1	1	
2	Con	straining metamorphic dome exhumation and fault activity
3	thr	cough hydrothermal monazite-(Ce)
-	2 Dat	ing exhumation and fault activity of the Lenontine Dome and
	2 Dat	cimples Pault activity of the hepotethe bone and
	5 Rho	ine-simpion Fault regions through hydrothermal monazite-(te)
4	4 Chr	ristian A. Bergemann
5	51,	2
6	6 , E	dwin Gnos
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8	8, A	Alfons Berger
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10	10 F	milie Janots
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21	21 IST	Perre University of Grenoble, France
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23	23 Swe	dish Museum of Natural History, Stockholm, Sweden
24	24 Cor	respondence:Christian Bergemann (christian.bergemann@unige.ch)
25	Abs	stract.Zoned monazite-(Ce) from Alpine fissures/clefts is used to gain new insights into the exhumation
	his	story of the
26	Cen	stral Alpine Lepontine metamorphic dome, and timing of deformation along the Rhone-Simplon fault
20		relat Alphie Beponetine metamorphic dome, and timing of deformation along the knone Simpion fault
	20	me on the domers
	25 Abs	stract.Zoned hydrothermal monazite-(Ce) from
	fis	sures/clefts is used to gain new insights into the exhumation history
	26 of	the Lepontine Dome in the Central Alps, and timing of deformation along the Rhone-Simplon Fault
	zo	one on the dome's
27	27 wes	stern termination. These hydrothermal monazites-(Ce) directly date deformation and changes in physiochemical
	con	ditions
28	thr	cough crystallization
	age	es, in contrast to commonly employed cooling-based methods. The 480 SIMS measurement ages
20	fro	20 individual anutals moved again the interval between 10 and t
29	TIO	in 20 Individual crystals fecold ages over a time interval between 19 and 5
	Ma,	with individual grains recording ages over as
30	lif	etime of 2 to 7.5 Ma. The
	age	e range combined with age distribution and internal crystal structure help to distinguish between
	are	eas whose deformational history was dominated by distinct tectonic events or continuous exhumation. The comb
31	ina	ution of
32	thi	s age data with geometrical considerations and spatial distribution give a more precise exhumation/cooling
	hi	story for the
33	2 2 2	In the east and couth of the study region, the units underwort menagiter (Co)
55	are	a. In the east and south of the study region, the units underwent monazite-(te)
	gro	wth at 19-12.5 and 16.5-10.5 Ma, followed
34	by	a central group of monazite-(Ce) ages at 15-10 Ma and the movements and related cleft monazites-(Ce) are
	you	ingest at the10
35	wes	tern border with 13-7 Ma. A last phase around <mark>8-7</mark> Ma is limited to clefts of
	th	ne Simplon normal fault and related strike
36	sli	p faults as the Rhone and Rhine-Rhone faults. The large data-set
	spr	read over significant metamorphic structures shows that
27	+bo	anophing of alofta, fluid flow and monagita (Co) atability is direct linked to the monduments
51	che	- opening of creres, fruid from and monazice-(ce) stability is direct finked to the geodynamic
	ev	rolution in space and time.
38	1	Introduction
39	Met	amorphic domes like the Lepontine area of the Central Alps often experienced a complex tectono-metamorphic
	evo	lution.15
40	In	this case an interplay between exhumation and deformation during doming and activity of

		large fault systems that dominate
41		the western parts of the area. Although much of the (thermo)chronological history of the area is well known,
		hydrothermal
42		monazite-(Ce) ages complement existing cooling ages of
		zircon fission track, Rb-Sr in biotite and apatite fission track/apatite
43		U-Th/He by providing crystallization and dissolution-precipitation ages that date low-T tectonic evolution.
	28	through crystallization
		ages. 480 SIMS spot analyses from 20 individual crystals, including co-type material of the monazite-
	29	(Nd) type locality, record ages over a time interval $of \sim 19$ and 2.7 Ma, with individual grains recording
		age ranges of 2 to5
	30	7.5 Myr. The combination of
	31	exhumation bistory for the area. In the north-coast and south-west of the Longatine Dome units
	JT	underwent monazite-(Ce)
	32	growth at 19-12.5 and 16.5-10.5
		Ma respectively, followed by crystallization of monazite-(Ce) in the central part at 15-10 Ma.
	33	Fissure monazites-(Ce) are younger at the western limit of the dome with 13-7 Ma. A last age group around 8-5
		Ma is limited to
	34	fissures/clefts associated with the Simplon normal fault and related strike-slip faults such as the Rhone
		Fault. The large data-set10
	35	spread over significant metamorphic structures shows that the fissure mineral crystal-rock interaction,
		fluid flow and monazite-
	36	(Ce) stability are directly linked to the Lepontine Dome's evolution in space and
		time. A comparison between hydrothermal
	37	monazite-(Ce) thermo-chronometric data suggests that hydrothermal monazite-(Ce) dating could allow to identify
	38	aleas of
	39	1 Introduction15
	40	Metamorphic domes often experience a complex tectono-metamorphic
		evolution (e.g.Schmidet al., 2004; Stecket al., 2013).
	41	For the Lepontine Dome of the European Alps, this evolution is
		an interplay between exhumation and deformation during
	42	doming and motion along large fault systems that dominate the western regions of the dome.
		Although much of the retrograde
	43	orogenic evolution of the area is well known, hydrothermal
	лл	chronometers by providing crystallization and dissolution-precipitation ages that directly
		date low-T tectonic activity.20
44	45	Monazite, (LREE, Th, U) PO
45	46	4
46		, is considered an excellent mineral for dating of geologic processes (e.g., Parrish, 1990) that is20
47		highly resistant to radiation damage <mark>(e.g., Meldrum et</mark> al., 1998, 1999, 2000) and shows negligible Pb loss
		through diffusion
		(Cherniak et al., 2004; Cherniak and Pyle, 2008). Nonetheless, monazite remains geologically reactive after cr
48		ystallization. It
	47	, is considered an excellent mineral for the dating of geologic processes (e.g.Parrish, 1990).
	48	It is nightly resistant to radiation damage (e.g.Meldrumet al., 1998, 1999, 2000) and shows negligible PD loss
49	49	1
50	10	Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
51		Manuscript under review for journal Solid Earth
52		Discussion started: 5 February 2019
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54		©Author(s) 2019. CC BY 4.0 License.
55	50	err everyteres discolution reconstallization, thereby recording new area through mediation of budyous fluids
56		(e a . Sevioux-
57		Guillaume et al., 2012; Janots et al., 2012; Grand
		(Cherniaket al., 2004; Cherniak and Pyle, 2008). Nonetheless, monazite remains reactive after crystallization,
	51	as it can expe-
		rience dissolution-recrystallization facilitated through hydrous fluids (e.g.Seydoux-Guillaumeet al., 2012; Ja
	52	notset al., 2012;
	53	Grand
58	54	,
JJ		Homme et al., 2010).

60	Alpine fissures and clefts occasionally containing monazite-(Ce) are voids partially filled by crystals	
	that crystallized on	
61	the cleft walls from hydrous fluids during late stage Alpine metamorphism (Mullis et al., 1994; Mullis,	
	1996). Dating such	
<i>c</i> 0	mineralization is often difficult due to later overprinting along with multiple stages of fluid activity (Pu:	rd
62	y and obsider (1072) F	
<i>c</i> 2	and Stalder, 1973).5	
03	Alpine fissures in some metasediments and metagranitoids have long been known to contain	
C A	erustale (Niggli et al. 1040) but it is only recently that some of these	
04	crystars (Niggir et al., 1940), but it is only recently that some of these	
65	2012) Although other minerals like mices and adularia are common in alnine figsures, they are often	
00	affected by overpres-	
66	sure/excess argon. (e.g., Purdy and Stalder, 1973), and it is not always clear if these ages represent	
0.0	crystallization or cooling	
67	(e.g., Rauchenstein-Martinek, 2014). The Alpine fissures and clefts in the Lepontine region formed after the	
	metamorphic peak,10	
68	in relation to extensional tectonic activity. In accordance with this tectonic activity,	
	fissures and clefts are oriented roughly per-	
69	pendicular to lineation	
	and foliation of the host rock. The fluid that intruded during fissure formation (300-500	
70	·	
71	C; Mullis et al.,	
	1994; Mullis, 1996) interacts with the wall rock. This triggered dissolution and precipitation of minerals in	h
72	both host rock and	
	fissure, causing the formation of a porous alteration halo in the surrounding wall rock. Complex growth domain	in
73	s are common	
	in hydrothermal monazites-(Ce) from such fissures showing both, dissolution and secondary growth (e.g., Jano	s
74	et al., 2012)15	
	as well as dissolution-reprecipitation reactions resulting in patchy grains (e.g., Gnos et al., 2015). In con	nt
75	rast to metamorphic	
	rocks, where monazite-(Ce) rarely exceeds 100µm, cleft monazite-(Ce) is commonly mm-sized with large individu	ıa
76	l growth	
	domains. This permits to date individual domains precisely by using SIMS (secondary ion mass spectrometry) as	ıd
70	even resolve	
70	growin duration (Janots et al., 2012; Berger et al., 2013; Bergemann et al., 2017, 2018, 2019).	
80	2 1 Evolution of the study area	
00	The formation of the mappe stack of the Alps caused by the collision of the European and Adriatic plates was	f
81	ollowed by	
	the development of several metamorphic domes (Tauern and Rechnitz in Austria, and Lepontine in the western A	lp
82	s; e.g.	
	Schmid et al., 2004). Their formation was related to crustal shortening associated with coeval orogen paralle	el
83	extension (e.g.,	
	Mancktelow, 1992; Ratschbacher et al., 1991; Ratschbacher et al., 1989; Steck and Hunziker, 1994). The Wester	rn
84	and Contral25	
85		
	Alps with the Lepontine metamorphic dome have consequently had a complex tectonic and metamorphic history.	
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86	Ally with the Lepontine metamorphic dome have consequently had a complex tectonic and metamorphic history. Early high-pressure metamorphism in the Western Alpine Sesia-Lanzo Zone during subduction below the Southern lps is	A
86	Alps with the Lepontine metamorphic dome have consequently had a complex tectonic and metamorphic history. Early high-pressure metamorphism in the Western Alpine Sesia-Lanzo Zone during subduction below the Southern lps is dated at 75-65 Ma (e.g.Ruffet et al., 1997; Duchêne et al., 1997; Rubatto et al., 1998). This was followed by	A
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	59	Stalder, 1973). Fissures and clefts in some metasediments and metagranitoids have long been known to contain
	<i>c</i> 0	well-developed
	60	monazite-(Ce) crystals (Niggliet al., 1940), but it is only recently that some of these
	C 1	Were dated (e.g.Gasquetet al., 2010;
	ΟŢ	Danotset al.,
		2012). Although other minerals like micas and adularia are common in alpine fissures, they are often affected
	62	by overpressure/excess
	<u> </u>	argon, (e.g., Furdy and Stalder, 1973), and it is not always clear if these ages represent crystallizationic
	63	or cooling (e.g., Rauchenstein-Martinek, 2014). The
	C A	rissures and clerts in the Lepontine region formed after the metamorphic
	04	peak, in relation to extensional tectonic activity. Accordingly, fissures and clefts are oriented roughly
	65	lineation
	00	and foliation of the bost rock. The fluid that intruded during figure formation (300-500
91	66	and forfactor of the nost fock. The finite that included during fissure formation (500-500
92	00	C in some regions were reached diachronously from south to north in time
		around 30-19 Ma and accompanied by limited magmatic activity from 33 Ma down to ca. 22 Ma (yon Blanckenburg et
93		al., 1991;
		Romer et al., 1996; Schärer et al., 1996; Oberli et al., 2004; Rubatto et al. 2009; Janots et al., 2009). Prog
94		rade metamorphism
	67	C; Mulliset al., 1994;
		Mullis, 1996) interacted with the wall rock. This triggered dissolution and precipitation of minerals in both
	68	host rock and
		fissure, leading to the formation of a porous alteration halo in the surrounding wall rock. Complex growth dom
	69	ains are common15
		in hydrothermal monazite-(Ce) from such fissures showing both, dissolution and secondary growth (e.g.Janotset
	70	al., 2012;
		Bergemannet al., 2017, 2018), as well as dissolution-reprecipitation reactions resulting in patchy grains (e.
	71	g.Gnoset al.,
		2015). In contrast to metamorphic rocks, where monazite-(Ce) rarely exceeds 100µm, fissure monazite-(Ce) is co
	72	mmonly
		mm-sized, with large individual growth domains. This permits dating individual domains precisely by using seco
	73	ndary ion
		mass spectrometry (SIMS), resolve growth duration and identify phases and single events of tectonic activity
	74	(e.g.Janotset al.,20
	75	2012; Bergeret al., 2013; Bergemannet al., 2017, 2018, 2019).
		The aim of this study is to illustrate that hydrothermal monazite-(Ce) dating provides information about the t
	76	ectonic evolution
	77	of the Lepontine Dome.
	78	2 Geological setting
	79	2.1 Evolution of the study area25
		The formation of the nappe stack of the European Alps caused by the collision of the European and Adriatic pla
	80	tes was followed
	0.1	by the development of several metamorphic areas (Tauern, Rechnitz in the Eastern Alps, and Lepontine in the Ce
	8 T	ntral Alps;e.g.
	0.0	Schmidet al., 2004). Their formation was related to crustal shortening associated with coeval orogen-parallel
	82	extension (e.g.
	0.2	Mancktelow, 1992; Ratschbacheret al., 1989; Ratschbacheret al., 1991). The Western and Central Alps with the L
	00	epontine
	04	For have consequencily had a complex tectoric and metamorphic history.50
	85	larry high pressure metamorphism in the western kipine sesta banzo zone auting subduction below the Southern k
	00	is dated at 75-65 Ma (e o Ruffetet al . 1997: Rubattoet al . 1998: Regiset al . 2014). This was followed by un
	86	derthrusting
	20	and nappe stacking fromca.42 Ma on during continental collision linked with a transition from high-P/low-T to
	87	barrow type
95	88	2
96		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
97		Manuscript under review for journal Solid Earth
98		Discussion started: 5 February 2019
99		c and a second
100		©Author(s) 2019. CC BY 4.0 License.
101	89	
102		was followed by staggered exhumation in the Ticino and Toce culminations of the Lepontine dome.
		Accelerated Cooling Delow

103		500
		Figure 1.Map of the Lepontine Dome, modified from Stecket al.(2013) and Schmidet al.(2004). Colored areas mark
	90	the areal division in
	91	the context of this study.
		metamorphism (medium P/T;e.g.Köppel and Grünenfelder, 1975; Markleyet al., 1998; Herwartzet al., 2011; Bostone
	92	t al.,
	93	2017). Peak metamorphic conditions in the Lepontine area (in excess of 650
	94	
	95	C in some regions) were reached diachronously
	96	from south to north around 30-19 Ma (e.g.Schäreret al., 1996). Barrovian metamorphism was followed by
		exhumation starting
	97	in the east and
		migrating to the west of the Lepontine Dome, with vertical displacement along the Insubric Line starting as
1.0.4	98	early as 30 Ma (e.g.Hurford, 1986; Steck and Hunziker, 1994). Accelerated cooling below 500
104	99	•
102		c occurred at 20 Ma first in the central Lepontine (Huriord, 1986). This was followed in the
106		cooling of the Ticino dome between 22 and 17 Ma (Steck and Hunziker, 1994; Pubatto et
TOO		al 2009) after which exhumation
107		slowed down. To the west, the Toce dome experienced phases of accelerated cooling somewhat later in the time
		of 18-15 Ma
		and 12-10 Ma (Campani et al., 2014). The later cooling phase was related to detachment along the Rhone-Simplon
108		Fault (Steck5
109		and Hunziker, 1994; Campani et al., 2014).
		While most of the Lepontine area is marked by doming and associated deformation events, the western and southw
110		estern
111		limits of the study area are dominated by the Rhone-Simplon Fault system, its <mark>extensions</mark>
		to the Rhine-Rhone Line to the north
112		along the Aar <mark>massif</mark> and the Centovalli Fault to the <mark>south. The extensional</mark> Simplon Fault zone (SFZ) was
		already active during
113		thrusting in the external <mark>alpine</mark> domain (e.g.,
		Grosjean et al., 2004), with transpressional movements in the hanging wall of the10
114		dextral ductile Simplon shear zone occurring from ca. 32 Ma on (Steck, 2008).
		The ductile-brittle transition of the SFZ was
115		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010).
115		The ductile-brittle transition of the SFZ <mark>was</mark> constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault
115 116		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011) with the wowngoot displacement activity dated to
115 116 117		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to
115 116 117		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to ca. 5-3 Ma (Campani et al., 2010).
115 116 117 118		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to ca. 5-3 Ma (Campani et al., 2010). 2.2 The study Area15 The study area comprises roughly half of the Lepontine metamorphic dome (Fig. 2), from the Tambo nappe, east o
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115 116 117 118 119 120		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to ca. 5-3 Ma (Campani et al., 2010). 2.2 The study Area15 The study area comprises roughly half of the Lepontine metamorphic dome (Fig. 2), from the Tambo nappe, east o f the Forcola fault, over the central Lepontine dome to the Val d'Ossola, south of the Centovalli Fault, and the southern Go tthard nappe and
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115 116 117 118 119 120 121 122 123 124 125		The ductile-brittle transition of the SF2 was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SF2 and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to ca. 5-3 Ma (Campani et al., 2010). 2.2 The study areals The study area comprises roughly half of the Lepontine metamorphic dome (Fig. 2), from the Tambo nappe, east o f the Forcola fault, over the central Lepontine dome to the Val d'Ossola, south of the Centovalli Fault, and the southern Go thard nappe and Aar massif to the north. See Fig. 1 for the tectonic position of the samples. The total number of 20 monazite- (Ce) samples dated in this study and 6 samples described in the literature (Janots et al., 2012; Berger et al., 2013; Berger mann et al., 2017) were divided into four groups roughly correlating to tectonic subdivisions of the area (Fig. 2). These are (1) the area to the east20 of the Forcola Fault (East; 2 samples), (2) the central Ticino dome and southern Gotthard nappe (Center; 7 sam ples), (3) the Toce dome, bounded by the Rhone-Simplon Fault to the west and adjacant south-western Gotthard nappe and parts of the Aar massif (West; 10 samples), and (4) the area to the south of the Centovalli and southern Simplon faults (South; the area to the ast
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<ol> <li>115</li> <li>116</li> <li>117</li> <li>118</li> <li>119</li> <li>120</li> <li>121</li> <li>122</li> <li>123</li> <li>124</li> <li>125</li> <li>126</li> <li>127</li> <li>128</li> <li>129</li> <li>130</li> </ol>		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to ca. 5-3 Ma (Campani et al., 2010). 2.2 The study Areal5 The study area comprises roughly half of the Lepontine metamorphic dome (Fig. 2), from the Tambo nappe, east o f the Forcola fault, over the central Lepontine dome to the Val d'Ossola, south of the Centovalli Fault, and the southern Go thard nappe and Aar massif to the north. See Fig. 1 for the tectonic position of the samples. The total number of 20 monazite- (Ce) samples dated in this study and 6 samples described in the literature (Janots et al., 2012; Berger et al., 2013; Berger mann et al., 2017) were divided into four groups roughly correlating to tectonic subdivisions of the area (Fig. 2). These are (1) the area to the east20 of the Forcola Fault (East; 2 samples), (2) the central Ticino dome and southern Gotthard nappe (Center; 7 sam ples), (3) the Toce dome, bounded by the Rhone-Simplon Fault to the west and adjacant south-western Gotthard nappe and parts of the Aar massif (Mest; 10 samples), and (4) the area to the south of the Centovalli and southern Simplon faults (South; 1 sample). Most of the samples were provided by mineral collectors, as hydrothermal cleft monazite-(Ce) is uncommon and often difficult to detect in the field when covered by dirt or chlorite. See Table 1 for location details.25 3 Analytical techniques Monazites-(Ce) were individually polished to the level of a central cross section and assembled in mounts of s everal grains.
<ol> <li>115</li> <li>116</li> <li>117</li> <li>118</li> <li>119</li> <li>120</li> <li>121</li> <li>122</li> <li>123</li> <li>124</li> <li>125</li> <li>126</li> <li>127</li> <li>128</li> <li>129</li> <li>130</li> </ol>		The ductile-brittle transition of the SF2 was constrained to the time between 14.5 and 10 Ma [Campani et al., 2010). Brittle deformation of the SF2 and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to ca. 5-3 Ma (Campani et al., 2010). 2.2 The study Area15 The study area comprises roughly half of the Lepontine metamorphic dome (Fig. 2), from the Tambo nappe, east o f the Forcola fault, over the central Lepontine dome to the Val d'Ossola, south of the Centovalli Fault, and the southern Go thard nappe and Aar massif to the north. See Fig. 1 for the tectonic position of the samples. The total number of 20 monazite- (Cc) samples dated in this study and 6 samples described in the literature (Janots et al., 2012; Berger et al., 2013; Berge mann et al., 2017) were divided into four groups roughly correlating to tectonic subdivisions of the area (Fig. 2). These are (1) the area to the east20 of the Forcola Fault (East; 2 samples), (2) the central Ticino dome and southern Gotthard nappe and parts of the Aar massif (West; 10 samples), and (4) the area to the south of the Centovalli and southern Simplon faults (South; 1 sample). Most of the samples were provided by mineral collectors, as hydrothermal cleft monazite-(Ce) is uncommon and often difficult to detect in the field when covered by dirt or chlorite. See Table 1 for location details.25 3 Analytical techniques Monazites-(Ce) were individually polished to the level of a central cross section and assembled in mounts of s everal grains. Backscatter electron (BSE) images were then obtained. Secondary ion mass spectrometry (SINS) spot analyses (Fi
115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131		The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campani et al., 2010). Brittle deformation of the SFZ and Centovalli fault continued after this (Zwingmann and Mancktelow, 2004; Surace et al., 2011), with the youngest displacement activity dated to ca. 5-3 Ma (Campani et al., 2010). 2.2 The study Areal5 The study area comprises roughly half of the Lepontine metamorphic dome (Fig. 2), from the Tambo nappe, east o f the Forcola fault, over the central Lepontine dome to the Val d'Ossola, south of the Centovalli Fault, and the southern Go thard nappe and Aar massif to the north. See Fig. 1 for the tectonic position of the samples. The total number of 20 monazite- (Ce) samples dated in this study and 6 samples described in the literature (Janots et al., 2012; Berger et al., 2013; Berge mann et al., 2017) were divided into four groups roughly correlating to tectonic subdivisions of the area (Fig. 2). These are (1) the area to the east20 of the Forcola Fault (East; 2 samples), (2) the central Ticino dome and southern Gotthard nappe (Center; 7 sam ples), (3) the Toce dome, bounded by the Rhone-Simplon Fault to the west and adjacant south-western Gotthard nappe and parts of the Aar massif (West; 10 samples), and (4) the area to the south of the Centovalli and southern Simplon faults (South; 1 sample). Most of the samples were provided by mineral collectors, as hydrothermal cleft monazite-(Ce) is uncommon and often difficult to detect in the field when covered by dirt or chlorite. See Table 1 for location details.25 3 Analytical techniques Monazites-(Ce) were individually polished to the level of a central cross section and assembled in mounts of s everal grains. Backscatter electron (BSE) images were then obtained. Secondary ion mass spectrometry (SIMS) spot analyses (Fi g. 4) were

		placed according to compositional domains visible in these images in order to capture the crystallization hist
		ory. As far as
		possible, the placement of measurement spots located near cracks or holes was avoided, as the Th-Pb isotope sy
133		stem may be30
134		disturbed in these areas (Janots et al., 2012; Berger et al., 2013).
	100	C first occurred at~26 Ma in5
	101	the central Lepontine Dome (Hurford, 1986). This was followed in the
	1.0.0	eastern Lepontine Dome and along the Insubric Line
	102	between 22 and 1/ Ma by a period of rapid cooling (Steck and Hunziker, 1994; Rubattoet
	103	slowed down. The area to the west in the surrounding of
	TOO	the Rhone-Simplon Line experienced phases of accelerated cooling
	104	somewhat later at 18-15 Ma and 12-10 Ma (Campaniet al., 2014).
	105	The western and southwestern limits of the study area are dominated by the Rhone-Simplon Fault system, its
		extensions10
	106	to the Rhine-Rhone Line to the <mark>north</mark> along the Aar <mark>Massif</mark> and the Centovalli Fault to the
		south (Fig. 1). The extensional
	107	Simplon Fault zone (SFZ) was active contemporaneous with thrusting in the external Alpine domain (e.g.,
		Grosjeanet al.,
	108	2004). The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campaniet
		al., 2010).
	109	Brittle deformation of the SFZ and Centovalli Fault continued after this (Zwingmann and Mancktelow, 2004;
	110	Suraceet al.,
105	110	2011), with the youngest displacement activity dated toca.5-3 Ma (Campaniet al., 2010).15
136	111	Solid Farth Discusshttps://doi_org/10_5194/se-2019-10
137		Manuscript under review for journal Solid Earth
138		Discussion started: 5 February 2019
139		c
140		©Author(s) 2019. CC BY 4.0 License.
141	112	
142		3000
143		2000
144		
145		
140		
148		SE
149		(c)
150		Bett11
151		Kleml
152		Klem3
153		Gr aeserl
154		Gr aeser3
155		Klem2
156		3000
157		2000
150		
160		
161		N N
162		(d)
163		Luc ol
164		Salz2
165		Duth3
166		Blas1
167		Duth2
168		S CONTRACTOR OF
170		1000
171		
172		
173		Vals
174		Tamb
175		Forcola Fault

176	Tambo
177	Adula
178	(e)
179	SWNE
180	SN
181	Verampio
182	Antigorio
183	Antigorio
184	Monte Rosa
185	Simplon Line
186	
187	
188	2000
189	Vani5
190	Van14
191	Durol, Z
192	
193	
195	
196	
197	
198	Luo 1
199	Klem 1
200	Vani 4
201	Vani 5
202	Graeser 3
203	Klem 2
204	Bett 11
205	Schiess 1
206	Duro 1,2
207	Graeser 1
208	Vani 6
209	lem 3
210	uth 3
211	uth 2
212	
213	Vals
214	
215	SdIZ Z
217	
218	
219	(d)
220	(e)
221	Mzt
222	Group 1: 17-15 Ma
223	Group 2: 14-11 Ma
224	Group 3: 10-7 Ma
225	External massif
226	Gotthard cover
227	Gotthard crystalline
228	European crystalline
229	European cover
230	Briançonnais crystalline
231	Piemont-Liguria
232	Valais crystalline
233	Adriatic cover
234	southalpine
235	Valais cover
230	Rianconnais cover
238	
200	Figure 1.Geological-geometric situation of the study area. (a) Tectonic sketch man modified after Steck et al.
220	(2013) and Schmid et al

240		(2004); (b) Tectonic section over the Simplon Fault zone into the western Lepontine, based on Campani et al.
0.41		(2014); (c) Tectonic section
241		through the western Northern Steep Belt, modified and extended after Leu (1986); (d) Tectonic section through
0.4.0		the eastern Northern Steep
Z 4 Z		the Freeze course foult and alter Manual at al. (2008); (e) Sketch of the Situation at
212		che Forcola normal lault, see also Meyre et al., (1998) and berger
243		Th-Dh analyzes were conducted at the Swedich Myseum of Natural History (NordSIM facility) on a Camera
244		The D analyses were conducted at the Swedish Museum of Natural history (Nordsim facility) on a cameta
211		SIMS instrument Analytical methods and correction procedures followed those described by Harrison et al. (199
2.4.5		5). Kirkland
246		et al. (2009) and Janots et al. (2012), using a -13kV O
247		2-
248		primary beam of ca. 6nA and nominal 15µm diameter. The mass
		Figure 2.Tectonic overview over the study area. (a) Tectonic sketch map modified after Schmidet al.(2004) and
	113	Stecket al.(2013), sample
	114	BLAU is from Janotset al.(2012);
		(b) Tectonic section over the Simplon Fault zone into the western Lepontine, based on Campaniet al.
	115	(2014); (c) Tectonic section
		through the western Northern Steep Belt, modified and extended after Leu (1986); (d) Tectonic section <mark>through</mark>
	116	the eastern Northern Steep Belt, redrawn after Wiederkehret al.(2008); (e) Tectonic section across
		the Forcola normal fault, see also <mark>Meyre</mark>
	117	et al., (1998) and Bergeret al.(2005). Profiles (b)-(e) are not to scale with map (a).
249	118	4
250		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
251		Manuscript under review for journal Solid Earth
252		Discussion started: 5 February 2019
253		
254	110	©Author(s) 2019. CC BY 4.0 License.
256	117	Table 1.Information on sample localities for all analyzed grains. Sample GRAESER1
		has identification number NMBa 10226, VALS has
	120	Table 1.Information on sample localities for all analyzed grains. Sample GRAESER 1
		has identification number NMBa 10226, VALS has
257	121	NMBE43124.
258		SampleLocalityLatitude Longitude Altitude (m)
259		BETT11Bettelbach,46
	122	R <mark>egion S</mark> ampleLocalityLatitude Longitude Altitude (m)
	123	SouthVANI 6Cava Maddalena, Beura46
	124	
	125	04.30'8
	126	
	127	17.71'260
	128	WestBETT 11Bettelbach,46
260	129	
261	1 2 2	
262	130	25.62'8
263	130 131	° 25.62'8 ° 11.70/1460
263	130 131 132 133	25.62'8 11.70'1460 Niederwald Comp
263 264 265	130 131 132 133	25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46
263 264 265 266	130 131 132 133	25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46
263 264 265 266 267	130 131 132 133	25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8
263 264 265 266 267 268	130 131 132 133	25.62'8 • 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 • 34.68'8 •
263 264 265 266 267 268 269	130 131 132 133	25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790
263 264 265 266 267 268 269 270	130 131 132 133	25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun
263 264 265 266 267 268 269 270 271	130 131 132 133	25.62'8 11.70'1460 Niederwald, Goms BLASIPiz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DUROIDoru, Gantertal,46
263 264 265 266 267 268 269 270 271 272	130 131 132 133 133	25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DURO1Doru, Gantertal,46
263 264 265 266 267 268 269 270 271 272 272	130 131 132 133 133 134 135 136	25.62'8 21.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DURO1Doru, Gantertal,46 2 17.63'8
263 264 265 266 267 268 269 270 271 272 273 273 274	130 131 132 133 133 133 134 135 136 137	25.62'8 25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DURO1Doru, Gantertal,46 2 17.63'8 2
263 264 265 266 267 268 269 270 271 272 271 272 273 274 275	130 131 132 133 133 133 134 135 136 137 138	25.62'8 25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DUROLDORU, Gantertal,46 17.63'8 02.07'1160
263 264 265 266 267 268 270 271 272 273 274 275 276	130 131 132 133 133 134 135 136 137 138 139	25.62'8 25.62'8 11.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DURO1Doru, Gantertal,46 20 17.63'8 20 02.07'1160 Simplon
263 264 265 266 267 268 269 270 271 272 273 274 275 276 277	130 131 132 133 133 134 135 136 137 138 139 140	25.62'8 21.70'1460 Niederwald, Goms BLAS1Piz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DURO1Doru, Gantertal,46 2 17.63'8 2 02.07'1160 Simplon DURO2Doru, Gantertal,46
263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278	130 131 132 133 133 134 135 136 137 138 139 140	25.62'8 21.70'1460 Niederwald, Goms PLASIPiz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DURO1Doru, Gantertal,46 20.07'1160 Simplon DURO2Doru, Gantertal,46 34.68' 8 34.68' 8 35.00 36.00 36.00 37.63' 8 36.00
263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279	130 131 132 133 133 135 136 137 138 139 140 141 142	25.62'8 21.70'1460 Niederwald, Goms DLASIPiz Blas,46 34.68'8 43.98'2790 Val Nalps, Sedrun DUROlDoru, Gantertal,46 20.07'1160 Simplon DURO2Doru, Gantertal,46 34.68'8'8 34.6

281	144	02.07'1160
282	145	Simplon
283		DUTH2Lago Sucro,46
284		
285		33.80'8
286		•
287		41.50'2620
288		Val Cadlimo
289		DUTH3Lago Retica, Lagi46
290		° 24. 457 9
291		0 <sup>4,4</sup> 0
293		53.57/2400
294		di Campo Blenio
295		DUTH6Pizzo Rüscada, Valle46
	146	DUTH 6Pizzo Rüscada, Valle46
296	147	0
297	148	24.57'8
298	149	•
299	150	40.09/2420
301	TUT	GRAESERILärcheltini. Binntal~46
001	152	GRAESER 1Lärcheltini, Binntal46
302	153	o
303		22.25'~8
	154	22.3'8
304	155	•
305		14.89'~1860
306	1.5.0	GRAESER3Wannigletscher,~46
	156	14.9'1860
307	158	•
308	100	19.46′~8
	159	19.5'8
309	160	•
310		12.98'~2720
	161	23.4'2560
311	162	Cherbadung, Binntal
312		KLEMIGrosses Arsch, 46
	163	GRAESER 4Monte Glove,46
	164	
	166	
	167	13 0/2720
	168	Val Formazza
	169	KLEM 1Grosses Arsch,46
313	170	•
314	171	26.71'8
315	172	o
316		16.33'~1900
	173	16.33' 1900
317	1/4	Blinnental
JIU	175	KLEM 2Alpe Devero,46
319	176	0
320	177	22.16'8
321	178	٥
322	179	18.44'2340
323	180	Val Antigorio
324	1.0-	KLEM3Griessgletscher46
305	181	KLEM JGriessgietscher46
32.6	183	26.59'8
327	184	۰
328	185	19 46' 2840

329		LUC01Lucomagno46
	186	SCHIESS 1Schiessbach/Simplon46
330	187	0
331		33.79 <sup>7</sup> 8
	188	18.13'8
332	189	0
333		48.10/1915
334		SALZ2Piz Scai~46
	190	04.18/1760
	191	VANI 4Montecrstese46
335	192	o
336		34.5'~8
	193	09.60/8
337	194	
338		45.75'~2/40
222	105	
	196	VANI 5Crino Baceno46
340	197	o
341	101	18.13'8
	198	15.13'8
342	199	o
343		04.18'1760
344		TAMB1Pizzo Tambo, Splügen46
	200	19.14'710
	201	CenterBLAS 1Piz Blas,46
345	202	0
346		30.48/9
	203	34.68'8
347	204	•
348		18.35'2460
349	0.05	VALSVals, Valsertal~46
	205	43.9872790
	200	Naips, Searan
	207	
	200	33 80/8
	210	•
	211	41.50'2620
	212	Val Cadlimo
	213	DUTH 3Lago Retica, Lagi46
	214	•
	215	34.45'8
	216	•
	217	53.57'2400
	218	di Campo Blenio
	219	LUCO 1Lucomagno46
350	220	
351	0.01	37.337~9
250	221	-
352	222	° 17 29/~2150
354		VANT4Montecretese46
001	223	48.10/1915
	224	SALZ 2Piz Scai46
355	225	o
356		09.60'8
	226	34.5'8
357	227	o
358		19.18'370
359		VANI5Crino Baceno46
	228	45.8' 2740
	229	EastTAMB 1Pizzo Tambo, Splügen46
360	230	
361		15.13'8

	231	30.4819
362	232	٥
363		19.14'710
364		VANI6Cava Maddalena, Beura46
	233	18.35'2460
	2.3.4	VALSVals, Valsertal46
365	235	•
366	200	04 3078
000	236	27. 27.0
267	230	-
367	231	
368		
		spectrometer was operated at +10kV and a mass resolution of ca. 4300 (M/AM, at 10% peak height), with data col
369		lected
		in peak hopping mode using an ion-counting electron multiplier. Unknowns were calibrated against monazite-(Ce)
370		standard
	238	17.3'3150
371	239	5
372		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
373		Manuscript under review for journal Solid Earth
374		Discussion started: 5 February 2019
375		c
376		©Author(s) 2019. CC BY 4.0 License.
377	240	
		Figure 2.Map of the Lepontine metamorphic dome, modified from Stecket al.(2013) and Schmidet al.(2004). Colore
378		d areas mark areal
		division in the context of this study. Published monazite-(Ce) locations (grey stars) are from Janotset al.(20
379		12), Bergeret al.(2013) and
380		Bergemannet al.(2017).
381		44069 (Aleinikoff et al., 2006). Lead isotope signals were corrected for common Pb contribution using measured
	241	2.2 The study area
		The study area comprises the part of the Lepontine Dome in which mineralized fissures/clefts are commonly foun
	242	d (Fig. 1)
	212	a (199. 1),
	212	ast (authorst
	243	est/southwest
	0.4.4	south of the tentovalli Fault, and the southern Gotthard happe to the north (see Fig. 2 for the tectonic posit
	244	ion of the samples).
		The 20 monazite-(Ce) samples dated in this study were divided into four groups (Fig. 1). These are (1) the are
	245	a to the westb
		of the Adula nappe (East; 2 samples), (2) the Lepontine Dome east of the Verzasca anticline including part of
	246	the southern
		Gotthard nappe (Center; 5 samples), (3) the west equally bound by the Verzasca anticline, the Rhone-Simplon Fa
	247	ult to the west
		and adjacant south-western Gotthard nappe (West; 12 samples), and (4) the area to the south of the Centovalli
	248	and southern
	249	Simplon Faults (South; 1 sample).
	250	3 Study approach and techniques10
	251	3.1 Monazite-(Ce) crystallization and alteration under hydrothermal conditions
		The possibility of hydrothermal monazite-(Ce) crystallization within an open fissure/cleft depends on the chem
	252	ical composition
		of the aqueous fluid filling it. Following the initial formation of a fissure/cleft, the intruding metamorphic
	253	fluid (300-500
	254	
	2.5.5	C:
		Mulliset al 1994 Mullis 1996) leaches and partly dissolves the surrounding bost rock and leads to crystal
	256	lization of mineral
	200	nbaga an the figure (aleft well under chemical equilibrium conditions. If the resulting chemical equilibrium
	057	phases on the fissure/cieft wait under chemical equilibrium conditions. If the resulting chemical equilibrium
	237	
	050	phase, cleic minerals and chose parts of the Wall rock accessible to the fluid is disturbed, a new cycle of di
	258	ssolution and crys-
		tallization within the cleft occurs. Chemical disequilibration is generally triggered by tectonic activity cau
	259	sing a deformation
		of the fissure/cleft and results in sudden changes in the P-T conditions, the influx of a new fluid, or the ex
	260	posure of previously
		unaltered wall rock (e.g.Mulliset al., 1994; Rollandet al., 2003; Sharpet al., 2005). Since the fissure/cleft
	261	remains fluid

262	filled, these mechanisms of (partial) dissolution and precipitation of newly formed cleft minerals occurs repe
	atedly, resulting20
	in the strong zonation, alteration and dissolution features of most cleft minerals (e.g.Mullis, 1996; Sharpet
263	al., 2005; Heijboer,
	2006). Therefore the mineral association of a cleft is the result of a series of equilibrium states and does n
264	ot represent a mineral
	γ paragenesis. This means that each crystal or crystal part was during its formation in chemical equilibrium wit
265	h the surrounding
200	n the suffounding
	fluid, so that each primary chemical zone within a crystal represents a change in the cieft fluid chemical com
266	position.
267	Hydrothermal monazite-(Ce) typically crystallizes at temperatures below~350
268	
269	c/~300
270	•
271	C (Gnoset al., 2015; Bergemann25
272	et al., 2017, 2018). Due to the presence of fluid in the cleft, it continues to be reactive down to 200
273	•
274	C or somewhat below
	(e.g.Townsendet al., 2000; Bergemannet al., 2018). During the formation of a grain, any tectonic a
275	ctivity that changes
	the chemical equilibrium within a cleft, causes the crystal to develop a primary chemical zonation usually vis
276	ible in RSE
210	images lifter crustallization monagite (Co) shows practically no ULTE De diffusion at the provalent D m and
077	images. After crystallization, monazite-(ce) shows practically no o-in-po dilusion at the prevalent p-i condi-
211	CIONS (CHEFNIAK
	and Pyle, 2008). However, the changing chemical conditions in a hydrothermal environment may not only cause ne
278	w growth30
	around an existing grain, but can result in partial (re-)crystallization/dissolution-reprecipitation in equili
279	brium with the cleft
280	fluid (e.g.Janots et al, 2012; Bergemannet al., 2017; Grand
281	r de la companya de l
282	Hommeet al., 2018). The dissolution-reprecipitation processes
283	6
284	
	Figure 3.BSE image of monazite-(Ce) samples showing different kinds of internal primary and alteration structu
285	Figure 3.BSE image of monazite-(Ce) samples showing different kinds of internal primary and alteration structu res. (A) The dark grain
285	Figure 3.BSE image of monazite-(Ce) samples showing different kinds of internal primary and alteration structu res. (A) The dark grain areas of the grain, primarily located close to rims and inclusions, display sharp irregularly shaped borders a
285	Figure 3.BSE image of monazite-(Ce) samples showing different kinds of internal primary and alteration structu res. (A) The dark grain areas of the grain, primarily located close to rims and inclusions, display sharp irregularly shaped borders a nd porosity. These areas consist
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285 286 287 288 290 291 292 293 294 295 294 295 296 297 298 299 300	<pre>Figure 3.85E image of monazite-(Ce) samples showing different kinds of internal primary and alteration structu res. (A) The dark grain areas of the grain, primarily located close to rims and inclusions, display sharp irregularly shaped borders a nd porosity. These areas consist of secondary monazite that isca.2.5 Myr younger than the pristine lighter grain parts (Fig. 5b). Image (B) sho ws part of a large grain with partially preserved sector-like zonation. Indications for alteration are irregularly shaped secondary zonatio n, both patchy in the middle and wavy on the right side, as well as porosity and fractures. The light rim visible at the top likely represents a late overgrowth but yields some of the oldest ages of the grain, predating those of some of the interior grain parts by several million years (Fig. 5t). The grain in (C) displays multiple rime combined with sector-like zonation around a central part. Although the grain shows practically n o alteration features, the outer rim has the oldest and most homogeneous age pattern, with the central part possessing a wider age range with s one significantly younger ages (Fig. 5m, Supplement Table 1). The youngest ages were found in part of the inner rim, postdating all othe r ages measured in the second rim or center by several million years. may be initiated on any part of the crystal in contact with the surrounding fluid. A self-sustaining reaction front propagates in this case into the mineral for as long as the interfacial fluid remains connected to a flu id reservoir (e.g.Putnis, 2002, 2009). The alteration is therefore not limited to grain rims, but commonly occurs along mineral inclusion inte rfaces, cracks and microcracks due to which also internal parts of a crystal may be altered (Fig. 3a, b; Grand interfaces, cracks and microcracks due to which also internal parts of a crystal may be altered (Ce) formation temperature vietem areafe. </pre>
285 286 287 288 290 291 292 293 294 295 294 295 296 297 298 299 300	<pre>Figure 3.BSE image of monazite-(Ce) samples showing different kinds of internal primary and alteration structu res. (A) The dark grain areas of the grain, primarily located close to rims and inclusions, display sharp irregularly shaped borders a nd porosity. These areas consist of secondary monazite that isca.2.5 Myr younger than the pristine lighter grain parts (Fig. 5b). Image (B) sho ws part of a large grain with partially preserved sector-like zonation. Indications for alteration are irregularly shaped secondary zonatio n, both patchy in the middle and wavy on the right side, as well as porosity and fractures. The light rim visible at the top likely represents a late overgrowth but yields some of the oldest ages of the grain, predating those of some of the interior grain parts by several million years (Fig. 5t). The grain in (C) displays multiple rims combined with sector-like ronation around a central part. Although the grain shows practically n o alteration features, the outer rim has the oldest and most homogeneous age pattern, with the central part possessing a wider age range with s ome significantly younger ages (Fig. 5m, Supplement Table 1). The youngest ages were found in part of the inner rim, postdating all othe r ages measured in the second rim or center by several million years. may be initiated on any part of the crystal in contact with the surrounding fluid. A self-sustaining reaction front propagates in this case into the mineral for as long as the interfacial fluid remains connected to a flu id reservoir (e.g.Putnis, 2002, 2009). The alteration is therefore not limited to grain rims, but commonly occurs along mineral inclusion inte rfaces, cracks and microcracks due to which also internal parts of a crystal may be altered (Fig. 3a, b; Grand i formmet al., 2018). These processes may be active as long as conditions in the cleft stay within the monazite-(Ce) formation temperature window and5 </pre>
285 286 287 288 289 290 291 292 293 294 295 295 295 295 297 298 299 300 301	<pre>Figure 3.BSE image of monazite-(Ce) samples showing different kinds of internal primary and elteration structu res. (A) The dark grain areas of the grain, primarily located close to rims and inclusions, display sharp irregularly shaped borders a nd porosity. These areas consit of secondary monazite that isca.2.5 Myr younger than the pristine lighter grain parts (Fig. 5b). Image (B) sho ws part of a large grain with partially preserved sector-like zonation. Indications for alteration are irregularly shaped secondary zonatio n, both patchy in the middle and wavy on the right side, as well as porosity and fractures. The light rim visible at the top likely represents a late overgrowth but yields some of the oldest ages of the grain, predating those of some of the interior grain parts by several million years (Fig. 5t). The grain in (C) displays multiple rims combined with sector-like zonation around a central part. Although the grain shows practically n o alteration features, the outer rim has the oldest and most homogeneous age pattern, with the central part possessing a wider age range with s ome significantly younger ages (Fig. 5m, Supplement Table 1). The youngest ages were found in part of the inner rim, postdating all othe r ages measured in the second rim or center by several million years. may be initiated on any part of the crystal in contact with the surrounding fluid. A self-sustaining reaction front propagates in this case into the mineral for as long as the interfacial fluid remains connected to a flu id reservoir (e.g.Putnis, 2002, 2009). The alteration is therefore not limited to grain rims, but commonly occurs along mineral inclusion inte rfaces, cracks and microcracks due to which also internal parts of a crystal may be altered (Fig. 3a, b; Grand furgaces, tracks and microcracks due to which also internal parts of a crystal may be altered (Fig. 3a, b; Grand furgace, tracks and microcracks due to which also internal parts of a crystal may be altered (Fig. 3a, b; Grand furgace). The processes ma</pre>

303	<sup>3</sup> temperature (Budzynet al., 2011). Therefore, several (re-)crystallization or dissolution-precipitation cycles
	may occur over
	the active lifespan of a monazite-(Ce) crystal (e.g.Bergemannet al., 2018, 2019). Later reactions may be aided
30	4 by porosity
	and fractures in the primary and secondary monazite-(Ce), induced by the previous dissolution-reprecipitation/
30	5 recrystallization
	events, by bringing an increased crystal volume into direct contact with the fluid (Putnis, 2002, 2009). Possi
30	6 ble signs of these10
	alteration processes recognizable in BSE images are irregularly shaped (Fig. 3 a, b) or weak (Fig. 3 b) intern
30	7 al zonation, or
30	8 7
30	9
	cross-cutting by secondary zones (Fig. 5 j, k), as well as a high porosity (Fig. 3 a, b;e.g.Gnoset al., 2015;
31	0 Bergemannet al.,
	2017, 2018). Micro-scale alteration along cracks, inclusions and porosity may produce altered areas within a c
31	1 rystal that cannot
31	2 be recognized in BSE images but yield a different age (Fig. 3c; Grand
31	3 ′
31	4 Hommeet al., 2018). Dissolution-precipitation processes
	may sometimes largely preserve the chemical composition of an affected crystal part, possibly due to only smal
31	5 1 pore fluid
	volumes involved in the reaction that did not equilibrate completely with the fluid surrounding the crystal, c
31	6 onsequently areas5
	affected by alteration that posses different chemical compositions may have reprecipitated simultaneously (Gra
31	7 nd
31	8 /
31	9 Hommeet
32	0 al., 2016; Bergemannet al., 2017, 2018).
32	13.2 Analytical techniques
	Most of the samples were provided by mineral collectors, as hydrothermal cleft monazite-(Ce) is uncommon and o
32	2 ften difficult
02.	to detect in the field when covered by dirt or chlorite. See Table 1 for location details. Mo
32	3  nazites-(Ce) were individually10
02	polished to the level of a central cross section and assembled in mounts of several grains. Backscatter electr
32	4 on (RSE) images
01	were then obtained using a Zeiss DSM940A electron microscope at the university of Geneva and a beam current of
32	sere chen obcarnea, abing a herbb bonsion erectron miterobecpe at the aniverbity of coneva and a beam carrent o
02	As the surface of the mounts has to remain flat for ion probe dating element mapping that would cause damage
32	to the enory
02	is not nessible. Secondary ion mass spectrometry (STMS) and analyses (Fig. 5) were placed according to visible
30.	To domains in
52	these images. We far as resaible, and measurements next to eracks yore avoided, as the Mh Dh isotore resourcement
2.01	enese images. As far as possible, spot measurements next to cracks were avoided, as the in-rb isotope measurem
32	A disturbed in such areas due to unsuconness in the comple surface (Instart al. 2010; Prosent al. 2012)
32	The product of the such areas due to unevenness in the sample surface (Janotset al., 2012; Bergeret al., 2013).
331	SIMC instrument Applutical methods and connection mereodynes follow like a second state of the second stat
	1 E) Viskland
33	
33	2 et al.(2009), and Janotset al.(2012), using a -13 kV 0
33	
33	4 primary beam ofca.6 nA and nominal 15µm diameter. The mass
-	spectrometer was operated at +10kV and a mass resolution of $ca.4300$ (M/ $\Delta$ M, at 10% peak height), with data colle
33	
	in peak hopping mode using an ion-counting electron multiplier. Unknowns were calibrated against monazite-(Ce)
33	6 standard
33	7 44069 (Aleinikoffet al., 2006). Lead isotope signals were corrected for common Pb contribution using measured
33	8 204
33	9 Pb and an
34	0 assumed present-day Pb isotope composition according to the model of Stacey and Kramers (1975). The measuremen
	t of
34	1 204
342	2 Pb
34	3 is subject to an unresolvable molecular interference by
34	4 232
34	5 Th
) 34	6 143

391	347	Nd
392	348	16
393	349	0
394	350	++
395	351	2
396		(also affecting
	352	, also affecting
397	353	206
398	354	Pb and
399	355	207
400	356	Pb to a lesser degree
401	357	through replacement of
402	200	10
100	359	0 by heavier 0-isotopes, which may result in an overestimation of common Pb concentrations. A25
404	360	correction was applied whenever the
405	361	232
406	362	Th
407	363	143
408	364	Nd
409	365	16
410	366	0
411	367	++
412	368	2
413		signal at mass 203.5 exceeded the average background signal on the5
414	369	signal at mass 203.5 exceeded the average background signal on the
414	370	ded by Steiger
415		and Jäger (1977). Th-Pb ages presented were corrected for common Pb and doubly charged
	371	and Jäger (1977). The Th-Pb ages were corrected for common Pb and doubly charged
416	372	232
417	373	Th
418	374	143
419	375	Nd
420	376	16
421	377	0
422	378	++
423	379	2
424		overlap and
420		A Populta
120		The complete ion-probe data set is given in the data Supplement Table 1 (PINCEL doi: still pending) see Tab
427		2 for an10
		overview and Figs. 4 and 7 for measurement positions and a graphical representation. As there are difficulties
428		with the U-
429		Pb system for hydrothermal monazite-(Ce) (Janots et al., 2012), only
430		208
431		Pb/
432		232
433		Th ages were used. For explanations on age
434		patterns across the grains, grouping and weighted mean age determination, see the discussion in Chapter 5.2.
435		o Solid Farth Discusshttps://doi.org/10.5104/so-2010-10
430		Manuscript under review for journal Solid Earth
438		Discussion started: 5 February 2019
439		c c c c c c c c c c c c c c c c c c c
440		©Author(s) 2019. CC BY 4.0 License.
	380	overlap and are
	381	reported at 2σuncertainties. Weighted mean age plots were done using Isoplot v. 3.75 (Ludwig, 2012).
	382	4 Th-Pb monazite-(Ce) dating30
		The dating of hydrothermal monazite-(Ce) differs from thermo-chronometers that posses a closure temperature in
	383	sofar, as a
	-	crystal may record several ages due to new crystallization or alteration of crystal parts. The grains directly
	384	record tectonic
	385	

	386	
		Figure 3.Back-scatter electron images of studied cleft monazite-(Ce). The zonation corresponds largely to vari
442		ations in Th contents. Spots
		refer to SIMS analysis spots, with colours indicating chemical and age domains. The color of the frame indicat
443		es data for which it was
110		
444		possible to calculate weighted mean
445		208
446		Pb/
	387	Table 2.Overview list of the
447	388	232
448		Th ages.
449		7
450		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
451		Manuscript under review for journal Solid Earth
452		Discussion started: 5 February 2019
152		
433		
454		OAuthor(s) 2019. CC BY 4.0 License.
455		
		Figure 4.Back-scatter electron images of studied cleft monazite-(Ce). The zonation corresponds largely to vari
456		ations in Th contents. Spots
		refer to SIMS analysis spots, with colours indicating chemical and age domains. The color of the frame indicat
457		es data for which it was
458		possible to calculate weighted mean
	380	
4 5 0	200	
439	390	
460		
461		232
462		Th ages.
463		8
464		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
465		Manuscript under review for journal Solid Earth
466		Discussion started: 5 February 2019
467		
468		Obuthor(c) 2019 CC BV 4 0 License
400		eRachol (3) 2013. CC B1 4.0 BICCASE.
469		
		Table 2.Measurement spots AIGGI 1, 9, 11, BLANC2 7, 8, 23 and SALZ15 4 were excluded due to their location on
470		cracks or signs of
471		
		mineral inclusions.
472		mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range
472 473		mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma)(Ma)
472 473 474		mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma)(Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18
472 473 474 475		mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma)(Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26
472 473 474 475	391	mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted
472 473 474 475	391	mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted
472 473 474 475	391 392	mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples.
472 473 474 475	391 392 393	mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure# ofSpot age rangemin. agemax. ageWeighted meanMSWD# of
472 473 474 475	391 392 393 394	mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure# ofSpot age rangemin. agemax. ageWeighted meanMSWD# of analysesof sample (Ma) (Ma) (Ma) domain ages (Ma)points
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472 473 474 475	391 392 393 394 395 396	mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure# ofSpot age rangemin. agemax. ageWeighted meanMSWD# of analysesof sample (Ma) (Ma) domain ages (Ma)points SouthVANI 65a2416.80±0.31 - 10.62±0.1816.80±0.3110.62±0.1814.68±0.472.85 WestBETT 115b1910.55±0.33 - 7.34±0.2610.31±0.311ike mean age9.85±0.292.112
472 473 474 475	391 392 393 394 395 396 397	<pre>mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure# ofSpot age rangemin. agemax. ageWeighted meanMSWD# of analysesof sample (Ma) (Ma) domain ages (Ma)points SouthVANI 65a2416.80±0.31 - 10.62±0.1816.80±0.3110.62±0.1814.68±0.472.85 WestBETT 115b1910.55±0.33 - 7.34±0.2610.31±0.311ike mean age9.85±0.292.112 7.53±0.310.533</pre>
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472 473 474 475 476 477	391 392 393 394 395 396 397 398 398	<pre>mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure# ofSpot age rangemin. agemax. ageWeighted meanMSWD# of analysesof sample (Ma) (Ma) (Ma) domain ages (Ma) points SouthVANI 65a2416.80±0.31 - 10.62±0.1816.80±0.3110.62±0.1814.68±0.472.85 WestBETT 115b1910.55±0.33 - 7.34±0.2610.31±0.311ike mean age9.85±0.292.112 7.53±0.310.533 DURO13c, 4c9.96±0.180.30710.82±0.26 - 8.21±0.20 DURO 15c2510.82±0.26 - 8.21±0.2010.82±0.261ike mean age9.95±0.180.377 9. 50±0.230.654</pre>
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472 473 474 475 476 477 478	391 392 393 394 395 396 397 398 399 400	mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 BETT113b, 4c9.96±0.301.5910.55±0.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure# ofSpot age rangemin. agemax. ageWeighted meanMSWD# of analysesof sample (Ma) (Ma) (Ma) domain ages (Ma) points SouthVANI 65a2416.80±0.31 - 10.62±0.1816.80±0.3110.62±0.1814.68±0.472.85 WestBETT 115b1910.55±0.33 - 7.34±0.2610.31±0.3111ke mean age9.85±0.292.112 7.53±0.310.533 DUR013c, 4c9.96±0.180.30710.82±0.26 - 8.21±0.20 DUR0 15c2510.82±0.26 - 8.21±0.2010.82±0.261ike mean age9.95±0.180.377 9.50±0.230.654 8.34±0.200.294
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472 473 474 475 476 477 478 479 480 481 482 483 484 485	<ul> <li>391</li> <li>392</li> <li>393</li> <li>394</li> <li>395</li> <li>396</li> <li>397</li> <li>398</li> <li>399</li> <li>400</li> <li>401</li> <li>402</li> <li>403</li> <li>404</li> <li>405</li> <li>405</li> </ul>	<pre>mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Ma) VANI63a, 4a14.68±0.472.8516.80±0.31 - 10.62±0.18 serT113b, 4c9.96±0.301.5910.5550.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure# ofSpot age rangemin. agemax. ageWeighted meanMSWD# of analysesof sample (Ma) (Ma) d0main ages (Ma)points SouthVANI 6522416.80±0.31 - 10.62±0.1816.80±0.3110.62±0.1814.68±0.472.85 WestBETT 115b1910.55±0.33 - 7.34±0.2610.31±0.311ike mean age9.85±0.292.112 7.53±0.310.533 DUR013c, 4c9.96±0.180.30710.82±0.26 - 8.21±0.20 DUR0 15c2510.82±0.26 - 8.21±0.2010.82±0.261ike mean age9.95±0.180.377 9.50±0.230.654 8.34±0.200.294 DUR023d, 447.63±0.130.55811.48±0.28 - 7.02±0.18 DUR023d, 447.63±0.130.55811.48±0.28 - 7.02±0.18 7.18±0.180.504 GRASSER13e, 4e9.09±0.190.28512.14±0.30 - 7.57±0.19 7.9±0.261.77 GRASSER33f, 415.60±0.61 - 6.36±0.39 KLEMI3g, 408.43±0.200.94510.64±0.26 - 7.97±0.20 KLEM23h, 4h3.44±0.310.57513.65±0.33 - 9.47±0.40 DUR0 5c612.60±0.37 - 9.33±0.3212.60±0.371ike mean age1.90±0.271.512 9.74±0.221.513 GRASSER 155.11.4±0.30 - 7.57±0.1912.14±0.301ike mean age9.16±0.240.194 CHEM23h, 4h5.44±0.300.77 - 9.35±0.1912.14±0.301ike mean age9.16±0.240.194</pre>
472 473 474 475 476 477 478 479 480 481 482 483 484 485	<ul> <li>391</li> <li>392</li> <li>393</li> <li>394</li> <li>395</li> <li>396</li> <li>397</li> <li>398</li> <li>399</li> <li>400</li> <li>401</li> <li>402</li> <li>403</li> <li>404</li> <li>405</li> <li>406</li> </ul>	<pre>mineral inclusions. SampleFigure Weighted mean domain ages MSWD Number of pointsSample spot age range (Ma) (Wa) VANI633, 4a14.68±0.472.8516.68±0.31 - 10.62±0.18 BETTI135, 4&lt;9.96±0.301.5910.5550.33 - 7.34±0.26 Pb age range and significant minimum and maximum ages obtained for each grain, and weighted mean domain ages that could be calculated for the samples. Region SampleFigure* ofSpot age rangemin. agemax. ageReighted meanMSWD# of analyses of sample (Ma) (Ma) (Ma) domain ages (Ma) points SouthVANI 552416.80±0.31 - 10.62±0.1816.62±0.1814.68±0.472.85 WestBETT 115b1910.55±0.33 - 7.34±0.2610.31±0.311ike mean age9.85±0.292.112 7.53±0.310.533 DURO15x2510.82±0.26 - 8.21±0.20 DURO 15x2510.82±0.26 - 8.21±0.20 DURO 15x2510.82±0.26 - 8.21±0.20 DURO 25x2311.48±0.28 - 7.02±0.18 DURO234, 4d7.63±0.130.55811.48±0.28 - 7.02±0.18 DURO234, 4d7.63±0.130.55811.48±0.28 - 7.02±0.18 DURO 25d3211.48±0.28 - 7.02±0.28 CHENERASS, 415.60±0.61 - 6.36±0.39 CHENERASS, 415.30±0.200.37 - 7.57±0.1912.14±0.30±0.271.512 SHENERASS, 415.30±0.210.513 SHENERASS, 415.30±0.210.513 SHENERASS, 415.30±0.210.514±0.30 - 7.57±0.1912.14±0.30±0.271.512 SHENERASS, 415.30±0.210.514±0.24±0.24±0.24±0.24±0.24±0.24±0.24±0.2</pre>

	407	7.73±0.160.546
	408	GRAESER 35g1715.60±0.61 - 6.36±0.3915.60±0.616.36±0.39
	409	GRAESER 4Appendix212.25±0.51 - 11.88±0.4712.25±0.5111.88±0.47
	410	KLEM 15h2410.64±0.26 - 7.97±0.2010.64±0.267.97±0.208.43±0.200.945
	411	KLEM 25i1713.65±0.33 - 9.47±0.40like mean agelike mean age13.44±0.310.575
486	412	11.74±0.320.835
487	413	10.12±0.942.64
488		KLEM33i, 4i12.64±0.380.18512.96±0.46 - 8.43±0.32
	414	KLEM 35j2412.96±0.46 - 8.43±0.321ike mean age8.43±0.3212.50±0.340.656
489	415	11.99±0.662.36
490		SCHIESS13j, 4j9.69±0.602.449.94±0.25 - 6.78±0.18
491		VANI43k, 4k8.03±0.533.399.27±0.43 - 6.89±0.37
492		8.03±0.442.27
493		VANI531, 417.21±0.431.968.07±0.36 - 4.86±0.24
	416	10.17±0.522.47
	417	SCHIESS 15k279.94±0.25 - 6.78±0.186.90±0.181ike mean age9.78±0.220.415
	418	7.03+0.382.35
	419	VANT 451169.27+0.43 - 6.89+0.379.27+0.436.89+0.378.03+0.442.27
	420	VANT 55m208 07+0 36 - 2 69+0 117 45+0 222 69+0 117 21+0 431 96
494	421	5 53+0 603 55
495		RLASI3m. 4m12 83+0 392 0514 49+0 26 - 7 82+0 22
496		$\frac{1}{12} \frac{1}{12} \frac$
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199		0 73+0 301 810
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501		$\frac{1}{2} \frac{1}{2} \frac{1}$
JUI	400	Contemplate 15-1814 4010 26 7 8210 2014 4010 267 8210 2010 8210 202 05
	422	DUMU 25-1511014.4910.20 - 7.0210.2214.4910.207.0210.2212.0510.392.05
	423	$\sum_{n=1}^{n} \sum_{n=1}^{n} \sum_{n$
	424	$\frac{1}{1000} \frac{1}{1000} \frac{1}{1000$
	420	$\frac{1}{2} \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{i=1}^{2} \sum_{i=1}^{2} \sum_{i=1}^{2} \sum_{j=1}^$
502	420	5AL2 2512014.2010.74 - 10.5110.5914.2010.7411Ke mean age12.9010.252.217
3UZ		
EOO	427	
503	120	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11
503	428	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724
503	427 428 429	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74
503 504	427 428 429 430	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05
503 504 505	428 429 430	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57
503 504 505	427 428 429 430 431 432	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS5t4316.43±0.61 - 12.09±0.5716.43±0.611ike mean age15.27±0.351.17
503 504 505 506	427 428 429 430 431 432	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS5t4316.43±0.61 - 12.09±0.5716.43±0.611ike mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484
503 504 505 506 507	427 428 429 430 431 432	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS5t4316.43±0.61 - 12.09±0.5716.43±0.611ike mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577
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503 504 505 506 507 508 509 510	428 429 430 431 432 433 434	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS3t4316.43±0.61 - 12.09±0.5716.43±0.611ike mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion statted: 5 February 2019
503 504 505 506 507 508 509 510 511	428 429 430 431 432 433 434	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS5t4316.43±0.61 - 12.09±0.5716.43±0.611ike mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019
503 504 505 506 507 508 509 510 511 512	428 429 430 431 432 433 434	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS5t4316.43±0.61 - 12.09±0.5716.43±0.611ike mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c @Puthor(s) 2019, CC BY 4.0 License
503 504 505 506 507 508 509 510 511 512 513 514	428 429 430 431 432 433 434	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS5t40.983.05 VALS5t4316.43±0.61 - 12.09±0.57 4.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Quthor(s) 2019. CC BY 4.0 License.
503 504 505 506 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS5t4316.43±0.61 - 12.09±0.5716.43±0.611ike mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Diagrams showing
503 504 505 506 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 433	TAMB13s, 4s17.49±0.400.72419.02±0.47 - 8.32±0.11 EastTAMB 15s2419.02±0.47 - 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 - 12.09±0.57 VALS5t4316.43±0.61 - 12.09±0.5716.43±0.61like mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Diagrams showing activity instead of cooling through new/re-crystallization, ase.g.in the case of Ar-Ar dating in white micas.
503 504 505 506 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 435 435	<pre>TAMB13s, 4s17.49±0.400.72419.02±0.47 = 8.32±0.11 EastTAMB 15s2419.02±0.47 = 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 = 12.09±0.57 VALS5t4316.43±0.61 = 12.09±0.5716.43±0.61like mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Diagrams showing activity instead of cooling through new/re-crystallization, ase.g.in the case of Ar-Ar dating in white micas. Consequently,</pre>
503 504 505 506 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 435 435	<pre>TAMB13s, 4s17.49±0.400.72419.02±0.47 = 8.32±0.11 EastTAMB 15s2419.02±0.47 = 8.32±0.1119.02±0.478.32±0.1117.49±0.400.724 14.3±1.12.74 13.28±0.983.05 VALS3t, 4t15.27±0.351.1716.43±0.61 = 12.09±0.57 VALS5t4316.43±0.61 = 12.09±0.5716.43±0.611ike mean age15.27±0.351.17 14.70±0.410.816 12.48±0.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c @Author(s) 2019. CC BY 4.0 License. Figure 5.Diagrams showing activity instead of cooling through new/re-crystallization, ase.g. in the case of Ar-Ar dating in white micas. Consequently, unless coupled with fluid inclusion analysis, a hydrothermal monazite-(Ce) age in itself only provides a very</pre>
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503 504 505 506 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 433 434 435 435 436 437 438 439 440 441	<pre>Number 2019 10 10 10 10 10 10 10 10 10 10 10 10 10</pre>
503 504 505 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 433 434 435 435 436 437 438 439 440 441	<pre>Number 2019 11 11 11 11 11 11 11 11 11 11 11 11 1</pre>
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503 504 505 506 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 435 435 436 437 438 439 440 441 442 443	<pre>Non-Display and the second secon</pre>
503 504 505 506 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 433 434 435 436 437 438 439 440 441 442 443	TABLES, 417, 4920.400.72419.0220.47 - 8.3220.11 ZastTAMS 15s2419.0210.47 - 8.3210.1119.0210.478.3220.1117.4910.400.724 14.31.12.74 13.2840.983.05 VALSS1.415.2740.351.1716.4340.61 - 12.0940.57 VALSS1.4316.4340.61 - 12.0910.5716.4340.6111ke mean age15.27±0.351.17 14.70±0.410.816 12.4820.460.484 12.61±0.360.577 9 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Author(s) 2019. CC EY 4.0 License. Figure 5.Diagrams showing activity instead of cooling through new/re-crystallization, ase.g.in the case of Ar-Ar dating in white micas. Consequently, unless coupled with fluid inclusion analysis, a hydrothermal monazite-(Ce) age in itself only provides a very general idea of temperature conditions (ca.350-200 * C or somewhat below; Gnoset al., 2015; Bergemannet al., 2017, 2018) and more information on temperatures needs to come from a comparison with thermo(-chrono)meters. The SIMS spot analyses were distributed on the basis of domains visible in BSE images, among these the center and outerS rim if distinguishable, to capture the crystallization duration. In order to obtain more robust growth domain a ges, the selected domains were large enough to place a minimum of three messurement spots. The number of domains dated was limit
503 504 505 507 508 509 510 511 512 513 514 515	428 429 430 431 432 433 434 433 434 435 436 437 438 439 440 441 442 443 444	TABBIS, 4310.400.72419.0240.47 - 8.3240.11 RastTAMB 15s2419.0240.47 - 8.3240.1119.0240.478.3240.1117.4940.400.724 14.31.12.74 13.2820.983.05 VAIS35.4515.2740.351.1716.4340.61 - 12.0940.57 VAIS55.4316.4340.61 - 12.0940.5716.4340.6111ke mean age15.2740.351.17 14.7040.410.816 12.4820.460.484 12.610.360.577 9 Solid Barth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Author(s) 2019. CC BY 4.0 License. Figure 5.Diagrams showing activity instead of cooling through new/re-crystallization, ase.g.in the case of Ar-Ar dating in white micas. Consequently, unless coupled with fluid inclusion analysis, a hydrothermal monazite-(Ce) age in itself only provides a very general idea of temperature conditions (ca.350-200 C C or somewhat below; Gnoset al., 2015; Bergemannet al., 2017, 2018) and more information on temperatures needs to come from a comparison with thermo(-chrono)meters. The SIM spot analyses were distributed on the basis of domains visible in BSE images, among these the center and outer5 rim if distinguishable, to capture the crystallization duration. In order to obtain more robust growth domain a ges, the selected domains were large enough to place a minimu of three measurement spots. The number of domains dated was limit ed by

516	446	208
517	447	Pb/
518	448	232
519		Th ages for all samples. The colours indicate chemical domains with weighted mean
	449	Th ages were used, as the Th-Pb system is favorable in dating hydrothermal monazite-
	450	(Ce) due to high Th/U ratios at low U content, which preclude the use of the
	451	207
	452	Pb/
	453	235
	454	U system. Additionally, the high Th/U
	455	ratios and young age oft the samples also exacerbate the uncorrectable excess in
	456	
	457	
	459	The an10
	460	intermediate decay product of
	461	238
	462	U (Janotset al., 2012). This means that only
520	463	208
521	464	Pb/
522	465	232
523		Th
524		ages given where applicable.
	466	Th single or weighted mean ages
	467	instead of concordia ages should be used.
		Previous studies found no simple chemical criteria to identify altered zones and have shown that U-Th-Pb conte
	468	nts seem to
		be the easiest way to differentiate between zones, both primary and secondary (e.g.Gnoset al., 2015; Bergemann
	469	et al., 2017).
		Figure 5 includes plots showing compositional varation used as a basis for domain age calculations. The derive
	470	d spot ages15
	171	were grouped together on the basis of chemical composition representing crystal formation or replacement under
	4/1	changing
	472	n visible on BSE
	1/2	images. Whenever age clusters were found on the basis of these groups, weighted mean domain ages were calculat
	473	ed (Fig. 5),
	474	as these could be shown to date tectonic activity (Grand
	475	
	476	Hommeet al., 2016; Bergemannet al., 2017, 2018, 2019; Ricchiet
		al., 2019). Since any new crystallization or alteration associated with a change in chemical composition must
	477	have happened20
		in equilibrium with the surrounding fluid, any age cluster within a chemical group must be due to those crysta
	478	l parts' simul-
		taneous formation or alteration. Therefore, two chemically distinct groups that yield, within error, identical
	479	weighted mean
		ages, still signify two distinct crystal formation/alteration events closely following each other. In areas th
	480	at experienced strong
		and discrete tectonic events, usually in the vicinity of shear zones, this approach allows the calculation of
	481	domain ages for a
	100	majority of the analyzed spots from the dataset of a sample (e.g.Janotset al., 2012; Bergeret al., 2013; Berge
	402	Mannet al.,25
	483	r each grain.
	100	some of the weighted mean ages may only combine a small number of individual ages. This appears to be especial
	484	ly true for
	485	ages dating late stage events (e.g.Bergeret al., 2013; Grand
	486	· · · · · · · · · · · · · · · · · · ·
	487	Hommeet al., 2016; Bergemannet al., 2017, 2018).
		A problem in this approach, used in other areas of the Alps, is that large parts of the Lepontine Dome region
	488	experienced
		more than two distinct deformation events and/or phases of prolonged small scale tectonic activity, likely dur
	489	ing exhumation.30
		Experiments have shown that a reason for a large age scatter in crystal domains affected by alteration may be
	490	an incomplete

	491	age resetting due to the survival of primary monazite paposcale domains (Grand
	4.0.0	age resetting due to the survival of primary monazite nanostate domarno (orang
	492	
	493	Hommeet al., 2018). This may have caused
		the observed spread out age patterns without age clusters in zones visible in BSE, which impede the calculatio
	494	n of weighted
		mean ages (Fig. 5). Especially prolonged phases of low-intensity tectonic activity would presumably repeatedly
	495	cause small
	496	volumes of monazite-(Ce) to reprecipitate during re-equilibration of the fluid chemistry.35
525	497	10
526		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
527		Manuscript under review for journal Solid Earth
528		Discussion started: 5 February 2019
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	498	
		Figure 4.Time diagram combining identified peaks from the inset and weighted mean ages of all samples from the
	499	Lepontine Dome. The inset
		shows an age probability density plot representing the dataset of each region (Fig. 1) according to the number
	500	of ages per 0.5 Myr interval. In
		the time diagram, darker colors represent peaks or plateaus from the inset indicating times of intense monazit
	501	e formation/alteration. Lighter
		shades mark the remaining times for which more than one age was recorded, indicating either only limited tecto
	502	nic activity or mixing ages.
	503	Black error bars indicate weighted mean ages from this study.
	504	11
	505	
		Additionally, as stated above, altered areas may preserve their overall chemical composition but consist of a
	506	submicroscopic
	507	mix of different phases (e.g.Grand
	508	
	509	Hommeet al., 2016), and analyses belonging to the same chemical group may therefore
		show a large age scatter. The limited number of analyses per grain would therefore result in m
	510	any individual ages being
		discarded for these areas. Accordingly, events may, especially in larger grains, not be recognized if looking
	511	at the well defined
		weighted mean ages only. To avoid this, the entire dataset of each region was plotted according to the number
	512	of ages per 0.55
		Myr interval to identify age clusters across the grains of a given region (Fig. 4 inset). The identified age p
	513	eaks and phases for
		which a significant number of ages were obtained were then combined with the weighted average ages to visualiz
	514	e distinct
	011	events or phases of tectonic activity (Fig. 4) Age neaks of a region's dataset and weighted mean ages of indi-
	515	vidual graine
	919	anarally agree with some phases of age recording visible in the overall age record not identified through we
	516	ighted mean ages
	JIO	Tynee mean ayes.
	517	ror the interpretation of the data, weighted mean ages are preferable to proport deformation events. However,
	J±7	at reast there and of the are record within a comple must have a geological significance since their recording
	F 1 0	beginning and end of the age record within a sample must have a geological significance since their recording
	910	must nave been
	- 1 0	triggered by tectonic activity, even if one assumes all ages in between to be simply mixing ages. Accordingly,
	219	weighted mean
		ages are in the following generally discussed as precise ages, while spot ages are treated as approximate age
	520	S.
	521	4.1 Results
		The ion-probe measurement data set is given in the data Appendix Table AI and can be found in the PANGAEA data
	522	
		(https://doi.org/10.1594/PANGAEA.898689). The age data of the individual samples and the whole data
	523	set cover a large
		range ofca.16 Myr, covering the time between~19 and 2.7 Ma. Individual grains record ages over a lifetime of 2
	524	to 7.5 Myr.
		An overview over the individual age ranges and the weighted mean domain ages that could be calculated for the
	525	individual
		samples is shown in Table 2. Figure 5 shows the measurement positions, weighted mean domain ages, where availa
	526	ble, a
	JZ /	

	graphical representation of the measured ages and a chemical for each sample the best shows the different grou
	ps.20
	Sample GRAESER 4 (Appendix Fig. A1; Appendix Table A1) is a grain (co-type) from the monazite-(Nd) type locali
528	ty
	(Graeser and Schwander, 1987). Due to very low Th contents only two spots yielded ages of 11.88±0.47 and 12.25
529	±0.51
530	Ma, clearly indicating that the monazite-(Nd) crystallized coevally with monazite-(Ce).
	Typical for hydrothermal cleft/fissure monazite, the contents of Th and U are generally relatively low compare
531	d to monazite
	from other geological environments (Appendix Table A1; Janotset al., 2012). With Th contents generally ranging
532	between25
	5000 and 60000 ppm, with (parts) individual samples considerably lower (down to 1000 ppm) or higher (up to 110
533	סטר בות הייניט אין אייניט א 100 חמת (אייניט אייניט איינ
000	while II contents are below 1000 nnm (only KIEM 3 up to 3300 nnm), resulting in high Th/II ratios of up to sever
624	while o contents are below 1000 ppm (only Kiew 5 up to 5500 ppm), resulting in high 10/0 factos of up to sever
J34	ar nundred.
	Lead contents snow a spread from a few up to several nundred ppm, with common PD contents generally considerad
535	TÀ PETOM
536	10%. However, a number of measurements in GRAESER 3 and TAMB 1 show very high common Pb contents above 70%
	with a maximum of 99%. With the exception of sample BLAS 1, all sample grains show at the least some alteratio
537	n features30
	(irregular, wavy or unclear zonation, porosity) and can roughly be divided into five partly overlapping groups
538	on the basis of
539	their appearance in BSE images (Fig. 5): (1) Sector like zonation:
540	DUTH 6 shows some signs of alteration and complex zonation in the inner part of the grain.
541	12
542	
	GRAESER 3 shows no clear signs of alteration, but an extreme zonation in both Th (~1800-113000 ppm) and U (~10
543	-680
	ppm) contents according to visible zonation and elevated (>10%) to extreme (65-99%) common Pb contents. The ag
544	es derived
011	from the low The measurements should be treated with coution as they show a greater spread at higher error that
EAE	Tiom the low in measurements should be treated with caution, as they show a greater spread at higher error that
545	
in rr -	modellamente
J46	measurements.
546 547	VANI 4 shows in places strong signs of alteration.5
546 547	WANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela
547 548	Measurements. VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low
547 548 549	WANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%.
547 548 549	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat
546 547 548 549 550	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features.
546 547 548 549 550	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (>3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co
546 547 548 549 550 551	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (>3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co mmon Pb
546 547 548 549 550 551 552	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (>3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co mmon Pb contents are elevated but remain below 25%.10
546 547 548 549 550 551 552 553	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (>3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co mmon Pb contents are elevated but remain below 25%.10 (2) Sector like + oscillatory/ring zonation:
546 547 548 549 550 551 552 553	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (>3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co mmon Pb contents are elevated but remain below 25%.10 (2) Sector like + oscillatory/ring zonation: BLAS 1 shows no visible signs of alteration, but the interior part of the crystal gives younger ages than the
546 547 548 549 550 551 552 553 554	VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (>3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co mmon Pb contents are elevated but remain below 25%.10 (2) Sector like + oscillatory/ring zonation: BLAS 1 shows no visible signs of alteration, but the interior part of the crystal gives younger ages than the outer part.
546 547 548 549 550 551 552 553 554 555	<pre>Wassing the set of the set o</pre>
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546 547 550 551 552 553 554 555 556 557 558 557 558 559 560 561 562 563 564 563 564 565 566	<pre>measurements. VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 20%. VADS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (&gt;3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co mmon Pb contents are elevated but remain below 25%.10 (2) Sector like + oscillatory/ring zonation: BLAS 1 shows no visible signs of alteration, but the interior part of the crystal gives younger ages than the outer part. DURO 1 has strong zonation with only minor signs of alteration. KLEM 1 shows signs of alteration, and the zonation is diffuse in places like the center and part of the rim. SCHIESS 1 shows in parts strong alteration signs and the primary zonation is cut in places.15 (3) Clear distinction between primary and altered zones: EETT 11 is the only sample that is featureless, but it shows altered areas around holes and along rims. LUCO 1 is largely featureless with right and interior parts showing an intricate secondary zonation pattern. (4) Weak zonation with minor alteration features:20 DUTH 2 displays only weak remnants of oscillatory zonation that is cut and transitions in places into a diffuse pattern SALZ 2 shows means of sector-like combined with complex zonation. (5) Weak zonation with strong alteration features: DUCA 2 displays remnants of oscillatory zonation.25 DUTH 3 has partly preserved oscillatory zonation. GRAESES 1 shows remains of sector combined with oscillatory zonation, but strong zonation in the altered parts of about the strong zonation with strong alteration features; DUCA 2 displays remains of sector combined with oscillatory zonation, but strong zonation in the altered parts of about the strong zonation with sparts of he grain having a diffuse pattern.</pre>
546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 563 564 565 566 566 567 568	<pre>measurements. VANI 4 shows in places strong signs of alteration.5 VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are rela tively low at 1600-10800 ppm, and common Pb contents elevated but mostly below 208. VALS, by far the largest analyzed grain, that shows in places only weak zonation with sometimes strong alterat ion features. Thorium contents are low (&gt;3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Co mmon Pb contents are elevated but remain below 25%.10 (2) Sector like + oscillatory/ring zonation: BLAS 1 shows no visible signs of alteration, but the interior part of the crystal gives younger ages than the outer part. DURO 1 has strong zonation with only minor signs of alteration. KLEM 1 shows in parts strong alteration signs and the primary zonation is cut in places.15 (3) Clear distinction between primary and altered zones: BETT 11 is the only sample that is featureless, but it shows altered areas around holes and along rimm. VANI 6 displays oscillatory-complex zonation, with clearly discernible altered grain parts around pores and al ong rimm. LUCO 1 is largely featureless with right and interior parts showing an intricate secondary zonation pattern. (4) Weak zonation with minor alteration features:20 DUTH 2 displays only weak remnants of sector-like zonation. (5) Weak zonation with strong alteration features: DURO 2 displays correnants of oscillatory zonation that is cut and transitions in places into a diffuse patter a. SAL2 2 shows remains of sector-like combined with complex zonation. (5) Weak zonation with strong alteration features: DURO 2 displays remaints of oscillatory zonation .25 DURO 3 displays remaints of sector-like zonation. (6) Weak zonation with strong alteration features: DURO 2 displays remaints of sector combined with oscillatory zonation, but strong zonation in the altered parts of the Numeric</pre>

		ommon
	572	Pb contents below 20%.30
	5/3	RLEM 2 has a diffuse internal structure and elevated common PD contents that remain below 21%.
	E 7 4	TAMB I has in (>5500 ppm) contents that do not allow the identification of clear chemical groups, weighted mea
	574	n ayes could therefore only be calculated for spots located in close provimity that give a similar age. While most of
	575	the measurements
		have common Pb contents of >5%, five measurements show very high contents of 72-96%, but despite this appear u
	576	ndisturbed.
	577	13
531	578	
532		Figure <mark>6.Diagrams showing</mark>
	579	Figure
		5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the dif
		ferent groups within a
	590	(right) chew
533	581	208
534	582	Pb/
535	583	232
536		Th ages for all samples. The colours indicate chemical domains with weighted mean
	584	Th ages.
	585	14
	586	
		Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show
	587	the different groups within a
		sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams
	588	(right) show
537	589	208
538	590	232
540	551	Th
541		ages given where applicable.
542		11
543		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
544		Manuscript under review for journal Solid Earth
545		Discussion started: 5 February 2019
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549	593 594	CAuthor(s) 2019. CC BY 4.0 License. Th ages. 15 Figure 7.Diagrams showing
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549	593 594 595 596 597	CAuthor(s) 2019. CC BY 4.0 License. Th ages. 15 Figure 7.Diagrams showing Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the dif ferent groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208
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		5 Discussion
560		5.1 Hydrothermal monazite-(Ce) crystallization
561		Hydrothermal fissure monazite-(Ce) typically crystallizes at temperatures below 350
562		•
563		C (Gnos et al., 2015; Bergemann et al.,
564		2017, 2018) down to somewhere in the range of 200
565		
566		C or slightly below (e g Townsend et al. 2000) Crystallization and
500		to of stightly below (e.g. townsend et al., 2000). Crystallization and
		Tater reactions occur when the fissure fiund is brought into disequilibrium. This may be caused by tectonic ev
567		ents for a numberb
		of reasons: by volume changes due to deformation, partial collapse of the fissure walls bringing the fluid int
568		o contact with
569		unaltered wallrock or the influx of new fluid.
		After crystallization, monazite-(Ce) shows practically no U-Th-Pb diffusion (Cherniak and Pyle, 2008). Howeve
570		r, replace-
		ment mechanisms that may be active in a hydrothermal environment may cause (re-)crystallization and possibly n
571		ew growth
		around an existing grain or dissolution-reprecipitation. From the fluid film, a secondary monazite-(Ce) phase
572		precipitates at10
		the surface of the primary phase. The self-sustaining reaction front propagates into the mineral for as long a
573		s the interfacial
		fluid retains a connection to a fluid reservoir. This dissolution-reprecipitation process may be initiated on
574		any part of the crystal
575		10
575		12 0-1:1 Eauth Diamag - https://doi.out/10.5104/cz.0010.10
570		Solid Ealth Discuss., https://doi.org/10.5194/Se-2019-10
577		Manuscript under review for journal Solid Earth
578		Discussion started: 5 February 2019
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580		©Author(s) 2019. CC BY 4.0 License.
	608	Th ages.
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582 583 584 585 586 587 588 590 591 592 593 594 595 595		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rims, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand Amme et al., 2018). These processes may be active as long as conditions in the cleft stay within the monazite-(Ce) stability fiel d. Therefore, sev- eral (re-)crystallization or dissolution-precipitation cycles may occur over the active lifespan of a monazite -(Ce) crystal. Later reactions may be aided by secondary porosity and fracturing induced by the previous dissolution-reprecipitatio n/recrystallization5 events, by bringing an increased crystal volume into direct contact with the fluid. 5.2 Monazite-(Ce) Th-Fb single and weighted mean ages As detailed above, SIMS spot analyses were placed across the samples according to growth domains visible in BS E images (Fig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represen t crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zon ation visible on BSE10 images to calculate, whenever possible, weighted mean domain ages (Fig. 7). It appears that dissolution-precip itation may largely preserve the chemical composition of an affected crystal part, this would mean that area s with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were onl y in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multipl</pre>
582 583 584 585 586 587 588 590 591 592 593 593 594 595 595 596		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rims, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand Momme et al., 2018). These processes may be active as long as conditions in the cleft stay within the monazite-(Ce) stability fiel d. Therefore, sev- eral (re-)crystallization or dissolution-precipitation cycles may occur over the active lifespan of a monazite -(Ce) crystal. Later reactions may be aided by secondary porosity and fracturing induced by the previous dissolution-reprecipitation n/recrystallization5 events, by bringing an increased crystal volume into direct contact with the fluid. 5.2 Monazite-(Ce) Th-Fb single and weighted mean ages As detailed above, SIMS spot analyses were placed across the samples according to growth domains visible in BS E images (Fig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represen t crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zon ation visible on BSE10 images to calculate, whenever possible, weighted mean domain ages (Fig. 7). It appears that dissolution-precip itation may largely preserve the chemical composition of an affected crystal part, this would mean that area s with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were onl y in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multipl e mixing ages of</pre>
582 583 584 585 586 587 588 590 591 592 593 593 594 595 596 597		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rims, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand Momme et al., 2018). These processes may be active as long as conditions in the cleft stay within the monazite-(Ce) stability fiel d. Therefore, sev- eral (re-)crystallization or dissolution-precipitation cycles may occur over the active lifespan of a monazite -(Ce) crystal. Later reactions may be aided by secondary porosity and fracturing induced by the previous dissolution-reprecipitation n/recrystallization5 events, by bringing an increased crystal volume into direct contact with the fluid. 5.2 Monazite-(Ce) Th-Fb single and weighted mean ages As detailed above, SIMS spot analyses were placed across the samples according to growth domains visible in BS E images (Fig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represen t crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zon ation visible on BSE10 images to calculate, whenever possible, weighted mean domain ages (Fig. 7). It appears that dissolution-precip itation may largely preserve the chemical composition of an affected crystal part, this would mean that area s with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were onl y in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multipl e mixing ages of different chemical domains as a distinct event. In areas that experienced few and discrete tectonic events, th</pre>
582 583 584 585 586 587 588 590 591 592 593 593 594 595 595 596 597 598		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rims, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand Homme et al., 2018). These processes may be active as long as conditions in the cleft stay within the monazite-(Ce) stability fiel d. Therefore, sev- eral (re-)crystallization or dissolution-precipitation cycles may occur over the active lifespan of a monazite -(Ce) crystal. Later reactions may be aided by secondary porosity and fracturing induced by the previous dissolution-reprecipitation n/recrystallization5 events, by bringing an increased crystal volume into direct contact with the fluid. 5.2 Monazite-(Ce) Th-Pb single and weighted mean ages As detailed above, SIMS spot analyses were placed across the samples according to growth domains visible in BS E images (Pig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represen t crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zon ation visible on BSE10 images to calculate, whenever possible, weighted mean domain ages (Fig. 7). It appears that dissolution-precip itation may largely preserve the chemical composition of an affected crystal part, this would mean that area s with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were onl y in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multipl e mixing ages of different chemical domains as a distinct event. In areas that experienced few and discrete tectonic events, th is approach allows15</pre>
582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rims, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand definition of the second of t</pre>
582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rims, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand / domme et al., 2018). These processes may be active as long as conditions in the Cleft stay within the monazite-(Ce) stability fiel d. (Therefore, sev- eral (re-)crystallization or dissolution-precipitation cycles may occur over the active lifespan of a monazite -(Ce) crystal. Later reactions may be aided by secondary porosity and fracturing induced by the previous dissolution-reprecipitation a/recrystallization5 events, by bringing an increased crystal volume into direct contact with the fluid. 5.2 Monazite-(Ce) Th-Th single and weighted mean ages As detailed above, SIMS spot analyses were placed across the samples according to growth domains visible in BS E images (Fig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represen t crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zon ation visible on BSE10 images to calculate, whenever possible, weighted mean domain ages (Fig. 7). It appears that dissolution-precip itation may largely preserve the chemical composition of an affected crystal part, this would mean that area a with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were onl y in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multipl e mixing ages of different chemical domains as a distinct event. In areas that experienced few and discrete tectonic events, th is approach allows15 the calculation of domain ages for most analyzed spots of the dataset of a sample (e.g.Janots et al., 2012; Be remenn et al.,</pre>
582 583 584 585 586 587 590 591 592 593 594 595 596 597 598 599		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rins, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand domme et al., 2018). These processes may be active as long as conditions in the cleft stay within the monazite-(Ce) stability fiel d. Therefore, sev- eral (re-)crystallization or dissolution-precipitation cycles may occur over the active lifespan of a monazite -(Ce) cystal. Later reactions may be aided by secondary porosity and fracturing induced by the previous dissolution-reprecipitation //recrystallization5 events, by bringing an increased crystal volume into direct contact with the fluid. 5.2 Monazite-(Ce) Th-Db single and weighted mean ages As detailed above, SIMS spot analyses were placed across the samples according to growth domains visible in BS E images (Fig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represen t crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zon ation visible on BSE10 images to calculate, whenever possible, weighted mean domain ages (Fig. 7). It appears that dissolution-precipitation may largely preserve the chemical composition of an affected crystal part, this would mean that area s with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were onl y in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multipl e mixing ages of different chemical domains as a distinct event. In areas that experienced few and discrete tectonic events, th is approach allows15 the calculation of domain ages for most analyzed spots of the dataset of a sample (e.g.Janots et al., 2012). Be rependent et al., 2013). However, large parts of the study erea everyteeneed more than two distinct deformation events end/or otherest and the al.,</pre>
582 583 584 585 586 587 590 591 592 593 594 595 596 595 596 597 598 599		<pre>in contact with the surrounding fluid. It is therefore not limited to grain rins, but commonly occurs along mi neral inclusion interfaces, cracks and microcracks, that may be invisible in BSE images (Grand ) nomme et al., 2018). These processes may be active as long as conditions in the cleft stay within the monarite-(Ce) stability fiel d. Therefore, sev- eral (re-)crystallization or dissolution-precipitation cycles may occur over the active lifespan of a monarite -(Ce) crystal. Later reactions may be aided by secondary porosity and fracturing induced by the previous dissolution-reprecipitation n/recrystallization5 events, by bringing an increased crystal volume into direct contact with the fluid. 5.2 Monarite-(Ce) Th-Fb single and weighted mean ages As detailed above, SIMS spot analyses were placed across the samples according to growth domains visible in BS E images (Pig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represen t crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zon ation visible on BSE10 images to calculate, whenever possible, weighted mean domain ages (Fig. 7). It appears that dissolution-precipi itation may largely preserve the chemical composition of an affected crystal part, this would mean that area a with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were onl y in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multipl e mixing ages of different chemical domains as a distinct event. In areas that experienced few and discrete tectonic events, th is approach allows15 the calculation of domain ages for most analyzed spots of the dataset of a sample (e.g.Janots et al., 2012; Be rgemann et al., 2017). However, large parts of the study area experienced more than two distinct deformation events and/or pha area of prolonged</pre>

601		activity. New growth on an existing crystal results in sharp boundaries between zones. But dissolution-repreci
		pitation processes
		may lead to irregularly shaped altered zones within a crystal, which may or may not be visible on a BSE image.
602		If this happens
		multiple times the limited number of analyses per grain will result in many individual ages being discarded. M
603		eaning that 20
000		events may not be recommined then looking only at the weighted mean ages. We avoid this, the entire dataset of
		events may not be recognized when looking only at the weighted mean ages. To avoid this, the entire dataset of
604		each region
		was additionally plotted according to the number of ages per 0.5 Ma intervals to identify age clusters (Fig.
605		1, appendix). In the
		next step the peaks or plateaus of the age histogram were plotted according to their relative intensity. They
606		were then combined
		with the weighted average ages (this study; Janots et al., 2012; Berger et al., 2013; Bergemann et al., 2017)
607		to visualize distinct
		events or phases of tectonic activity (Fig. 8). As only a limited number of analyses are possible to obtain fo
608		r each grain, some25
		weighted mean ages combine only a small number of individual ages. This is especially true for ages dating mul
609		tiple late
000		tipic face
		stage events that presumably happened at relatively low temperatures. In such cases only those weighted mean a
610		ges were kept
		whose geologic significance is also indicated by other dating techniques such as fault gouge dating, specifica
611		lly close to the
		Rhone-Simplon line. Otherwise, these ages are included in the overall age range of the sample in question give
612		n in Tab. 2.
		Another reason for a spread out age pattern may be a grain experiencing prolonged phases of low-intensity tect
613		onic activity of30
		multiple small deformation events during exhumation. In which case only small volumes of monazite-(Ce) would r
614		enrecipitate
011		due to disequilibration during deformation. This leads tendentially to unclear crystal constions that make it
C1 E		due to disequilibration during deformation. This feads condentially to uncreal crystal zonations that make it
CI0		difficult to correctly
616		13
617		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
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618 619 620 621		Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c ©Author(s) 2019. CC BY 4.0 License.
618 619 620 621		Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c ©Author(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show
618 619 620 621	611	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c ©Author(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a
618 619 620 621	611	<pre>Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c @Author(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams</pre>
618 619 620 621	611	<pre>Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c @Author(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show</pre>
618 619 620 621	611 612	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C OAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show
618 619 620 621	611 612 613	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208
618 619 620 621	611 612 613 614	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/
618 619 620 621	611 612 613 614 615	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232
618 619 620 621	611 612 613 614 615 616	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages.
618 619 620 621	611 612 613 614 615 616 617	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages.
618 619 620 621	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18
618 619 620 621	611 612 613 614 615 616 617 618	<pre>Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure</pre>
618 619 620 621	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed
618 619 620 621	611 612 613 614 615 616 617 618	<pre>Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and</pre>
618 619 620 621	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade
618 619 620 621 622 623	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor (s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black
618 619 620 621 622 623	611 612 613 614 615 616 617 618	<pre>Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC EY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201</pre>
618 619 620 621 622 623 624 625	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor (s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 205 Pb/ 202 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and
618 619 620 621 622 623 624 625	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate meighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc
618 619 620 621 622 623 624 625 626	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages
618 619 620 621 622 623 624 625 625 626 627	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals.
618 619 620 621 622 623 624 625 625 626 627 628	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C Cauthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Fb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals.
618 619 620 621 622 623 624 625 625 626 627 628 622	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 Pebruary 2019 C Author(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 208 208 207 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergeman et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14
618 619 620 621 622 623 624 625 625 626 627 628 629 622	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 Courthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fever ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Verure ording to the ording to for the ording to the tortion of the tortion of the tortion of the study.
618 619 620 621 622 623 624 625 625 626 627 628 629 630	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 Couthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 PF/ 232 Th ages. 18 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Jancts et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth
618 619 620 621 622 623 624 625 626 625 626 627 628 629 630 631	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C Cuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Fb/ 232 Th ages. 16 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth
618 619 620 621 622 623 624 625 626 627 628 629 630 631 632	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 Couthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 209 Pb/ 209 Pigure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 e
618 619 620 621 621 622 623 624 625 626 627 628 629 630 631 632 633	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 Couthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 208 Pb/ 208 Pb/ 208 Pb/ 208 Pigure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2018 6 Outhor(s) 2019. CC EY 4.0 License.
618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 CAuthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 Pb/ 232 Th ages. 18 Figure  8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shade s indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (2012), The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Author(s) 2019. CC BY 4.0 License.
618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started: 5 February 2018 c Author(s) 2019. CC EY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 206 P6/ 232 Th ages. 14 Figure 8.Time diagram combining identified peaks and weighted mean ages derived from the data displayed in Fig. 1, appendix, and weighted mean average ages. The color intensity indicates the amount of spot ages in this range. Lighter shades i indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (201 2), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region acc ording to the number of ages per 0.5 Ma intervals. 14 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started; 5 February 2018 c Author(s) 2019. CC EY 4.0 License. identify growth rones on ESE images (compare Gnos et al., 2015; Bergemann et al., 2018). As opposed to areas x
618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635	611 612 613 614 615 616 617 618	Manuscript under review for journal Solid Earth Discussion started; 5 February 2018 Coluthor(s) 2019. CC BY 4.0 License. Figure 5.Visualization by sample of all SIMS analyses conducted for this study. Chemical plots that best show the different groups within a sample (left), BSE images(center) with colored ovals representing analysis spots being to scale, age diagrams (right) show 208 208 208 208 209 209 209 209 209 209 209 209 209 209

636		record individual, stronger deformation events that tend to show a sharper zonation (compare Janots et al., 20
		12; Berger et al.,
637		2013; Bergemann et al., 2017, 2019).
638		5.3 Monazite-(Ce) ages and Lepontine history
		Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation occurred over time in differe
639		nt parts of the5
		study region, as it passed through the monazite-(Ce) stability field. The time interval recorded within indivi
640		dual monazite-(Ce)
		crystals spans from 2.5 Ma to 7 Ma for individual grains (Fig. 7, Table??). The recorded time interval within
641		individual grains
		is generally longer in the South and East regions of the study area (Fig. 2). The total age range covers the t
642		ime from ca. 19 to 5
		Ma. The monazite-(Ce) chronologic record can be seen to start in the eastern- and southernmost regions (Fig.
643		9). The recorded
6.4.4		activity then moves to the northeastern and central to the western area. Younger ages in the west progressivel
644		y concentrate only
645		et recorded
010		monazite-(Ce) ages of 19-17 Ma from the eastern edge of the study area (Figs. 7s. 9a) coincide with a phase of
646		rapid exhumation
		and cooling between 22 and 17 Ma (Steck and Hunziker, 1994; Rubatto et al., 2009). At that time, temperatures
647		in parts of
648		the north-western area (northern Ticino Dome) were still prograde at 450-430
	619	Figure
		6.Figure modified from Stecket al.(2013), with cooling ages compiled by Steck and Hunziker (1994), and complet
		ed with data from
		Kelleret al.(2005), Rahn (2005), Elfertet al.(2013) and Bostonet al.(2017). Cleft monazite crystallization age
	620	s of samples from this study,
		located in the vicinity of the cross section (Figs. 1, 2 are shown for comparison. Note that monazite from roc
	621	ks gives T-max, considerably
	622	higher than the crystallization temperature of the hydrothermal cleft/fissure monazite-(Ce) variety.
	623	5 Hydrothermal monazite-(Ce) ages compared to thermochronometry
		Hydrothermal monazite-(Ce) crystallization and alteration occur typically in a temperature window of ca. 350 -
640	624	200
649	620	
000		from allapite dating. After this, temperatures must have decreased to lower temperatures during exhumation, as
651		hydrothermall5
001		monazite-(Ce) crystallization in the north(east)ern area started at around 16 Ma in the Valsertal (sample VAL
652		S, Fig. 7t) and
		then at the southern edge of the Gotthard nappe at 14-15 Ma (Fig. 9b). This may indicate crystallization durin
653		g a deformation
654		phase indicated by 17-14 Ma
	626	C (Gnos
		et al., 2015; Bergemannet al., 2017, 2018) independent of the local cooling rate. In many areas the oldest rec
	627	orded hydrother-
	628	mal monazite-(Ce) ages are predated by
655	629	40
656	630	Ar/
657	631	39
658		Ar biotite ages interpreted as dating recrystallization (Wiederkehr et al., 2009).
650		The monazite-(te) age record for the entire (north)eastern region continues until ca. 13 Ma after which the re
660		the Valsertal where cooling below 180
661		•
662		C is dated at around 12 Ma (zircon U/Th-He; Price et al., 2018). The age range of the20
		Valsertal sample of 16-12 Ma perfectly coincides with hydrothermal cleft monazite-(Ce) ages from within the Go
663		tthard nappe
		of ca. 16-12 Ma (Janots et al., 2012; Ricchi et al., in review), after which monazite activity moved into the
664		Lepontine dome
		south of the Gotthard nappe. Locally within in the dome, in the northern part of the western region, zircon fi
665		ssion track (ZFT)
		ages of 10-9 Ma in the border area of Ticino dome and Gotthard nappe (Janots et al., 2009) are equal to the la
666		st widely recorded
661		

		hydrothermal monazite-(Ce) ages of around 10 Ma. One sample records ages of 9-8 Ma (BLAS1; Fig. 4m) that is in
		agreement25
		with K/Ar fault gouge data of 8.9±0.2 to 7.9±02 Ma close to BLAS1 and SALZ2 (Alp Transit tunnel; Zwingmann et
668		al.,
		2010), as fault gouge ages seem to typically coincide with the end of monazite-(Ce) growth (see below; Bergema
669		nn et al.,
670		2017).
671		While
	632	Ar white mica cooling ages, and are slightly predated by to coincide with ZFT
	633	ages (Gnoset al., 2015; Grand
	634	
	635	Hommeet al., 2016; Bergemannet al., 2017, 2019; Ricchiet al., 2019). This seguence is also5
		found in most parts of the Lepontine Dome as shown for samples located in vicinity of the NE-SW cross section
	636	(Fig. 6), based
	000	on Stecket al. (2013) Moreover it is also well visible in (Fig. 6) that monavite in clefts starts to crysta
	637	llize much later than
	620	renzaite in the metamerphic weeks (data from Könnel and Cyönenfelder 1075 and Destanat al. 2017)
	030	monazite in the metamorphic focks (data from kopper and Grunenferder, 1973, and Bostonet al., 2017).
	620	A comparison of monazite-(ce) crystallization ages with ages obtained with thermochronometers, whose closure t
	639	emper-
		atures depend on the cooling rate, seems to allow the identification of areas experiencing low cooling rates a
	640	t the time of 10
		hydrothermal monazite growth. In such cases, monazite has a larger time window to record tectonic activity, an
	641	d.
672	642	40
673	643	Ar/
674	644	39
675		Ar cleft muscovite ages of 15.60±0.30 to 14.71±0.13 Ma (Rauchenstein-Martinek, 2014) slightly south
		of LUCO1 coincide with the earliest monazite-(Ce) crystallization, this differs markedly from the situation fu
676		rther west or30
		in the Aar and Mont Blanc massifs (Bergemann et al., 2017; 2019). There, as discussed below, ZFT ages predate
677		or mirror
678		primary monazite-(Ce) crystallization and are in turn predated by
	645	Ar
	646	19
	647	
		white mica ages coincide with the beginning of the monazite-(Ce) age record and ZFT ages coincide with or even
	648	postdate
		the youngest found monazite-(Ce) ages. This is the case in (1) the central region of the study area, where the
	649	youngest white
	650	mica cooling ages of 15.1±0.70 to 16.30±0.23 Ma
		(Allazet al., 2011) located west of sample DUTH 2 and south of sample
		LUCO 1 (Fig. 1) coincide with the earliest monazite-(Ce) crystallization dated at ca. 14.3 to 14.7 Ma, and ZFT
	651	ages of 9.7
		+0.5 Ma Ma (Janotset al.2009) coincide with the late phase of monazite-(Ce) age recording around 10 Ma. Also
	652	(2) in the5
		vicinity of sample VANT 6 south of the RSF (Fig. 1) the ZFT ages, ranging from 12 0+2 6 to 7 1+1 6 Ma (Kellere
	653	t al
	654	2005) overlap with the voundest monavite-(Ce) spot ages of around 12 5 to 10 6 Ma. There are no
679	655	An
600	656	
000	050	20
001	100	
682		Ar white mica ages. The coincidence of these ZFT
683		
	658	Ar white mica ages
		in direct vicinity of VANI 6. However, the sample is located in an area that does not show the jump in cooling
	659	ages found
		along the rest of the brittle Rhone-Simplon Fault bordering the Lepontine Dome to the west (Kelleret al., 200
	660	5; Campaniet
		al., 2010). A similar age pattern was also found outside the study area, in (3) the Eastern Alps in Austria, i
	661	n an area affected10
		by Cretaceous Eo-Alpine Barrow-type metamorphism (Bergemannet al., 2018). There, primary monazite-(Ce) mean ag
	662	es of
	663	90.6±1.3 to 89.2±1.8 Ma coincide with
684	664	40
685	665	Ar/

686	666	39
687		Ar
		muscovite cooling ages with the hydrothermal monazite-(Ce) crystallization suggests slow cooling rates during
688		15
689		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
690		Manuscript under review for journal Solid Earth
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693		©Author(s) 2019. CC BY 4.0 License.
694		
		Figure 9.Overview maps of the study area showing the distribution of the monazite-(Ce) age record over time. W
695		eighted mean average ages
		are given near the stars representing the corresponding sample locations. Note the shift over time from the ou
696		ter regions of the Lepontine
697		dome to the internal areas and then to the shear zones bounding its western limit.
698		16
699		Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
700		Manuscript under review for journal Solid Earth
701		Discussion started: 5 February 2019
702		
703		OAuthor(s) 2019. CC BY 4.0 License.
704		
		continued deformation (Bergemann et al., 2018) for the time from around 15 Ma until ca. 9 Ma, as the systems c
705		losed only at
706		the lower end of the closure temperature window in this case.
		To the west, an early phase of accelerated cooling in the area was dated to 18-15 Ma (Steck and Hunziker, 199
707		4; Campani et
		al., 2010), evidence of which is also preserved in the oldest monazite-(Ce) data of 17 Ma (Fig. 7a) from sou
708		th of the Rhone-
		Simplon Fault (RSF). Zircon fission track ages of 14-11 Ma (Hurford, 1986) and cleft adularia ages between 12.
709		92±0.17 Ma5
		and 10.82±0.12 Ma (Rauchenstein-Martinek, 2014) from south of the western Gotthard slightly predate to coincid
710		e with a
		later phase cooling and increased tectonic activity in the western Lepontine area. Primary monazite-(Ce) cryst
711		allization in parts
		of the northwestern and central Lepontine as well as the central Aar massif occurs at around 12 Ma, followed b
/12		y monazite-
710		(Ce) crystallization in the westernmost area around II-10 Ma dating exhumation (Fig. 9 c,d). Multiple monazite
/13		- (ce) samples
714		are related to 10
/ 1 4		are related tolo
715		processes during backtolding of the northern steep beit (in the sense of Milnes 1974), dating it to ca. 10 Ma
716		1024. Stock and Wynriker, 1004. Company et al. 2014)
110		The 12-10 Ma cooling phase of the western Lepentine was related to detachment mewements along the Phase-Simple
717		The 12-10 Ma cooting phase of the western repontine was related to detachment movements atong the knone-simplo
/ _ /		" Rault This time interval marks the end of the hydrothermal monagite-(Ce) age record in the han
718		ging well of the Phone-
/ 10		Simplon Fault Correspondingly 12-10 Ma also marks the beginning of monazite-(Ce) crystallization to the east
719		of the fault 15
110		first in the vicinity of the Mar massif (Figs $7  c$ d i) and then also further south (Fig. 7k). Primary monar
720		ite-(Ce) crystallization
120		ages along the eastern side of the RSE are tendentially predating, but still in close agreement with zircon fi
721		ssion track ages in
121		this area. In the case of sample VANI6 from south of the RSF (Fig. 7a) ZFT ages of this area show a scatter fr
722		om 12 to 7 Ma
		(Keller et al., 2005) that overlap with the voungest monazite-(Ce) age spots. Monazite-(Ce) ages of 9-7.5 Ma i
723		ndicate continued
-		exhumation of the western region and the central areas leave the hydrothermal monazite-(Ce) stability field at
724		this time (Fig.20
		9f). The number of weighted mean ages (i.e. clear age patterns within the crystals) staggered over a relativel
725		y short time (Fig.
		8), suggest deformation pulses during brittle tectonics along the Rhone-Simplon/Centovalli Faults and corrobor
726		ates evidence
727		

		of continued deformation along the southern RSF and the Centovalli Fault (Zwingmann and Mancktelow, 2004; Sura
		ce et al.,
		2011). The youngest widely recorded monazite-(Ce) age group for the western Lepontine dates to around 7 Ma (Fi
728		gs. 7 b, d, j-1;
		9f). This coincides with young fault gouge data of 8-6 in this region (Zwingmann and Mancktelow, 2004, Surace
729		et al., 2011)25
		Overall, the 10-7 Ma time interval is characterized by phases of strike-slip deformation along the extended Rh
730		one-Simplon
		fault system. This is recorded through hydrothermal monazite-(Ce) and fault gouge illite crystallization that
731		was not restricted
		to the south-western Lepontine but also recorded in faults bounding the Mont Blanc massif (Bergemann et al., 2
732		019). The ages
		of 8-7 Ma of the sample with the youngest recorded age (VANI5) among the studied monazites-(Ce) are concurrent
733		with the
		youngest recorded ages of all other samples along the Rhone-Simplon fault system. The sample comes from an are
734		a where30
		hydrothermal gold mineralization occurred and the youngest age group of VANI5 give a weighted mean age of 5.53
735		±0.60
736		Ma that coincides with ZFT ages of 6.4-5.5 Ma (Keller et al., 2005). The area also has a muscovite
	667	Ar white mica ages of 88.4±0.4 to 84.3±0.7 Ma (Dallmeyeret al., 1996)
		and the youngest monazite spot ages of around 70 Ma coincide with ZFT ages that show a considerable spread of
	668	ca./0-50 Ma
	6.60	(Kurzet al., 2011; van Gelderet al., 2015). The three areas have in common that exhumation/cooling rates were
	669	low (Stecket
	670	al., 2013; Fugenschunet al., 2000) during the time of hydrothermal monazite-(te) crystallization.15
	671	d at the lower
	071	a at the lower
	672	end of their respective temperature windows, while monazite-(te) crystarrization presumably occurred during th
	673	
	070	C temperature window (Gnoset al., 2015: Bergemannet al., 2017, 2018) This may indicate that the coincidence of
	674	f
	0,1	
737	675	40
737 738	675 676	40 Ar/
737 738 739	675 676 677	40 Ar/ 39
737 738 739 740	675 676 677	40 Ar/ 39 Ar age of 10.56
737 738 739 740	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp
737 738 739 740 741	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al.,
737 738 739 740 741	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar
737 738 739 740 741 742	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea.
737 738 739 740 741 742 743	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17
737 738 739 740 741 742 743 744	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
737 738 739 740 741 742 743 744 745	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth
737 738 739 740 741 742 743 744 745 746	675 676 677	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019
737 738 739 740 741 742 743 744 745 746 747	675 676 677	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 677	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Ar
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Ar
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 678	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679	40 Ar/ 39 Ar age of 10.56 ±0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c OAuthor(s) 2019. CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 678 679 680	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite- (Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Cauthor(s) 2019. CC EY 4.0 License. Ar white mica ages with the beginning of monazite- (Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite- (Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 678 679 680 681	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Cauthor(s) 2019. CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution
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737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683	40 Ar/ 39 Ar age of 10.56 10.11 MA (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 MA (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite- (Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Cauthor(s) 2019. CC EY 4.0 License. Ar White mica ages with the beginning of monazite- (Ce) crystallization and 2FT ages overlapping with the latest h ydrothermal monazite- (Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite- (Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite- (Ce) crystallization and dissolution-reprecipitation varied in space and time in t he study region as it passed through the monazite- (Ce) crystallization recording window. The growth duration recorded by the s pot age range
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683	40 Ar/ 39 47 age of 10.56 ±0.31 Ma (Pettk et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C CAuthor(s) 2019. CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation varied in space and time in t he study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystall spans from 2.5 Ma to 7 Myr (Table 2, Fig. 5). The total age range of the study region and the study region and the study region and the study region and the substantion for the growth duration recorded by the s pot age range
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683 684	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2018 Cauthor(s) 2019. CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and 2FT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation varied in space and time in t he study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization 7 Myr (Table 2, Fig. 5). The total age range of all grains covers
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683 684 685	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Cauthor(s) 2019. CC BY 4.0 License. Ar White mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation varied in space and time in t he study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization space from 2.5 Ma to 7 Myr (Table 2, Fig. 5). The total age range of all grains covers the time fromca.19 to 2.7 Ma.25
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683 684 684	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 c Author(s) 2019. CC BY 4.0 License. Ar White mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation varied in space and time in t he study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystals spans from 2.5 Ma to 7 Myr (Table 2, Fig. 5). The total age range of all grains covers the time fromca.19 to 2.7 Ma.25 The monazite-(Ce) age record starts in the eastern region (Fig. 1) of the study area at the edges of the Lepon
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683 684 685 686	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 6 Cauthor(s) 2019. CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite-(Ce) crystallization and discolution-reprecipitation varied in space and time in t he study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystalls spans from 2.5 Ma to 7 Myr (Table 2, Fig. 5). The total age range of all grains covers the time fromca.19 to 2.7 Ma.25 The monazite-(Ce) age range store the eastern region (Fig. 1) of the study area at the edges of the Lepon tine Dome (Fig.
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683 684 685 686	40 Ar/ 39 Ar age of 10.56 t0.31 Ma (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar a. 17 Solid Earth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 d Mountor(s) 2019. CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation varied in space and time in t he study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) age record starts in the eastern region (Fig. 1) of the study ar
737 738 739 740 741 742 743 744 745 746 747 748	675 677 677 677 680 681 682 683 684 685 686 686 687	40 Ar/ 39 Ar age of 10.56 C.J.M (Pettke et al., 1999) that postdates other white mica ages of the area by 4-5 Ma (see summary in Camp ani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same ar ea. 7 Bolid Barth Discuss., https://doi.org/10.5194/se-2019-10 Manuscript under review for journal Solid Earth Discussion started: 5 February 2019 C. Author(s) 2019, CC BY 4.0 License. Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest h ydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tect onic activity.20 6 Monazite-(Ce) ages and late Lepontine Dome evolution Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation varied in space and time in t he study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) crystallization recording window. The growth duration recorded by the s pot age range within individual monazite-(Ce) age record starts in the eastern region (Fig. 1) of the study area at the edges of the Lepon time Dome (Fig. 7a), with the earliest ages around 19 Ma (sample TAME 1; Figs. 4, 5s), slightly postdated by sample VALS some hat to the
737 738 739 740 741 742 743 744 745 746 747 748	675 676 677 678 679 680 681 682 683 684 685 685 686 687	40 Ar/ 39 Ar age of 10.56 At age of 10.57 At a

689	around 14.7 - 14.3 Ma. The parallel monazite-(Ce) age record for the central and eastern regions continues unt
	ilca.12.5 Ma
	after which it ends in the east, with the exception of isolated spot ages of~8.3 Ma in the east (TAMB 1) and
690	7.8 Ma in the30
	center (BLAS 1). The western area (Fig. 1) has a more heterogeneous age record with starting dates being diach
691	ronous within
	the area from east to west/south-west (Figs. 7b-e). The oldest ages are around 13.6 Ma (KLEM 2) with the area
692	in which ages
	are recorded progressively spreading west, until by ca. 10 Ma most samples from the western region record age
693	s. After this,
694	20
695	
	the age record ends first in the central region and then the easternmost western region atca.9.5 Ma. The recor
696	d continues in
	most of the western region (Fig. 7e), until it becomes progressively more localized by~7.5 towards the west an
697	d the vicinity
	of the Rhone-Simplon Fault system (Fig. 7f). The youngest widely recorded monazite-(Ce) age group for this are
698	a dates to
	around 7 Ma (Fig. 7f), and only one sample (VANI 5) records ages down to around 5 Ma, with a single spot age o
699	f~2.7
	Ma. The southern region (Fig. 1) at the very edge of the Lepontine Dome, separated from most of the Western re
700	aion by the5
	Rhone-Simplon Fault, shows a similar age range as the eastern region. As in the east, the monazite-(Ce) age re-
701	cord starts early
702	at call 6 8 Maland continues somewhat further down to around 10 6 Ma (Fig. 5a-d)
102	Overall the monazite-(Ce) chronologic record shows a clear east-west trend without large age jumps within the
703	Iopontino
105	Depondence.
704	bome. The record starts in the eastern- (and southern) parts of the study area, with the activity then moving
704	through the central
705	to the western area, where it progressively concentrates on the large fault systems in the west of the Leponti
/05	ne Dome.iu
700	The oldest recorded monazite-(ce) ages were found in the eastern area (TAMB 1; Fig. 1) and fail into two group
706	s, around
	19 Ma and a mean age at 17.49±0.4 Ma (Figs. 4, Tab. 2), during which time the area around TAMB I experienced a
/0/	time
	of rapid exhumation and cooling (Steck and Hunziker, 1994). The nearby Forcola Fault (Fig. 1) was estimated to
708	have been
	active sometime around 25-18 Ma on the basis of Rb-Sr and K-Ar cooling ages (Meyreet al., 1998). In this conte
709	xt, the
	monazite-(Ce) ages would date the final deformation phases of such normal faults as the Forcola Fault. Notabl
710	y, these faults,15
	and possibly the Forcoloa Fault itself, may have been active far longer, as suggested by monazite-(Ce) ages do
711	wn to~8.3 Ma
	(Figs. 5s, Tab. 2). The youngest ages even postdate apatite fission track ages (AFT; Fig. 6), which may have b
712	een facilitated by
	the late circulation of hot fluids, something which could be shown for hydrothermal monazite-(Ce) of the Lauzi
713	ere and Mont
	Blanc Massifs (Janotset al., 2019; Bergemannet al., 2019). North of TAMB 1, the sample VALS age record starts
714	slightly
715	later at~16.5 Ma that then runs parallel to that of TAMB 1 (Figs. 5s, t).20
	In the central area close to the sample locations, temperatures were still prograde up until the time of 19-18
716	Ma at 450-430
717	•
718	c
	(Janotset al., 2009) as deduced from allanite dating. After this time, conditions must have decreased to lower
719	temperatures
	during exhumation, as the hydrothermal monazite-(Ce) age record started after around 16-15 Ma in the Gotthard
720	Nappe and
	eastern Lepontine Dome (Fig. 7b) and continued to later than~13 Ma (Fig. 7c). After this time the age record r
721	eceded from
722	the eastern region, which cooled below 180
723	•
724	C around 12 Ma (e.g. Priceet al., 2018, zircon U/Th-He), and the Gotthard Nappe25
	west- and southwards into the Lepontine Dome. This would date the decoupling of the Gotthard Nappe which exper
725	ienced a

	726	rapid exhumation due to steepening during backfolding (Wiederkehret al., 2009; Ricchiet al., 2019) from the Le
		pontine Dome
		toca.13-12 Ma, as the samples of the central area south of the Gotthard Nappe show a continued widespread age
	727	record down
		to~9 Ma (Fig. 7d). During this time interval (Fig. 7c) primary monazite-(Ce) crystallizes also along the rest
	728	of the extended
	729	Rhone-Simplon Fault system (Grand
	730	
	731	Hommeet al., 2016; Bergemannet al., 2017, 2019; Ricchiet al., 2019). Where it dates30
		in some areas a switch from thrusting/transtensional movements to pure strike-slip deformation through the for
	732	mation of a new
		cleft generation with a different orientation associated with strong hydrothermal fluid activity (Bergemannet
	733	al., 2017, 2019;
		Janotset al., 2019). Since in the study area clefts outside the Gotthard Nappe, where they are horizontal, are
	/34	vertical whether
		they formed during extension or later strike-slip deformation, such a switch in deformation style cannot be pr
	735	oven. But it might
	/36	21
	131	
	700	Figure 7.0verview maps of the study area showing the monazite-(Ce) age record over time and space. Note the sh
	/38	lit over time from the
	7 2 0	southern and eastern regions of the Lepontine Dome to the central and Western areas and finally to the areas c
	/39	lose to the shear zones bounding
	740	its western limit. Weighted mean ages, quoted hear the stars representing the corresponding sample locations,
	/40	indicate individual deformation
	7 / 1	events that could be identified for a grain within a given time interval. Published hydrothermal monazite-(te)
	741	recations (grey stars) of the
	742	areas aujacent to the bepontine bome are from banotset ar.(2012), bergeret ar.(2013) and kitchiet ar.(2013).
749	744	
750		6 Conclusions
		Hydrothermal fissure monazite-(Ce) always dates crystallization and not cooling due to system closure and ofte
751		n shows com-
		plex recrystallization features. It provides an important record of the shifting tectonic activity
752		associated with the regions
		exhumation history within the monazite stability field. A comparison between hydrothermal monazite-(Ce) sample
753		s from dif-
		ferent parts of the Lepontine metamorphic dome shows that age clusters within individual crystals from a simpl
754		y exhuming area5
		have a less clear age distribution than samples from fault zone areas, or fast exhuming areas. Monazite-(Ce)
755		(re)crystallization/
756		dissolution-reprecipitation during exhumation is in these areas connected to
		repeated tectonic activity of small intensity, while
		distinct events or short periods of intense tectonic activity of fault zones appear to result in larger, more
757		homogenous crystal
758		zones that are easier to date.
759		The
		explain the progressive restriction of the monazite-(Ce) age record areas to samples from the vicinity of majo
	745	r fault zones in
	746	the western Lepontine Dome (Figs. 7d-f).
		11 Ma (Fig. 7d) marks the end of the hydrothermal monazite-(Ce) age record in the hanging wall of the Rhone-Si
	747	mplon
		Fault (southern region, Fig. 1) which had continued since~16.8 Ma, largely parallel to that in the eastern reg
	748	ion (Figs. 7a-d).
		At the same time, 11-10 Ma also marks the beginning of monazite-(Ce) crystallization in the foot wall of the R
	749	hone-Simplon5
		Fault ((Figs. 1, 7d). The primary monazite-(Ce) crystallization ages of the western area tend to postdate, but
	750	are still in close
		agreement with zircon fission track ages (Fig. 6). Samples of the western region often yield well constrained
	751	weighted mean
		ages (Fig. 5), which might suggest a dominance of strong individual tectonic events. This in mind, weighted me
	752	an ages in the
		western zone (Fig. 4) may suggest deformation during brittle tectonics along the extended Rhone-Simplon Fault
	753	system.
	154	

		The mean age group around 12 Ma, found in the eastern part of the western zone (Figs. 4, 7c) is related to the exhumed10
		deeper part of the Simplon Fault (Hartel and Herwegh 2012), whereas the younger ages are more close to the loc
	755	alized and
		late Simplon Fault. The 12 Ma age also falls together with the switch in deformational style elsewhere in the
	756	Western Alps
		- discussed above, and is followed by a group from~10-7 Ma (Figs. 4, 7d). These two age groups are also recorded
	757	in the
		central Lepontine (sample DUTH 6; Fig. 5e). After 10 Ma, the weighted mean ages show a spread down toca.7 Ma b
	758	ut
	759	are progressively restricted to the westernmost areas close to
		the fault zones (Figs. 4, 7e, f). The ages likely mark phases of15
		tectonic activity and corroborate evidence of continuing deformation along the Rhone-Simplon Fault (e.g. Zwing
	760	mann and
		Mancktelow, 2004; Campaniet al., 2010; Suraceet al., 2011). Only one sample in this group (VANI 5; Fig. 7f) yi
	761	elds ages
		younger thanca.7 Ma, with a weighted mean age around 5.5 Ma and a spot age of $\sim$ 2.7 Ma (Fig. 5m). The sample com
	762	es
		from an area where strong late-stage hydrothermal activity occurred, and the $\sim 5.5$ Ma age coincides with ZFT age
	763	s of 6.4-5.4
		Ma that are younger than those found in most of the region (Kelleret al., 2006). This coincidence of ages youn
	764	ger than in20
		the surrounding areas may indicate a resetting of the ZFT ages through the hydrothermal activity. These phases
	765	of strike-slip
	766	deformation are not local to the western Lepontine Dome, but seem to have affected the extended Rhone-Simplon
	766	Fault system
	769	,
	769	Hommeet al 2016, Bergemannet al 2017 2019, Bicchiet al
	770	2019)
	771	7 Summary25
		Hydrothermal fissure monazite-(Ce) offers the possibility to date tectonic activity in the brittle
	772	domain for extended time
		periods, as it could be shown to provide a record of the shifting tectonic activity within the Lepontine Dome
	773	associated with
		the regionsal exhumation history. A comparison between hydrothermal monazite-(Ce) samples from diff
	774	erent parts of the
		Lepontine Dome and thermo-chronometric data suggest that hydrothermal monazite-(Ce) dating might be used to id
	775	entify
	776	areas of slow exhumation/cooling rates during ongoing tectonic activity. The
760	777	232
761	778	Th-
762	779	208
763		Pb monazite-(Ce) crystallization data records prolonged hydrothermal activity between 19 and 5 Ma con-10
764		tribute to the understanding of the tectonic evolution of the Central Alps in a temperature range of ca.
	700	SSU-200
	700	records prolonged hydrothermal activity betweenel9 and 2.7 May and contribute
	101	to the understanding of the tectonic evolution
	782	of the Central Alps in a temperature range of roughly 350-200
765	783	o
766		C. The oldest
		ages of 19-17 Ma come from the eastern- and southernmost regions of the study area (Fig. 1), in the hanging w
767		all of the For-
		cola and Rhone-Simplon faults defining the borders of the metamorphic dome. Within the dome, monazite-(Ce) cry
768		stallization
769		started in the
		northern Ticino dome and eastern Gotthard nappe around 15 Ma and show signs of slow exhumation. Further
770		west, in the Toce dome, primary crystallization occurred in the
		western Gotthard nappe and the central Aar massif at 12-1015
771		Ma. Younger ages of 9-7 Ma in the west of the study area record the progressive concentration of
		tectonic activity along the
172	704	large fault systems of the Rhone-Simplon Fault and the Rhine-Rhone Line.
	785	c. The monazice-(ce) age record revears a relatively smooth

		east-west age trend within the Lepontine Dome. The record starts in the eastern- (and southern) parts of the s
		tudy area, with
	786	23
	787	
		Figure 8.Backscatter electron image of monazite-(Nd) co-type material sample GRAESER 4 with the ovals represen
	788	ting the two measure-
	789	ment spots that yielded a Th-Pb age to scale.
		the recorded activity then moving through the central to the western area, where it progressively concentrates
	790	on the large fault
		systems of the western Lepontine Dome. The oldest ages of $\sim 19-17$ Ma come from the eastern- and southernmost reg
	791	ions
	792	of the study area in the banging wall of the Forcela and Phone-Simplon normal faults. Within
	192	the dome monazite-(Ca)
	703	ervetallization started in the
	, 55	eastern Lenontine Dome as well as the eastern Cotthard Name around 16-15 Ma. Further west
	791	primary crystallization occurred in the western Cotthard name at 13-10
	, , , ,	Ma. Younger ages of $9-7$ Ma in the west of the study 5
	795	area record the progressive restriction of the recorded tectonic activity
	, 55	to the extended Phone-Simpler Foult system
772	706	Competing interests No competing interests are present
115	190	competing interests we competing interests are present.
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		Vanini, and M. Walter in20
776		organizing monazite-(Ce) samples for this study.
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