Supplement of Solid Earth, 11, 437–467, 2020
https://doi.org/10.5194/se-11-437-2020-supplement
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Solid Earth
Open Access

Supplement of

Cenozoic deformation in the Tauern Window (Eastern Alps) constrained by in situ Th-Pb dating of fissure monazite

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Supplementary information for section “**4.2 Monazite dating and composition**”

Western Tauern Window

Monazite grain INNB1 (Fig. 3a, Table 1) Th and U content respectively ranges between 26,500 – 8700 and 1100 – 260 ppm (Table 3). Discrete Th-enriched zones are visible on the BSE image (lighter areas). Only an age range of 11.5 ± 0.2 – 10.4 ± 0.2 Ma can be provided for this grain due to isotopic heterogeneity (Table 4). Spot analysis 8 was not considered because it is an outlier and has a high uncertainty with respect to the other analysis of this grain (Table 3).

ZEI1 grain (Fig. 3b, Table 1) is texturally homogeneous and no discrete chemical trends are observed, Th and U content is respectively ranging between 9200 – 1200 and 390 – 45 ppm (Table 3). A weighted mean age of 10.0 ± 0.2 Ma (MSWD = 1.8, n = 20; Table 4) was calculated for this grain (ZEI1-A domain). However, younger dates are also observed disseminated through the grain (ZEI1-B domain, blue symbols on Fig. 3b), likely affected by dissolution (e.g. spot analysis 5 is close to a dissolution track) reflecting later monazite crystallization down to ~7 Ma (Table 4).

SCHR1 monazite sample (Fig. 3c, Table 1) is a large grain, nicely displaying core-to-rim oscillatory zoning. Three domains were identified in this grain according to chemical and textural evidences. From core to rim (from domain SCHR1-A to SCHR1-C), the average Th content decreases (~41,000, ~25,000 and ~17,500 ppm respectively), the scatter in U content increases (420 – 500, 310 – 510 and 210 – 500 ppm respectively; Table 3) and calculated weighted mean ages slightly decrease (SCHR1-A : 20.9 ± 0.6 Ma, MSWD = 1.7, n = 6; SCHR1-B : 20.3 ± 0.2 Ma, MSWD = 0.98, n = 16; SCHR1-C : 19.7 ± 0.4 Ma, MSWD = 1.00, n = 6; Table 4).

MAYR4 (Fig. 3d, Table 1) Th and U content is quite heterogeneous, respectively ranging between 7000 – 1200 and 390 – 81 ppm (Table 3). The grain being chemically and isotopically heterogeneous, it is not possible to calculate a consistent weighted mean age (MSWD < 3) so only the spot date range is considered for this grain (11.8 ± 0.2 – 8.9 ± 0.2 Ma, Table 4). However, it has to be noted that most of the analyses record an age close to ~11 Ma.

PFIT1 grain (Fig. 3e, Table 1) is regularly zoned, with a core (PFIT1-A) and a thick darker rim (PFIT1-B) clearly visible on the BSE image, with average Th/U ratios of 140 and 12 respectively. This grain suffered chemical disequilibrium, resulting in replacement of parts of its core (patchy texture, spots 1 to 5) and resulting in mixed chemistry and dates between domain A and B (dark open symbols on Fig. 3d, Table 3). PFIT1-A and PFIT1-B domains record monazite growth at 17.3 ± 0.3 Ma (MSWD = 1.2, n = 9) and at 13.2 ± 0.3 Ma (MSWD = 0.38, n = 5) respectively (Table 4). Based on chemical, textural and chronological observations, the spots located in the altered domain seem to be a mix of PFIT1-A and B, for this reason these analyses were not considered (Table 3).

BURG2 (Fig. 3f, Table 1) is one of the smallest grain analysed (~300µm by ~100µm). Th and U contents are low, between 1100 – 530 and 160 -18 ppm respectively (Table 3). The scatter of the spot ages do not allow to calculate a consistent weighted mean age for this grain so we only consider their range, 17.1 ± 0.4 – 12.1 ± 0.3 Ma (Table 4). Note the presence of cracks, which could correspond to dissolution trails that might explain the younger dates provided by spot analyses 7 and 13 (Table 3), or which may only be the result of the polishing of the grain. Analysis 12 was discarded because of a high uncertainty (Table 3).

PLAN1 (Fig. 3g, Table 1) is a large grain showing internal regular zoning. PLAN1-A domain constitute the major part of the grain and shows Th and U contents ranging between 14,200 – 1500 and 1200 – 180 ppm (Table 3). A weighted mean age of 11.9 ± 0.2 (MSWD =

2.2, n = 37; Table 4) was calculated for this domain. Three spot analyses located in the core of the mineral (PLAN1-B domain) provides younger dates ranging between 9.9 ± 0.3 and 7.8 ± 0.2 Ma and have an average Th/U ratio of 5 (Table 3). These analyses likely record a later phase of monazite crystallization and were considered in the spot date range of this grain (Table 4). Spot analysis 22 was discarded due to high uncertainty (Table 3).

Central Tauern Window

SCHEI1 grain (Fig. 4a, Table 1) is a strongly zoned grain subdivided in three domains (SCHEI1-A, B and C) according to textural and chemical observations. SCHEI1-A domain displays the highest Th content (brightest top-left part of the grain on BSE image) and a low U content (respectively of 60,700 and 320 ppm on average, Table 3). A weighted mean age of 18.3 ± 1.1 Ma (MSWD = 2.0, n = 4; Table 4) was calculated for this domain. A second bright zone is visible on BSE image in the centre of the grain (SCHEI1-B domain), showing slightly lower Th content, nearly identical U content (respectively 52,000 and 360 ppm on average, Table 3) and a younger weighted mean age of 17.4 ± 0.4 Ma (MSWD = 1.5, n = 5; Table 4). Lower Th and U content (respectively ranging between 37,300 – 8800 and 1100 – 420 ppm, Table 3) are observed for SCHEI1-C domain, a darker zones on BSE image at the bottom of the grain and close to the grain/rock boundary were a thin patchy texture is observed. This third domain provides a younger weighted mean age of 16.6 ± 0.2 Ma (MSWD = 1.9, n = 23; Table 4), likely reflecting later monazite crystallization.

HOPF2 crystal (Fig. 4b, Table 1) is composed of one core (HOPF2-A) surrounded by a rim (HOPF2-B). These two domains seem to be replaced by domain HOPF2-C (dissolution front). HOPF2-A corresponds to a lighter coloured core in the centre of the grain, clearly displaying higher Th and U contents (up to 62,600 and 170 ppm respectively). Compared to the other two domains, HOPF2-A chemistry is more heterogeneous and may explain the observed scatter of dates (between 13.7 ± 0.4 and 11.0 ± 0.3 Ma; Tables 3 and 4). HOPF2-B and C are nearly identical chemically (average Th and U content of 29,000 and 50 ppm respectively) and isotopically, respectively providing calculated average ages of 12.2 ± 0.4 Ma (MSWD = 2.6, n = 8) and 12.2 ± 0.5 Ma (MSWD = 2.9, n = 6; Table 4). This suggests that domain B and C formed simultaneously.

GART1 (Fig. 4c, Table 1) displays two distinct chemical trends with respective average Th/U ratios of 64 (GART1-A) and 390 (GART1-B). A weighted mean age of 16.3 ± 0.2 Ma (MSWD = 0.69, n = 10; Table 4) was calculated for GART1-A domain, but only the age range is provided for GART1-B domain due to isotopic heterogeneity (16.6 ± 0.3 – 14.4 ± 0.4 Ma, Fig. 4c, Table 4). Analyses 3 and 4 were not considered due to high uncertainty and spot 6 was removed because it was analysed too close from the previous spot which seems to affect the calculated age (Table 3).

NOWA3 grain (Fig. 4d, Table 1) can be texturally and chemically divided in three domains, NOWA3-A, B and C corresponding to distinct grey zones on BSE image, respectively displaying an average Th/U ratio of 66, 53 and 250 ppm (Table 3). The scatter of dates of domain NOWA3-A do not allows to calculate a consistent weighted mean age and only the age range is provided (16.4 ± 0.7 – 13.8 ± 0.8 Ma, Fig. 4d). Domains NOWA3-B and C provide nearly identical weighted mean ages within uncertainty, respectively equal to 15.8 ± 0.5 Ma (MSWD = 0.27, n = 5) and 14.9 ± 1.1 Ma, (MSWD = 2.4, n = 5; Table 4). Analysis 8 was not considered due to high uncertainty (Table 3).

In GART3 (Fig. 4e, Table 1), a slightly darker core is visible on the upper part of the grain (GART3-A) with a clustered composition (average Th and U content of 10,000 – 8400 and 160 – 85 ppm respectively). Only an age range between 15.8 ± 0.6 – 13.4 ± 0.4 Ma can be provided for this domain. GART3-B domain corresponds to a large portion of the grain displaying oscillatory zoning, it is chemically heterogeneous (average Th and U content ranging between 13,800 – 4400 and 480 – 130 ppm respectively) and provides an average age of 15.0 ± 0.5 Ma (MSWD = 2.3, n = 11; Table 4). GART3-C domain corresponds to the rim of the crystal, it is quite homogeneous in U content (~150 ppm) and more variable Th content (8000 – 3300 ppm; Table 3). As for GART3-A domain, no reliable average age could be calculated for this domain due to isotopic heterogeneity. Spot analysis 2 was not considered due to high uncertainty (close to 1) compared to the other analyses of this grain (Table 3).

STEI2 (Fig. 4f, Table 1) Th and U contents range between 19,400 – 5140 and 600 – 260 ppm respectively (Table 3). We can notice that the upper part of the grain (spots 6 to 10) displays lower Th content. A weighted mean age of 17.2 ± 0.2 Ma (MSWD = 0.24, n = 20) was calculated for this grain (Table 4).

KNOR1 (Fig. 4g, Table 1) chemistry shows three clusters which correspond to distinct grey zones visible on the BSE image (Table 3). KNOR1-A domain is the richest in Th (12,300 – 7200 ppm) and U (240 – 150 ppm) yielding a weighted mean age of 10.8 ± 0.3 Ma (MSWD = 1.02, n = 5; Table 4). A similar age was obtained for the other two domains (KNOR1-B: 10.6 ± 0.3 Ma, MSWD = 1.6, n = 8; KNOR1-C: 10.4 ± 0.2 Ma, MSWD = 1.4, n = 8) with distinct Th/U ratios (220 and 100 on average for domain B and C respectively). Analyses 4 and 17 (orange and blue open symbols on figure 4g; Table 3) were not considered in the weighted mean age calculations because these two dates do not nicely fit the rest of the population (older). Some isotopic heterogeneities may explain this scatter, however, there are no reasons to discard these dates (e.g. Pbc relation, inclusion) so they are included in the age range of this grain.

Eastern Tauern Window

KAIS6 grain (Fig. 5a, Table 1) displays three distinct chemical clusters. KAIS6-A domain is the richest in Th and U contents (average Th = 33,000 and U = 9 ppm), KAIS6-B is intermediate in composition (average Th = 21,000 and U = 4 ppm), whereas KAIS6-C is the poorest (average Th = 12,300 and U = 3 ppm; Table 3). Scattered Th and U content is observed for domain KAIS6-D, ranging between 32,300 – 10,500 and 14 – 3 ppm respectively (Table 3). The first three domains provide a similar age of 21.2 ± 0.5 Ma (KAIS6-A, MSWD = 0.64, n = 6), 20.9 ± 0.2 Ma (KAIS6-B, MSWD = 0.53, n = 24) and of 20.6 ± 0.5 Ma (KAIS6-C, MSWD = 0.34, n = 7; Table 4). KAIS6-D domain displays a younger age of 18.8 ± 0.5 (MSWD = 1.5, n = 10; Table 4), most probably related to the presence of dissolution trails (red dashed lines on figure 5a). The calculated weighted mean ages from domains A, B and C show that KAIS6 main crystallization is recorded at ~21 Ma and dissolution trails reflect that a later phase of monazite precipitation likely occurred at ~19 Ma. Analyses 48 and 49 are located too close to the grain border and on a crack network respectively, influencing their chemistry (lower Th content compared to other analyses from domain A), for these reasons those data were discarded (Table 3).

SALZ18 (Fig. 5b, Table 1) Th and U content ranges between 12,500 – 440 and 37 – 11 ppm respectively (Table 3) and no distinct textural domains are observed. An average age of 18.3 ± 0.4 Ma (SALZ18-A, MSWD = 2.6, n = 14) was calculated for this grain (Table 4). Spot analysis 15 (orange open symbols on figure 5b) was not considered in the weighted mean age calculation because it does not fit the data population of domain A. This younger date sits on a dissolution trail, likely recording later monazite crystallization, and for this reason this data is however included in the total spot date range of the grain (Tables 3 and 4).

LOHN4 (Fig. 5c, Table 1) is a big crystal (~2600µm-long) showing a dense network of cracks in its core, radially spreading towards the rim. This monazite was probably a regular zoned grain before being subject to chemical disequilibrium, mainly affecting the core which very likely had the largest chemical potential with respect to the final fluid. Two domains were defined for this grains according to chemical and textural observations. LOHN4-A has an average Th/U ratio equal to 1020 (Table 3) and spot analyses attributed to this domain are mainly located far from the altered core. An average age of 21.1 ± 0.2 Ma (MSWD = 1.4, n = 50) was calculated for this first domain (Table 4). The spot analyses of the second domain (LOHN4-B) are mainly located near to alteration features (in the patchy core, near to dissolution trails and dissolution spots disseminated within the grain), showing a lower Th/U ratio (~760) and providing a younger average age of 18.4 ± 0.6 Ma (MSWD = 1.3, n = 7; Table 4).

ORT1 (Fig. 5d, Table 1) is a regular zoned grain with a Th and U content ranging between 7400 – 3200 and 370 – 95 ppm (Table 3). A weighted mean age of 18.4 ± 0.3 Ma (MSWD = 1.07, n = 13) was calculated for this sample (Table 4). Spot analysis 15 was not considered due to high uncertainty (Table 3).

EUKL2 (Fig. 5e, Table 1) rim composition has an average Th/U ratio equal to 970 (Table 3) and records an age at 21.7 ± 0.4 Ma (MSWD = 0.56, n = 7; Table 4).

HOAR1 (Fig. 5f, Table 1) is a grain composed of a monazite aggregate. A patchy texture is observed on the left side of the monazite aggregate (HOAR1-A) and seems to provide a slightly older age of 20.4 ± 0.2 Ma (MSWD = 0.80, n = 6, Fig. 5f) compared to the well-developed crystals visible on the right part of the aggregate (HOAR1-B) providing an age of 19.9 ± 0.3 Ma (MSWD = 0.95, n = 25). Th and U content respectively ranges between 19,700 – 650 and 320 – 80 ppm in HOAR1-A domain and between 6610 – 640 and 270– 45 ppm in HOAR1-B domain (Table 3). Analysis 15 was not considered due to high uncertainty (Table 3).

Monazite MOKR1 (Fig. 5g, Table 1) is composed by an oscillatory internal domain (MOKR1-A) and by a rim (MOKR1-B) showing distinct chemical trends (average Th/U ratio equal to 10 and 85 respectively; Table 3). MOKR1-A domain displays scattered dates ranging between 22.6 ± 0.4 and 14.4 ± 0.2 Ma, but two age plateaus are observed around 20.5 Ma (spots analyses 23 to 29) and 18 Ma (spots analyses 7 to 12). The core of the grain likely suffered chemical disequilibrium due to high chemical potential with the final fluid, most probably resulting in dissolution and reprecipitation of monazite, explaining the age scatter and one anomalously young date observed (spot analysis 20). No weighted mean ages were calculated for MOKR1-A domain given the complex link between texture and age in this domain. A weighted mean age of 18.8 ± 0.5 Ma (MSWD = 2.9, n = 12) was obtained for MOKR1-B domain (Table 4). Analysis 19 was removed from the dataset because no $^{208}Pb/^{204}Pb$ value was measured for this spot (Table 3).

SAND1 monazite domains (Fig. 5h, Table 1) show two distinct chemical trends with average Th/U ratios of 21 (SAND1-A, rim) and 4 (SAND1-B, core; Table 3). As for LOHN4 and MOKR1 grains, younger ages are recorded in the core of the crystal compared to the rim, likely related to local dissolution and reprecipitation of monazite in the core due to chemical disequilibrium (presence of dissolution spots, Fig. 5h). A weighted mean age of 17.0 ± 0.8 Ma (MSWD = 1.8, n = 7) was calculated for SAND1-B domain (Table 4). Scattered and mostly older dates are observed in SAND1-A domain, ranging between 22.0 ± 0.3 to 17.0 ± 0.6 Ma (Fig. 5h, Table 3). Spot analysis 28 is chemically closer to SAND1-B composition but provides an old date, similar to SAND1-A domain. This spot analysis, which possibly provides a pristine age, was linked to SAND1-B domain but not considered in the age calculation (open symbol marked in blue). Spot analyses written in italic in Table 3 were removed from the dataset (high uncertainty, unreliable age, missing $^{208}Pb/^{204}Pb$ value).

REIS1 grain (Fig. 5i, Table 1) Th/U ratio ranges between 10 and 1 (Table 3). Higher Th content is observable in the left-upper part of the BSE image (light-grey region). An average age of 16.2 ± 0.5 Ma (MSWD = 2.9, n = 13, Table 4) was calculated for the main part of the grain (REIS1-A domain). However, the grain displays some local alteration features such as dissolution trails (red-dashed line on figure 5i), one notably affecting spot 30 yielding a particularly young date suggesting late monazite crystallization. Four other spot analyses disseminated through the grain provide the same younger age, suggesting that these parts of the grain were also locally affected by dissolution and recrystallization of monazite. A weighted mean age of 13.6 ± 0.6 Ma (MSWD = 0.25, n = 5, Table 4) was calculated for these younger dates grouped in REIS1-B domain which is characterized by a low Th/U ratio of ~1. Spot analyses 22 and 26 were discarded due to high uncertainty and are written in italic (Table 3).