2.83 | 2.81 | 4.74 | 5.78 | 0.76 |
| Rb/Sr | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.04 | 0.04 | 0.05 | 0.05 | 0.03 | 0.03 | 0.01 | 0.06 | 0.01 |
| Sr/Y | 10.2 | 10.3 | 9.76 | 9.59 | 7.36 | 7.48 | 11.2 | 11.4 | 14.1 | 13.9 | 13.5 | 13.4 | 13.4 | 13.5 | 14.2 | 14.2 | 149 | 15.5 | 400 |
| La/Yb | 10.3 | 9.88 | 17.6 | 17.3 | 7.44 | 7.34 | 9.59 | 9.29 | 12.2 | 12.6 | 8.09 | 8.37 | 9.62 | 9.44 | 12.4 | 12.6 | 15.4 | 2.00 | 12.5 |

**Supplementary Data 4** Whole-rock Sr–Nd isotopic compositions of the studied calc-silicate zones and marble.

| Samples | | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ | ±σ | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd$ | ±σ | $^{87}Sr/^{86}Sr$(14Ma) | $I_{Nd}$(14Ma) | $\varepsilon_{Nd}$(0) | $\varepsilon_{Nd}$(14Ma) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Garnet zones | TM-21-11.1 | 0.042671 | 0.716106 | 6 | 0.129811 | 0.511822 | 5 | 0.716098 | 0.511810 | -15.9 | -15.8 |
| | TM-21-11.2 | 0.041465 | 0.715527 | 7 | 0.119959 | 0.511778 | 2 | 0.715518 | 0.511767 | -16.8 | -16.6 |
| | TM-21-11.3 | 0.071739 | 0.716570 | 8 | 0.160480 | 0.511872 | 7 | 0.716555 | 0.511857 | -14.9 | -14.9 |
| Epidote zones | TM-21-11.4 | 0.019518 | 0.718982 | 8 | 0.140399 | 0.511800 | 4 | 0.718978 | 0.511787 | -16.3 | -16.2 |
| | TM-21-11.5 | 0.016962 | 0.722362 | 7 | 0.132653 | 0.511780 | 4 | 0.722359 | 0.511768 | -16.7 | -16.6 |
| Amphibole zones | TM-21-11.6 | 0.107776 | 0.724025 | 10 | 0.141451 | 0.511780 | 6 | 0.724004 | 0.511767 | -16.7 | -16.6 |
| | TM-21-11.7 | 0.151928 | 0.724118 | 6 | 0.135722 | 0.511752 | 4 | 0.724088 | 0.511740 | -17.3 | -17.2 |
| Mixing zones | TM-21-11.8 | 0.076550 | 0.721464 | 5 | 0.119896 | 0.511732 | 4 | 0.721449 | 0.511721 | -17.7 | -17.5 |
| Marble | MD-21-10.1 | 0.031309 | 0.722528 | 9 | 0.080871 | 0.511964 | 7 | 0.722522 | 0.511957 | -13.1 | -12.9 |

**Supplementary Data 5** The bulk rock silicate oxygen isotopic compositions of the calc-silicate zones and C-O isotopic compositions of the calcite.

| Bulk-rock silicate oxygen isotopes | | $\delta^{18}O_{V\text{-}SMOW}$‰ |
|---|---|---|
| Garnet zones | TM-21-11.1 | 9.8 |
| | TM-21-11.2 | 9.6 |
| | TM-21-11.3 | 8.6 |
| Epidote zones | TM-21-11.4 | 10.2 |
| | TM-21-11.5 | 9.9 |
| Amphibole zones | TM-21-11.6 | 9.3 |
| | TM-21-11.7 | 9.8 |

| Carbonate O-C isotopes of carbon-bearing samples | | | |
|---|---|---|---|
| Samples | | $\delta^{13}C_{V\text{-}PDB}$‰ | $\delta^{18}O_{V\text{-}SMOW}$‰ |
| Garnet zones | TM-21-11.1 | -4.21 | 14.41 |
| | TM-21-11.3 | -4.42 | 14.20 |
| Mable | MD-21-10.1 | -13.02 | 15.01 |
| | MD-21-10.1 | -13.18 | 14.93 |

**Supplementary Data 6** In-situ calcite strontium isotopic data from the garnet zones and marble.

| Mineral | $^{87}Sr/^{86}Sr$ | SE | Mineral | $^{87}Sr/^{86}Sr$ | SE |
|---|---|---|---|---|---|
| Cc (Type A1) | 0.723801 | 0.000126 | Cc (Garnet zones) | 0.716026 | 0.000082 |
| Cc (Type A1) | 0.723267 | 0.000141 | Cc (Garnet zones) | 0.716040 | 0.000093 |
| Cc (Type A1) | 0.723919 | 0.000143 | Cc (Garnet zones) | 0.715780 | 0.000090 |
| Cc (Type A1) | 0.723435 | 0.000145 | Cc (Garnet zones) | 0.715801 | 0.000092 |
| Cc (Type A1) | 0.723770 | 0.000142 | Cc (Garnet zones) | 0.715790 | 0.000088 |
| Cc (Type A1) | 0.723777 | 0.000154 | Cc (Garnet zones) | 0.715915 | 0.000090 |
| Cc (Type A1) | 0.723832 | 0.000156 | Cc (Garnet zones) | 0.715837 | 0.000090 |
| Cc (Type A1) | 0.723045 | 0.000139 | Cc (Garnet zones) | 0.715923 | 0.000088 |
| Cc (Type A1) | 0.723694 | 0.000147 | Cc (Garnet zones) | 0.715966 | 0.000092 |
| Cc (Type A1) | 0.724011 | 0.000135 | Cc (Garnet zones) | 0.715839 | 0.000094 |
| Cc (Type A2) | 0.723470 | 0.000335 | Cc (Garnet zones) | 0.715493 | 0.000082 |
| Cc (Type A2) | 0.723978 | 0.000371 | Cc (Garnet zones) | 0.715369 | 0.000090 |
| Cc (Type A2) | 0.722788 | 0.000351 | Cc (Garnet zones) | 0.715421 | 0.000075 |
| Cc (Type A2) | 0.724002 | 0.000303 | Cc (Garnet zones) | 0.715627 | 0.000103 |
| Cc (Type A2) | 0.723375 | 0.000280 | Cc (Garnet zones) | 0.715507 | 0.000104 |
| Cc (Type A2) | 0.723628 | 0.000317 | Cc (Garnet zones) | 0.715422 | 0.000095 |
| Cc (Type A2) | 0.723572 | 0.000319 | Cc (Garnet zones) | 0.715141 | 0.000098 |
| Cc (Type A2) | 0.723080 | 0.000342 | Cc (Garnet zones) | 0.715552 | 0.000115 |
| | | | Cc (Garnet zones) | 0.715474 | 0.000111 |
| | | | Cc (Garnet zones) | 0.715220 | 0.000101 |
| | | | Cc (Garnet zones) | 0.715194 | 0.000087 |
| | | | Cc (Garnet zones) | 0.715090 | 0.000087 |
| | | | Cc (Garnet zones) | 0.714901 | 0.000099 |
| | | | Cc (Garnet zones) | 0.715280 | 0.000092 |

**Supplementary Data 7** Zircon U-Pb age data of the studied calc-silicate zones.

| Spots | Contents (ppm) | | | Th/U | Isotopic ratios | | | | | | Age (Ma) | | | | Pb-correctd age (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pb | Th | U | | $^{207}Pb/^{235}U$ | 2σ | $^{206}Pb/^{238}U$ | 2σ | $^{207}Pb/^{206}Pb$ | 2σ | $^{207}Pb/^{235}U$ | 2σ | $^{206}Pb/^{238}U$ | 2σ | |
| Garnet zones | | | | | | | | | | | | | | | |
| G.1 | 6.83 | 423 | 3210 | 0.13 | 0.0139 | 0.0013 | 0.0019 | 0.0001 | 0.0527 | 0.0057 | 14.0 | 1.3 | 12.2 | 0.3 | 12.2 |
| G.2 | 6.92 | 346 | 3250 | 0.11 | 0.0129 | 0.0015 | 0.0020 | 0.0001 | 0.0491 | 0.0055 | 13.0 | 1.5 | 12.6 | 0.4 | 12.6 |
| G.3 | 5.18 | 406 | 2330 | 0.17 | 0.0137 | 0.0013 | 0.0020 | 0.0001 | 0.0502 | 0.0057 | 13.8 | 1.3 | 13.2 | 0.5 | 13.2 |
| G.4 | 3.01 | 105 | 1310 | 0.08 | 0.0179 | 0.0025 | 0.0021 | 0.0001 | 0.0609 | 0.0089 | 18.0 | 2.5 | 13.7 | 0.8 | 13.7 |
| G.5 | 4.80 | 406 | 2030 | 0.20 | 0.0124 | 0.0021 | 0.0021 | 0.0001 | 0.0436 | 0.0080 | 12.5 | 2.2 | 13.4 | 0.6 | 13.4 |
| G.6 | 7.79 | 199 | 3700 | 0.05 | 0.0121 | 0.0012 | 0.0019 | 0.0001 | 0.0447 | 0.0049 | 12.2 | 1.2 | 12.5 | 0.4 | 12.5 |
| G.7 | 6.75 | 403 | 2980 | 0.14 | 0.0145 | 0.0016 | 0.0021 | 0.0001 | 0.0485 | 0.0057 | 14.6 | 1.6 | 13.3 | 0.4 | 13.3 |
| G.8 | 6.40 | 392 | 2980 | 0.13 | 0.0130 | 0.0016 | 0.0020 | 0.0001 | 0.0469 | 0.0057 | 13.1 | 1.6 | 13.1 | 0.5 | 13.1 |
| G.10 | 3.66 | 121 | 1500 | 0.08 | 0.0166 | 0.0029 | 0.0023 | 0.0002 | 0.0510 | 0.0088 | 16.7 | 2.9 | 14.5 | 0.9 | 14.5 |
| G.11 | 6.19 | 461 | 2700 | 0.17 | 0.0127 | 0.0018 | 0.0020 | 0.0001 | 0.0454 | 0.0073 | 12.8 | 1.8 | 13.2 | 0.6 | 13.2 |
| G.13 | 3.14 | 263 | 1250 | 0.21 | 0.0167 | 0.0024 | 0.0022 | 0.0001 | 0.0536 | 0.0091 | 16.7 | 2.4 | 13.9 | 0.6 | 13.9 |
| G.14 | 3.07 | 163 | 1200 | 0.14 | 0.0138 | 0.0029 | 0.0022 | 0.0001 | 0.0468 | 0.0099 | 13.9 | 2.9 | 14.1 | 0.6 | 14.1 |
| G.15 | 5.50 | 452 | 2520 | 0.18 | 0.0133 | 0.0021 | 0.0021 | 0.0001 | 0.0468 | 0.0076 | 13.4 | 2.1 | 13.5 | 0.7 | 13.5 |
| G.16 | 13.8 | 329 | 6760 | 0.05 | 0.0134 | 0.0012 | 0.0019 | 0.0000 | 0.0526 | 0.0051 | 13.6 | 1.2 | 12.0 | 0.3 | 12.0 |
| G.17 | 3.21 | 163 | 1300 | 0.13 | 0.0175 | 0.0024 | 0.0022 | 0.0001 | 0.0546 | 0.0075 | 17.6 | 2.4 | 14.1 | 0.8 | 14.1 |
| G.18 | 6.21 | 466 | 2930 | 0.16 | 0.0121 | 0.0015 | 0.0018 | 0.0001 | 0.0480 | 0.0066 | 12.2 | 1.5 | 11.9 | 0.4 | 11.9 |
| G.19 | 4.49 | 315 | 1890 | 0.17 | 0.0143 | 0.0020 | 0.0021 | 0.0001 | 0.0481 | 0.0069 | 14.4 | 2.0 | 13.6 | 0.6 | 13.6 |
| G.20 | 5.41 | 469 | 2420 | 0.19 | 0.0143 | 0.0018 | 0.0020 | 0.0001 | 0.0510 | 0.0063 | 14.4 | 1.8 | 13.0 | 0.6 | 13.0 |
| G.21 | 2.84 | 143 | 1200 | 0.12 | 0.0155 | 0.0022 | 0.0021 | 0.0001 | 0.0507 | 0.0089 | 15.6 | 2.2 | 13.7 | 0.7 | 13.7 |
| G.22 | 4.04 | 385 | 1820 | 0.21 | 0.0154 | 0.0024 | 0.0020 | 0.0001 | 0.0562 | 0.0100 | 15.5 | 2.4 | 12.6 | 0.7 | 12.6 |
| G.23 | 1.80 | 130 | 778 | 0.17 | 0.0141 | 0.0036 | 0.0020 | 0.0001 | 0.0500 | 0.0130 | 14.1 | 3.6 | 13.1 | 0.9 | 13.1 |
| G.25 | 6.20 | 427 | 2770 | 0.15 | 0.0143 | 0.0021 | 0.0020 | 0.0001 | 0.0537 | 0.0091 | 14.4 | 2.1 | 12.7 | 0.4 | 12.7 |
| G.26 | 3.61 | 275 | 1580 | 0.17 | 0.0124 | 0.0025 | 0.0020 | 0.0001 | 0.0445 | 0.0094 | 12.5 | 2.5 | 13.0 | 0.7 | 13.0 |
| G.27 | 2.07 | 171 | 870 | 0.20 | 0.0139 | 0.0026 | 0.0022 | 0.0001 | 0.0476 | 0.0091 | 13.9 | 2.6 | 14.1 | 0.9 | 14.1 |
| G.28 | 2.87 | 163 | 1160 | 0.14 | 0.0140 | 0.0026 | 0.0021 | 0.0001 | 0.0494 | 0.0100 | 14.1 | 2.6 | 13.5 | 0.7 | 13.5 |
| G.29 | 3.69 | 266 | 1550 | 0.17 | 0.0134 | 0.0023 | 0.0021 | 0.0001 | 0.0458 | 0.0080 | 13.5 | 2.3 | 13.2 | 0.7 | 13.2 |
| G.31 | 4.44 | 207 | 1840 | 0.11 | 0.0162 | 0.0023 | 0.0022 | 0.0001 | 0.0557 | 0.0083 | 16.3 | 2.3 | 14.3 | 0.7 | 14.3 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G.32 | 2.30 | 162 | 1080 | 0.15 | 0.0128 | 0.0028 | 0.0020 | 0.0001 | 0.0448 | 0.0096 | 12.9 | 2.8 | 12.9 | 0.7 | 12.9 |
| G.33 | 6.74 | 428 | 3200 | 0.13 | 0.0123 | 0.0014 | 0.0019 | 0.0001 | 0.0460 | 0.0062 | 12.4 | 1.4 | 12.1 | 0.5 | 12.1 |
| G.34 | 2.81 | 242 | 1180 | 0.21 | 0.0141 | 0.0025 | 0.0021 | 0.0001 | 0.0510 | 0.0093 | 14.2 | 2.5 | 13.6 | 0.6 | 13.6 |
| G.35 | 5.10 | 453 | 2370 | 0.19 | 0.0127 | 0.0016 | 0.0019 | 0.0001 | 0.0479 | 0.0073 | 12.8 | 1.6 | 12.0 | 0.5 | 12.0 |
| G.38 | 5.07 | 423 | 2100 | 0.20 | 0.0121 | 0.0018 | 0.0021 | 0.0001 | 0.0449 | 0.0081 | 12.2 | 1.8 | 13.4 | 0.7 | 13.4 |
| G.39 | 3.83 | 181 | 1610 | 0.11 | 0.0139 | 0.0021 | 0.0022 | 0.0001 | 0.0485 | 0.0084 | 14.0 | 2.1 | 14.0 | 0.6 | 14.0 |
| G.40 | 2.36 | 148 | 953 | 0.16 | 0.0132 | 0.0031 | 0.0021 | 0.0001 | 0.0430 | 0.0100 | 13.3 | 3.1 | 13.8 | 0.7 | 13.8 |
| G.41 | 3.25 | 293 | 1450 | 0.20 | 0.0140 | 0.0021 | 0.0020 | 0.0001 | 0.0525 | 0.0082 | 14.1 | 2.1 | 13.0 | 0.6 | 13.0 |
| G.42 | 4.22 | 331 | 1780 | 0.19 | 0.0147 | 0.0021 | 0.0022 | 0.0001 | 0.0501 | 0.0071 | 14.8 | 2.1 | 13.8 | 0.7 | 13.8 |
| G.43 | 3.11 | 151 | 1270 | 0.12 | 0.0143 | 0.0025 | 0.0021 | 0.0001 | 0.0476 | 0.0085 | 14.4 | 2.5 | 13.8 | 0.5 | 13.8 |
| G.44 | 5.06 | 366 | 2220 | 0.16 | 0.0139 | 0.0019 | 0.0020 | 0.0001 | 0.0503 | 0.0071 | 14.0 | 1.9 | 12.8 | 0.5 | 12.8 |
| G.45 | 10.5 | 283 | 5220 | 0.05 | 0.0123 | 0.0012 | 0.0019 | 0.0000 | 0.0453 | 0.0050 | 12.4 | 1.2 | 12.1 | 0.3 | 12.1 |
| G.46 | 6.45 | 696 | 2770 | 0.25 | 0.0140 | 0.0022 | 0.0020 | 0.0001 | 0.0491 | 0.0078 | 14.1 | 2.2 | 12.8 | 0.5 | 12.8 |
| G.47 | 2.86 | 197 | 1200 | 0.16 | 0.0130 | 0.0027 | 0.0021 | 0.0001 | 0.0451 | 0.0097 | 13.1 | 2.7 | 13.5 | 0.6 | 13.5 |
| G.48 | 3.10 | 121 | 1210 | 0.10 | 0.0188 | 0.0030 | 0.0022 | 0.0001 | 0.0630 | 0.0110 | 18.9 | 3.0 | 14.3 | 0.7 | 14.3 |
| G.49 | 2.97 | 169 | 1270 | 0.13 | 0.0153 | 0.0025 | 0.0021 | 0.0001 | 0.0513 | 0.0079 | 15.4 | 2.5 | 13.8 | 0.7 | 13.8 |
| G.50 | 2.40 | 120 | 1000 | 0.12 | 0.0168 | 0.0034 | 0.0021 | 0.0001 | 0.0590 | 0.0120 | 16.9 | 3.4 | 13.4 | 0.7 | 13.4 |
| G.51 | 4.25 | 202 | 1800 | 0.11 | 0.0133 | 0.0028 | 0.0021 | 0.0001 | 0.0480 | 0.0110 | 13.4 | 2.8 | 13.7 | 0.5 | 13.7 |
| G.52 | 9.97 | 504 | 4710 | 0.11 | 0.0122 | 0.0011 | 0.0019 | 0.0001 | 0.0450 | 0.0053 | 12.3 | 1.1 | 12.2 | 0.5 | 12.2 |
| G.53 | 8.07 | 403 | 3870 | 0.10 | 0.0133 | 0.0015 | 0.0019 | 0.0001 | 0.0517 | 0.0063 | 13.4 | 1.5 | 12.1 | 0.4 | 12.1 |
| G.54 | 3.72 | 350 | 1430 | 0.24 | 0.0158 | 0.0022 | 0.0022 | 0.0001 | 0.0550 | 0.0090 | 15.9 | 2.2 | 13.9 | 0.7 | 13.9 |
| G.55 | 1.54 | 120 | 640 | 0.19 | 0.0113 | 0.0038 | 0.0022 | 0.0002 | 0.0400 | 0.0130 | 11.3 | 3.8 | 14.2 | 1.1 | 14.2 |
| G.56 | 3.07 | 158 | 1290 | 0.12 | 0.0155 | 0.0028 | 0.0021 | 0.0001 | 0.0524 | 0.0094 | 15.6 | 2.7 | 13.2 | 0.5 | 13.2 |
| G.57 | 3.51 | 190 | 1500 | 0.13 | 0.0120 | 0.0021 | 0.0021 | 0.0001 | 0.0404 | 0.0075 | 12.1 | 2.1 | 13.3 | 0.7 | 13.3 |
| G.58 | 3.79 | 207 | 1740 | 0.12 | 0.0127 | 0.0019 | 0.0020 | 0.0001 | 0.0473 | 0.0077 | 12.8 | 1.9 | 13.0 | 0.6 | 13.0 |
| G.60 | 3.19 | 137 | 1330 | 0.10 | 0.0183 | 0.0024 | 0.0021 | 0.0001 | 0.0612 | 0.0095 | 18.4 | 2.4 | 13.4 | 0.7 | 13.4 |
| G.61 | 2.49 | 134 | 1080 | 0.12 | 0.0142 | 0.0026 | 0.0020 | 0.0001 | 0.0520 | 0.0110 | 14.3 | 2.6 | 13.0 | 0.8 | 13.0 |
| G.63 | 13.1 | 373 | 6320 | 0.06 | 0.0116 | 0.0010 | 0.0019 | 0.0000 | 0.0440 | 0.0041 | 11.7 | 1.0 | 12.2 | 0.2 | 12.2 |
| Amphibole zones | | | | | | | | | | | | | | | |
| A.33 | 0.60 | 1.18 | 150 | 0.01 | 0.0330 | 0.0110 | 0.0033 | 0.0004 | 0.0850 | 0.0310 | 32.0 | 11.0 | 21.0 | 2.2 | 20.3 |
| A.2 | 0.43 | 0.55 | 158 | 0.00 | 0.0230 | 0.0069 | 0.0023 | 0.0002 | 0.0730 | 0.0240 | 22.9 | 6.8 | 14.5 | 1.5 | 14.0 |
| A.3 | 0.28 | 1.01 | 62.5 | 0.02 | 0.0760 | 0.0240 | 0.0027 | 0.0004 | 0.2100 | 0.0690 | 72.0 | 22.0 | 17.6 | 2.7 | 14.0 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A.7 | 0.38 | 0.65 | 117 | 0.01 | 0.0350 | 0.0110 | 0.0025 | 0.0003 | 0.0970 | 0.0350 | 34.0 | 11.0 | 15.9 | 1.8 | 14.8 |
| A.8 | 0.31 | 0.03 | 76.0 | 0.00 | 0.0510 | 0.0180 | 0.0029 | 0.0004 | 0.1700 | 0.0660 | 50.0 | 17.0 | 18.6 | 2.3 | 17.0 |
| A.10 | 0.25 | 2.54 | 95.5 | 0.03 | 0.0218 | 0.0094 | 0.0021 | 0.0003 | 0.1070 | 0.0490 | 21.5 | 9.3 | 13.7 | 2.0 | 13.2 |
| A.11 | 0.90 | 3.29 | 285 | 0.01 | 0.0229 | 0.0072 | 0.0028 | 0.0002 | 0.0670 | 0.0210 | 22.9 | 7.2 | 18.0 | 1.6 | 18.0 |
| A.13 | 3.14 | 23.4 | 1130 | 0.02 | 0.0163 | 0.0029 | 0.0024 | 0.0001 | 0.0506 | 0.0098 | 16.4 | 2.9 | 15.7 | 0.8 | 15.7 |
| A.16 | 0.62 | 4.03 | 214 | 0.02 | 0.0222 | 0.0056 | 0.0026 | 0.0002 | 0.0620 | 0.0170 | 22.2 | 5.5 | 16.9 | 1.5 | 16.6 |
| A.17 | 0.70 | 1.80 | 272 | 0.01 | 0.0228 | 0.0066 | 0.0024 | 0.0002 | 0.0690 | 0.0210 | 22.7 | 6.5 | 15.6 | 1.4 | 15.3 |
| A.22 | 1.43 | 18.3 | 547 | 0.03 | 0.0180 | 0.0049 | 0.0023 | 0.0002 | 0.0500 | 0.0140 | 18.1 | 4.9 | 14.7 | 1.1 | 14.7 |
| A.23 | 1.62 | 5.16 | 641 | 0.01 | 0.0185 | 0.0042 | 0.0024 | 0.0002 | 0.0590 | 0.0140 | 18.6 | 4.2 | 15.3 | 1.1 | 15.3 |
| A.24 | 0.52 | 1.17 | 221 | 0.01 | 0.0164 | 0.0061 | 0.0022 | 0.0003 | 0.0560 | 0.0210 | 16.3 | 6.1 | 14.4 | 1.6 | 14.4 |
| A.28 | 0.71 | 0.88 | 253 | 0.00 | 0.0310 | 0.0097 | 0.0023 | 0.0004 | 0.1000 | 0.0380 | 30.7 | 9.6 | 14.9 | 2.3 | 13.9 |
| A.29 | 0.43 | 1.77 | 155 | 0.01 | 0.0227 | 0.0070 | 0.0024 | 0.0003 | 0.0700 | 0.0270 | 22.6 | 7.0 | 15.1 | 2.0 | 14.7 |
| A.34 | 0.38 | 2.15 | 81.1 | 0.03 | 0.0770 | 0.0260 | 0.0030 | 0.0003 | 0.1780 | 0.0680 | 73.0 | 24.0 | 19.0 | 2.2 | 15.5 |
| A.35 | 0.63 | 3.38 | 161 | 0.02 | 0.0590 | 0.0170 | 0.0026 | 0.0003 | 0.1630 | 0.0480 | 58.0 | 16.0 | 16.8 | 2.2 | 14.5 |
| A.36 | 0.49 | 0.63 | 158 | 0.00 | 0.0256 | 0.0092 | 0.0028 | 0.0004 | 0.0730 | 0.0260 | 25.3 | 9.0 | 17.7 | 2.5 | 17.0 |
| A.39 | 0.37 | 0.76 | 152 | 0.01 | 0.0300 | 0.0110 | 0.0022 | 0.0004 | 0.1530 | 0.0760 | 29.0 | 11.0 | 14.1 | 2.4 | 14.0 |
| A.41 | 1.74 | 9.40 | 461 | 0.02 | 0.0580 | 0.0110 | 0.0025 | 0.0002 | 0.1670 | 0.0340 | 57.0 | 10.0 | 16.0 | 1.3 | 13.8 |
| A.43 | 0.37 | 10.5 | 85.0 | 0.12 | 0.0740 | 0.0230 | 0.0034 | 0.0005 | 0.1620 | 0.0550 | 71.0 | 21.0 | 21.9 | 3.4 | 20.0 |
| A.44 | 0.52 | 0.62 | 193 | 0.00 | 0.0154 | 0.0070 | 0.0027 | 0.0003 | 0.0420 | 0.0200 | 15.3 | 7.0 | 17.2 | 2.0 | 17.1 |
| A.45 | 0.69 | 1.67 | 225 | 0.01 | 0.0380 | 0.0110 | 0.0023 | 0.0003 | 0.1230 | 0.0370 | 37.0 | 11.0 | 15.0 | 1.8 | 14.1 |
| A.47 | 0.44 | 2.06 | 171 | 0.01 | 0.0263 | 0.0090 | 0.0024 | 0.0004 | 0.0770 | 0.0280 | 26.1 | 8.8 | 15.7 | 2.2 | 15.0 |
| A.49 | 0.39 | 2.32 | 157 | 0.01 | 0.0228 | 0.0094 | 0.0024 | 0.0003 | 0.0850 | 0.0390 | 22.5 | 9.2 | 15.1 | 1.6 | 15.1 |
| A.50 | 0.51 | 0.36 | 141 | 0.00 | 0.0370 | 0.0120 | 0.0026 | 0.0003 | 0.1040 | 0.0350 | 37.0 | 12.0 | 16.6 | 1.9 | 15.8 |
| A.51 | 0.46 | 0.70 | 179 | 0.00 | 0.0118 | 0.0060 | 0.0023 | 0.0003 | 0.0380 | 0.0210 | 11.8 | 6.0 | 14.8 | 1.7 | 14.8 |
| A.53 | 0.31 | 0.53 | 106 | 0.00 | 0.0350 | 0.0120 | 0.0027 | 0.0004 | 0.0860 | 0.0320 | 35.0 | 11.0 | 17.3 | 2.3 | 17.0 |
| A.55 | 0.77 | 2.70 | 248 | 0.01 | 0.0192 | 0.0051 | 0.0026 | 0.0002 | 0.0570 | 0.0180 | 19.2 | 5.1 | 16.9 | 1.4 | 16.9 |
| A.56 | 0.56 | 5.70 | 156 | 0.04 | 0.0430 | 0.0130 | 0.0026 | 0.0003 | 0.1340 | 0.0470 | 42.0 | 13.0 | 16.7 | 2.0 | 15.2 |
| A.57 | 0.63 | 1.04 | 233 | 0.00 | 0.0296 | 0.0084 | 0.0023 | 0.0003 | 0.1030 | 0.0340 | 29.5 | 8.3 | 14.6 | 1.6 | 14.2 |
| Epidote zones | | | | | | | | | | | | | | | |
| E.26 | 3.71 | 126 | 410 | 0.31 | 0.1890 | 0.0260 | 0.0039 | 0.0003 | 0.3640 | 0.0520 | 178 | 24 | 24.8 | 1.8 | 24.8 |
| E.43 | 1.89 | 125 | 374 | 0.33 | 0.0900 | 0.0150 | 0.0027 | 0.0002 | 0.2390 | 0.0400 | 87.0 | 14 | 17.5 | 1.5 | 17.5 |
| E.56 | 1.64 | 148 | 571 | 0.26 | 0.0251 | 0.0062 | 0.0022 | 0.0002 | 0.0850 | 0.0180 | 25.1 | 6.1 | 14.4 | 1.5 | 14.4 |

**Supplementary Data 8** Zircon trace elements of the studied calc-silicate zones.

| Spots | Ti | Y | Nb | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu | Hf | Ta | HREE | T/°C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Garnet zones | | | | | | | | | | | | | | | | | | | | | |
| G.1 | 3.7 | 860 | 5.75 | 0.00 | 12.9 | 0.01 | 0.36 | 1.13 | 0.27 | 10.8 | 4.59 | 62.9 | 26.4 | 137 | 32.5 | 348 | 78.7 | 14400 | 5.71 | 596 | 660 |
| G.2 | 0 | 911 | 8 | 0.01 | 12.4 | 0.01 | 0.40 | 1.09 | 0.28 | 10.4 | 4.48 | 63.0 | 27.9 | 143 | 35.5 | 399 | 88.5 | 15000 | 6.20 | 666 | |
| G.3 | 3 | 940 | 4.18 | 0.01 | 14.3 | 0.02 | 0.63 | 1.85 | 0.48 | 12.2 | 5.11 | 68.8 | 29.6 | 146 | 36.0 | 375 | 84.1 | 12400 | 2.46 | 641 | 644 |
| G.4 | 0.99 | 520 | 3.32 | 0.00 | 7.18 | 0.00 | 0.15 | 0.78 | 0.26 | 5.61 | 2.42 | 34.9 | 15.9 | 83.3 | 21.4 | 248 | 59.5 | 10950 | 3.53 | 412 | 567 |
| G.5 | bd. | 920 | 4.58 | 0.00 | 13.9 | 0.02 | 0.33 | 1.34 | 0.35 | 12.3 | 4.87 | 65.2 | 27.9 | 141 | 34.4 | 365 | 81.6 | 13400 | 3.29 | 622 | |
| G.6 | 0.53 | 519 | 3.5 | 0.00 | 9.62 | 0.01 | 0.19 | 0.69 | 0.16 | 5.30 | 2.21 | 32.9 | 15.2 | 83.3 | 21.2 | 248 | 59.8 | 16400 | 4.62 | 412 | 529 |
| G.7 | 2.1 | 820 | 5.94 | 0.00 | 12.1 | 0.01 | 0.14 | 1.20 | 0.29 | 9.80 | 4.18 | 58.9 | 25.1 | 128 | 31.7 | 331 | 74.5 | 14900 | 5.09 | 565 | 618 |
| G.8 | 2.3 | 843 | 5.62 | 0.00 | 12.0 | 0.01 | 0.25 | 1.19 | 0.19 | 9.40 | 4.15 | 57.1 | 26.1 | 132 | 32.7 | 345 | 76.9 | 14700 | 5.32 | 587 | 624 |
| G.10 | 3.3 | 589 | 4.06 | 0.00 | 8.09 | 0.01 | 0.19 | 0.72 | 0.31 | 6.60 | 2.81 | 38.8 | 17.4 | 93.0 | 24.1 | 283 | 65.9 | 12600 | 4.00 | 466 | 651 |
| G.11 | 4.4 | 752 | 4.51 | 0.00 | 15.2 | 0.01 | 0.40 | 1.57 | 0.36 | 10.7 | 4.17 | 53.8 | 23.5 | 117 | 27.9 | 304 | 66.7 | 13200 | 3.45 | 516 | 674 |
| G.13 | 0 | 542 | 2.29 | 0.00 | 11.8 | 0.01 | 0.32 | 0.79 | 0.33 | 7.00 | 2.51 | 37.0 | 16.3 | 88.0 | 21.0 | 232 | 54.6 | 11300 | 1.49 | 396 | |
| G.14 | 2.4 | 790 | 4.13 | 0.00 | 9.50 | 0.01 | 0.33 | 1.32 | 0.37 | 9.50 | 3.80 | 53.2 | 22.2 | 119 | 31.8 | 381 | 89.0 | 10100 | 3.93 | 621 | 627 |
| G.15 | 3.9 | 1030 | 4.62 | 0.00 | 13.9 | 0.04 | 0.63 | 2.55 | 0.63 | 16.2 | 5.82 | 77.0 | 32.1 | 171 | 39.7 | 444 | 98.0 | 12400 | 3.46 | 753 | 664 |
| G.16 | 1.6 | 1210 | 11.4 | 0.00 | 13.8 | 0.01 | 0.39 | 1.66 | 0.25 | 14.1 | 5.85 | 88.9 | 38.0 | 192 | 46.8 | 487 | 111 | 19800 | 21.9 | 837 | 598 |
| G.17 | 2.8 | 431 | 2.93 | 0.00 | 10.1 | 0.00 | 0.25 | 0.62 | 0.25 | 5.20 | 1.86 | 26.9 | 11.9 | 64.1 | 17.5 | 209 | 48.9 | 12100 | 2.45 | 340 | 639 |
| G.18 | bd. | 782 | 4.98 | 0.00 | 14.6 | 0.02 | 0.46 | 1.30 | 0.34 | 10.2 | 4.41 | 55.9 | 24.4 | 121 | 29.4 | 310 | 70.9 | 13100 | 4.10 | 531 | |
| G.19 | 3.2 | 596 | 3.44 | 0.00 | 12.8 | 0.01 | 0.36 | 1.16 | 0.35 | 7.41 | 3.09 | 40.8 | 17.3 | 90.0 | 22.2 | 249 | 55.1 | 12400 | 2.45 | 416 | 649 |
| G.20 | bd. | 990 | 4.08 | 0.01 | 14.4 | 0.02 | 0.61 | 1.71 | 0.40 | 14.3 | 5.63 | 75.3 | 30.8 | 150 | 35.3 | 369 | 80.9 | 12700 | 3.09 | 635 | |
| G.21 | 1.5 | 521 | 3.17 | 0.00 | 8.70 | 0.02 | 0.22 | 0.79 | 0.34 | 5.34 | 2.60 | 35.0 | 15.5 | 82.0 | 21.6 | 248 | 59.6 | 11800 | 3.04 | 411 | 594 |
| G.22 | 2.4 | 861 | 3.28 | 0.00 | 14.0 | 0.03 | 0.50 | 1.52 | 0.45 | 12.9 | 4.86 | 64.5 | 26.3 | 132 | 31.8 | 330 | 73.1 | 12600 | 2.40 | 567 | 627 |
| G.23 | 4.1 | 368 | 1.93 | 0.00 | 8.04 | 0.00 | 0.19 | 0.39 | 0.21 | 3.94 | 1.69 | 23.6 | 10.6 | 59.9 | 16.1 | 188 | 46.8 | 10700 | 1.23 | 311 | 668 |
| G.25 | 0 | 880 | 5.96 | 0.00 | 13.4 | 0.02 | 0.17 | 1.02 | 0.32 | 9.60 | 4.67 | 61.6 | 26.3 | 140 | 33.5 | 353 | 79.0 | 14400 | 4.73 | 606 | |
| G.26 | 0 | 648 | 2.79 | 0.00 | 11.5 | 0.00 | 0.16 | 1.16 | 0.26 | 7.70 | 3.19 | 44.9 | 19.6 | 103 | 25.2 | 277 | 63.6 | 12300 | 2.10 | 469 | |
| G.27 | 0 | 428 | 2.14 | 0.00 | 9.30 | 0.00 | 0.23 | 0.52 | 0.18 | 4.21 | 1.75 | 24.5 | 12.5 | 65.7 | 17.8 | 219 | 55.0 | 11600 | 1.38 | 358 | |
| G.28 | 4 | 594 | 3.6 | 0.00 | 9.80 | 0.00 | 0.35 | 0.63 | 0.28 | 6.60 | 2.46 | 38.2 | 17.0 | 96.0 | 26.0 | 304 | 77.5 | 12300 | 2.73 | 504 | 666 |
| G.29 | 2.1 | 1050 | 2.57 | 0.00 | 11.2 | 0.03 | 0.82 | 2.25 | 0.86 | 16.2 | 6.13 | 80.0 | 32.7 | 167 | 39.2 | 446 | 102 | 10900 | 2.90 | 754 | 618 |
| G.31 | 8.5 | 704 | 4.6 | 0.00 | 12.0 | 0.01 | 0.45 | 1.24 | 0.34 | 8.60 | 3.47 | 47.5 | 20.3 | 112 | 29.2 | 343 | 83.2 | 11900 | 4.27 | 567 | 731 |
| G.32 | 0 | 334 | 2.06 | 0.00 | 8.49 | 0.00 | 0.21 | 0.54 | 0.17 | 3.58 | 1.58 | 21.5 | 9.70 | 53.5 | 14.3 | 169 | 40.0 | 10100 | 1.68 | 277 | |
| G.33 | 0 | 918 | 6.5 | 0.00 | 14.0 | 0.00 | 0.33 | 1.07 | 0.28 | 9.70 | 4.86 | 64.0 | 28.3 | 144 | 34.6 | 366 | 83.1 | 16400 | 6.15 | 628 | |

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G.34 | 3.3 | 605 | 1.93 | 0.00 | 10.4 | 0.00 | 0.46 | 1.18 | 0.40 | 8.70 | 3.17 | 42.6 | 18.5 | 97.2 | 23.9 | 266 | 61.4 | 10900 | 1.17 | 449 | 651 |
| G.35 | 4.3 | 1050 | 4.17 | 0.00 | 15.9 | 0.03 | 0.74 | 2.62 | 0.58 | 16.0 | 6.25 | 80.6 | 32.4 | 161 | 38.5 | 423 | 89.4 | 12700 | 2.46 | 712 | 672 |
| G.38 | 2.9 | 477 | 2.92 | 0.00 | 11.4 | 0.00 | 0.15 | 0.77 | 0.19 | 5.15 | 2.33 | 32.7 | 14.4 | 80.0 | 20.5 | 242 | 58.4 | 15700 | 2.28 | 401 | 641 |
| G.39 | 0.6 | 643 | 3.44 | 0.00 | 10.7 | 0.03 | 0.25 | 1.21 | 0.22 | 7.90 | 3.15 | 44.4 | 19.1 | 104 | 26.8 | 313 | 72.0 | 11700 | 4.03 | 516 | 536 |
| G.40 | 0 | 450 | 2.76 | 0.00 | 8.41 | 0.02 | 0.25 | 0.56 | 0.26 | 5.01 | 2.04 | 28.6 | 13.3 | 69.4 | 19.1 | 222 | 54.0 | 10480 | 2.14 | 365 | |
| G.41 | 0.44 | 715 | 2.25 | 0.00 | 13.2 | 0.00 | 0.35 | 1.07 | 0.45 | 9.70 | 3.76 | 49.9 | 21.5 | 108 | 28.2 | 320 | 74.4 | 13000 | 1.63 | 531 | 518 |
| G.42 | bd. | 1240 | 2.68 | 0.00 | 13.3 | 0.05 | 1.06 | 3.71 | 0.84 | 20.6 | 7.80 | 98.0 | 39.3 | 202 | 48.7 | 520 | 114 | 10500 | 2.67 | 885 | |
| G.43 | 4.7 | 704 | 4.29 | 0.22 | 10.8 | 0.09 | 0.63 | 1.16 | 0.28 | 7.20 | 3.09 | 44.6 | 20.5 | 113 | 31.1 | 348 | 84.0 | 11400 | 3.04 | 576 | 679 |
| G.44 | 3.6 | 599 | 3.77 | 0.00 | 11.3 | 0.02 | 0.23 | 1.09 | 0.31 | 8.02 | 3.27 | 43.4 | 18.7 | 93.8 | 23.1 | 247 | 51.9 | 11350 | 2.97 | 416 | 658 |
| G.45 | 0 | 933 | 7.36 | 0.00 | 12.9 | 0.01 | 0.29 | 1.16 | 0.25 | 9.85 | 4.62 | 64.5 | 28.3 | 146 | 35.6 | 383 | 84.5 | 17300 | 10.8 | 649 | |
| G.46 | bd. | 1450 | 2.96 | 0.00 | 20.6 | 0.04 | 1.00 | 3.09 | 0.83 | 23.5 | 9.20 | 117.0 | 45.6 | 218 | 50.8 | 504 | 108 | 13300 | 2.49 | 881 | |
| G.47 | 1 | 443 | 2.66 | 0.00 | 10.5 | 0.01 | 0.25 | 0.82 | 0.23 | 5.28 | 2.15 | 28.5 | 12.8 | 71.5 | 18.7 | 221 | 54.5 | 11400 | 1.87 | 366 | 567 |
| G.48 | 0.55 | 609 | 3.26 | 0.00 | 7.67 | 0.01 | 0.23 | 1.00 | 0.26 | 7.47 | 2.96 | 41.6 | 18.4 | 94.0 | 24.8 | 280 | 67.6 | 10400 | 3.10 | 466 | 531 |
| G.49 | 3.7 | 620 | 2.44 | 0.00 | 9.00 | 0.01 | 0.40 | 0.83 | 0.35 | 6.60 | 2.78 | 38.9 | 18.6 | 94.0 | 25.4 | 274 | 67.0 | 11400 | 1.97 | 460 | 660 |
| G.50 | 1.3 | 592 | 3.34 | 0.01 | 7.47 | 0.01 | 0.22 | 0.86 | 0.27 | 6.30 | 2.77 | 40.1 | 17.8 | 94.0 | 24.9 | 286 | 70.0 | 10100 | 2.81 | 475 | 584 |
| G.51 | 1.1 | 950 | 5.08 | 0.00 | 11.6 | 0.01 | 0.38 | 1.04 | 0.34 | 10.5 | 4.04 | 59.4 | 27.0 | 143 | 38.5 | 457 | 111 | 12000 | 3.25 | 750 | 573 |
| G.52 | 0 | 1030 | 6.83 | 0.00 | 15.4 | 0.01 | 0.50 | 1.28 | 0.32 | 12.9 | 5.46 | 74.8 | 31.8 | 160 | 38.5 | 409 | 88.3 | 16200 | 6.89 | 696 | |
| G.53 | 0 | 940 | 6.34 | 0.01 | 13.2 | 0.01 | 0.33 | 1.01 | 0.35 | 10.3 | 4.45 | 64.9 | 29.0 | 147 | 34.4 | 361 | 84.0 | 16300 | 7.29 | 626 | |
| G.54 | 3.1 | 773 | 1.4 | 0.00 | 13.9 | 0.02 | 0.57 | 1.60 | 0.51 | 9.70 | 4.20 | 57.8 | 23.7 | 123 | 30.4 | 341 | 77.9 | 11000 | 1.39 | 572 | 646 |
| G.55 | 3.5 | 348 | 1.7 | 0.00 | 7.00 | 0.00 | 0.09 | 0.29 | 0.17 | 2.82 | 1.43 | 21.6 | 9.60 | 56.0 | 14.9 | 175 | 43.6 | 13400 | 0.88 | 290 | 656 |
| G.56 | 5.3 | 652 | 3.6 | 0.01 | 8.80 | 0.01 | 0.33 | 1.01 | 0.30 | 7.96 | 3.25 | 44.5 | 19.2 | 104 | 27.3 | 309 | 76.9 | 10500 | 3.74 | 517 | 689 |
| G.57 | 0.53 | 837 | 3.74 | 0.00 | 9.60 | 0.01 | 0.38 | 1.27 | 0.28 | 9.17 | 3.86 | 56.4 | 25.3 | 134 | 34.8 | 392 | 96.0 | 9900 | 3.16 | 657 | 529 |
| G.58 | 3.4 | 710 | 4.4 | 0.00 | 11.9 | 0.02 | 0.40 | 1.04 | 0.31 | 8.30 | 3.34 | 46.3 | 21.1 | 110 | 28.6 | 329 | 79.0 | 12400 | 4.38 | 547 | 654 |
| G.60 | 7.6 | 690 | 4.3 | 0.00 | 9.10 | 0.00 | 0.15 | 0.93 | 0.21 | 7.20 | 3.01 | 43.6 | 19.7 | 104 | 28.0 | 328 | 79.0 | 13100 | 3.48 | 539 | 721 |
| G.61 | 2.2 | 471 | 3.09 | 0.01 | 8.11 | 0.01 | 0.17 | 0.76 | 0.18 | 5.29 | 2.07 | 31.3 | 14.0 | 73.2 | 19.7 | 221 | 53.1 | 10200 | 2.84 | 367 | 621 |
| G.63 | 2.3 | 1020 | 7.8 | 0.00 | 14.9 | 0.01 | 0.26 | 1.43 | 0.36 | 12.0 | 5.37 | 74.2 | 32.6 | 170 | 38.7 | 420 | 97.0 | 19600 | 11.8 | 726 | 624 |
| Amphibole zones | | | | | | | | | | | | | | | | | | | | | |
| A.33 | bd. | 17.3 | 0.61 | 0.00 | 0.16 | 0.00 | 0.00 | 0.05 | 0.03 | 0.45 | 0.14 | 1.27 | 0.34 | 1.28 | 0.23 | 2.69 | 0.51 | 15800 | 0.14 | 4.71 | |
| A.2 | 0.00 | 19.9 | 0.50 | 0.00 | 0.14 | 0.00 | 0.00 | 0.12 | 0.04 | 0.53 | 0.18 | 1.66 | 0.45 | 1.73 | 0.29 | 2.57 | 0.49 | 14400 | 0.12 | 5.08 | |
| A.3 | 0.00 | 41.2 | 0.58 | 0.00 | 0.08 | 0.00 | 0.00 | 0.05 | 0.02 | 0.8 | 0.26 | 3.19 | 0.90 | 3.32 | 0.59 | 4.78 | 0.95 | 16900 | 0.16 | 9.64 | |
| A.7 | 0.00 | 14.6 | 0.56 | 0.00 | 0.15 | 0.00 | 0.00 | 0.06 | 0.02 | 0.38 | 0.13 | 1.12 | 0.33 | 1.13 | 0.21 | 1.96 | 0.31 | 12900 | 0.11 | 3.61 | |
| A.8 | 0.00 | 56.6 | 0.68 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.28 | 0.20 | 3.39 | 1.40 | 6.72 | 1.44 | 14.4 | 3.31 | 9700 | 0.14 | 25.87 | |

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A.10 | 7.80 | 24.0 | 0.73 | 0.03 | 0.21 | 0.00 | 0.05 | 0.10 | 0.05 | 0.85 | 0.22 | 2.05 | 0.48 | 1.98 | 0.32 | 3.40 | 0.74 | 14700 | 0.14 | 6.44 | 723 |
| A.11 | 0.00 | 36.8 | 0.57 | 0.02 | 0.53 | 0.01 | 0.11 | 0.46 | 0.19 | 2.12 | 0.49 | 3.71 | 0.91 | 3.19 | 0.58 | 5.09 | 0.86 | 13400 | 0.14 | 9.72 | |
| A.13 | 0.57 | 24.5 | 1.71 | 0.01 | 1.99 | 0.02 | 0.32 | 0.88 | 0.34 | 2.27 | 0.34 | 2.33 | 0.54 | 1.6 | 0.29 | 3.01 | 0.59 | 15800 | 0.70 | 5.49 | 533 |
| A.16 | 0.00 | 19.8 | 0.44 | 0.05 | 1.28 | 0.01 | 0.13 | 0.18 | 0.05 | 0.5 | 0.18 | 1.57 | 0.49 | 1.61 | 0.33 | 2.86 | 0.60 | 14700 | 0.10 | 5.40 | |
| A.17 | 0.00 | 27.1 | 0.43 | 0.01 | 0.41 | 0.00 | 0.07 | 0.15 | 0.06 | 1.23 | 0.43 | 2.68 | 0.69 | 2.12 | 0.40 | 3.54 | 0.56 | 12900 | 0.10 | 6.62 | |
| A.22 | bd. | 28.8 | 0.58 | 0.00 | 1.27 | 0.00 | 0.06 | 0.44 | 0.17 | 1.42 | 0.31 | 2.50 | 0.68 | 2.44 | 0.44 | 3.87 | 0.82 | 15800 | 0.18 | 7.57 | |
| A.23 | 0.95 | 21.9 | 0.50 | 0.00 | 0.94 | 0.00 | 0.02 | 0.21 | 0.12 | 1.22 | 0.20 | 1.81 | 0.47 | 1.77 | 0.28 | 2.05 | 0.52 | 15600 | 0.12 | 4.62 | 564 |
| A.24 | 0.00 | 30.0 | 0.70 | 0.00 | 0.38 | 0.00 | 0.00 | 0.13 | 0.09 | 1.25 | 0.23 | 2.61 | 0.76 | 2.56 | 0.49 | 4.49 | 0.76 | 14400 | 0.15 | 8.30 | |
| A.28 | 0.00 | 31.8 | 0.61 | 0.00 | 0.23 | 0.00 | 0.00 | 0.04 | 0.09 | 1.12 | 0.34 | 2.45 | 0.71 | 2.54 | 0.48 | 3.98 | 0.76 | 21200 | 0.12 | 7.76 | |
| A.29 | bd. | 16.0 | 0.48 | 0.00 | 0.36 | 0.00 | 0.00 | 0.00 | 0.04 | 0.53 | 0.11 | 1.19 | 0.32 | 1.08 | 0.24 | 1.93 | 0.36 | 14500 | 0.11 | 3.61 | |
| A.34 | 0.00 | 22.2 | 0.57 | 0.00 | 0.19 | 0.00 | 0.02 | 0.04 | 0.00 | 0.35 | 0.16 | 1.30 | 0.48 | 1.94 | 0.38 | 3.49 | 0.51 | 14700 | 0.12 | 6.32 | |
| A.35 | 0.00 | 25.8 | 0.69 | 0.00 | 1.26 | 0.01 | 0.12 | 0.07 | 0.03 | 0.84 | 0.22 | 1.77 | 0.60 | 1.87 | 0.40 | 3.00 | 0.73 | 15400 | 0.12 | 6.00 | |
| A.36 | 0.00 | 22.0 | 0.60 | 0.00 | 0.12 | 0.00 | 0.00 | 0.01 | 0.05 | 0.7 | 0.19 | 1.51 | 0.52 | 1.74 | 0.36 | 2.84 | 0.59 | 14900 | 0.12 | 5.52 | |
| A.39 | 0.00 | 23.9 | 0.50 | 0.00 | 0.11 | 0.00 | 0.00 | 0.01 | 0.09 | 0.67 | 0.26 | 2.50 | 0.57 | 2.17 | 0.43 | 3.56 | 0.73 | 13200 | 0.09 | 6.89 | |
| A.41 | 6.60 | 20.7 | 0.56 | 0.04 | 1.64 | 0.02 | 0.15 | 0.28 | 0.10 | 1.14 | 0.22 | 1.97 | 0.50 | 1.77 | 0.31 | 2.35 | 0.52 | 14900 | 0.12 | 4.95 | 708 |
| A.43 | 0.00 | 23.2 | 0.63 | 0.00 | 0.73 | 0.02 | 0.44 | 0.41 | 0.11 | 0.85 | 0.17 | 1.87 | 0.52 | 1.86 | 0.34 | 3.15 | 0.70 | 16900 | 0.11 | 6.05 | |
| A.44 | 0.00 | 23.3 | 0.50 | 0.00 | 0.14 | 0.00 | 0.00 | 0.03 | 0.07 | 0.92 | 0.24 | 1.91 | 0.54 | 1.74 | 0.35 | 3.03 | 0.52 | 15100 | 0.12 | 5.64 | |
| A.45 | 0.00 | 29.5 | 0.46 | 0.00 | 0.23 | 0.00 | 0.00 | 0.07 | 0.04 | 1.17 | 0.32 | 2.63 | 0.68 | 2.38 | 0.42 | 3.70 | 0.64 | 14800 | 0.12 | 7.14 | |
| A.47 | 0.00 | 23.4 | 0.55 | 0.03 | 0.47 | 0.03 | 0.14 | 0.10 | 0.03 | 0.7 | 0.21 | 1.80 | 0.54 | 1.92 | 0.33 | 3.05 | 0.62 | 15100 | 0.12 | 5.92 | |
| A.49 | 0.00 | 21.5 | 0.58 | bd. | 0.41 | 0.00 | 0.04 | 0.13 | 0.04 | 0.97 | 0.18 | 1.91 | 0.51 | 2.02 | 0.34 | 3.37 | 0.64 | 13300 | 0.08 | 6.37 | |
| A.50 | 0.00 | 22.2 | 0.48 | 0.00 | 0.08 | 0.00 | 0.00 | 0.02 | 0.05 | 0.5 | 0.18 | 1.72 | 0.47 | 1.85 | 0.32 | 2.57 | 0.49 | 18700 | 0.21 | 5.22 | |
| A.51 | 0.00 | 22.8 | 0.61 | 0.00 | 0.17 | 0.00 | 0.01 | 0.05 | 0.02 | 0.89 | 0.18 | 1.59 | 0.51 | 1.71 | 0.34 | 2.82 | 0.55 | 16000 | 0.13 | 5.42 | |
| A.53 | 0.00 | 21.4 | 0.52 | 0.00 | 0.07 | 0.00 | 0.00 | 0.03 | 0.01 | 0.48 | 0.19 | 1.88 | 0.46 | 1.84 | 0.34 | 3.27 | 0.56 | 14500 | 0.12 | 6.01 | |
| A.55 | 0.00 | 29.0 | 0.58 | 0.01 | 0.37 | 0.00 | 0.01 | 0.05 | 0.10 | 0.83 | 0.24 | 2.35 | 0.70 | 2.61 | 0.43 | 4.20 | 0.79 | 15200 | 0.12 | 8.03 | |
| A.56 | bd. | 32.2 | 0.59 | 0.01 | 0.40 | 0.00 | 0.07 | 0.07 | 0.08 | 1.56 | 0.36 | 2.98 | 0.89 | 3.18 | 0.46 | 4.57 | 0.81 | 13500 | 0.11 | 9.02 | |
| A.57 | 0.00 | 22.0 | 0.50 | 0.00 | 0.24 | 0.00 | 0.00 | 0.10 | 0.09 | 0.84 | 0.22 | 1.80 | 0.49 | 1.65 | 0.32 | 3.16 | 0.52 | 16100 | 0.14 | 5.65 | |
| Epidote zones | | | | | | | | | | | | | | | | | | | | | |
| E.26 | 0.52 | 198 | 0.77 | 0.14 | 8.50 | 0.04 | 0.28 | 0.24 | 0.13 | 2.18 | 0.76 | 11.20 | 5.37 | 30.9 | 8.40 | 107 | 29.1 | 10700 | 0.16 | 175 | 528 |
| E.43 | 5 | 193 | 0.86 | 0.08 | 8.40 | 0.03 | 0.14 | 0.27 | 0.15 | 2.47 | 0.84 | 11.50 | 5.37 | 30.4 | 8.70 | 105 | 29.7 | 12700 | 0.16 | 174 | 685 |
| E.56 | 1.3 | 206 | 1.08 | 0.00 | 10.4 | 0.00 | 0.07 | 0.32 | 0.16 | 1.99 | 0.88 | 11.60 | 5.50 | 33.5 | 9.10 | 115 | 31.2 | 13400 | 0.29 | 189 | 584 |

**Supplementary Data 9** Compilation of the location, age, estimated areas and corresponding $CO_2$ flux of the Himalayan leucogranite. Longitude values represent the locations of the centers of leucogranite bodies. Estimated areas are calculated in ArcGIS and PS software based on published geological mapping.

| Region | Longitude | Area | $CO_2$ flux | Age (Ma) | Basis | References |
|---|---|---|---|---|---|---|
| **Tethyan Himalayan Sequence** | | | | | | |
| 1. Zanskar(Gianbul) | 77.0 | 589 | 78~470 | 20.6~19.5 | U/Pb monazite ages | Noble and Searle, 1995 |
| | | | | 21.2 ± 0.6 | Weighted mean of Th/Pb momazite ages | Horton et al., 2015 |
| | | | | 22.1 ± 0.4 | Weighted mean of Th/Pb momazite ages | Horton et al., 2015 |
| | | | | 21.3 ± 0.1 | Weighted mean of U/Pb uraninite, xenotime, and | Walker et al., 1999 |
| | | | | 21.4 ± 0.1 | Weighted mean of U/Pb uraninite ages | Walker et al., 1999 |
| | | | | 22.1 ± 0.4 | Weighted mean of U/Pb monazite ages | Walker et al., 1999 |
| | | | | 22.2 ± 0.2 | Weighted mean of U/Pb monazite ages | Dezes et al., 1999 |
| | | | | 22.7 ± 0.9 | Weighted mean of Th/Pb monazite ages | Robyr et al., 2006 |
| | | | | 22.7 ± 0.9 | Weighted mean of Th/Pb monazite ages | Robyr et al., 2006 |
| | | | | 23.3 ± 0.9 | Weighted mean of Th/Pb monazite ages | Robyr et al., 2006 |
| | | | | 24.0 ± 0.3 | Weighted mean of U/Pb monazite ages | Finch et al., 2014 |
| | | | | 26.6 ± 0.2 | Weighted mean of Th/Pb monazite ages | Robyr et al., 2006 |
| 2. Leo Pargil | 78.7 | 205 | 27~164 | 17.9 ± 0.1 | Weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | 18.6 ± 0.1 | Weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | 19.0 ± 0.2 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 19.0 ± 0.3 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 19.1 ± 0.3 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 19.2 ± 0.2 | Youngest weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | 19.3 ± 0.2 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 19.6 ± 0.1 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 19.9 ± 0.1 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 20.1 ± 0.3 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 20.2 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | 20.7 ± 0.2 | Youngest weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | 21.7 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | 21.5 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | 21.8 ± 0.4 | Youngest weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | ~22.0 | Mean of U/Pb zircon ages | Leech, 2008 |
| | | | | 22.1 ± 0.3 | Weighted mean of youngest Th/Pb monazite | Lerderer et al., 2013 |
| | | | | 26.2 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| | | | | 29.0 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lerderer et al., 2013 |
| 3. Grula Mandhata | 82.0 | 59 | 8~47 | 11.2 ± 0.1 | Weighted mean of U/Pb zircon ages | Cheng et al., 2020 |
| | | | | 12.7 ± 0.5 | Weighted mean of U/Pb zircon ages | Cheng et al., 2020 |
| | | | | 18.6 ± 0.9 | Weighted mean of U/Pb zircon ages | Pullen et al., 2011 |
| | | | | 17.2 ± 1.3 | Weighted mean of U/Pb zircon ages | Pullen et al., 2011 |
| 4. Mustang-Dlou-Mugu | 83.5 | 1329 | 175~1061 | 21.3 ± 0.1 | Weighted mean of Th/Pb monazite ages | Lihter et al., 2020 |
| 5. Changgo-Kung Tang | 84.5 | 1705 | 225~1361 | 34.4 ± 0.5 | Intercept U/Pb zircon ages | Larson et al., 2010 |
| | | | | 18.5 ± 0.4 | Weighted mean of U/Pb zircon ages | Larson et al., 2010 |
| | | | | 17.3 ± 0.3 | Weighted mean of U/Pb zircon ages | Larson et al., 2010 |
| 6. Malashan | 85.5 | 76 | 10~61 | 17.8 ± 2.2 | Weighted mean of U/Pb zircon ages | Aoya et al., 2005 |
| | | | | 17.6 ± 1.2 | Youngest weighted mean of U/Pb zircon ages | Zhang JJ et al., 2012 |
| | | | | 18.6 ± 5.6 | Weighted mean of U/Pb zircon ages | Aoya et al., 2005 |
| 7. Paiku | 85.7 | 309 | 41~247 | 19.3 ± 3.9 | Weigted mean of U/Pb zircon ages | Kawakami et al., 2007 |
| 8. Xiaru | 86.3 | 263 | 35~210 | ~35 .0 | Weighted mean of U/Pb zircone ages | Liu et al., 2015 |
| 9. Dingri-Suzuo | 86.4 | 200 | 26~160 | 16.1 ± 0.1 | Weighted mean of U/Pb zircon ages | Fan et al., 2021 |
| | | | | 16.3 ± 0.1 | Weighted mean of U/Pb zircon ages | Fan et al., 2021 |
| | | | | 16.2 ± 0.1 | Weighted mean of U/Pb zircon ages | Fan et al., 2021 |
| | | | | 16.1 ± 0.2 | Weighted mean of Th/Pb monazite ages | Fan et al., 2021 |
| | | | | 16.3 ± 0.2 | Weighted mean of Th/Pb monazite ages | Fan et al., 2021 |
| | | | | 16.1 ± 0.1 | Weighted mean of Th/Pb monazite ages | Fan et al., 2021 |
| 10. Ama Drime- | 87.6 | 233 | 31~186 | 12.5 ± 0.9 | Youngest weigted mean of Th/Pb monazite ages | Kali et al., 2010 |
| | | | | 13.5 ± 0.3 | Weigted mean of Th/Pb monazite ages | Kali et al., 2010 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | 16.9 ± 0.4 | Weighetd mean of U/Pb monazite ages | Leloup et al., 2010 |
| | | | | 16.0 ± 0.6 | Youngest Weighted mean of U/Pb monazite ages | Leloup et al., 2010 |
| 11. Lhagoi Kangri | 87.5 | 91 | 13~72 | 15.1 ± 0.5 | Weighted mean of U/Pb monazite ages | Scharer et al., 1986 |
| 12. Mabja | 87.9 | 106 | 14~85 | 11.2 ± 0.5 | concordant U/Pb zircon and xenotime age | King et al., 2011 |
| | | | | 8.8 ± 0.2 | concordant U/Pb zircon, monazite and xenotime | King et al., 2011 |
| | | | | 9.2 ± 0.9 | Weigted mean of U/Pb monazite ages | Scharer et al., 1986 |
| | | | | 9.8 ± 0.7 | Weigted mean of U/Pb monazite ages | Scharer et al., 1986 |
| | | | | 14.4 ± 0.2 | Weighted mean of U/Pb monazite ages | Zhang et al., 2004 |
| | | | | 23.1 ± 0.8 | Weighed mean of U/Pb zircon ages | Lee et al., 2006 |
| 13. Kuday | 88.4 | 132 | 17~105 | 14.5 ± 0.9 | Weighted mean of U/Pb zircon age | King et al., 2011 |
| | | | | 16.2 ± 0.4 | Weighted mean of U/Pb zircon age | Lee and Whitehouse, |
| | | | | 21.5 ± 0.4 | Weighted mean of U/Pb zircon age | Lee and Whitehouse, |
| | | | | 22.6 ± 0.4 | Low intercept of U/Pb xenotime age | King et al., 2011 |
| | | | | 27.5 ± 1.0 | concordant U/Pb zircon age | King et al., 2011 |
| | | | | 27.5 ± 0.5 | Weighted mean of U/Pb zircon age | Zhang et al., 2004 |
| | | | | 28.1 ± 0.4 | concordant U/Pb zircon age | King et al., 2011 |
| | | | | 35.0 ± 0.8 | Weighted mean of U/Pb zircon age | Lee and Whitehouse, |
| 14. Kampa | 88.5 | 181 | 24~145 | 23.3 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lin et al., 2020 |
| | | | | 22.7 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lin et al., 2020 |
| | | | | 24.0 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lin et al., 2020 |
| | | | | 24.6 ± 0.2 | Weighted mean of Th/Pb monazite ages | Lin et al., 2020 |
| | | | | 27.1 ± 0.8 | Weighted mean of U/Pb zircon ages | Lin et al., 2020 |
| | | | | 25.9 ± 0.5 | Weighted mean of U/Pb zircon ages | Lin et al., 2020 |
| | | | | 25.7 ± 0.8 | Weighted mean of U/Pb zircon ages | Lin et al., 2020 |
| | | | | 26.2 ± 0.6 | Weighted mean of U/Pb zircon ages | Lin et al., 2020 |
| 15. Kangmar | 89.4 | 66 | 9~53 | 18.5 ± 0.1 | Biotite Ar-Ar ages | Liu et al., 2004 |
| | | | | 17.6 ± 0.1 | Biotite Ar-Ar ages | Liu et al., 2004 |
| 16. Ramba | 90.0 | 31 | 4~25 | 7.6 ± 0.2 | Weighted mean of U/Pb zircon ages | Liu et al., 2014 |
| | | | | 7.7 ± 0.2 | Weighted mean of U/Pb xenotime ages | Liu et al., 2014 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | 7.9 ± 0.2 | Weighted mean of U/Pb xenotime ages | Liu et al., 2014 |
| | | | | 8.0 ± 0.5 | Weighted mean of U/Pb zircon ages | Liu et al., 2014 |
| | | | | 8.1 ± 0.2 | Weighted mean of U/Pb monazite ages | Liu et al., 2014 |
| | | | | 8.1 ± 0.3 | Weighted mean of U/Pb monazite ages | Liu et al., 2014 |
| | | | | 8.3 ± 0.5 | Weighted mean of U/Pb zircon ages | Liu et al., 2014 |
| | | | | 28.2 ± 5.2 | Weighted mean of U/Pb zircone ages | Liu et al., 2014 |
| | | | | 44.1 ± 0.8 | U/Pb zircone age | Liu et al., 2014 |
| | | | | 44.3 ± 0.5 | U/Pb zircone age | Liu et al., 2014 |
| 17. Yardoi-Dala | 92.0 | 81 | 11~65 | 20.3 ± 1.9 | Mean of U/Pb zircon ages | Yan et al., 2012 |
| | | | | ~43 Ma | Mean of U/Pb zircon ages | Gao et al., 2020 |
| | | | | 17~18 Ma | Mean of U/Pb zircon ages | Gao et al., 2020 |
| 18. Cuonadong-Ridang | 92.1 | 126 | 17~101 | 20.3 ± 0.2 | Weighted mean of Th/Pb monazite ages | Han et al., 2020 |
| | | | | 16.9 ± 0.1 | Weighted mean of U/Pb zircon ages | Wang et al.,2023 |
| **Greater Himalayan Sequence** | | | | | | |
| 19. Garhwal-Gangotri | 78.7 | 74 | 10~59 | 22.4 ± 0.5 | Th/Pb monazite age (unknown) | Harrison et al., 1997 |
| 20. Shiviling | 79.4 | 382 | 50~305 | 21.9 ± 0.5 | Th/Pb monazite age (unknown) | Harrison et al., 1997 |
| | | | | 23.0 ± 0.4 | Weighted mean of youngest U/Pb monazite ages | Searle et al., 1999 |
| 21. Malari | 79.5 | ＜10 | 1~8 | 19.0 ± 0.5 | Weighted mean of U/Pb zircon ages | Sachan et al., 2010 |
| | | | | 18.1 ± 1.0 | Weighted mean of U/Pb zircon ages | Sachan et al., 2010 |
| 22. Bura Buri | 82.5 | 227 | 30~181 | 23.6 ± 0.8 | Weighted mean of U/Pb monazite ages | Carosi et al., 2013 |
| 23. Dhaulagiri- | 84.0 | < 10 | 1~8 | 22.1 + 0.6/- | Weighted mean of U-Pb zircon ages | Hodge et al., 1996 |
| 24. Manaslu | 84.7 | 442 | 58~353 | 17.6 ± 0.3 | Single population of U/Pb monazite ages | Harrison et al., 1999 |
| | | | | 19.3 ± 0.3 | Weighted mean of U/Pb monazite ages | Harrison et al., 1999 |
| | | | | 22.4 ± 0.5 | Weighted mean of Th/Pb monazite ages | Harrison et al., 1995b |
| | | | | 25.0 ± 0.5 | U/Pb monazite ages | Deniel et al., 1987 |
| 25. Gyirong-Langtang | 85.4 | 477 | 63~381 | ~16.1 | U/Pbmonazite ages | Liao et al., 2003 |
| | | | | 20.0 ± 1.7 | Youngest weighted mean of U/Pb zircon ages | Zhang et al., 2012 |
| | | | | 21.8 ± 1.3 | Youngest weighted mean of U/Pb zircon ages | Zhang et al., 2012 |
| 26. Shisha Pangma | 85.8 | 336 | 44~269 | 17.3 ± 0.4 | Weighted mean of U/Pb monazite ages | Searle et al., 1997 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 27. Nyalam | 86.4 | 127 | 17~102 | 14.1 ± 1.4 | Youngest weighted mean of U/Pb zircon ages | Wang et al., 2013 |
| | | | | 16.8 ± 0.6 | Weighted mean of U/Pb monazite ages | Scharer et al., 1986 |
| 28. Rongbuk | 86.6 | 208 | 27~166 | 16.4 ± 0.1 | Youngest weighted mean of Th/Pb monazite ages | Cottle et al., 2015 |
| | | | | 22.0 ± 1.0 | Weighted mean of Th/Pb momazite ages | Harrison et al., 1995b |
| | | | | 21.6--20.6 | U/Pb xenotime ages | Hodges et al., 1992 |
| | | | | 16.4 ± 0.6 | Weighted mean of Th/Pb monazite ages | Murphy and Harrison, |
| | | | | 16.8 ± 0.8 | Weighted mean of Th/Pb monazite ages | Murphy and Harrison, |
| | | | | 15.6 ± 0.1 | Weighted mean of Th/Pb monazite ages | Cottle et al., 2015 |
| | | | | 15.4 ± 0.1 | Weighted mean of Th/Pb monazite ages | Cottle et al., 2015 |
| | | | | 15.3 ± 0.1 | Weighted mean of Th/Pb monazite ages | Cottle et al., 2015 |
| 29. Everest-Lhotse | 86.9 | 288 | 38~230 | 20.5--21.3 | Younget cluster of U/Pb monazite and xenotime | Simpson et al., 2000 |
| | | | | 15.6 ± 0.2 | Youngest weighted mean of U/Pb xenotime ages | Streule et al., 2010 |
| | | | | 16.0 ± 0.6 | Youngest weighted mean of U/Pb monazite ages | Streule et al., 2010 |
| | | | | 16.1 ± 0.2 | Youngest weighted mean of U/Pb monazite ages | Streule et al., 2010 |
| | | | | 23.2 ± 0.8 | Weighted mean of U/Pb zircon ages | Streule et al., 2010 |
| | | | | 23.8 ± 0.2 | Weighted mean of U/Pb zircon ages | Streule et al., 2010 |
| | | | | 14.3 ± 0.6 | Weigted mean of U/Pb monazite ages | Scharer et al., 1986 |
| 30. Kanchenjunga- | 88.6 | <10 | 1~8 | 13.2 ± 0.3 | Youngest weighted mean of U/Pb monazite ages | Kellett et al., 2013 |
| | | | | 14.5 ± 0.1 | Youngest weighted mean of U/Pb/Th monazite | Kellett et al., 2013 |
| | | | | 14.7 ± 0.1 | Youngest weighted mean of U/Pb/Th monazite | Kellett et al., 2013 |
| | | | | 17.0 ± 1.6 | Weighted mean of Th/Pb monazite ages | Edwards et al., 2002, |
| 31. Yadong-Dingga- | 89.0 | 281 | 37~225 | ~22.9 | Weighted mean of U/Pb zircon ages | Wu et al., 1998 |
| | | | | 12.9~11.7 | U/Pb zircon ages | Gou et al., 2016 |
| | | | | 13.1~12.2 | U/Pb zircon ages | Gou et al., 2016 |
| | | | | 17.3~14.1 | U/Pb zircon ages | Gou et al., 2016 |
| | | | | 20.7~19.2 | U/Pb zircon ages | Gou et al., 2016 |
| | | | | 20.9~18.6 | U/Pb zircon ages | Gou et al., 2016 |
| 32. Wagya La-Chongba | 89.9 | 125 | 16~99 | ~11.9 | Mean of U/Pb zircon ages | Wu et al., 1998 |
| 33. Masang Kang-Paro | 90.2 | 590 | 78~471 | 14--13 | U/Pb monazite ages | Searle and Godin, 2003 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | 24--23 | U/Pb monazite ages | Searle and Godin, 2003 |
| 34. Khula Kanggri- | 90.8 | 1129 | 149~901 | 12.5 ± 0.15 | Weighted mean of Th/Pb monazite ages | Edwards and Harrison, |
| | | | | 19.1 ± 0.1 | Weighted mean of Th/Pb monazite ages | Yang et al., 2024 |
| | | | | 19.0 ± 0.1 | Weighted mean of Th/Pb monazite ages | Yang et al., 2024 |
| | | | | 18.5 ± 0.1 | Weighted mean of Th/Pb monazite ages | Yang et al., 2024 |
| | | | | 19.0 ± 0.2 | Weighted mean of Th/Pb monazite ages | Yang et al., 2024 |
| 35. Lakang-Kuju | 91.5 | 68 | 9~54 | 23.4 ± 0.2 | Weighted mean of U/Pb zircon ages | Zhang et al., 2020 |
| | | | | 16.5 ± 0.1 | Weighted mean of U/Pb zircon ages | Zhang et al., 2020 |
| | | | | 23.9 ± 0.1 | Weighted mean of Th/Pb monazite ages | Zhang et al., 2020 |
| | | | | 16.9 ± 0.1 | Weighted mean of Th/Pb monazite ages | Zhang et al., 2020 |
| 36. Tsona-Yamarong- | 91.5 | 106 | 14~84 | 21.4 ± 0.2 | Weighted mean of Th/Pb monazite ages | Ji et al., 2022 |
| | | | | 16.4 ± 0.2 | Weighted mean of Th/Pb monazite ages | Ji et al., 2022 |