



Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Preservation of Permian allanite within an Alpine eclogite facies shear zone at Mt Mucrone, Italy: Mechanical and chemical behavior of allanite during mylonitization

B. Cenko-Tok^{a,*}, E. Oliot^b, D. Rubatto^c, A. Berger^d, M. Engi^a, E. Janots^e, T.B. Thomsen^a, P. Manzotti^a, D. Regis^a, C. Spandler^f, M. Robyr^a, P. Goncalves^b

^a Institute of Geological Sciences, Baltzerstrasse 1+3, University of Bern, CH-3012 Bern, Switzerland

^b UMR-CNRS 6249 Chrono-Environnement, Université de Franche-Comté, 16, route de Gray, F-25030, Besançon Cedex, France

^c Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia

^d University of Copenhagen, Inst. Geografi. Geol., 1350 Copenhagen, Denmark

^e ISTERRE (UMR5025), Université Joseph Fourier, Grenoble, France

^f James Cook University, School of Earth and Environmental Sciences, Townsville, Qld 4811, Australia

ARTICLE INFO

Article history:

Received 20 August 2010

Accepted 24 January 2011

Available online xxx

Keywords:

Western Alps

Sesia zone

Mt Mucrone

Allanite

U–Th–Pb ages

Shear zone

ABSTRACT

This study addresses the mechanical and chemical behavior of allanite during shear zone formation under high-pressure metamorphism. Understanding physico-chemical processes related to the retention or resetting of Pb isotopes in allanite during geological processes is essential for robust petrochronology.

Dating of allanite in meta-granodiorite showing variable amounts of strain (from an undeformed protolith to mylonite) at Monte Mucrone (Sesia Zone, NW Italy) gave surprising results. Based on structural and petrographic observations the shear zones at Mt Mucrone are Alpine, yet allanite located within an eclogite facies mylonite yielded Permian ages ($^{208}\text{Pb}/^{232}\text{Th}$ average age: 287 ± 7 Ma). These mm-sized allanite grains are rimmed by an aggregate of coarse-grained garnet + phengite, thought to derive from former epidote. These aggregates were immersed in a weak matrix that experienced granular flow, and they were thus chemically and mechanically shielded during Alpine mylonitization. In undeformed samples (8a and 8b), two populations of epidote group minerals were found. Allanite forms either coronas around Permian monazite or individual grains with patchy zoning. Both types yield Permian ages ($^{208}\text{Pb}/^{232}\text{Th}$ age: 291 ± 5 Ma). On the other hand, grains of REE-rich clinozoisite of Cretaceous age are found in undeformed rocks. These grains appear as small fragments with embayed surface outlines and minute satellites or rims around Permian allanite. These (re)crystallized grains are Sr-rich and show mosaic zoning.

These results indicate that allanite crystals retained their chemical and isotopic characteristics, and thus their Permian age, as a result of strong strain partitioning between the epidote group porphyroclasts and the eclogite facies matrix in HP-mylonites. The observed partial mobilization of Pb isotopes, which lead to the Cretaceous-aged rims or grains in undeformed samples was facilitated by (re)crystallization of allanite and not by mere Pb diffusion alone under the HP conditions.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Allanite ($\text{CaREE}(\text{Al}, \text{Fe}^{3+})_2(\text{Mg}, \text{Fe}^{2+})\text{Si}_3\text{O}_{12}(\text{OH})$) is an accessory mineral that occurs in a wide range of rock types. This epidote-group mineral can incorporate weight percents of LREE as well as Th and U at weight percent level (Gieré and Sorensen, 2004). Allanite is a promising petrochronometer, as it may yield ages that can be correlated with physico-chemical conditions, based on petrological observations. A number of studies have reported on its textural and chemical relationships to rock-forming minerals and on evidence of

its stability in *PT*-space (Gregory et al., 2009; Hermann, 2002; Janots et al., 2006, 2008; Wing et al., 2003). Recent advances in allanite U–Th–Pb ion microprobe dating yield reliable ages despite the fact that allanite contains significant amounts of common Pb (Gregory et al., 2007; Rubatto et al., 2008; Smith et al., 2009). Correct age interpretations of any mineral chronometer hinges on our understanding of the chemical and physical behavior of that mineral during crustal processes, including metamorphism and deformation. Whereas the petrology and geochemistry of allanite have been addressed repeatedly, little is known so far regarding the effects of deformation and recrystallization on allanite U–Th–Pb systematics. Knowing its behavior during deformation is key to understanding allanite geochronological data from deformed rocks. For instance, if during the development of a shear zone allanite (or REE-rich clinozoisite) was to recrystallize, along with other rock forming minerals, then the

* Corresponding author at: Université Montpellier 2, Géosciences Montpellier, UMR5243, Place Eugène Bataillon, 34095 Montpellier, France.

E-mail address: benedicte.cenki-tok@gm.univ-montp2.fr (B. Cenko-Tok).

recrystallized allanite grains could potentially be dated to constrain the age of shear zone formation.

In this study we report allanite ion microprobe U–Th–Pb ages from an Alpine eclogite-facies shear zone within the Mt Mucrone granodioritic intrusion (NW Italy). Both the shear zones and the age of high pressure (HP) metamorphism are well documented in this area (Früh-Green, 1994; Rubatto et al., 1999; van Roermund et al., 1979). Here we investigated i) the mechanical and chemical behavior of allanite during mylonitization, ii) the influence of recrystallization processes on U–Th–Pb isotopic ratios. This paper is the first attempt to test whether allanite can be used to infer the age of deformation.

2. Geological setting and macroscopic description of the shear zone

The Sesia Zone is a large Austroalpine continental terrane located in the Internal Western Alps (Fig. 1). It is composed of a polymetamorphic basement intruded by early Permian granites and gabbros (Compagnoni, 1977; Rubatto et al., 1999). The Sesia Zone underwent Alpine subduction (Babist et al., 2006; Compagnoni, 1977) under HP condition (ca. 1.4–1.6 GPa and 500–600 °C; Oberhänsli et al., 1985; Pognante, 1989) during Late Cretaceous to Early Palaeocene

times, ca. 70–65 Ma (Duchêne et al., 1997; Ramsbotham et al., 1994; Rubatto et al., 1999).

The decimeter-wide shear zone and surrounding weakly deformed rocks investigated in this study were sampled within the Mt Mucrone granodioritic body (Oberhänsli et al., 1985). The intrusion age of this granodiorite and related gabbros was determined by zircon U–Pb dating at ca. 290 Ma (Bussy et al., 1998; Rubatto et al., 1999). Deformation and strain localization in the Mt Mucrone metagranitoid are considered monocyclic, as both the mylonitization and HP metamorphism are Alpine in age (Früh-Green, 1994; van Roermund et al., 1979). In the studied area, a pattern of millimeter to meter-size Alpine ductile shear zones crosscuts the undeformed protolith. Deformation at high-pressure conditions and metamorphism produced localized ductile deformation in sets of conjugate shear bands (Fig. 2) striking NE–SW. There is no apparent structural overprint related to the subsequent exhumation. The timing of the ductile deformation relative to the HP-mineral growth is controversial. According to van Roermund et al. (1979) these shear zones postdate the main eclogitic imprint. In contrast Nieto and Compagnoni (1994) proposed that they are early Alpine in age, i.e. postdating the prograde breakdown of albite to jadeite plus quartz, but predating the metamorphic peak.

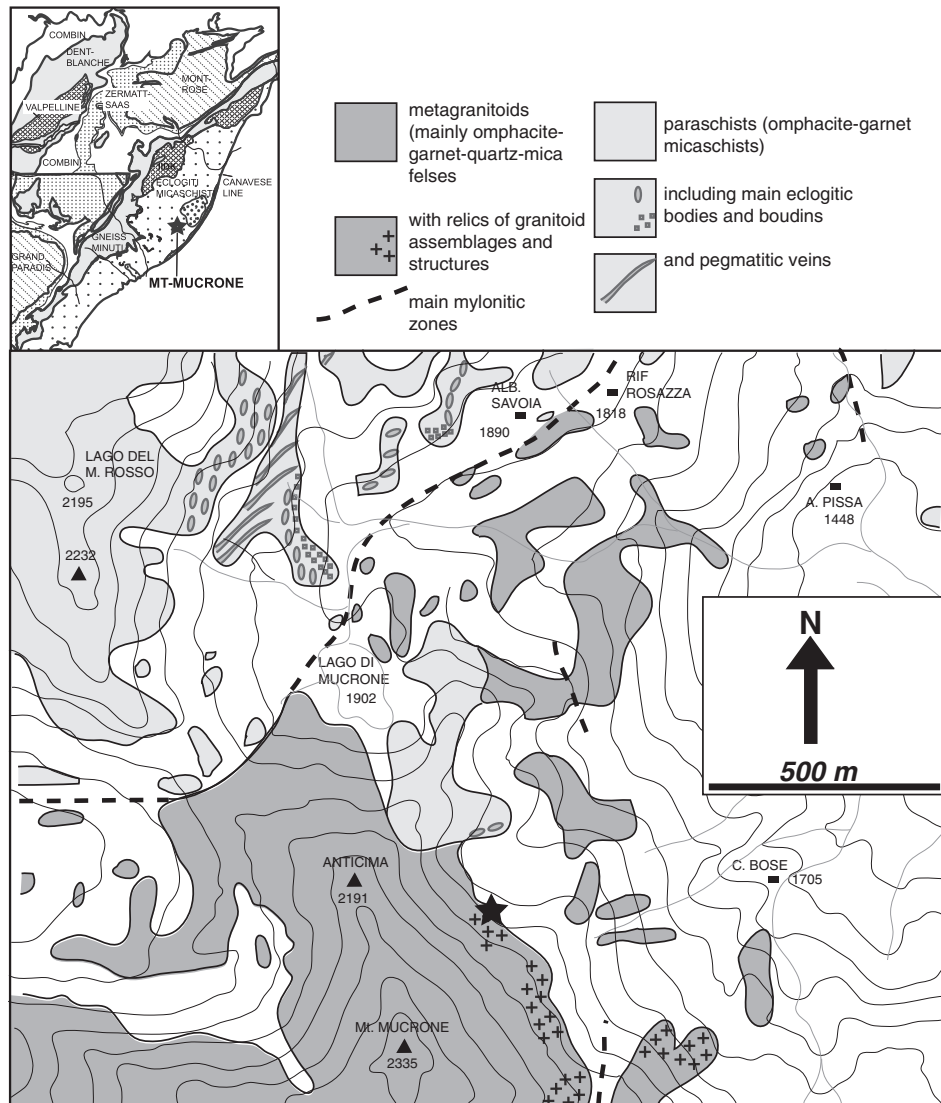


Fig. 1. Simplified map of Mt Mucrone modified from Oberhänsli et al. (1985). Star indicates sampling location.

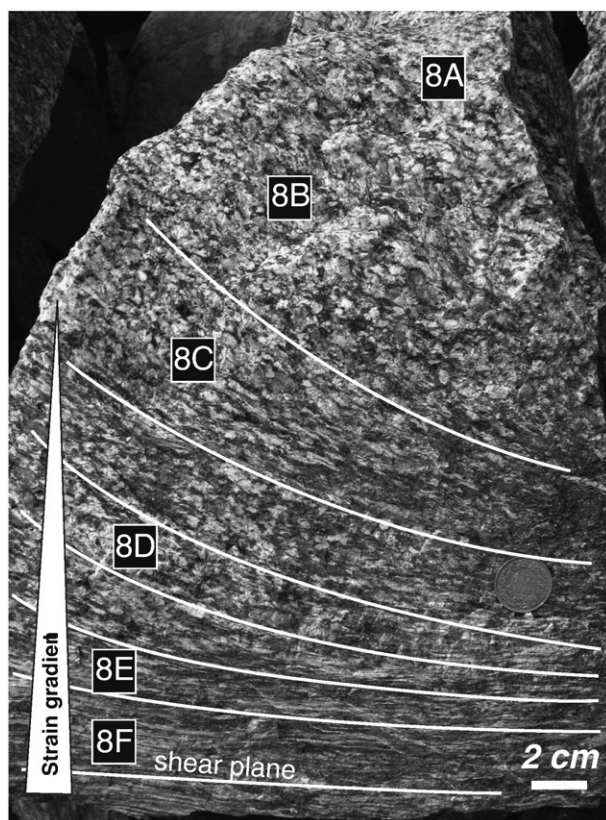


Fig. 2. Field picture of a metagranodiorite block depicting the finite strain gradient studied and sample location, from top (preserving magmatic textures) to bottom (fine-grained mylonite fabric).

3. Methods

Quantitative electron microprobe (EMP) compositional analyses for major elements and U–Th–Pb chemical dating were obtained on the JEOL JXA8200 at the University of Bern using the analytical procedure described in Scherrer et al. (2000) and refined by Janots et al. (2008). In addition, the REE contents of allanite, monazite and clinozoisite were obtained *in situ* by LA-ICP-MS analysis of polished thin sections at the Institute for Geological Sciences in Bern. The LA-ICP-MS system consists of an Elan 6100DRC-e quadrupole ICP-MS coupled to a GeoLas Pro 193 nm ArF excimer laser. Ablation was performed with an energy density on the sample of ca. 12 J/cm² using beam diameters of 24 to 44 μm and 8 Hz as repetition rate. The aerosol carrier gas was a mixture of He (ca. 1 l/min) and H₂ (ca. 0.007 l/min) gasses. Analyses were standardized using NIST SRM-612 glass as the external standard and ²⁷Al as the internal standard. The procedures for ICP-MS optimisation and data reduction are described in Janots et al. (2008).

Allanite grains for SHRIMP dating were mounted in epoxy and polished to expose the grain centers. High-contrast back-scattered electron (BSE) images were obtained at the Electron Microscopy Unit, The Australian National University, Canberra, with a Cambridge S360 scanning electron microscope using a voltage of 20 kV, beam current of ~2 nA and a working distance of 17 mm. U–Th–Pb data were obtained with a SHRIMP RG ion microprobe at the ANU in Canberra. Allanite U–Th–Pb analysis was as described by Gregory et al. (2007). For this study, the allanite were run in two separate sessions, with a 10 kV primary O₂[−] beam (at 4.0–6.5 nA) focused through a 120 μm aperture to form a ~25 μm diameter spot. Isotopic ratios were calibrated against TARA allanite (U–Pb and Th–Pb age of 417 Ma, Gregory et al. 2007). Bona allanite was used as secondary standard and yielded an average ²⁰⁸Pb/²³²Th age of 30.6 ± 0.8 Ma, which is

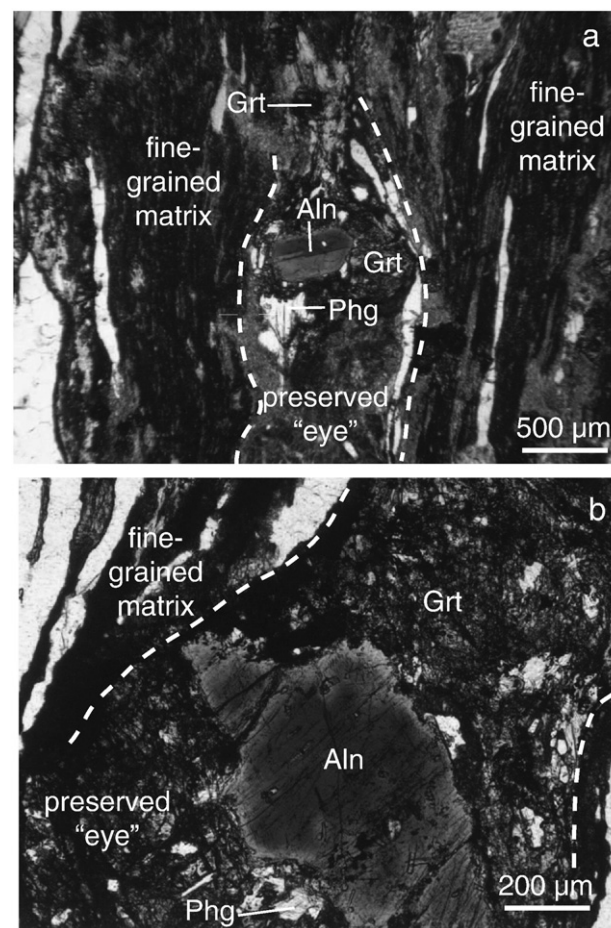


Fig. 3. Microphotographs showing allanite microtextures in mylonitic sample 8f. Allanite is located at the center of eyes, rimmed by garnet and randomly oriented phengite. White dashed lines represent limits between preserved “eyes” and fine-grained matrix. Mineral abbreviations from Kretz (1983).

within error of the reference age (30.1 ± 0.3 Ma, von Blanckenburg, 1992).

The two sessions had comparable 2σ calibration errors of 1.5–2.3% for both the Th and U system. Common Pb correction was based on the measured ²⁰⁷Pb/²⁰⁶Pb as detailed by Gregory et al. (2007). Additional details of the common Pb correction are discussed in the data presentation. Data reduction was conducted with the software Squid 2.5 (Ludwig, personal communication) which reproduces the procedure described by Gregory et al. (2007). Data were processed using Isoplot/Ex (Ludwig, 2003). Isotopic ratios and single ages are reported with 1σ errors, whereas mean ages are given at the 95% confidence level.

4. Samples

The granodiorite studied contains a primary assemblage of quartz, plagioclase, K-feldspar and biotite, with an eclogite-facies overprint inside and outside the shear zones (Oberhänsli et al. 1985). Reaction textures are described in detail by Fröh-Green (1994) and are summarized below for the samples investigated. One complete sequence of deformed materials was studied, representing different amounts of strain from undeformed (samples 8a, 8b), orthogneissic (samples 8c, 8d) to mylonitic (samples 8e, 8f) rocks (Fig. 2). Orthogneiss and mylonite domains form the shear zone. The entire deformation gradient is less than a meter across.

Despite intense Tertiary HP metamorphism, magmatic textures are well preserved in undeformed samples (e.g. 8a). The assemblage is

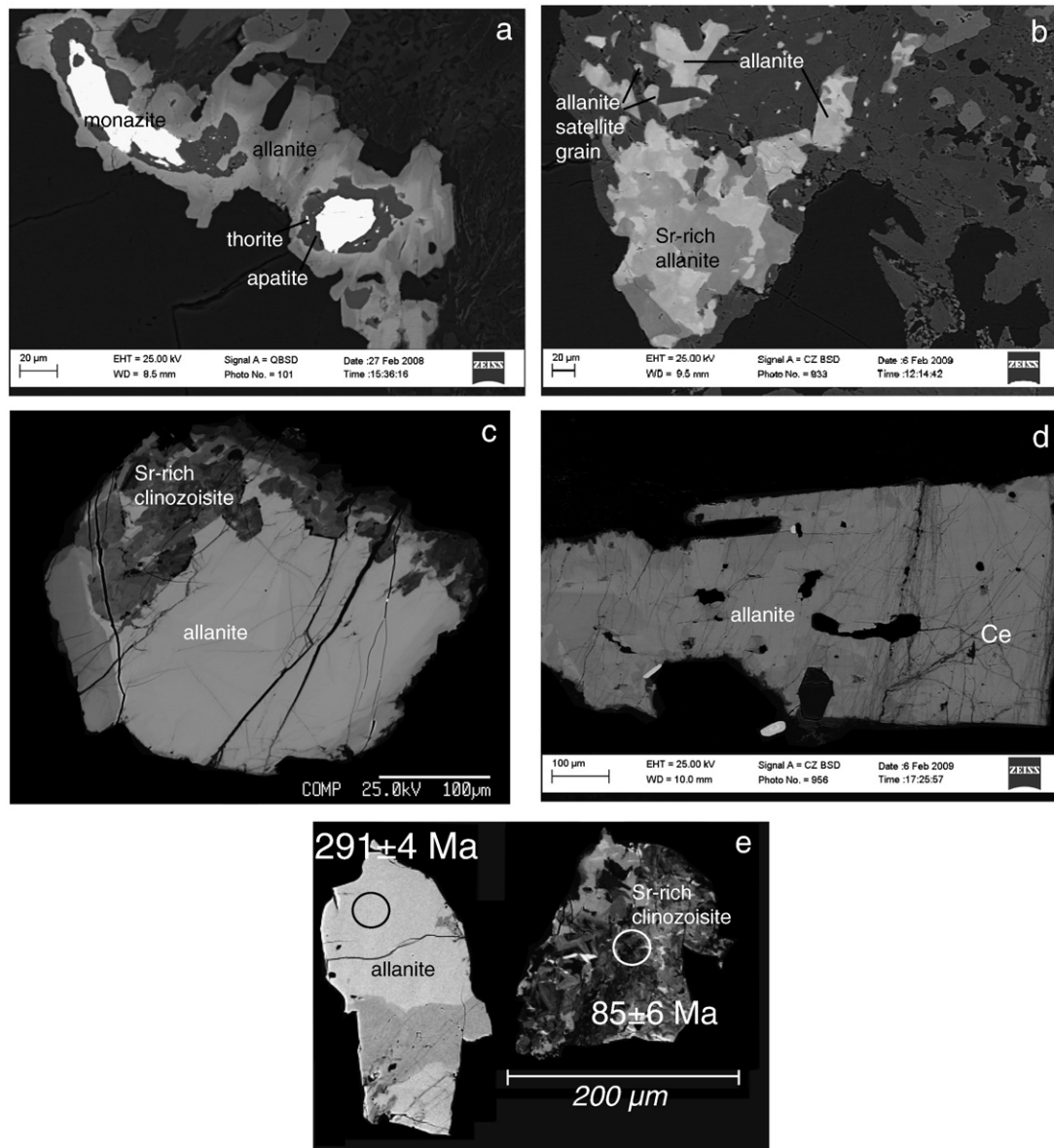


Fig. 4. Electron backscattered images of allanite microtextures and compositional maps. a) Two monazite grains surrounded by coronas of apatite, thorite and allanite (undeformed sample 8a); b) small fragmented mosaic allanite crystal with minute satellites (undeformed 8b); c) mosaic recrystallized rim around homogeneous allanite core (moderately deformed sample 8d); d) mm-sized patchy allanite in mylonite (8f); e) separated grains of Permian patchy allanite and Alpine mosaic allanite (undeformed sample 8b) with corresponding Th–Pb SHRIMP age (errors are 1σ).

mainly composed of magmatic biotite, K-feldspar, quartz and former plagioclase. Plagioclase is entirely replaced by aggregates of fine-grained ($<50\mu\text{m}$) zoisite, jadeitic clinopyroxene and quartz (Früh-Green, 1994). HP overprint textures are visible along grain boundaries of magmatic biotite and former plagioclase, where metamorphic reactions produced thin rims of phengite and garnet grains ($<200\mu\text{m}$). In other cases (8b), biotite is entirely transformed to a fine-grained aggregate of garnet and phengite.

The shear zone is mesoscopically evident owing to its darker color (Fig. 2), which is due to a strongly deformed matrix. The foliation in high-strain zones is marked by an alternation of monomineralic quartz ribbons and composite bands of fine-grained zoisite, phengite and jadeitic pyroxene ($<50\mu\text{m}$). Quartz shows grain size reduction from mm-size to a few tens of μm , and grain boundaries become irregular. In the orthogneiss, quartz locally presents undulatory extinction (sample 8c) and equigranular texture (8d). Garnet is present in composite bands as euhedral grains (typically $200\mu\text{m}$).

Locally the shape of mm-size relics of magmatic and late-magmatic minerals is preserved, even where replaced by metamorphic ones. The mylonitic foliation bends around these textural relics termed “eyes” in this contribution (Fig. 3a and b). Within these eyes, metamorphic phengite crystals are randomly oriented and coarser-grained (up to $200\mu\text{m}$).

Garnet in undeformed metagranodiorite (8a, 8b) is low in Ca ($X_{\text{Gro}} = 0.15$), whereas garnet grains in the mylonite matrix and at the border of the eyes are uniformly Ca-rich ($X_{\text{Gro}} = 0.50 \pm 0.05$). The absence of chemical zoning in garnet and the equally uniform phengite composition indicate that chemical equilibrium was closely approached in the texturally different parts of the mylonite, and under very similar conditions of P, T, and $a(\text{H}_2\text{O})$.

In summary, pronounced strain localization in the shear zone produced fine-grained HP-aggregates by breakdown of magmatic plagioclase and (partly) biotite. However, mm-sized “eyes” are preserved, even in mylonitic fabrics, in which coarse-grained garnet

plus phengite mantle relicts of allanite. It is essential to note that garnet + phengite located in the “eyes” (and therefore allanite) are in compositional equilibrium within the mylonitic system.

5. Results

5.1. Microtextures of REE-minerals

In the undeformed sample (8a), monazite and allanite are both present. Allanite forms rims around monazite, with apatite and thorite coronas between them (Fig. 4a). This texture is locally found within garnet–phengite coronas. In sample 8b two types of allanite occur. A first type occurs as larger pleochroic grains (>200 μm up to 1 mm; Fig. 3) rimmed by clinozoisite. These grains commonly show patchy zoning in BSE images (Fig. 4e left). In this contribution patchy zoning is defined by the combination of texturally homogeneous domains tens of μm in size. A second type of allanite consists of fragmented non-pleochroic grains (ca. 200 μm), with embayed borders surrounded by small (<50 μm) satellite grains. The fragmented grains and their satellites have mosaic zoning in BSE images (Fig. 4b and e right). Here a mosaic zoning consists of μm -scale domains that cannot be clearly singled out.

In orthogneissic samples (8c, 8d), allanite grains are larger (>200 μm to 1 mm) and pleochroic. These are usually zoned with an homogeneous to patchy bright core and a clinozoisite rim (Fig. 4c). These grains are located in the fine-grained matrix, locally but not necessarily associated with garnet.

In mylonitic samples (8e, 8f), allanite is commonly located at the center of the eyes containing garnet and phengite described previously (Fig. 3). It forms mm-sized prismatic grains with numerous fractures and micro-inclusion trails; no clinozoisite rim was observed. Apatite occurs as larger inclusions (1–20 μm) in allanite. Commonly garnet partially mantles allanite. In BSE pictures this allanite shows homogeneous to patchy zoning (Fig. 4d and e) with bands and patches distributed along fractures, suggesting that alteration was partly responsible for the observed chemical zoning. It is likely that recrystallization during late alteration and fracturing also affected the U–Pb isotopic signature as indicated by the tail of apparent ages younger than Permian (see below).

5.2. Allanite composition

The chemical compositions of the epidote group minerals range from allanite to clinozoisite to epidote (Fig. 5; Tables 1 and 2).

In the undeformed sample (8a), the content of $\sum \text{LREE}_2\text{O}_3$ in allanite coronas ranges from 9.0 to 18.6 wt.%, with $\sum \text{HREE}_2\text{O}_3 + \text{Y}_2\text{O}_3$ from 1.1 to 1.8 wt.% (Fig. 5a). Monazite and allanite present similar REE patterns, i.e. enriched in LREE with a strong negative Eu anomaly, but absolute concentrations are ca. 3 times higher in monazite than allanite (Fig. 6; Table 2).

Undeformed sample 8b contains two types of allanite (see above). Patchy grains have high REE contents with $\sum \text{LREE}_2\text{O}_3$ ranging from 16 to 20 wt.% and $\sum \text{HREE}_2\text{O}_3 + \text{Y}_2\text{O}_3$ from 1.2 to 2.0 wt.%. On the other hand, the mosaic grains with minute satellites vary in composition from allanite to REE-rich clinozoisite with $\sum \text{LREE}_2\text{O}_3$ contents, ranging from 4.8 to 15.1 wt.%, $\sum \text{HREE}_2\text{O}_3 + \text{Y}_2\text{O}_3$ from 0.1 to 0.4 wt.%, and SrO from 0.8 to 2.1 wt.% (Fig. 5; Tables 1 and 2). Some Sr-rich clinozoisite grains contain up to 1 wt.% Fe_2O_3 . Fig. 7 shows elemental maps for Ce, Ca, Sr and Th for the mosaic grain showed in Fig. 4b. REE patterns of Sr-rich clinozoisite grains have similar HREE as allanite, but 10 times lower LREE contents (Fig. 6; Table 2). A slightly positive Eu anomaly is present, suggesting that this clinozoisite formed from a reaction involving plagioclase which could either be plagioclase breakdown or a reaction between plagioclase and biotite. As clinozoisite contains Fe (Table 1), the second reaction is favored.

In orthogneissic samples (8c and 8d), patchy allanite cores are enriched in LREE and Th ($\sum \text{LREE}_2\text{O}_3$ from 15.1 to 21.9 wt.%, ThO from 0.9 to 2.4 wt.%; Fig. 5). A first rim enriched in Y (Y_2O_3 from 1.3 to 2.6 wt.%) and depleted in LREE ($\sum \text{LREE}_2\text{O}_3$ from 3.4 to 12.4 wt.%) is followed by a clinozoisite rim enriched in Sr (SrO from 0.1 to 1.3 wt.%) with significantly lower but variable Th and LREE contents ($\sum \text{LREE}_2\text{O}_3$ from 0.1 to 11.4 wt.% and ThO₂ from 0.1 to 1.0%) (Fig. 4c; Table 2).

In mylonitic rocks (8e and 8f), allanite grains present homogeneous and patchy zoning (Fig. 4d and e left) and show variable LREE contents ($\sum \text{LREE}_2\text{O}_3$ from 15.5 to 21.2 wt.%). Th is enriched towards crystals boundaries (ThO from 1.1 to 2.2 wt.%).

It is noteworthy that variations in allanite composition do not correlate with the amount of strain experienced by the samples (cf. Figs. 5 and 6).

5.3. Allanite ion microprobe U–Th–Pb ages

U–Th–Pb SHRIMP dating was performed on allanite from two samples displaying contrasting degrees of deformation: undeformed sample 8b and mylonitic sample 8 f. In the undeformed granitoids the two allanite types observed in thin section yielded different Th/U, amounts of common Pb and ages (Table 3). Grains with homogeneous and occasionally patchy zoning have variable Th/U between 15 and 164. The grains show broad (10's–100's μm) compositional zoning including domains with patchy zoning. Patchy-zoned domains have

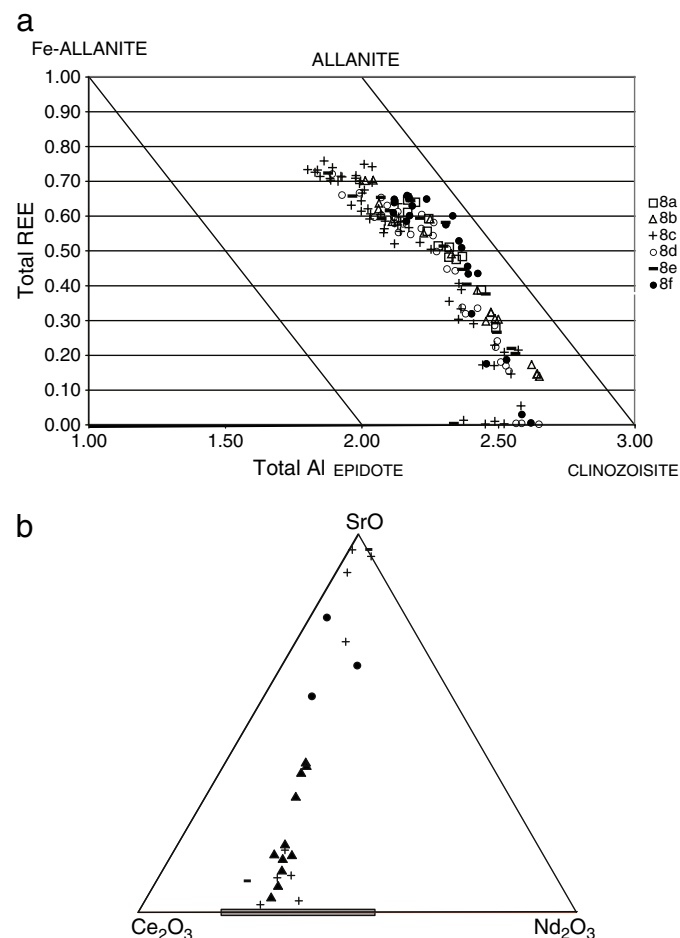


Fig. 5. a) EMPA chemical composition of epidote group minerals from all of the studied samples; b) Triangular plot showing variations in Sr of allanite and clinozoisite in moderately deformed samples 8b, 8c and 8d. Most of the grains contain hardly any Sr and plot within the shaded area on the join Ce_2O_3 – Nd_2O_3 .

Table 1
Representative EMPA analyses of the epidote group minerals.

	Allanite/epidote in mylonitic sample (8f)				Recrystallised allanite/epidote in undeformed sample (8b)			
	Homog. core	Homog. core	Patchy domain	Patchy domain	Bright BSE	Dark BSE	Dark BSE	Bright BSE
SiO ₂	35.58	34.09	36.95	38.90	34.66	35.85	36.94	35.75
TiO ₂	0.16	0.23	0.12	0.30	0.27	0.09	0.09	0.09
Al ₂ O ₃	23.97	20.88	26.11	28.99	22.55	25.06	27.24	24.89
Fe ₂ O ₃	–	–	1.88	5.98	0.09	0.46	1.17	0.80
MnO	–	0.05	0.18	0.08	–	–	–	–
FeO	8.21	10.09	5.30	0.28	9.04	6.98	4.83	6.78
CaO	15.01	10.88	19.14	24.00	13.66	16.41	18.89	16.40
MgO	0.32	0.48	0.10	0.01	0.42	0.20	0.12	0.22
SrO	–	–	–	0.21	0.81	1.23	1.60	1.19
Y ₂ O ₃	0.29	0.26	0.89	0.01	0.15	0.06	0.03	0.06
La ₂ O ₃	3.23	4.30	1.25	0.07	3.00	1.98	1.42	2.04
Ce ₂ O ₃	6.45	9.37	2.69	–	7.40	4.92	2.58	4.62
Pr ₂ O ₃	0.83	1.35	0.29	0.08	1.03	0.59	0.51	0.62
Nd ₂ O ₃	2.76	3.86	1.29	0.01	3.21	1.91	1.08	2.17
Sm ₂ O ₃	0.36	0.42	0.29	–	0.49	0.27	0.10	0.32
Gd ₂ O ₃	0.24	0.32	0.34	0.05	0.21	0.12	0.09	0.09
Dy ₂ O ₃	0.08	0.03	0.16	–	0.05	0.03	–	–
PbO	0.03	0.01	0.02	0.02	–	0.01	0.01	0.03
ThO ₂	1.13	1.41	0.42	–	2.08	2.23	1.76	2.04
UO ₂ corr	0.04	0.04	0.03	–	0.03	0.06	0.10	0.04
sum	98.69	98.07	97.45	99.20	99.95	99.69	100.15	99.35
sum(REE + Y)	14.24	19.91	7.20	0.22	15.54	9.89	5.81	9.95

lower Th/U than the homogeneous domains. Their Th–Pb system is highly radiogenic with <1.5% common Pb. The U–Pb system is variably contaminated with the high Th/U ratio domains having up to 24% common Pb. This allows the common Pb composition to be obtained by regressing the nine uncorrected U–Pb analyses in a Tera–Wasserburg-type diagram (Fig. 8a). The regression (MSWD 3.5) yields a common $^{207}\text{Pb}/^{206}\text{Pb}$ of 0.70 ± 0.13 which is slightly lower than the composition of 0.855 predicted by Stacey and Kramers (1975) model at 280 Ma. The corresponding $^{206}\text{Pb}/^{238}\text{U}$ age using the obtained common Pb composition is 270 ± 10 Ma. The same analyses also fit a regression (MSWD 4.4) to Stacey and Kramers model

Table 2
Representative LA-ICP-MS trace element composition of allanite, monazite and clinozoisite.

		Monazite	Allanite	Allanite	Clinozoisite
		24ala05	24ala03	24alc15	24alc14
MgO	wt.%	0.00	0.67	0.71	0.19
Al ₂ O ₃	wt.%	0.01	21.9	20.0	24.0
K ₂ O	wt.%	–	0.02	0.08	0.28
CaO	wt.%	0.88	10.7	12.1	19.1
TiO ₂	wt.%	–	0.24	0.63	0.19
MnO	wt.%	–	0.86	0.24	0.27
Sr	ppm	31	54	123	1460
Y	ppm	21,200	4700	3090	15,100
Zr	ppm	5	3	2	4
La	ppm	151,500	42,400	46,400	4380
Ce	ppm	267,300	93,300	90,900	9170
Pr	ppm	28,400	10,600	9520	1330
Nd	ppm	112,900	35,400	33,700	7550
Sm	ppm	17,200	5590	4690	3970
Eu	ppm	172	67	61	2200
Gd	ppm	12,100	3190	2520	5890
Dy	ppm	6040	1580	1010	4780
Ho	ppm	848	217	132	694
Er	ppm	1630	427	257	1310
Yb	ppm	541	242	137	511
Lu	ppm	51	27	16	51
Pb	ppm	1810	277	609	94
Th	ppm	79,400	8670	19,000	988
U	ppm	3880	796	454	890
Ba	ppm	1.3	1.7	4.5	17.6

common Pb (0.0855), with a corresponding age of 281 ± 8 Ma. The Th–Pb system is less sensitive to the common Pb correction and yields an average $^{208}\text{Pb}/^{232}\text{Th}$ age of 291 ± 5 Ma (Fig. 8b; MSWD 1.1, include 1.5% calibration error, common Pb according to Stacey and Kramers, 1975). Notably, the patchy zoned allanite has a tendency to younger ages, but at this level of precision all analyses form a single population.

In the same undeformed sample 8b, Sr-rich allanite–clinozoisite with a fine mosaic zoning forms isolated grains with minute satellites. This allanite–clinozoisite has Th/U <65, higher concentrations of U and Th (as indicated by higher count rates on ThO and UO peaks), but also much higher percent of common Pb in both systems with common $^{206}\text{Pb}_c$ generally >60% and $^{208}\text{Pb}_c$ in the range 20–65% (Fig. 8b). Accurate estimate of the common Pb composition for these analyses is difficult: the large uncertainty on the analyses makes the Tera–Wasserburg regression highly imprecise. Assuming a Stacey and Kramers (1975) model common Pb, and using the Th–Pb system, which is relatively more radiogenic, apparent ages of the nine analyses vary between 276 ± 5 and 66 ± 3 Ma (Table 3). The scatter in age reinforces the fact that regression to a single common Pb is not suitable, thus the Stacey and Kramers (1975) model is preferred.

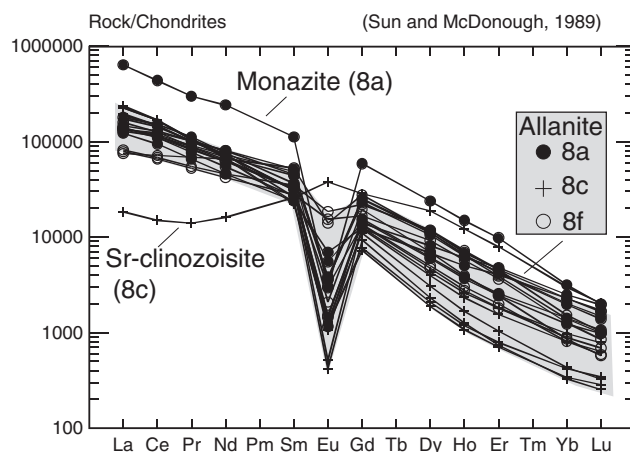


Fig. 6. LA-ICP-MS trace-element patterns for Permian monazite, allanite and Alpine Sr-rich clinozoisite.

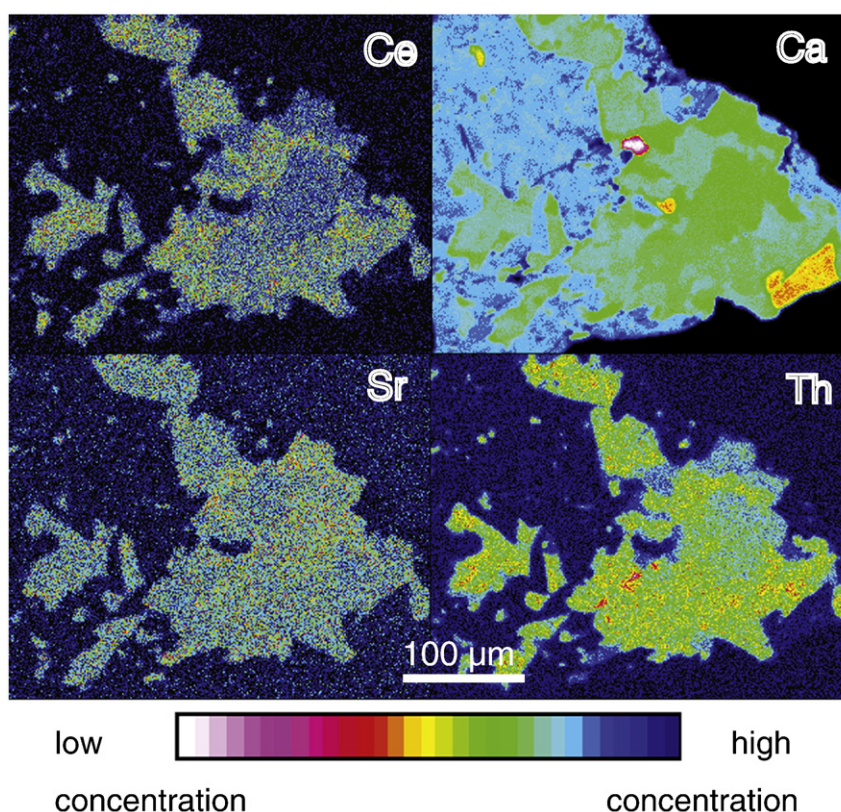


Fig. 7. Compositional map of mosaic grain shown in Fig. 4b (from undeformed sample 8b).

However, these ages are only indicative because of the uncertainty in the common Pb composition and the possibility of mixed analysis between Permian and Alpine domains. In order to check this hypothesis, four Sr EMPA measurements were made around each of the 18 SHRIMP spots and Sr element mapping on critical grains. These data (not shown here) show clearly that the three intermediate spots are mixed analyses (Fig. 8b). Therefore it is possible to clearly distinguish a group of Permian grains, a group of Alpine grains and three mixed analyses.

The coarse allanite (mm-size grains) from mylonite 8f is generally homogeneous or shows patchy zoning in BSE (Fig. 4d and e left). Th/U varies from ~50–140 (Table 3), comparable to the Permian allanite in granitoid 8b. The amount of common Pb is reasonably low for the Th–Pb system ($^{208}\text{Pb}_c$ 1–12%), but high in the U–Pb system ($^{206}\text{Pb}_c$ 6–65%). A free regression of the 19 analyses (MSWD 1.6) returns a common $^{207}\text{Pb}/^{206}\text{Pb}$ of 0.863 ± 0.035 (Fig. 8c), which is within error of what is predicted by the Stacey and Kramers model. The corresponding $^{206}\text{Pb}/^{238}\text{U}$ age is 287 ± 8 Ma. This is in line with the $^{208}\text{Pb}/^{232}\text{Th}$ average age of 287 ± 7 Ma (Fig. 8d; MSWD 2.4, include 2.0% calibration error, common Pb according to Stacey and Kramers 1975).

In summary, the main differences between grains showing Permian and Alpine ages are:

- (i) *Texture*: up to mm-sized Permian porphyroclasts compared to smaller Alpine grains (these are either minute satellites or tiny rims around Permian grains);
- (ii) *Chemical zoning*: homogenous or patchy Permian grains, compared to Alpine grains with mosaic BSE zoning;
- (iii) *Major element contents*: Sr enrichment and lower REE contents in Alpine grains when compared to Permian allanite;
- (iv) *REE patterns*: Permian allanite enriched in LREE with a strong negative Eu anomaly; Alpine grains depleted in LREE with a slight positive Eu anomaly.

6. Discussion

Two age populations are found in the samples studied: i) Permian allanite and monazite, (ii) late Cretaceous allanite and clinozoisite. The significance of this age difference is best understood by considering the mechanisms of i) formation of Permian allanite, ii) preservation of allanite microstructures and composition in mylonite, and iii) (re)crystallization of allanite and the role of deformation.

6.1. Formation of Permian allanite

Allanite crystals located both inside and outside the shear zone, especially those texturally associated to the HP mineral assemblage garnet and phengite show Permian ages (ca. 290 Ma). This age is identical within error to that of zircon in the granitoids ($293 \pm \frac{1}{2}$ Ma; Bussy et al., 1998). As allanite locally surrounds Permian monazite (Fig. 4a), these ages and textural relations are interpreted as indicating monazite formation during granitoids crystallization (Bea, 1996), followed by allanite formation. The monazite–allanite reaction texture is therefore either magmatic or a product of high temperature alteration after the granodiorite reached its solidus (Berger et al., 2009; Broska et al., 2000). Several processes can be invoked for the breakdown of monazite to allanite including a change in Ca activity of the crystallizing magma (Broska et al., 2000), magma mingling (Dini et al., 2004), or a late-magmatic reaction upon cooling of the pluton (Petrik and Broska, 1994). Alternatively allanite formation may have been related to brittle fractures that developed during late stage crystallization or after cooling of the magmatic body. Brittle fracturing may have occurred at a late magmatic stage, when fluid/melt pressures and strain rates were high (Bouchez et al., 1992; Davidson et al., 1994). Even though such brittle fractures are not preserved in the field, these may have been active in order to drain the late

Table 3
SHRIMP U–Th–Pb analyses of allanite.

Mylonitic granitoid 8f															ALL 207 corr	
Spot name		% ²⁰⁸ Pb _c	²³² Th/ ²³⁸ U	Total ²³⁸ U/ ²⁰⁶ Pb	% err	Total ²⁰⁷ Pb/ ²⁰⁶ Pb	% err	²⁰⁶ Pb*/ ²³⁸ U	% err	²⁰⁸ Pb*/ ²³² Th	% err	²⁰⁶ Pb*/ ²³⁸ U age	1 sigma err	²⁰⁸ Pb*/ ²³² Th age	1 sigma err	BSE zoning
MUC-12	65	11.9	90	8.31	2.2	0.5756	5.08	0.04171	3.5	0.01347	3.3	263	28	270	9	Homogeneous core
MUC-19	53	8.1	89	10.41	5.0	0.4755	3.67	0.04529	2.2	0.01349	2.6	286	19	271	7	Patchy crystal
MUC-14	61	10.4	92	8.95	7.1	0.5438	0.39	0.04317	2.3	0.01349	2.6	272	19	271	7	Homogeneous core
MUC-18	23	4.0	48	17.53	2.1	0.2369	4.10	0.04388	0.8	0.01367	2.6	277	7	274	7	Patchy crystal
MUC-20	32	4.3	66	15.85	2.1	0.3048	0.59	0.04318	0.7	0.01381	2.5	272	6	277	7	Patchy crystal
MUC-15	16	2.1	58	19.06	2.1	0.1796	0.67	0.04411	0.7	0.01403	2.5	278	6	282	7	Homogeneous core
MUC-16	37	4.5	81	14.09	2.2	0.3450	0.67	0.04507	0.7	0.01405	2.5	284	6	282	7	Patchy crystal
MUC-13	30	2.8	99	15.59	2.2	0.2933	0.63	0.04484	0.7	0.01411	2.5	283	6	283	7	Homogeneous core
MUC-9	38	4.5	86	13.71	2.2	0.3588	0.54	0.04506	0.7	0.01432	2.5	284	6	287	7	Homogeneous core
MUC-7	32	2.8	107	14.98	2.2	0.3058	0.65	0.04565	0.7	0.01436	2.5	288	6	288	7	Homogeneous core
MUC-4	45	6.2	80	12.44	2.1	0.4131	0.47	0.04420	0.7	0.01437	2.5	279	6	288	7	Homogeneous core
MUC-6	39	4.1	99	13.33	2.2	0.3675	2.69	0.04555	1.0	0.01448	2.5	287	8	291	7	Patchy crystal
MUC-11	45	6.2	83	11.88	5.0	0.4144	4.50	0.04620	2.1	0.01451	2.6	291	19	291	7	Patchy crystal
MUC-10	36	4.4	82	13.82	2.1	0.3395	0.54	0.04645	0.7	0.01454	2.5	293	6	292	7	Homogeneous core
MUC-8	33	3.7	85	14.60	2.1	0.3182	3.11	0.04579	0.9	0.01467	2.5	289	8	294	7	Homogeneous core
MUC-3	57	10.4	77	9.06	2.2	0.5125	0.42	0.04710	0.7	0.01472	2.5	297	7	295	7	Homogeneous core
MUC-1	22	3.4	53	16.74	2.1	0.2296	0.51	0.04653	0.7	0.01490	2.5	293	6	299	8	Homogeneous core
MUC-5	54	5.3	138	9.46	2.4	0.4852	0.61	0.04877	0.8	0.01539	2.5	307	8	309	8	Homogeneous core
MUC-2	6	1.2	37	19.72	2.0	0.1033	0.66	0.04749	0.7	0.01547	2.5	299	6	310	8	Homogeneous core
												WA	95% cl	WA	95% cl	
												287	4	287	5	
Undeformed granitoid 8b															All 207 corr	
	7-corr %com 206	7-corr %com 208	²³² Th/ ²³⁸ U	Total ²³⁸ U/ ²⁰⁶ Pb	% err	Total ²⁰⁷ Pb/ ²⁰⁶ Pb	% err	7corr 206*/ 238	% err	7corr 208*/ 232	% err	207corr206Pb/ 238U age	1s err	207corr208Pb/ 232Th age	1s err	
MUC-3	92.4	52.2	64	8.3	5.1	0.78	2.1	0.00908	23.2	0.00326	4.6	58	16	66	3	MOSAIC crystal
MUC-10	86.8	64.4	16	18.4	1.6	0.74	6.0	0.00715	10.4	0.00332	16.0	46	19	67	11	mosaic crystal
MUC-14	75.9	32.9	38	22.6	9.9	0.65	8.1	0.01068	12.8	0.00373	8.3	68	20	75	6	Mosaic crystal
MUC-6R	78.9	50.8	31	12.3	10.8	0.67	7.9	0.01717	51.7	0.00417	11.5	110	37	84	10	Mosaic rim
MUC-13	80.3	38.6	40	15.5	13.5	0.69	3.6	0.01270	52.7	0.00424	7.2	81	17	85	6	Mosaic crystal
MUC-7	74.8	33.7	36	19.3	1.7	0.64	0.4	0.01301	7.1	0.00436	1.5	83	2	88	1	Mosaic crystal
MUC-8	60.4	22.3	32	24.3	22	0.53	13.0	0.01626	48.6	0.00563	7.3	104	32	114	8	Mosaic rim
MUC-5	80.4	33.6	53	9.5	11.5	0.69	3.4	0.02063	12.8	0.00649	3.8	132	25	131	5	Mosaic crystal
MUC-16	15.6	4.5	25	20	1.7	0.18	14.0	0.04219	4.2	0.01377	1.8	266	11	276	5	Mosaic and patchy
MUC-17	4.8	1.1	28	22	1.6	0.09	0.8	0.04326	1.7	0.01424	1.5	273	4	286	4	Patchy crystal
MUC-12	3.7	1.5	15	23	1.6	0.08	0.6	0.04190	1.6	0.01427	1.5	265	4	286	4	Patchy crystal
MUC-9	3.7	1.1	21	21.5	1.6	0.08	0.7	0.04490	1.7	0.01436	1.5	283	5	288	4	Homogeneous core
MUC-4	3.3	1.4	16	22.2	1.6	0.08	0.6	0.04360	1.6	0.01443	1.5	275	4	290	4	Patchy crystal
MUC-15	18.1	1.1	135	18.2	2.2	0.2	1.1	0.04499	2.9	0.01444	1.5	284	6	290	4	Homogeneous core
MUC-11	22.9	1.4	142	17	2.7	0.24	1.4	0.04538	4.1	0.01450	1.5	286	8	291	4	Homogeneous core
MUC-6C	24.4	1.3	164	16.1	2.8	0.25	1.5	0.04702	4.2	0.01479	1.5	296	8	297	5	Homogeneous core
MUC-1	3.4	1.3	18	21.2	1.6	0.08	0.6	0.04555	1.6	0.01480	1.5	287	5	297	4	Homogeneous core
MUC-2	13.7	0.9	118	18.2	2	0.16	1.1	0.04749	2.4	0.01486	1.5	299	6	298	5	Homogeneous core

Pb_c = common lead.
Pb* = radiogenic lead.
WA = weighted average.

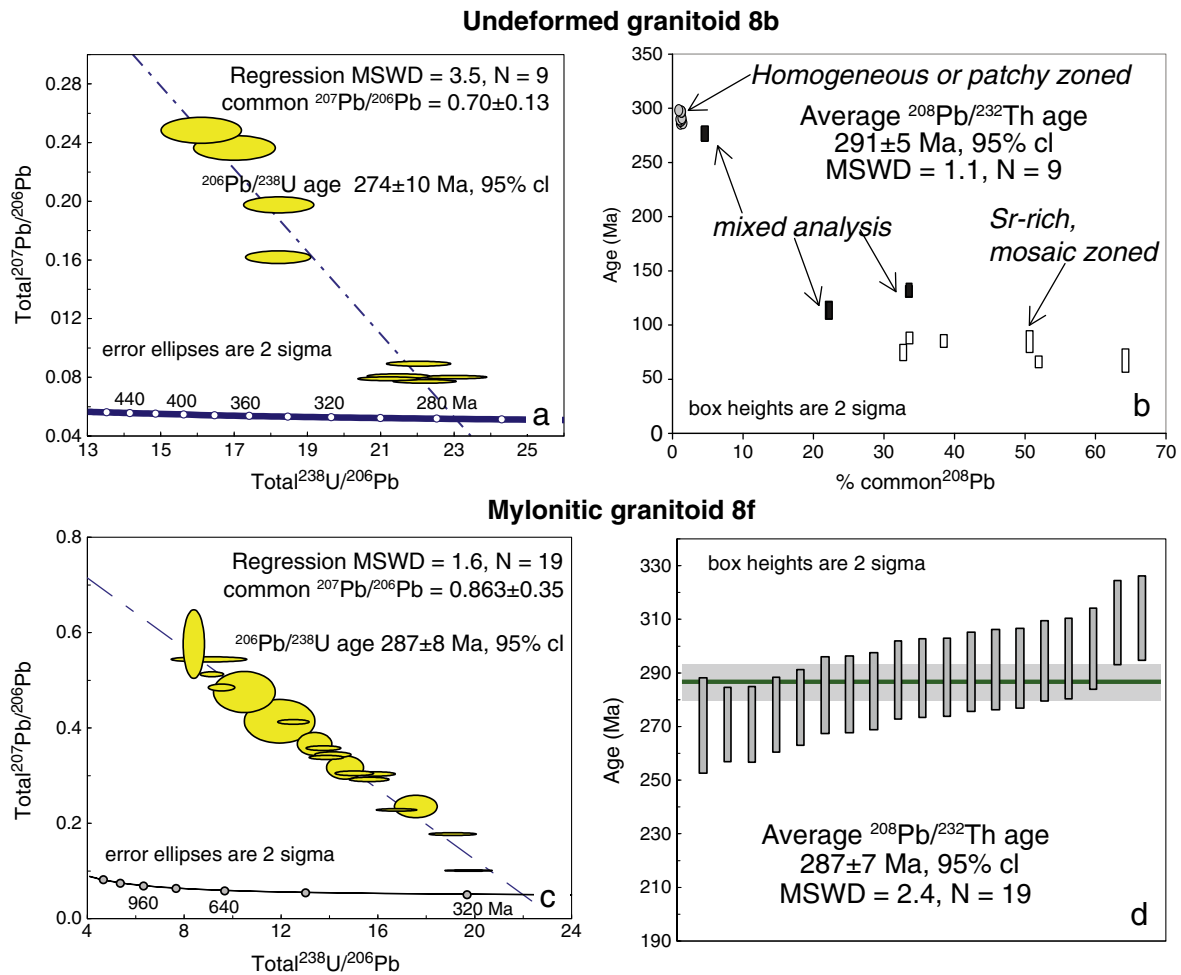


Fig. 8. a) Tera-Wasserburg plot of allanite analyses (uncorrected for common Pb) from undeformed granitoid 8b. Only the analyses from homogeneous and patchy zoned allanite are plotted; b) Percent of common ^{208}Pb versus Th–Pb age for allanite analyses from the undeformed granitoids 8b. Ages are calculated assuming a [Stacey and Kramers \(1975\)](#) common Pb composition; c) Tera-Wasserburg plot of allanite analyses uncorrected for common Pb from mylonite 8 f. The common $^{207}\text{Pb}/^{206}\text{Pb}$ intercept is within limit of error of the [Stacey and Kramers \(1975\)](#) model; d) Average Th–Pb age (ordered by age) for the same analyses from mylonite 8 f. See text for details.

magmatic fluid that lead to the formation of allanite crystals that are significantly larger than those occurring in the adjacent granodiorite. The phases produced depend on the fluid/melt ratio in such fractures. An increase in Ca activity may have stabilized allanite instead of monazite, for example because of the breakdown of magmatic plagioclase.

6.2. Preservation of Permian allanite in an Alpine HP shear zone

A most surprising observation in this study is the large allanite grains found in fine-grained mylonite, where these in fact are coarser than in the undeformed metagranodiorite. Equally remarkable is the finding that some allanite grains, all across the range of strain observed, retain a rather uniform chemical and isotopic composition when compared to the less deformed samples.

In mylonitic samples, allanite is located at the center of “eyes” or clasts, i.e. textural relics preserved within shear bands. In these cases chemical equilibration is absent or limited to the polycrystalline rim of randomly oriented phengite + garnet. Allanite thus shows unusual resilience in shear zones, showing no grain size reduction related to strong deformation, in contrast to the matrix minerals, quartz, phengite and pyroxene. The partial preservation of chemically reactive allanite clasts is attributed to the effects of shielding. Consequently recrystallization of allanite was inhibited, reflecting a noteworthy interplay between reactions kinetics and deformation mechanisms.

In more detail, several observations in the mylonitic matrix reflect localized high strain: i) ductile reorientation of regional gneissic foliation in zones of concentrated shear ([Fig. 2](#)); ii) continuous decrease in matrix grain size from gneiss to mylonite; iii) development of the fine-grained polyphase mixed matrix ([Kruse and Stünitz, 1999](#)); and iv) development of elongate monomineralic quartz bands ([Früh-Green, 1994](#); [van Roermund et al., 1979](#)). These observations indicate that the main deformation process was granular flow ([Paterson, 1995](#)) and, in monomineralic layers, dislocation creep. Granular flow processes include different types of grain scale mass transfer that facilitate local equilibration between minerals ([Berger and Rosenberg, 2003](#)). This is not the case for the preserved eyes. The microstructural difference between the deforming matrix and eyes is based on several observations:

- Orientation of mica:** In the matrix, white mica defines the main mylonitic foliation; in the eyes, phengite flakes are randomly distributed ([Fig. 3](#)).
- Grain size:** Differences up to three orders of magnitude between the matrix and the eyes ([Fig. 3](#)).
- Mineral assemblage and grain fabric:** The difference in the size and orientation of grains may indicate different mechanisms of reaction. More importantly, the conclusion is that the preserved allanite were either stable with the HP assemblage garnet and phengite or close enough to equilibrium to drive only a very sluggish transformation. Notably, there is no

secondary Th- or LREE-rich phase observed in the coarse reaction rim.

A key observation is the difference in grain size of Permian allanite: In the protolith 0.2–1 mm grains are typical, whereas relics in the mylonite eyes can be several mm in size. This may indicate a primary genetic difference, e.g. the latter type formed in late-magmatic or pegmatite veins in the granitoid. Such heterogeneities could well have been reactivated during Alpine ductile, solid-state deformation (e.g. [Mancktelow and Pennacchioni, 2005](#)) in the Alpine orogenic cycle. To account for the coarse-grained polycrystalline rim around the allanite relics, the Permian grains may have been initially rimmed by clinozoisite (from the breakdown of calcic plagioclase) in greenschist facies. The shielding effect of this proposed scenario becomes evident when we take into account the relative resistance of epidote group minerals to ductile deformation. Experiments by [Stünitz and Tullis \(2001\)](#) showed that large clinozoisite crystals resulting from plagioclase breakdown remain strong during such deformation. Epidote group minerals behave as rigid clasts in a fine-grained matrix of feldspar, provided granular flow is the dominant deformation process. It is difficult to make a general rule from this observation, as strength contrast between minerals and matrix depends on various factors (e.g. deformation mechanisms, temperature, and strain rate), and fluids enhance recrystallization kinetics.

In summary, the occurrence of large allanite grains is tentatively explained by a late- to post-magmatic, Permian crystallization in veins. Such veins would have made likely sites of strain concentration during Alpine convergence, thus initiating the development of mylonite zones. Within these, allanite relics were preserved owing to their relative mechanical strength.

6.3. Significance of the Alpine allanite

It should be stressed once more that only a very minor portion of the allanite grains studied show extensive recrystallization. Fragmented mosaic grains of allanite (to clinozoisite) are, at least in part, Sr-rich, and in the undeformed sample (8b) yield late Cretaceous apparent ages ([Table 3, Fig. 8b](#)). The Permian age is well constrained by magmatic allanite in the same sample, and ~65 Ma is a stage of HP metamorphism known from other areas in the Sesia zone ([Duchêne et al., 1997; Ramsbotham et al., 1994; Rubatto et al., 1999](#)).

Partial recrystallization of the mosaic zoned allanites is one explanation for the apparent scatter in ages obtained from these domains. The calculated ages may be affected by uncertainties in the correction of initial Pb and the possible matrix bias between the allanite standard and the more clinozoisite-rich composition of the analyzed samples. Despite these analytical issues, the late Cretaceous ages undoubtedly reflect Alpine HP-recrystallization. The scatter in these data also raises the question of the mobility of Pb during recrystallization under high strain conditions in the presence of fluid. In magmatic systems, [Romer and Siegesmund \(2003\)](#) found that radiogenic Pb from the precursor mineral can be partially incorporated in secondary allanite, resulting in a too high apparent age for the latter.

Recrystallization in the Mucrone sample produced some partial and localized Pb loss, but failed to completely reset the U–Pb isotopic system. The large variations in Sr and common Pb within Alpine allanite and clinozoisite reported in this study raise the question of the common Pb source. Incorporation of Sr in epidote group minerals and phosphates in HP environments has been linked to areas where calcic plagioclase and titanite are unstable ([Krenn and Finger, 2004; Nagasaki and Enami, 1998](#)). Unraveling the source of initial Pb is beyond the scope of this paper, but we recognize that the effects of Pb mobility on the initial common Pb is crucial to interpret dates from grains with high common Pb that recrystallized under HP metamorphic conditions.

In general, recrystallization processes are controlled by several physico-chemical factors, the availability of fluid, and the amount of deformation. In the Mucrone body, the (local) presence of an aqueous fluid during HP metamorphism is evident from the prograde breakdown reaction of plagioclase to form jadeite and zoisite ([Früh-Green, 1994](#)). However, petrographic evidence does not indicate that the replacement of allanite is spatially linked to plagioclase breakdown, i.e. to the availability of fluid. As the composition of allanite changes little in samples taken across the strain gradient ([Figs. 5 and 6](#)), it appears that deformation alone is not the major factor controlling allanite metamorphic recrystallization and isotopic resetting.

7. Conclusions

The preservation of Permian allanite within an Alpine eclogite facies shear zone at Mt Mucrone is attributed to mechanical and chemical shielding during mylonite formation. We propose that Permian allanite grains (several millimeters in size) crystallized in late magmatic (or early post-intrusive) fractures, and that these cores were subsequently mantled by clinozoisite/epidote. Alpine shearing reworked the mechanical heterogeneities left by the veins. During the HP metamorphic transformations, the allanite were largely unaffected, whereas their mantle reacted statically, but at conditions very similar to the mylonite, in which they now reside. The resistance of allanite to deformation is remarkable and has implications on the interpretation of allanite ages in deformed rocks.

In this study, deformation did not play a major role in triggering metamorphic recrystallization and isotopic resetting of allanite. However, it is essential to record microstructures and link these to mineral separates (or *in situ* domains) chosen for age dating. Allanite is a highly retentive geochronometer, not only in terms of its thermal stability, but also owing to its mechanical strength and thus its reluctance to recrystallize under stress. The composition, notably elevated Sr-contents of recrystallized grains, allows the recognition of metamorphic allanite, which yielded indicative Cretaceous ages. While these grains occur within little deformed and orthogneissic metagranodiorite, but not the high-strain part of the HP shear zone, well-equilibrated metamorphic assemblages in each of these domains reflect identical *P–T* conditions. Based on the petrographic and geochemical data from this study, mylonite formation must have occurred at the same conditions as the metamorphic overprint, and shall be Cretaceous in age.

Acknowledgements

We thank M. Zucali, M. Herwegh and J. Darling for discussions. Financial support from Swiss National Fund for our work in the Western Alps (Grants 200020-109637, 200021-117996/1) is gratefully acknowledged. The electron microprobe at the University of Bern is also partly funded by SNF (Grant 200021-103479/1). The Centre for Advance Microscopy at ANU is thanked for access to the SEM facility. C. Hetherington and C. Gregory are thanked for careful reviews of this manuscript and I. Buick for his editorial handling.

References

- Babist, J., Handy, M.R., Konrad-Schmolke, M., Hammerschmidt, K., 2006. Precollisional, multistage exhumation of subducted continental crust: the Sesia Zone, western Alps. *Tectonics* 25 [10.1029/2005TC001927](#).
- Bea, F., 1996. Residence of REE, Y, Th and U in granites and crustal protoliths; implications for the chemistry of crustal melts. *Journal of Petrology* 37 (3), 521–552.
- Berger, A., Rosenberg, C.L., 2003. Preservation of chemical residue–melt equilibria in natural anatexites: the effects of deformation and rapid cooling. *Contributions to Mineralogy and Petrology* 144 (4), 416–427.
- Berger, A., Rosenberg, C.L., Schaltegger, U., 2009. Stability and isotopic dating of monazite and allanite in partially molten rocks: examples from the Central Alps. *Swiss Journal of Geosciences* 102 (1), 15–29.

- Bouchez, J.L., Delas, C., Gleizes, G., Nedelec, A., Cuney, M., 1992. Submagmatic microfractures in granites. *Geology* 20 (1), 35–38.
- Broska, I., Petrik, I., Williams, C.T., 2000. Coexisting monazite and allanite in peraluminous granulites of the Tribec Mountains, Western Carpathians. *American Mineralogist* 85 (1), 22–32.
- Bussy, F., Venturini, G., Hunziker, J., Martinotti, G., 1998. U–Pb ages of magmatic rocks of the western Austroalpine Dent-Blanche-Sesia Unit. *Schweizerische Mineralogische Und Petrographische Mitteilungen* 78, 163–168.
- Compagnoni, R., 1977. The Sesia-Lanzo Zone: high pressure–low temperature metamorphism in the Austroalpine continental margin. *Rendiconti della Società Italiana di Mineralogia e Petrologia* 33, 335–374.
- Davidson, C., Schmid, S.M., Hollister, L.S., 1994. Role of melt during deformation of the deep crust. *Terra Nova* 6 (2), 133–142.
- Dini, A., Rocchi, S., Westerman, D.S., 2004. Reaction microtextures of REE–Y–Th–U accessory minerals in the Monte Capanne pluton (Elba Island, Italy): a possible indicator of hybridization processes. *Lithos* 78 (1–2), 101–118.
- Duchêne, S., et al., 1997. The Lu–Hf dating of garnets and the ages of the Alpine high-pressure metamorphism. *Nature* 387 (586–589).
- Früh-Green, G.L., 1994. Interdependence of deformation, fluid infiltration and reaction progress recorded in eclogitic metagranitoids (Sesia Zone, western Alps). *Journal of Metamorphic Geology* 12 (3), 327–343.
- Gieré, R., Sorensen, S.S., 2004. Allanite and other REE-rich epidote-group minerals. *Reviews in Mineralogy and Geochemistry* 56, 431–493.
- Gregory, C.J., et al., 2007. Allanite micro-geochronology: a LA-ICP-MS and SHRIMP U–Th–Pb study. *Chemical Geology* 245, 162–182.
- Gregory, C.J., Buick, I.S., Hermann, J., Rubatto, D., 2009. Mineral-scale trace element and U–Th–Pb age constraints on metamorphism and melting during the Petermann Orogeny (Central Australia). *Journal of Petrology* 50 (2), 251–287.
- Hermann, J., 2002. Allanite: thorium and light rare earth element carrier in subducted crust. *Chemical Geology* 192 (3–4) PII S0009-2541(02)00222-X.
- Janots, E., et al., 2006. Evolution of the REE mineralogy in HP–LT metapelites of the Sebti complex, Rif, Morocco: monazite stability and geochronology. *Lithos* 87 (3–4), 214–234.
- Janots, E., et al., 2008. Prograde metamorphic sequence of REE minerals in pelitic rocks of the Central Alps: implications for allanite–monazite–xenotime phase relations from 250 to 610 degrees C. *Journal of Metamorphic Geology* 26 (5), 509–526.
- Krenn, E., Finger, F., 2004. Metamorphic formation of Sr-apatite and Sr-bearing monazite in a high-pressure rock from the Bohemian Massif. *American Mineralogist* 89 (8–9), 1323–1329.
- Kretz, R., 1983. Symbols for rock-forming minerals. *American Mineralogist* 68, 277–279.
- Kruse, R., Stünitz, H., 1999. Deformation mechanisms and phase distribution in mafic high-temperature mylonites from the Jotun Nappe, southern Norway. *Tectonophysics* 303, 223–249.
- Ludwig, K.R., 2003. Isoplot/Ex version 3.0. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronological Centre Special Publication, Berkeley. 70 pp.
- Mancktelow, N.S., Pennacchioni, G., 2005. The control of precursor brittle fracture and fluid–rock interaction on the development of single and paired ductile shear zones. *Journal of Structural Geology* 27, 645–661.
- Nagasaki, A., Enami, M., 1998. Sr-bearing zoisite and epidote in ultra-high pressure (UHP) metamorphic rocks from the Su–Lu province, eastern China: an important Sr reservoir under UHP conditions. *American Mineralogist* 83, 240–247.
- Nieto, J.M., Compagnoni, R., 1994. Metamorphism versus deformation in the eclogitized granulites of the Monte Mucrone area, Sesia-Lanzo Zone, Italian Western Alps: 16th IMA meeting, Pisa, 4–8 Sept., 1994. Abs.Vol.
- Oberhänsli, R., Hunziker, J.C., Martinotti, G., Stern, W.B., 1985. Geochemistry, geochronology and petrology of Monte Mucrone – an example of eo-Alpine eclogitization of Permian granulites in the Sesia-Lanzo zone, western Alps, Italy. *Chemical Geology* 52 (2), 165–184.
- Paterson, M.S., 1995. A theory for granular flow accommodated by material transfer via an intergranular fluid. *Tectonophysics* 245, 135–151.
- Petrik, I., Broska, I., 1994. Petrology of 2 granite types from the Tribec mountains, western Carpathians – an example of allanite (+ magnetite) versus monazite dichotomy. *Geological Journal* 29 (1), 59–78.
- Pognante, U., 1989. Lawsonite, blueschist and eclogite formation in the southern Sesia zone (western Alps, Italy). *European Journal of Mineralogy* 1, 89–104.
- Ramsbotham, W., Inger, S., Cliff, R.A., Rex, D., Barnicoat, A.C., 1994. Time constraints on the structural and metamorphic evolution of the southern Sesia-Lanzo zone, Western Italian Alps. *Mineralogical Magazine* 58A, 758–759.
- Romer, R.L., Siegesmund, S., 2003. Why allanite may swindle about its true age. *Contribution to Mineralogy and Petrology* 146, 297–307.
- Rubatto, D., Gebauer, D., Compagnoni, R., 1999. Dating of eclogite-facies zircons: the age of Alpine metamorphism in the Sesia-Lanzo Zone (Western Alps). *Earth and Planetary Science Letters* 167 (3–4), 141–158.
- Rubatto, D., Muntener, O., Barnhoorn, A., Gregory, C., 2008. Dissolution–reprecipitation of zircon at low-temperature, high-pressure conditions (Lanzo Massif, Italy). *American Mineralogist* 93 (10), 1519–1529.
- Scherrer, N.C., Engi, M., Gnos, E., Jakob, V., Liechti, A., 2000. Monazite analysis; from sample preparation to microprobe age dating and REE quantification. *Schweizerische Mineralogische Und Petrographische Mitteilungen* 80 (1), 93–105.
- Smith, M.P., Storey, C., Jeffries, T., Ryan, C., 2009. *In situ* U–Pb and trace element analysis of accessory minerals in the Kiruna district, Norrbotten, Sweden: new constraints on the timing and origin of mineralization. *Journal of Petrology* 50 (11), 2063–2094.
- Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead evolution by a two-stage model. *Earth and Planetary Science Letters* 26, 207–221.
- Stünitz, H., Tullis, J., 2001. Weakening and strain localization produced by syn-deformational reaction of plagioclase. *International Journal of Earth Sciences* 90, 136–148.
- van Roermund, H., Lister, G.S., Williams, P.F., 1979. Progressive development of quartz fabrics in a shear zone from Monte Mucrone, Sesia-Lanzo Zone, Italian Alps. *Journal of Structural Geology* 1 (1), 43–52.
- von Blanckenburg, F., 1992. Combined high-precision chronometry and geochemical tracing using accessory minerals: applied to the Central-Alpine Bergell intrusion (central Europe). *Chemical Geology* 100, 19–40.
- Wing, B.A., Ferry, J.M., Harrison, T.M., 2003. Prograde destruction and formation of monazite and allanite during contact and regional metamorphism of pelites: petrology and geochronology. *Contributions to Mineralogy and Petrology* 145 (2), 228–250.