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 7265 and 21,420 and 196-896 ppm (Table 3). Discrete Th-enriched zones are visible on the BSE image (lighter areas). An average age was calculated for this grain at 11.8 ± 0.5 Ma (MSWD = 2.8, n = 7; Table 5). Analysis 8 was not considered due to high uncertainty.

ZEI1 grain (Fig. 3b, Table 1) can be subdivided in two domains (ZEI1-A and B) according to chemical and textural observations. The average Th/U ratio and calculated age of domain A are respectively equal to 23 and 10.3 ± 0.3 Ma (MSWD = 1.9, n = 14; Tables 3 and 5). The average Th/U ratio of domain B is higher (= 80) but the calculated average age is identical within error to domain A (10.0 ± 0.5 Ma, MSWD = 2.7, n = 7). The chemistry of domain ZEI1-C (spots 3, 9, 12 and 18; Th/U ~17) closely follows domain ZEI1-A and provides the youngest average age calculated for this grain at 7.7 ± 0.9 Ma (MSWD = 2.4, n = 4). This age has to be considered with caution, as is remains unclear why ~2 Ma younger spot dates are randomly found within domain A (no textural, chemical or instrumental evidences). Spot 20 texturally belongs to domain B but displays a lower Th/U ratio of 8 and seems to be located on an inclusion (black open diamond and circle on figure 3b), for these chemical and textural reasons this spot was discarded.

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 (417-499, 312-510 and 211-499 ppm respectively; Table 4) and calculated weighted mean ages slightly decrease (SCHR1-A : 20.8 ± 0.6 Ma, MSWD = 1.7, n = 6; SCHR1-B :

20.3 ± 0.2 Ma, MSWD = 1.11, n = 16; SCHR1-C: 19.7 ± 0.4 Ma, MSWD = 0.97, n = 6; Table 5).

MAYR4 (Fig. 3d, Table 1) Th and U content is quite heterogeneous, respectively ranging between 1038 and 4371 and 41-310 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 (12.8 ± 0.6 - 9.6 ± 0.5 Ma, Table 5). However, it has to be noted that most of the analyses record an age close to 11 Ma. Analyses 6 and 11 were not considered due to high uncertainty (Table 3).

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 139 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 (Table 4). PFIT1-A and PFIT1-B domains record monazite growth at 17.1 ± 0.4 Ma (MSWD = 1.4, n = 9) and at 13.1 ± 0.3 Ma (MSWD = 0.76, n = 5) respectively (Table 5). 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 4).

BURG2 (Fig. 3f, Table 1) is one of the smallest grain analysed (~300µm by ~100µm). Th and U contents are low, between 87 and 188 and 3 -14 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, 18.4 ± 0.9 - 13.9 ± 0.9 Ma (Table 5). Analyses 12 and 13 were discarded because they are outliers and/or have a high uncertainty (Table 3).

PLAN1 (Fig. 3g, Table 1) is a large grain showing internal regular zoning. Based on chemical observations, two domains were defined (PLAN1-A and B, Table 3). PLAN1-A domain is quite homogeneous in composition with Th and U values clustering around an

average value of 2800 and 260 ppm respectively yielding a weighted mean age calculated at 13.0 ± 0.2 (MSWD = 0.86, n = 17). Spot analyses 11 and 12 clearly display higher Th and U content (up to 39,046 and 3026 respectively) and younger dates (between ~11 and 8 Ma). No textural reasons (e.g. inclusions) seem to explain this discrepancy, thus the analyses were considered in the spot date range of this grain (Table 5). Analyses 1, 3 to 9, 13, 15 to 22, 27, 31, 35, 37 and 40 were not considered due to high uncertainty and/or age-Pbc relation (Table 3).

Central Tauern Window

SCHEI1 grain (Fig. 4a, Table 1) is strongly zoned and most of the Th and U content ranges between 5055 and 64,103 and 170 – 518 ppm respectively (domain SCHEI1-A; Table 3). A weighted mean age of 18.0 ± 0.2 Ma (MSWD = 2.2, n = 20) was calculated for this domain (Table 5). Spots 10, 27, 33 and 34 are located close to the grain/rock boundary were a thin patchy texture is observed and seem to follow a distinct chemical trend (average Th/U ratio of 16). These analyses were grouped in domain SCHEI1-B and a weighted mean age of 16.5 ± 0.4 Ma (MSWD = 0.74, n = 4) was calculated. Analyses 5 to 9, 15, 30 and 32 were not considered due to high uncertainty and/or age-Pbc relation (Table 3).

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 colored core in the centre of the grain, clearly displaying higher Th and U contents (up to 62,586 and 173 ppm respectively). Compared to the other two domains, HOPF2-A chemistry is more heterogeneous and may explain the observed scatter of dates (between 13.5 ± 0.3 and 10.9 ± 0.3 Ma; Tables 4 and 5). HOPF2-B and C are nearly identical chemically (average Th and U content of 29,000 and 50 ppm respectively) and isotopically, so the analyses of these two domains were grouped together in

order to be able to calculate a statistically consistent weighted mean age of 12.1 ± 0.3 Ma (MSWD = 2.9, n = 14; Table 5). Thus assuming that domain B and C formed simultaneously.

GART1 (Fig. 4c, Table 1) displays two distinct chemical trends with respective average Th/U ratios of 60 (GART1-A) and 400 (GART1-B). Very similar weighted mean ages of 17.0 ± 0.2 Ma (MSWD = 1.2, n = 10) and of 16.9 ± 0.3 Ma (MSWD = 1.3, n = 9) were calculated for these two domains (Table 5). Analyses 3 and 4 were not considered due to high uncertainty and age-Pbc relation 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) displays 3 chemical clusters (average Th/U ratio of 90, 50, and 400 for NOWA3-A, B and C respectively; Table 3) corresponding to distinct grey zones on BSE image providing average ages identical within uncertainty (NOWA3-A: 17.1 ± 0.7 Ma, MSWD = 2.6, n = 6 ; NOWA3-B: 17.3 ± 0.4 Ma, MSWD = 0.82, n = 5 ; NOWA3-C: 17.2 ± 0.9 Ma, MSWD = 1.6, n = 5 ; Table 5). Analyses 1 and 4 to 11 were not considered due to high uncertainty and/or age-Pbc relation (Table 3).

In GART3 (Fig. 4e, Table 1), a slightly darker core is visible on the upper part of the grain (GART3-A), corresponding to an average Th/U ratio of 112 and a weighted mean age of 18.3 ± 1.2 Ma (MSWD = 1.6, n = 6; Tables 3 and 5). GART3-B domain corresponds to a large portion of the grain displaying oscillatory zoning, with average Th/U ratio of 49 and an average age of 17.3 ± 0.8 Ma (MSWD = 2.3, n = 9; Table 5). GART3-C composition is much clustered (average Th and U content equal to 4000 and 100 respectively), this domain corresponds to the rim and provides an average age of 16.0 ± 0.8 Ma (MSWD = 0.41, n = 5). Spot analyses 2, 19 and 20 were not considered due to high uncertainty (Table 3).

STEI2 (Fig. 4f, Table 1) Th and U contents range between 12,353 and 2676 and 407 – 131 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 17.6 ± 0.2 Ma (MSWD = 1.4, n = 20) was calculated for this grain (Table 5).

KNOR1 (Fig. 4g, Table 1) chemistry shows three clusters which correspond to distinct grey zones visible on the BSE image (Table 4). KNOR1-A domain is the richest in Th (7199 - 12,269 ppm) and U (149 - 239 ppm) yielding a weighted mean age of 10.7 ± 0.5 Ma (MSWD = 1.7, n = 5; Table 5). A similar age was obtained for the other two domains (KNOR1-B: 10.5 ± 0.2 Ma, MSWD = 1.5, n = 8; KNOR1-C: 10.3 ± 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 5 and 17 (orange and blue open symbols on figure 4g; Table 4) 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 4). The three domains provide a similar age of 21.0 ± 0.4 Ma (KAIS6-A, MSWD = 0.71, n = 6), 20.8 ± 0.2 Ma (KAIS6-B, MSWD = 0.58, n = 24) and of 20.6 ± 0.3 Ma (KAIS6-C, MSWD = 0.56, n = 7; Table 5). Several analyses (domain D on Table 4) are affected by the presence of dissolution trails (red dashed lines on figure 5a) leading to younger dates ranging between 19.4 ± 0.5 and 16.9 ± 0.5 Ma. The calculated weighted mean ages from domains A, B and C show that KAIS6 main crystallization is recorded at ~ 21 Ma. Dissolution trails reflect that a later phase of monazite

precipitation likely occurred down to ~17Ma, thus these younger dates were considered in the final spot age range of the grain. 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 4).

SALZ18 (Fig. 5b, Table 1) Th and U content ranges between 443 and 12,452 and 11 – 37 ppm respectively (Table 4) and no distinct textural domains are observed. An average age of 18.2 ± 0.4 Ma (SALZ18-A, MSWD = 2.8, n = 14) was calculated for this grain (Table 5). 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 (Table 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 4) and spot analyses attributed to this domain are mainly located far from the altered core. An average age of 21.0 ± 0.2 Ma (MSWD = 2.3, n = 50) was calculated for this first domain (Table 5). 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 18.2 ± 0.6 Ma (MSWD = 1.8, n = 7; Table 5).

ORT1 (Fig. 5d, Table 1) is a regular zoned grain with a Th and U content ranging between 1902 and 3755 and 48 – 241 ppm (Table 3). A weighted mean age of 20.1 ± 0.3 Ma

(MSWD = 0.82, n = 13) was calculated for this sample (Table 5). Spot analyses 6 and 15 were 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 4) and records an age at 21.7 ± 0.3 Ma (MSWD = 1.08, n = 7; Table 5).

HOAR1 (Fig. 5f, Table 1) is a patchy grain composed of a monazite aggregate with little compositional variation (average Th/U ratio equal to 30; Table 3). The error on the individual spot dates is quite high for this grain (1σ = 1 on average). A weighted mean age of 22.3 ± 0.6 Ma (MSWD = 3.0, n = 24) was calculated for the well-developed aggregates composing the grains (HOAR1-A) and a second nearly identical weighted mean age of 20.7 ± 1.2 Ma (MSWD = 2.9, n = 5) was calculated for the more patchy part (HOAR1-B; Table 5). Analyses 5, 15 and 32 were not considered due to high uncertainty and age-Pbc relation (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 12 and 96 respectively; Table 3). A weighted mean age of 20.6 ± 0.7 Ma (MSWD = 1.4, n = 15) was calculated for domain A without considering spot 20 (red open symbols on figure 5g). Analysis 20 provides a younger date at 14.3 ± 0.9, most likely recording a later crystallization event. No textural or analytical reasons allow to discard this analysis which is considered in the final spot age range of the grain. For domain B, a weighted mean age of 20.6 ± 0.6 Ma (MSWD = 2.0, n = 12) was obtained (Table 5). Analyses 7, 10 and 11 were not considered due to high uncertainty and age-Pbc relation (Table 3).

SAND1 monazite domains (Fig. 5h, Table 1) show two distinct chemical trends with average Th/U ratios of 5 (SAND1-A, core) and 34 (SAND1-B, rim; Table 3). A weighted mean age of 21.3 ± 2.1 Ma (MSWD = 2.0, n = 5) was calculated for the first domain (Table 5). The scatter of dates in the second domain do not allow to calculate a consistent weighted

mean age so only the age range, 24.8 ± 1.2 to 17.2 ± 1.1 Ma, is presented in figure 5h for this domain. As for HOAR1, the error on the individual spot dates is high (1σ = 1 on average) and spot analyses with an error bigger than 2 were not considered (Table 3).

REIS1 grain (Fig. 5i, Table 1) is quite homogeneous in composition with a Th/U ratio ranging between 1 and 7. Higher Th content is observable in the left-upper part of the BSE image (light-grey region, particularly spots 28 and 32, Table 3). An average age of 17.3 ± 1.2 Ma (MSWD = 2.6, n = 13) was calculated for this grain (Table 5). The grain does not display any major alteration features except some local dissolution trails, one notably affecting spot 30 (orange open symbols on figure 5i) and yielding a particularly young date, for this reason this analysis was not considered in the weighted mean age. But it is included in the age range because it likely records late stage of activity (Table 3). Spot analyses 23, 25, 26 and 34 to 36 were discarded due to the high uncertainty related to very low Th content.