- 923 Removals + 968 Additions

Constraining metamorphic dome exhumation and fault activity
through hydrothermal monazite-(Ce)

Dating exhumation and fault activity of the Lepontine Dome and
Rhone-Simplon Fault regions through hydrothermal monazite-(Ce)

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Abstract.Zoned monazite-(Ce) from Alpine fissures/clefts is used to gain new insights into the exhumation history of the
Central Alpine Lepontine metamorphic dome, and timing of deformation along the Rhone-Simplon fault zone on the dome's

Abstract.Zoned hydrothermal monazite-(Ce) from
fissures/clefts is used to gain new insights into the exhumation history
of the Lepontine Dome in the Central Alps, and timing of deformation along the Rhone-Simplon Fault zone on the dome's

western termination. These hydrothermal monazites-(Ce) directly date deformation and changes in physiochemical conditions

through crystallization
ages, in contrast to commonly employed cooling-based methods. The 480 SIMS measurement ages
from 20 individual crystals record ages over a time interval between 19 and 5
Ma, with individual grains recording ages over a5
lifetime of 2 to 7.5 Ma. The
age range combined with age distribution and internal crystal structure help to distinguish between
areas whose deformational history was dominated by distinct tectonic events or continuous exhumation. The comb
ination of
this age data with geometrical considerations and spatial distribution give a more precise exhumation/cooling history for the
area. In the east and south of the study region, the units underwent monazite-(Ce)
growth at 19-12.5 and 16.5-10.5 Ma, followed
by a central group of monazite-(Ce) ages at 15-10 Ma and the movements and related cleft monazites-(Ce) are youngest at the10
western border with 13-7 Ma. A last phase around 8-7 Ma is limited to clefts of
the Simplon normal fault and related strike
slip faults as the Rhone and Rhine-Rhone faults. The large data-set
spread over significant metamorphic structures shows that
the opening of clefts, fluid flow and monazite-(Ce) stability is direct linked to the geodynamic evolution in space and time.

1 Introduction
Metamorphic domes like the Lepontine area of the Central Alps often experienced a complex tectono-metamorphic evolution.15
In this case an interplay between exhumation and deformation during doming and activity of

large fault systems that dominate
the western parts of the area. Although much of the (thermo)chronological history of the area is well known, hydrothermal
monazite-(Ce) ages complement existing cooling ages of
zircon fission track, Rb-Sr in biotite and apatite fission track/apatite
U-Th/He by providing crystallization and dissolution-precipitation ages that date low-T tectonic evolution.
through crystallization
ages. 480 SIMS spot analyses from 20 individual crystals, including co-type material of the monazite-
(Nd) type locality, record ages over a time interval of~19 and 2.7 Ma, with individual grains recording
age ranges of 2 to5
7.5 Myr. The combination of
this age data with geometrical considerations and spatial distribution give a more precise young
exhumation history for the area. In the north-east and south-west of the Lepontine Dome, units
underwent monazite-(Ce)
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.
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
fissures/clefts associated with the Simplon normal fault and related strike-slip faults such as the Rhone
Fault. The large data-set10
spread over significant metamorphic structures shows that the fissure mineral crystal-rock interaction,
fluid flow and monazite-
(Ce) stability are directly linked to the Lepontine Dome's evolution in space and
time. A comparison between hydrothermal
monazite-(Ce) thermo-chronometric data suggests that hydrothermal monazite-(Ce) dating could allow to identify
areas of
slow exhumation/cooling rates during ongoing tectonic activity.

1 Introduction15

Metamorphic domes often experience a complex tectono-metamorphic
evolution (e.g.Schmidt al., 2004; Stecket al., 2013).
For the Lepontine Dome of the European Alps, this evolution is
an interplay between exhumation and deformation during
doming and motion along large fault systems that dominate the western regions of the dome.
Although much of the retrograde
orogenic evolution of the area is well known, hydrothermal
monazite-(Ce) ages complement existing cooling ages of thermo-
chronometers by providing crystallization and dissolution-precipitation ages that directly
date low-T tectonic activity.20
Monazite, (LREE,Th,U)PO
4
, is considered an excellent mineral for dating of geologic processes (e.g., Parrish, 1990) that is20
highly resistant to radiation damage (e.g., Meldrum et 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 crystallization. It
, is considered an excellent mineral for the dating of geologic processes (e.g.Parrish, 1990).
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1
Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
Manuscript under review for journal Solid Earth
Discussion started: 5 February 2019

can experience dissolution-recrystallization, thereby recording new ages through mediation of hydrous fluids
(e.g., Seydoux-
Guillaume et al., 2012; Janots et al., 2012; Grand
(Cherniaket al., 2004; Cherniak and Pyle, 2008). Nonetheless, monazite remains reactive after crystallization,
as it can expe-
rience dissolution-recrystallization facilitated through hydrous fluids (e.g.Seydoux-Guillaumeet al., 2012; Ja
notset al., 2012;
Grand
'
Homme et al., 2016).

Alpine fissures and clefts occasionally containing monazite-(Ce) are voids partially filled by crystals that crystallized on the cleft walls from hydrous fluids during late stage Alpine metamorphism (Mullis et al., 1994; Mullis, 1996). Dating such mineralization is often difficult due to later overprinting along with multiple stages of fluid activity (Purdy and Stalder, 1973).

Alpine fissures in some metasediments and metagranitoids have long been known to contain well-developed monazite-(Ce) crystals (Niggli et al., 1940), but it is only recently that some of these could be dated (Gasquet et al., 2010; Janots et al., 2012). Although other minerals like micas and adularia are common in alpine fissures, they are often affected by overpres-sure/excess argon, (e.g., Purdy and Stalder, 1973), and it is not always clear if these ages represent crystallization or cooling (e.g., Rauchenstein-Martinek, 2014). The Alpine fissures and clefts in the Lepontine region formed after the metamorphic peak, in relation to extensional tectonic activity. In accordance with this tectonic activity, fissures and clefts are oriented roughly per-pendicular to lineation and foliation of the host rock. The fluid that intruded during fissure formation (300-500 $^\circ$C; Mullis et al., 1994; Mullis, 1996) interacts with the wall rock. This triggered dissolution and precipitation of minerals in both host rock and fissure, causing the formation of a porous alteration halo in the surrounding wall rock. Complex growth domains are common in hydrothermal monazites-(Ce) from such fissures showing both, dissolution and secondary growth (e.g., Janots et al., 2012) as well as dissolution-reprecipitation reactions resulting in patchy grains (e.g., Gnos et al., 2015). In contrast to metamorphic rocks, where monazite-(Ce) rarely exceeds 100µm, cleft monazite-(Ce) is commonly mm-sized with large individual growth domains. This permits to date individual domains precisely by using SIMS (secondary ion mass spectrometry) and even resolve growth duration (Janots et al., 2012; Berger et al., 2013; Bergemann et al., 2017, 2018, 2019).

2 Geological setting

2.1 Evolution of the study area

The formation of the nappe stack of the Alps caused by the collision of the European and Adriatic plates was followed by the development of several metamorphic domes (Tauern and Rechnitz in Austria, and Lepontine in the western Alps; e.g. Schmid et al., 2004). Their formation was related to crustal shortening associated with coeval orogen parallel extension (e.g., Mancktelow, 1992; Ratschbacher et al., 1991; Ratschbacher et al., 1989; Steck and Hunziker, 1994). The Western and Central 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 Alps is dated at 75-65 Ma (e.g.Ruffet et al., 1997; Duchêne et al., 1997; Rubatto et al., 1998). This was followed by underthrusting and nappe stacking from ca. 42 Ma on during continental collision linked with a transition from high-P to high-T metamorphism (e.g. Köppel and Grünenfelder, 1975; Markleyet al., 1998; Herwartz et al., 2011; Boston et al., 2017). Peak metamorphic conditions in the Lepontine area in excess of 650

Hommeet al., 2016).

Fissures and clefts occasionally contain hydrothermal monazite-(Ce). They represent voids partially filled by crystals that precipitated on the fissure walls from hydrous fluids during late stage metamorphism (Mulliset al., 1994; Mullis, 1996).

Dating such mineralization is often difficult due to later overprinting along with multiple stages of fluid activity (Purdy and

Stalder, 1973). Fissures and clefts in some metasediments and metagranitoids have long been known to contain well-developed monazite-(Ce) crystals (Niggliet al., 1940), but it is only recently that some of these were dated (e.g.Gasquetet al., 2010; Janotset al., 2012). Although other minerals like micas and adularia are common in alpine fissures, they are often affected by overpressure/excess argon, (e.g., Purdy and Stalder, 1973), and it is not always clear if these ages represent crystallization or cooling (e.g., Rauchenstein-Martinek, 2014). The fissures and clefts in the Lepontine region formed after the metamorphic peak, in relation to extensional tectonic activity. Accordingly, fissures and clefts are oriented roughly perpendicular to the lineation and foliation of the host rock. The fluid that intruded during fissure formation (300-500 $^{\circ}$

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 (von Blanckenburg et al., 1991; Romer et al., 1996; Schärer et al., 1996; Oberli et al., 2004; Rubatto et al. 2009; Janots et al., 2009). Prograde metamorphism

C; Mulliset al., 1994; Mullis, 1996) interacted with the wall rock. This triggered dissolution and precipitation of minerals in both host rock and fissure, leading to the formation of a porous alteration halo in the surrounding wall rock. Complex growth domains are common in hydrothermal monazite-(Ce) from such fissures showing both, dissolution and secondary growth (e.g.Janotset al., 2012; Bergemannet al., 2017, 2018), as well as dissolution-reprecipitation reactions resulting in patchy grains (e.g.Gnoset al., 2015). In contrast to metamorphic rocks, where monazite-(Ce) rarely exceeds 100μm, fissure monazite-(Ce) is commonly mm-sized, with large individual growth domains. This permits dating individual domains precisely by using secondary ion mass spectrometry (SIMS), resolve growth duration and identify phases and single events of tectonic activity (e.g.Janotset al., 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 tectonic evolution of the Lepontine Dome.

2 Geological setting

2.1 Evolution of the study area

The formation of the nappe stack of the European Alps caused by the collision of the European and Adriatic plates was followed by the development of several metamorphic areas (Tauern, Rechnitz in the Eastern Alps, and Lepontine in the Central Alps;e.g. Schmidet al., 2004). Their formation was related to crustal shortening associated with coeval orogen-parallel extension (e.g. Mancktelow, 1992; Ratschbacheret al., 1989; Ratschbacheret al., 1991). The Western and Central Alps with the Lepontine 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 Alps is dated at 75-65 Ma (e.g.Ruffetet al., 1997; Rubattoet al., 1998; Regiset al., 2014). This was followed by underthrusting and nappe stacking fromca.42 Ma on during continental collision linked with a transition from high-P/low-T to barrow type

Solid Earth Discuss., https://doi.org/10.5194/se-2019-10
Manuscript under review for journal Solid Earth
Discussion started: 5 February 2019

was followed by staggered exhumation in the Ticino and Toce culminations of the Lepontine dome. Accelerated cooling below

500

Figure 1. Map of the Lepontine Dome, modified from Steck et al. (2013) and Schmid et al. (2004). Colored areas mark the areal division in the context of this study.

metamorphism (medium P/T; e.g. Köppel and Grünenfelder, 1975; Markley et al., 1998; Herwartz et al., 2011; Boston et al., 2017). Peak metamorphic conditions in the Lepontine area (in excess of 650 °C in some regions) were reached diachronously from south to north around 30-19 Ma (e.g. Schärer et al., 1996). Barrovian metamorphism was followed by exhumation starting in the east and migrating to the west of the Lepontine Dome, with vertical displacement along the Insubric Line starting as early as 30 Ma (e.g. Hurford, 1986; Steck and Hunziker, 1994). Accelerated cooling below 500 °C occurred at 26 Ma first in the central Lepontine (Hurford, 1986). This was followed in the east by a period of rapid cooling of the Ticino dome between 22 and 17 Ma (Steck and Hunziker, 1994; Rubatto et al., 2009) after which exhumation 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 Fault (Steck and Hunziker, 1994; Campani et al., 2014).

While most of the Lepontine area is marked by doming and associated deformation events, the western and southwestern limits of the study area are dominated by the Rhone-Simplon Fault system, its extensions to the Rhine-Rhone Line to the north along the Aar massif and the Centovalli Fault to the south. The extensional Simplon Fault zone (SFZ) was already active during thrusting in the external alpine domain (e.g., Grosjean et al., 2004), with transpressional movements in the hanging wall of the dextral ductile Simplon shear zone occurring from ca. 32 Ma on (Steck, 2008). 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 Area

The study area comprises roughly half of the Lepontine metamorphic dome (Fig. 2), from the Tambo nappe, east of the Forcola fault, over the central Lepontine dome to the Val d'Ossola, south of the Centovalli Fault, and the southern Gotthard 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; Bergemann 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 east of the Forcola Fault (East; 2 samples), (2) the central Ticino dome and southern Gotthard nappe (Center; 7 samples), (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.

3 Analytical techniques

Monazites-(Ce) were individually polished to the level of a central cross section and assembled in mounts of several grains. Backscatter electron (BSE) images were then obtained. Secondary ion mass spectrometry (SIMS) spot analyses (Fig. 4) were placed according to compositional domains visible in these images in order to capture the crystallization history. As far as possible, the placement of measurement spots located near cracks or holes was avoided, as the Th-Pb isotope system may be disturbed in these areas (Janots et al., 2012; Berger et al., 2013).

C first occurred at~26 Ma in the central Lepontine Dome (Hurford, 1986). This was followed in the eastern Lepontine Dome and along the Insubric Line between 22 and 17 Ma by a period of rapid cooling (Steck and Hunziker, 1994; Rubattoet al., 2009) after which exhumation slowed down. The area to the west in the surrounding of the Rhone-Simplon Line experienced phases of accelerated cooling somewhat later at 18-15 Ma and 12-10 Ma (Campaniet al., 2014). The western and southwestern limits of the study area are dominated by the Rhone-Simplon Fault system, its extensions to the Rhine-Rhone Line to the north along the Aar Massif and the Centovalli Fault to the south (Fig. 1). The extensional Simplon Fault zone (SFZ) was active contemporaneous with thrusting in the external Alpine domain (e.g., Grosjeanet al., 2004). The ductile-brittle transition of the SFZ was constrained to the time between 14.5 and 10 Ma (Campaniet al., 2010). Brittle deformation of the SFZ and Centovalli Fault continued after this (Zwingmann and Mancktelow, 2004; Suraceet al., 2011), with the youngest displacement activity dated toca.5-3 Ma (Campaniet al., 2010).

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3000
2000
1000
0
[m]
NW
SE
(c)
Bett11
Klem1
Klem3
Gr aeser1
Gr aeser3
Klem2
3000
2000
1000
0
[m]
N
(d)
Luc o1
Salz2
Duth3
Blas1
Duth2
S
2000
1000
0
[m]
Vals
Tamb
Forcola Fault

Tambo
Adula
(e)
SWNE
SN
Verampio
Antigorio
Antigorio
Monte Rosa
Simplon Line
0
[m]
2000
Vani5
Vani4
Duro1,2
Schiess1
Vani6
(b)
K
D
D
Luo 1
Klem 1
Vani 4
Vani 5
Graeser 3
Klem 2
Bett 11
Schiess 1
Duro 1,2
Graeser 1
Vani 6
lem 3
uth 3
uth 2
c
Vals
Tamb1
Salz 2
Blas 1
(b)
(c)
(d)
(e)
Mzt
Group 1: 17-15 Ma
Group 2: 14-11 Ma
Group 3: 10-7 Ma
External massif
Gotthard cover
Gotthard crystalline
European crystalline
European cover
Briançonnais crystalline
Piemont-Liguria
Valais crystalline
Adriatic cover
Southalpine
Valais cover
Valais crystalline
Briançonnais cover
(a)

Figure 1.Geological-geometric situation of the study area. (a) Tectonic sketch map modified after Steck et al. (2013) and Schmid et al.

(2004); (b) Tectonic section over the Simplon Fault zone into the western Lepontine, based on Campani et al. (2014); (c) Tectonic section through the western Northern Steep Belt, modified and extended after Leu (1986); (d) Tectonic section through the eastern Northern Steep Belt, redrawn after Wiederkehr et al. (2008); (e) Sketch of the situation at the Forcola normal fault, see also Meyre et al., (1998) and Berger et al. (2005).

Th-Pb analyses were conducted at the Swedish Museum of Natural History (NordSIM facility) on a Cameca IMS1280 SIMS instrument. Analytical methods and correction procedures followed those described by Harrison et al. (1995), Kirkland et al. (2009) and Janots et al. (2012), using a -13kV O

2-

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 Stecket al.(2013), sample BLAU is from Janotset al.(2012); (b) Tectonic section over the Simplon Fault zone into the western Lepontine, based on Campaniet al. (2014); (c) Tectonic section through the western Northern Steep Belt, modified and extended after Leu (1986); (d) Tectonic section through the eastern Northern Steep Belt, redrawn after Wiederkehret al.(2008); (e) Tectonic section across the Forcola normal fault, see also Meyre et al., (1998) and Bergeret al.(2005). Profiles (b)-(e) are not to scale with map (a).

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Table 1.Information on sample localities for all analyzed grains. Sample GRAESER1 has identification number NMBa 10226, VALS has

Table 1.Information on sample localities for all analyzed grains. Sample GRAESER 1 has identification number NMBa 10226, VALS has NMBE43124.

SampleLocalityLatitude Longitude Altitude (m)

BETT11Bettelbach,46

Region SampleLocalityLatitude Longitude Altitude (m)

SouthVANI 6Cava Maddalena, Beura46

◦

04.30’8

◦

17.71’260

WestBETT 11Bettelbach,46

◦

25.62’8

◦

11.70’1460

Niederwald, Goms

BLAS1Piz Blas,46

◦

34.68’8

◦

43.98’2790

Val Nalps, Sedrun

DURO1Doru, Gantertal,46

◦

17.63’8

◦

02.07’1160

Simplon

DURO2Doru, Gantertal,46

◦

17.64’8

◦

02.07’1160
Simplon
DUTH2Lago Sucro,46
◦
33.80’8
◦
41.50’2620
Val Cadlimo
DUTH3Lago Retica, Lagi46
◦
34.45’8
◦
53.57’2400
di Campo Blenio
DUTH6Pizzo Rüscada, Valle46
DUTH 6Pizzo Rüscada, Valle46
◦
24.57’8
◦
40.09’2420
di Prato (Lavizzara)
GRAESER1Lärcheltini, Binntal~46
GRAESER 1Lärcheltini, Binntal46
◦
22.25’~8
22.3’8
◦
14.89’~1860
GRAESER3Wannigletscher,~46
14.9’1860
GRAESER 3Wannigletscher,46
◦
19.46’~8
19.5’8
◦
12.98’~2720
23.4’2560
Cherbadung, Binntal
KLEM1Grosses Arsch,46
GRAESER 4Monte Giove,46
◦
21.9’8
◦
13.0’2720
Val Formazza
KLEM 1Grosses Arsch,46
◦
26.71’8
◦
16.33’~1900
16.33’1900
Blinnental
KLEM2Alpe Devero,46
KLEM 2Alpe Devero,46
◦
22.16’8
◦
18.44’2340
Val Antigorio
KLEM3Griessgletscher46
KLEM 3Griessgletscher46
◦
26.59’8
◦
19.46’2840

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LUCO1Lucomagno46
SCHIESS 1Schiessbach/Simplon46
∘
33.79’8
18.13’8
∘
48.10’1915
SALZ2Piz Scai~46
04.18’1760
VANI 4Montecrstese46
∘
34.5’~8
09.60’8
∘
45.75’~2740
SCHIESS1Schiessbach/Simplon46
19.18’370
VANI 5Crino Baceno46
∘
18.13’8
15.13’8
∘
04.18’1760
TAMB1Pizzo Tambo, Splügen46
19.14’710
CenterBLAS 1Piz Blas,46
∘
30.48’9
34.68’8
∘
18.35’2460
VALSVals, Valsertal~46
43.98’2790
Val Nalps, Sedrun
DUTH 2Lago Sucro,46
∘
33.80’8
∘
41.50’2620
Val Cadlimo
DUTH 3Lago Retica, Lagi46
∘
34.45’8
∘
53.57’2400
di Campo Blenio
LUCO 1Lucomagno46
∘
37.33’~9
33.79’8
∘
17.28’~3150
VANI4Montecrstese46
48.10’1915
SALZ 2Piz Scai46
∘
09.60’8
34.5’8
∘
19.18’370
VANI5Crino Baceno46
45.8’2740
EastTAMB 1Pizzo Tambo, Splügen46
∘
15.13’8
```

30.48’9

∘

19.14’710

VANI6Cava Maddalena, Beura46

18.35’2460

VALSVals, Valsertal46

∘

04.30’8

37.3’9

∘

17.71’260

spectrometer was operated at +10kV and a mass resolution of ca. 4300 (M/ΔM, at 10% peak height), with data collected

in peak hopping mode using an ion-counting electron multiplier. Unknowns were calibrated against monazite-(Ce) standard

17.3’3150

5

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Figure 2.Map of the Lepontine metamorphic dome, modified from Stecket al.(2013) and Schmidet al.(2004). Colored areas mark areal
division in the context of this study. Published monazite-(Ce) locations (grey stars) are from Janotset al.(2012), Bergeret al.(2013) and
Bergemannet al.(2017).

44069 (Aleinikoff et al., 2006). Lead isotope signals were corrected for common Pb contribution using measured

2.2 The study area

The study area comprises the part of the Lepontine Dome in which mineralized fissures/clefts are commonly found (Fig. 1),
from the Tambo nappe, east of the Forcola Fault, over the central Lepontine Dome to the Simplon Fault in the west/southwest
south of the Centovalli Fault, and the southern Gotthard nappe to the north (see Fig. 2 for the tectonic position of the samples).
The 20 monazite-(Ce) samples dated in this study were divided into four groups (Fig. 1). These are (1) the area to the west5
of the Adula nappe (East; 2 samples), (2) the Lepontine Dome east of the Verzasca anticline including part of the southern
Gotthard nappe (Center; 5 samples), (3) the west equally bound by the Verzasca anticline, the Rhone-Simplon Fault to the west
and adjacant south-western Gotthard nappe (West; 12 samples), and (4) the area to the south of the Centovalli and southern
Simplon Faults (South; 1 sample).

3 Study approach and techniques10

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 chemical composition
of the aqueous fluid filling it. Following the initial formation of a fissure/cleft, the intruding metamorphic fluid (300-500

∘

C;

Mulliset al., 1994; Mullis, 1996) leaches and partly dissolves the surrounding host rock, and leads to crystallization of mineral
phases on the fissure/cleft wall under chemical equilibrium conditions. If the resulting chemical equilibrium between fluid15
phase, cleft minerals and those parts of the wall rock accessible to the fluid is disturbed, a new cycle of dissolution and crys-
tallization within the cleft occurs. Chemical disequilibration is generally triggered by tectonic activity causing a deformation
of the fissure/cleft and results in sudden changes in the P-T conditions, the influx of a new fluid, or the exposure of previously
unaltered wall rock (e.g.Mulliset al., 1994; Rollandet al., 2003; Sharpet al., 2005). Since the fissure/cleft remains fluid

filled, these mechanisms of (partial) dissolution and precipitation of newly formed cleft minerals occurs repeatedly, resulting in the strong zonation, alteration and dissolution features of most cleft minerals (e.g.Mullis, 1996; Sharpet al., 2005; Heijboer, 2006). Therefore the mineral association of a cleft is the result of a series of equilibrium states and does not represent a mineral paragenesis. This means that each crystal or crystal part was during its formation in chemical equilibrium with the surrounding fluid, so that each primary chemical zone within a crystal represents a change in the cleft fluid chemical composition.

Hydrothermal monazite-(Ce) typically crystallizes at temperatures below $\sim$350 °C/$\sim$300 °C (Gnoset al., 2015; Bergemann et al., 2017, 2018). Due to the presence of fluid in the cleft, it continues to be reactive down to 200 °C or somewhat below (e.g.Townsendet al., 2000; Bergemannet al., 2018). During the formation of a grain, any tectonic activity that changes the chemical equilibrium within a cleft, causes the crystal to develop a primary chemical zonation usually visible in BSE images. After crystallization, monazite-(Ce) shows practically no U-Th-Pb diffusion at the prevalent P-T conditions (Cherniak and Pyle, 2008). However, the changing chemical conditions in a hydrothermal environment may not only cause new growth around an existing grain, but can result in partial (re-)crystallization/dissolution-reprecipitation in equilibrium with the cleft fluid (e.g.Janots et al, 2012; Bergemannet al., 2017; Grand'Hommeet al., 2018). The dissolution-reprecipitation processes

Figure 3.BSE image of monazite-(Ce) samples showing different kinds of internal primary and alteration structures. (A) The dark grain areas of the grain, primarily located close to rims and inclusions, display sharp irregularly shaped borders and porosity. These areas consist of secondary monazite that isca.2.5 Myr younger than the pristine lighter grain parts (Fig. 5b). Image (B) shows part of a large grain with partially preserved sector-like zonation. Indications for alteration are irregularly shaped secondary zonation, 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 no alteration features, the outer rim has the oldest and most homogeneous age pattern, with the central part possessing a wider age range with some significantly younger ages (Fig. 5m, Supplement Table 1). The youngest ages were found in part of the inner rim, postdating all other 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 fluid reservoir (e.g.Putnis, 2002, 2009). The alteration is therefore not limited to grain rims, but commonly occurs along mineral inclusion interfaces, cracks and microcracks due to which also internal parts of a crystal may be altered (Fig. 3a, b; Grand'Hommeet al., 2018). These processes may be active as long as conditions in the cleft stay within the monazite-(Ce) formation temperature window and stability field, and appear to be largely temperature independent with only slightly increasing reaction speeds with increasing 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 by porosity and fractures in the primary and secondary monazite-(Ce), induced by the previous dissolution-reprecipitation/ recrystallization events, by bringing an increased crystal volume into direct contact with the fluid (Putnis, 2002, 2009). Possible signs of these alteration processes recognizable in BSE images are irregularly shaped (Fig. 3 a, b) or weak (Fig. 3 b) internal zonation, or cross-cutting by secondary zones (Fig. 5 j, k), as well as a high porosity (Fig. 3 a, b;e.g.Gnoset al., 2015; Bergemannet al., 2017, 2018). Micro-scale alteration along cracks, inclusions and porosity may produce altered areas within a crystal that cannot be recognized in BSE images but yield a different age (Fig. 3c; Grand'Hommeet al., 2018). Dissolution-precipitation processes may sometimes largely preserve the chemical composition of an affected crystal part, possibly due to only small pore fluid volumes involved in the reaction that did not equilibrate completely with the fluid surrounding the crystal, consequently areas affected by alteration that posses different chemical compositions may have reprecipitated simultaneously (Grand'Hommeet al., 2016; Bergemannet al., 2017, 2018).

3.2 Analytical techniques

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. Monazites-(Ce) were individually polished to the level of a central cross section and assembled in mounts of several grains. Backscatter electron (BSE) images were then obtained, using a Zeiss DSM940A electron microscope at the university of Geneva and a beam current of 3.5 nA. As the surface of the mounts has to remain flat for ion probe dating, element mapping that would cause damage to the epoxy is not possible. Secondary ion mass spectrometry (SIMS) spot analyses (Fig. 5) were placed according to visible domains in these images. As far as possible, spot measurements next to cracks were avoided, as the Th-Pb isotope measurements may be disturbed in such areas due to unevenness in the sample surface (Janotset al., 2012; Bergeret al., 2013).

Th-Pb analyses were conducted at the Swedish Museum of Natural History (Nordsim facility) on a CAMECA ims1280 SIMS instrument. Analytical methods and correction procedures followed those described by Harrisonet al.(1995), Kirkland et al.(2009), and Janotset al.(2012), using a -13 kV O_2^- primary beam ofca.6 nA and nominal 15μm diameter. The mass spectrometer was operated at +10kV and a mass resolution ofca.4300 (M/ΔM, at 10% peak height), with data collected in peak hopping mode using an ion-counting electron multiplier. Unknowns were calibrated against monazite-(Ce) standard 44069 (Aleinikoffet al., 2006). Lead isotope signals were corrected for common Pb contribution using measured ^{204}Pb and an assumed present-day Pb isotope composition according to the model of Stacey and Kramers (1975). The measurement of ^{204}Pb is subject to an unresolvable molecular interference by ^{232}Th ^{143}

Nd
16
O
++
2
(also affecting
, also affecting
206
Pb and
207
Pb to a lesser degree
through replacement of
16
O with heavier O-isotopes), which may result in an overestimation of common Pb concentrations. A
O by heavier O-isotopes, which may result in an overestimation of common Pb concentrations. A25
correction was applied whenever the
232
Th
143
Nd
16
O
++
2
signal at mass 203.5 exceeded the average background signal on the5
signal at mass 203.5 exceeded the average background signal on the
ion-counting detector by three times its standard deviation. Age calculations use the decay constants recommended by Steiger
and Jäger (1977). Th-Pb ages presented were corrected for common Pb and doubly charged
and Jäger (1977). The Th-Pb ages were corrected for common Pb and doubly charged
232
Th
143
Nd
16
O
++
2
overlap and
are given at 2σuncertainties.
4 Results
The complete ion-probe data set is given in the data Supplement Table 1 (PANGEA, doi: still pending), see Tab. 2 for an10
overview and Figs. 4 and 7 for measurement positions and a graphical representation. As there are difficulties with the U-
Pb system for hydrothermal monazite-(Ce) (Janots et al., 2012), only
208
Pb/
232
Th ages were used. For explanations on age
patterns across the grains, grouping and weighted mean age determination, see the discussion in Chapter 5.2.
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overlap and are
reported at 2σuncertainties. Weighted mean age plots were done using Isoplot v. 3.75 (Ludwig, 2012).
4 Th-Pb monazite-(Ce) dating30
The dating of hydrothermal monazite-(Ce) differs from thermo-chronometers that posses a closure temperature in sofar, as a
crystal may record several ages due to new crystallization or alteration of crystal parts. The grains directly record tectonic
8

Figure 3.Back-scatter electron images of studied cleft monazite-(Ce). The zonation corresponds largely to variations in Th contents. Spots refer to SIMS analysis spots, with colours indicating chemical and age domains. The color of the frame indicates data for which it was possible to calculate weighted mean 208 Pb/

Table 2.Overview list of the

232

Th ages.

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Figure 4.Back-scatter electron images of studied cleft monazite-(Ce). The zonation corresponds largely to variations in Th contents. Spots refer to SIMS analysis spots, with colours indicating chemical and age domains. The color of the frame indicates data for which it was possible to calculate weighted mean

Th-

208

Pb/

232

Th ages.

8

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Table 2.Measurement spots AIGG1 1, 9, 11, BLANC2 7, 8, 23 and SALZ15 4 were excluded due to their location on cracks or signs of 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±0.31like 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±0.26like mean age9.95±0.180.377

9.50±0.230.654

8.34±0.200.294

DURO23d, 4d7.63±0.130.55811.48±0.28 - 7.02±0.18

DURO 25d3211.48±0.28 - 7.02±0.1811.48±0.28like mean age7.63±0.130.558

7.18±0.180.504

GRAESER13e, 4e9.03±0.190.28512.14±0.30 - 7.57±0.19

7.91±0.261.77

GRAESER33f, 4f15.60±0.61 - 6.36±0.39

KLEM13g, 4g8.43±0.200.94510.64±0.26 - 7.97±0.20

KLEM23h, 4h13.44±0.310.57513.65±0.33 - 9.47±0.40

DUTH 65e2612.60±0.37 - 9.33±0.3212.60±0.37like mean age11.90±0.271.512

9.74±0.221.513

GRAESER 15f3112.14±0.30 - 7.57±0.1912.14±0.30like mean age9.16±0.240.194

8.78±0.271.87

7.73±0.160.546
GRAESER 35g1715.60±0.61 – 6.36±0.3915.60±0.616.36±0.39
GRAESER 4Appendix212.25±0.51 – 11.88±0.4712.25±0.5111.88±0.47
KLEM 15h2410.64±0.26 – 7.97±0.2010.64±0.267.97±0.208.43±0.200.945
KLEM 25i1713.65±0.33 – 9.47±0.40like mean agelike mean age13.44±0.310.575
11.74±0.320.835
10.12±0.942.64
KLEM33i, 4i12.64±0.380.18512.96±0.46 – 8.43±0.32
KLEM 35j2412.96±0.46 – 8.43±0.32like mean age8.43±0.3212.50±0.340.656
11.99±0.662.36
SCHIESS13j, 4j9.69±0.602.449.94±0.25 – 6.78±0.18
VANI43k, 4k8.03±0.533.399.27±0.43 – 6.89±0.37
8.03±0.442.27
VANI53l, 4l7.21±0.431.968.07±0.36 – 4.86±0.24
10.17±0.522.47
SCHIESS 15k279.94±0.25 – 6.78±0.186.90±0.18like mean age9.78±0.220.415
7.03±0.382.35
VANI 45l169.27±0.43 – 6.89±0.379.27±0.436.89±0.378.03±0.442.27
VANI 55m208.07±0.36 – 2.69±0.117.45±0.222.69±0.117.21±0.431.96
5.53±0.603.55
BLAS13m, 4m12.83±0.392.0514.49±0.26 – 7.82±0.22
DUTH23n, 4n13.20±0.390.61414.34±0.41 – 11.15±0.43
DUTH33o, 4o13.48±0.531.8714.53±0.43 – 10.61±0.34
DUTH63p, 4p11.88±0.301.61112.60±0.37 – 9.33±0.32
9.73±0.301.810
LUCO13q, 4q14.23±0.230.77514.74±0.30 – 9.90±0.17
SALZ23r, 4r12.92±0.251.61114.28±0.74 – 10.51±0.39
CenterBLAS 15n1814.49±0.26 – 7.82±0.2214.49±0.267.82±0.2212.83±0.392.05
DUTH 25o1614.34±0.41 – 11.15±0.4314.34±0.4111.15±0.4313.41±0.702.05
DUTH 35p2614.53±0.43 – 10.61±0.3414.53±0.430.61±0.3413.48±0.531.87
LUCO 15q2514.74±0.30 – 9.90±0.1714.74±0.309.90±0.1714.23±0.230.775
SALZ 25r2814.28±0.74 – 10.51±0.3914.28±0.74like mean age12.98±0.252.217
10.95±0.371.59
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
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Manuscript under review for journal Solid Earth
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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 outer5
rim if distinguishable,to capture the crystallization duration. In order to obtain more robust growth domain ages, the selected
domains were large enough to place a minimum of three measurement spots. The number of domains dated was limited by
available machine time. Only

^{208}Pb/^{232}Th ages for all samples. The colours indicate chemical domains with weighted mean Th ages were used, as the Th-Pb system is favorable in dating hydrothermal monazite-(Ce) due to high Th/U ratios at low U content, which preclude the use of the ^{207}Pb/^{235}U system. Additionally, the high Th/U ratios and young age oft the samples also exacerbate the uncorrectable excess in ^{206}Pb due to the incorporation of ^{232}Th, an intermediate decay product of ^{238}U (Janotset al., 2012). This means that only ^{208}Pb/^{232}Th ages given where applicable. Th single or weighted mean ages 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 contents seem to be the easiest way to differentiate between zones, both primary and secondary (e.g.Gnoset al., 2015; Bergemannet al., 2017).

Figure 5 includes plots showing compositional varation used as a basis for domain age calculations. The derived spot ages were grouped together on the basis of chemical composition representing crystal formation or replacement under changing equilibrium chemical conditions, and, if possible, spatial distribution across the sample according to zonation visible on BSE images. Whenever age clusters were found on the basis of these groups, weighted mean domain ages were calculated (Fig. 5), as these could be shown to date tectonic activity (Grand'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 have happened in equilibrium with the surrounding fluid, any age cluster within a chemical group must be due to those crystal parts' simul-taneous formation or alteration. Therefore, two chemically distinct groups that yield, within error, identical weighted mean ages, still signify two distinct crystal formation/alteration events closely following each other. In areas that experienced strong and discrete tectonic events, usually in the vicinity of shear zones, this approach allows the calculation of domain ages for a majority of the analyzed spots from the dataset of a sample (e.g.Janotset al., 2012; Bergeret al., 2013; Bergemannet al., 2017, 2019; Ricchiet al., 2019). Although, as only a limited number of analyses are possible to be obtained for each grain, some of the weighted mean ages may only combine a small number of individual ages. This appears to be especially true for ages dating late stage events (e.g.Bergeret al., 2013; Grand'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 experienced more than two distinct deformation events and/or phases of prolonged small scale tectonic activity, likely during exhumation.

Experiments have shown that a reason for a large age scatter in crystal domains affected by alteration may be an incomplete

age resetting due to the survival of primary monazite nanoscale domains (Grand
'
Hommeet al., 2018). This may have caused the observed spread out age patterns without age clusters in zones visible in BSE, which impede the calculation of weighted mean ages (Fig. 5). Especially prolonged phases of low-intensity tectonic activity would presumably repeatedly cause small volumes of monazite-(Ce) to reprecipitate during re-equilibration of the fluid chemistry.35

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Figure 4.Time diagram combining identified peaks from the inset and weighted mean ages of all samples from the Lepontine Dome. The inset shows an age probability density plot representing the dataset of each region (Fig. 1) according to the number of ages per 0.5 Myr interval. In the time diagram, darker colors represent peaks or plateaus from the inset indicating times of intense monazite formation/alteration. Lighter shades mark the remaining times for which more than one age was recorded, indicating either only limited tectonic activity or mixing ages.
Black error bars indicate weighted mean ages from this study.

Additionally, as stated above, altered areas may preserve their overall chemical composition but consist of a submicroscopic mix of different phases (e.g.Grand
'
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 many individual ages being discarded for these areas. Accordingly, events may, especially in larger grains, not be recognized if looking at the well defined weighted mean ages only. To avoid this, the entire dataset of each region was plotted according to the number of ages per 0.55 Myr interval to identify age clusters across the grains of a given region (Fig. 4 inset). The identified age peaks and phases for which a significant number of ages were obtained were then combined with the weighted average ages to visualize distinct events or phases of tectonic activity (Fig. 4). Age peaks of a region's dataset and weighted mean ages of individual grains generally agree, with some phases of age recording visible in the overall age record not identified through weighted mean ages.
For the interpretation of the data, weighted mean ages are preferable to pinpoint deformation events. However, at least the10 beginning and end of the age record within a sample must have a geological significance since their recording must have been triggered by tectonic activity, even if one assumes all ages in between to be simply mixing ages. Accordingly, weighted mean ages are in the following generally discussed as precise ages, while spot ages are treated as approximate ages.

4.1 Results

The ion-probe measurement data set is given in the data Appendix Table A1 and can be found in the PANGAEA database15 (https://doi.org/10.1594/PANGAEA.898689). The age data of the individual samples and the whole dataset 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 to 7.5 Myr.
An overview over the individual age ranges and the weighted mean domain ages that could be calculated for the individual samples is shown in Table 2. Figure 5 shows the measurement positions, weighted mean domain ages, where available, a

graphical representation of the measured ages and a chemical for each sample the best shows the different groups.

Sample GRAESER 4 (Appendix Fig. A1; Appendix Table A1) is a grain (co-type) from the monazite-(Nd) type locality (Graeser and Schwander, 1987). Due to very low Th contents only two spots yielded ages of 11.88±0.47 and 12.25±0.51 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 compared to monazite from other geological environments (Appendix Table A1; Janotset al., 2012). With Th contents generally ranging between 5000 and 60000 ppm, with (parts) individual samples considerably lower (down to 1000 ppm) or higher (up to 110000 ppm), while U contents are below 1000 ppm (only KLEM 3 up to 3300 ppm), resulting in high Th/U ratios of up to several hundred. Lead contents show a spread from a few up to several hundred ppm, with common Pb contents generally considerably below 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 alteration features (irregular, wavy or unclear zonation, porosity) and can roughly be divided into five partly overlapping groups on the basis of their appearance in BSE images (Fig. 5): (1) Sector like zonation:

DUTH 6 shows some signs of alteration and complex zonation in the inner part of the grain.

GRAESER 3 shows no clear signs of alteration, but an extreme zonation in both Th (~1800-113000 ppm) and U (~10-680 ppm) contents according to visible zonation and elevated (>10%) to extreme (65-99%) common Pb contents. The ages derived from the low Th measurements should be treated with caution, as they show a greater spread at higher error than the other measurements.

VANI 4 shows in places strong signs of alteration.

VANI 5 displays in places only weak zonation with sometimes strong alteration signs. Thorium contents are relatively 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 alteration features. Thorium contents are low (>3500 ppm) with only an overgrowth rim showing higher contents (up to 12300 ppm). Common Pb contents are elevated but remain below 25%.

(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.

(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 rims.

VANI 6 displays oscillatory-complex zonation, with clearly discernible altered grain parts around pores 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:

DUTH 2 displays only weak remnants of sector-like zonation.

KLEM 3 shows weak remnants of oscillatory zonation that is cut and transitions in places into a diffuse pattern.

SALZ 2 shows remains of sector-like combined with complex zonation.

(5) Weak zonation with strong alteration features:

DURO 2 displays remnants of oscillatory zonation.

DUTH 3 has partly preserved oscillatory zonation with parts of the grain having a diffuse pattern.

GRAESER 1 shows remains of sector combined with oscillatory zonation, but strong zonation in the altered parts of the crystal.

GRAESER 4 shows remnants of sector zonation and has very low Th contents of just below 1100 ppm and elevated common
Pb contents below 20%.30
KLEM 2 has a diffuse internal structure and elevated common Pb contents that remain below 21%.
TAMB 1 has Th (>3300 ppm) contents that do not allow the identification of clear chemical groups. Weighted mean ages
could therefore only be calculated for spots located in close proximity that give a similar age. While most of the measurements
have common Pb contents of >5%, five measurements show very high contents of 72-96%, but despite this appear undisturbed.
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Figure 6.Diagrams showing
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 for all samples. The colours indicate chemical domains with weighted mean
Th ages.
14

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 given where applicable.
11
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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 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 for all samples. The colours indicate chemical domains with weighted mean
Th ages.
16

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 given where applicable.

5 Discussion

5.1 Hydrothermal monazite-(Ce) crystallization

Hydrothermal fissure monazite-(Ce) typically crystallizes at temperatures below 350 °C (Gnos et al., 2015; Bergemann et al., 2017, 2018) down to somewhere in the range of 200 °C or slightly below (e.g.Townsend et al., 2000). Crystallization and later reactions occur when the fissure fluid is brought into disequilibrium. This may be caused by tectonic events for a number of reasons: by volume changes due to deformation, partial collapse of the fissure walls bringing the fluid into contact with unaltered wallrock or the influx of new fluid.

After crystallization, monazite-(Ce) shows practically no U-Th-Pb diffusion (Cherniak and Pyle, 2008). However, replacement mechanisms that may be active in a hydrothermal environment may cause (re-)crystallization and possibly new growth around an existing grain or dissolution-reprecipitation. From the fluid film, a secondary monazite-(Ce) phase precipitates at the surface of the primary phase. The self-sustaining reaction front propagates into the mineral for as long as the interfacial fluid retains a connection to a fluid reservoir. This dissolution-reprecipitation process may be initiated on any part of the crystal

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Th ages.

17

in contact with the surrounding fluid. It is therefore not limited to grain rims, but commonly occurs along mineral 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 field. Therefore, several (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/recrystallization 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 BSE images (Fig. 4). The derived spot ages were grouped together on the basis of chemical composition thought to represent crystallization under homogeneous chemical conditions, and spatial distribution across the sample according to zonation visible on BSE 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 areas with different chemical compositions may have reprecipitated simultaneously. Despite this, spots of different chemical groups were only in a few, clear cases grouped together for weighted mean age calculation. This is to avoid the risk of mistaking multiple mixing ages of different chemical domains as a distinct event. In areas that experienced few and discrete tectonic events, this approach allows the calculation of domain ages for most analyzed spots of the dataset of a sample (e.g.Janots et al., 2012; Bergemann et al., 2017). However, large parts of the study area experienced more than two distinct deformation events and/or phases of prolonged activity. New growth on an existing crystal results in sharp boundaries between zones. But dissolution-reprecipitation processes may lead to irregularly shaped altered zones within a crystal, which may or may not be visible on a BSE image. If this happens multiple times the limited number of analyses per grain will result in many individual ages being discarded. Meaning that events may not be recognized when looking only at the weighted mean ages. To avoid this, the entire dataset of each region was additionally plotted according to the number of ages per 0.5 Ma intervals to identify age clusters (Fig. 1, appendix). In the next step the peaks or plateaus of the age histogram were plotted according to their relative intensity. They were then combined with the weighted average ages (this study; Janots et al., 2012; Berger et al., 2013; Bergemann et al., 2017) to visualize distinct events or phases of tectonic activity (Fig. 8). As only a limited number of analyses are possible to obtain for each grain, some weighted mean ages combine only a small number of individual ages. This is especially true for ages dating multiple late stage events that presumably happened at relatively low temperatures. In such cases only those weighted mean ages were kept whose geologic significance is also indicated by other dating techniques such as fault gouge dating, specifically close to the Rhone-Simplon line. Otherwise, these ages are included in the overall age range of the sample in question given in Tab. 2.

Another reason for a spread out age pattern may be a grain experiencing prolonged phases of low-intensity tectonic activity of multiple small deformation events during exhumation. In which case only small volumes of monazite-(Ce) would reprecipitate due to disequilibration during deformation. This leads tendentially to unclear crystal zonations that make it difficult to correctly

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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.

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 indicate fewer ages. Black error bars indicate weighted mean ages from this study, while grey bars indicate data from Janots et al. (2012), Berger et al. (2013) and Bergemann et al. (2017). The inset shows an age histogram representing the complete dataset of each region according to the number of ages per 0.5 Ma intervals.

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Manuscript under review for journal Solid Earth
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identify growth zones on BSE images (compare Gnos et al., 2015; Bergemann et al., 2018). As opposed to areas where crystals record individual, stronger deformation events that tend to show a sharper zonation (compare Janots et al., 2012; Berger et al., 2013; Bergemann et al., 2017, 2019).

5.3 Monazite-(Ce) ages and Lepontine history

Hydrothermal cleft monazite-(Ce) crystallization and dissolution-reprecipitation occurred over time in different parts of the study region, as it passed through the monazite-(Ce) stability field. The time interval recorded within individual monazite-(Ce) crystals spans from 2.5 Ma to 7 Ma for individual grains (Fig. 7, Table??). The recorded time interval within individual grains is generally longer in the South and East regions of the study area (Fig. 2). The total age range covers the time from ca. 19 to 5 Ma. The monazite-(Ce) chronologic record can be seen to start in the eastern- and southernmost regions (Fig. 9). The recorded activity then moves to the northeastern and central to the western area. Younger ages in the west progressively concentrate on the large fault systems of the Rhone-Simplon Fault and the proposed location of the Rhine-Rhone Line. The oldest recorded monazite-(Ce) ages of 19-17 Ma from the eastern edge of the study area (Figs. 7s, 9a) coincide with a phase of rapid exhumation and cooling between 22 and 17 Ma (Steck and Hunziker, 1994; Rubatto et al., 2009). At that time, temperatures in parts of the north-western area (northern Ticino Dome) were still prograde at 450-430

Figure 6.Figure modified from Stecket al.(2013), with cooling ages compiled by Steck and Hunziker (1994), and completed with data from Kelleret al.(2005), Rahn (2005), Elfertet al.(2013) and Bostonet al.(2017). Cleft monazite crystallization ages of samples from this study, located in the vicinity of the cross section (Figs. 1, 2 are shown for comparison. Note that monazite from rocks gives T-max, considerably higher than the crystallization temperature of the hydrothermal cleft/fissure monazite-(Ce) variety.

5 Hydrothermal monazite-(Ce) ages compared to thermochronometry

Hydrothermal monazite-(Ce) crystallization and alteration occur typically in a temperature window of ca. 350 – 200 °C 19-18 Ma (Janots et al., 2009) as deduced from allanite dating. After this, temperatures must have decreased to lower temperatures during exhumation, as hydrothermal monazite-(Ce) crystallization in the north(east)ern area started at around 16 Ma in the Valsertal (sample VALS, Fig. 7t) and then at the southern edge of the Gotthard nappe at 14-15 Ma (Fig. 9b). This may indicate crystallization during a deformation phase indicated by 17-14 Ma °C (Gnos et al., 2015; Bergemannet al., 2017, 2018) independent of the local cooling rate. In many areas the oldest recorded hydrothermal monazite-(Ce) ages are predated by ^{40}Ar/^{39}Ar biotite ages interpreted as dating recrystallization (Wiederkehr et al., 2009). The monazite-(Ce) age record for the entire (north)eastern region continues until ca. 13 Ma after which the record ends for the Valsertal where cooling below 180 °C is dated at around 12 Ma (zircon U/Th-He; Price et al., 2018). The age range of the Valsertal sample of 16-12 Ma perfectly coincides with hydrothermal cleft monazite-(Ce) ages from within the Gotthard nappe of ca. 16-12 Ma (Janots et al., 2012; Ricchi et al., in review), after which monazite activity moved into the Lepontine dome south of the Gotthard nappe. Locally within in the dome, in the northern part of the western region, zircon fission 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 last widely recorded hydrothermal monazite-(Ce) ages of around 10 Ma. One sample records ages of 9-8 Ma (BLAS1; Fig. 4m) that is in agreement 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 al., 2010), as fault gouge ages seem to typically coincide with the end of monazite-(Ce) growth (see below; Bergemann et al., 2017). While Ar white mica cooling ages, and are slightly predated by to coincide with ZFT ages (Gnoset al., 2015; Grand ' Hommeet al., 2016; Bergemannet al., 2017, 2019; Ricchiet al., 2019). This sequence is also found in most parts of the Lepontine Dome as shown for samples located in vicinity of the NE-SW cross section (Fig. 6), based on Stecket al., (2013). Moreover, it is also well visible in (Fig. 6) that monazite in clefts starts to crystallize much later than monazite in the metamorphic rocks (data from Köppel and Grünenfelder, 1975, and Bostonet al., 2017). A comparison of monazite-(Ce) crystallization ages with ages obtained with thermochronometers, whose closure temperatures depend on the cooling rate, seems to allow the identification of areas experiencing low cooling rates at the time of hydrothermal monazite growth. In such cases, monazite has a larger time window to record tectonic activity, and ^{40}Ar/^{39}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 further west or in the Aar and Mont Blanc massifs (Bergemann et al., 2017; 2019). There, as discussed below, ZFT ages predate or mirror primary monazite-(Ce) crystallization and are in turn predated by Ar 19

white mica ages coincide with the beginning of the monazite-(Ce) age record and ZFT ages coincide with or even postdate the youngest found monazite-(Ce) ages. This is the case in (1) the central region of the study area, where the youngest white 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 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 (2) in the vicinity of sample VANI 6 south of the RSF (Fig. 1) the ZFT ages, ranging from 12.0±2.6 to 7.1±1.6 Ma (Kelleret al., 2005), overlap with the youngest monazite-(Ce) spot ages of around 12.5 to 10.6 Ma. There are no ^{40}Ar/^{39}Ar white mica ages. The coincidence of these ZFT and 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 ages found along the rest of the brittle Rhone-Simplon Fault bordering the Lepontine Dome to the west (Kelleret al., 2005; Campaniet al., 2010). A similar age pattern was also found outside the study area, in (3) the Eastern Alps in Austria, in an area affected by Cretaceous Eo-Alpine Barrow-type metamorphism (Bergemannet al., 2018). There, primary monazite-(Ce) mean ages of 90.6±1.3 to 89.2±1.8 Ma coincide with ^{40}Ar/

^{39}Ar muscovite cooling ages with the hydrothermal monazite-(Ce) crystallization suggests slow cooling rates during

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Figure 9.Overview maps of the study area showing the distribution of the monazite-(Ce) age record over time. Weighted mean average ages are given near the stars representing the corresponding sample locations. Note the shift over time from the outer regions of the Lepontine dome to the internal areas and then to the shear zones bounding its western limit.

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continued deformation (Bergemann et al., 2018) for the time from around 15 Ma until ca. 9 Ma, as the systems closed only at 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, 1994; Campani et al., 2010), evidence of which is also preserved in the oldest monazite-(Ce) data of 17 Ma (Fig. 7a) from south of the Rhone-Simplon Fault (RSF). Zircon fission track ages of 14-11 Ma (Hurford, 1986) and cleft adularia ages between 12.92±0.17 Ma and 10.82±0.12 Ma (Rauchenstein-Martinek, 2014) from south of the western Gotthard slightly predate to coincide with a later phase cooling and increased tectonic activity in the western Lepontine area. Primary monazite-(Ce) crystallization in parts of the northwestern and central Lepontine as well as the central Aar massif occurs at around 12 Ma, followed by monazite-(Ce) crystallization in the westernmost area around 11-10 Ma dating exhumation (Fig. 9 c,d). Multiple monazite-(Ce) samples from locations in the Gotthard nappe and Aar-massif yield weighted average ages of 10 Ma. These age patterns are related to processes during backfolding of the northern steep belt (in the sense of Milnes 1974), dating it to ca. 10 Ma in this area (Steck, 1984; Steck and Hunziker, 1994; Campani et al., 2014).

The 12-10 Ma cooling phase of the western Lepontine was related to detachment movements along the Rhone-Simplon Fault. This time interval marks the end of the hydrothermal monazite-(Ce) age record in the hanging wall of the Rhone-Simplon Fault. Correspondingly, 12-10 Ma also marks the beginning of monazite-(Ce) crystallization to the east of the fault, first in the vicinity of the Aar massif (Figs. 7 c, d, j) and then also further south (Fig. 7k). Primary monazite-(Ce) crystallization ages along the eastern side of the RSF are tendentially predating, but still in close agreement with zircon fission track ages in this area. In the case of sample VANI6 from south of the RSF (Fig. 7a) ZFT ages of this area show a scatter from 12 to 7 Ma (Keller et al., 2005) that overlap with the youngest monazite-(Ce) age spots. Monazite-(Ce) ages of 9-7.5 Ma indicate continued exhumation of the western region and the central areas leave the hydrothermal monazite-(Ce) stability field at this time (Fig. 9f). The number of weighted mean ages (i.e. clear age patterns within the crystals) staggered over a relatively short time (Fig. 8), suggest deformation pulses during brittle tectonics along the Rhone-Simplon/Centovalli Faults and corroborates evidence of continued deformation along the southern RSF and the Centovalli Fault (Zwingmann and Mancktelow, 2004; Surace et al., 2011). The youngest widely recorded monazite-(Ce) age group for the western Lepontine dates to around 7 Ma (Figs. 7 b, d, j-l; 9f). This coincides with young fault gouge data of 8-6 in this region (Zwingmann and Mancktelow, 2004, Surace et al., 2011)25

Overall, the 10-7 Ma time interval is characterized by phases of strike-slip deformation along the extended Rhone-Simplon fault system. This is recorded through hydrothermal monazite-(Ce) and fault gouge illite crystallization that was not restricted to the south-western Lepontine but also recorded in faults bounding the Mont Blanc massif (Bergemann et al., 2019). The ages of 8-7 Ma of the sample with the youngest recorded age (VANI5) among the studied monazites-(Ce) are concurrent with the youngest recorded ages of all other samples along the Rhone-Simplon fault system. The sample comes from an area where30 hydrothermal gold mineralization occurred and the youngest age group of VANI5 give a weighted mean age of 5.53 ±0.60 Ma that coincides with ZFT ages of 6.4-5.5 Ma (Keller et al., 2005). The area also has a muscovite

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 ca.70-50 Ma (Kurzet al., 2011; van Gelderet al., 2015). The three areas have in common that exhumation/cooling rates were low (Stecket al., 2013; Fügenschuhet al., 2000) during the time of hydrothermal monazite-(Ce) crystallization.15

Due to the slow cooling rates, the Ar system closure and the end of fission track annealing would have occurred at the lower end of their respective temperature windows, while monazite-(Ce) crystallization presumably occurred during this ca. 350-200 °C temperature window (Gnoset al., 2015; Bergemannet al., 2017, 2018). This may indicate that the coincidence of

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 Campani et al., 2010), similar to the difference between the youngest recorded ages for monazite-(Ce) samples from the same area.

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Ar white mica ages with the beginning of monazite-(Ce) crystallization and ZFT ages overlapping with the latest hydrothermal monazite-(Ce) crystallization can be used as an indicator of slow exhumation/cooling rates during ongoing tectonic 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 the study region as it passed through the monazite-(Ce) crystallization recording window. The growth duration recorded by the spot 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 Lepontine Dome (Fig. 7a), with the earliest ages around 19 Ma (sample TAMB 1; Figs. 4, 5s), slightly postdated by sample VALS somewhat to the north of TAMB 1 at~16.5 Ma (Fig. 5t). While the age record continues in the east, it starts in the Central region (Fig. 1) around 14.7 - 14.3 Ma. The parallel monazite-(Ce) age record for the central and eastern regions continues untilca.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 7.8 Ma in the center (BLAS 1). The western area (Fig. 1) has a more heterogeneous age record with starting dates being diachronous 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 in which ages are recorded progressively spreading west, until by ca. 10 Ma most samples from the western region record ages. After this, the age record ends first in the central region and then the easternmost western region atca.9.5 Ma. The record continues in most of the western region (Fig. 7e), until it becomes progressively more localized by~7.5 towards the west and the vicinity of the Rhone-Simplon Fault system (Fig. 7f). The youngest widely recorded monazite-(Ce) age group for this area 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 of~2.7 Ma. The southern region (Fig. 1) at the very edge of the Lepontine Dome, separated from most of the Western region by the Rhone-Simplon Fault, shows a similar age range as the eastern region. As in the east, the monazite-(Ce) age record starts early at ca. 16.8 Ma and continues somewhat further down to around 10.6 Ma (Fig. 5a-d).

Overall, the monazite-(Ce) chronologic record shows a clear east-west trend without large age jumps within the Lepontine Dome. The record starts in the eastern- (and southern) parts of the study area, with the activity then moving through the central to the western area, where it progressively concentrates on the large fault systems in the west of the Lepontine Dome. The oldest recorded monazite-(Ce) ages were found in the eastern area (TAMB 1; Fig. 1) and fall into two groups, around 19 Ma and a mean age at 17.49±0.4 Ma (Figs. 4, Tab. 2), during which time the area around TAMB 1 experienced a time of rapid exhumation and cooling (Steck and Hunziker, 1994). The nearby Forcola Fault (Fig. 1) was estimated to have been active sometime around 25-18 Ma on the basis of Rb-Sr and K-Ar cooling ages (Meyreet al., 1998). In this context, the monazite-(Ce) ages would date the final deformation phases of such normal faults as the Forcola Fault. Notably, these faults, and possibly the Forcoloa Fault itself, may have been active far longer, as suggested by monazite-(Ce) ages down to~8.3 Ma (Figs. 5s, Tab. 2). The youngest ages even postdate apatite fission track ages (AFT; Fig. 6), which may have been facilitated by the late circulation of hot fluids, something which could be shown for hydrothermal monazite-(Ce) of the Lauziere and Mont Blanc Massifs (Janotset al., 2019; Bergemannet al., 2019). North of TAMB 1, the sample VALS age record starts slightly later at~16.5 Ma that then runs parallel to that of TAMB 1 (Figs. 5s, t).

In the central area close to the sample locations, temperatures were still prograde up until the time of 19-18 Ma at 450-430 °C (Janotset al., 2009) as deduced from allanite dating. After this time, conditions must have decreased to lower temperatures during exhumation, as the hydrothermal monazite-(Ce) age record started after around 16-15 Ma in the Gotthard Nappe and eastern Lepontine Dome (Fig. 7b) and continued to later than~13 Ma (Fig. 7c). After this time the age record receded from the eastern region, which cooled below 180 °C around 12 Ma (e.g. Priceet al., 2018, zircon U/Th-He), and the Gotthard Nappe west- and southwards into the Lepontine Dome. This would date the decoupling of the Gotthard Nappe which experienced a rapid exhumation due to steepening during backfolding (Wiederkehret al., 2009; Ricchiet al., 2019) from the Lepontine Dome toca.13-12 Ma, as the samples of the central area south of the Gotthard Nappe show a continued widespread age record down to~9 Ma (Fig. 7d). During this time interval (Fig. 7c) primary monazite-(Ce) crystallizes also along the rest of the extended Rhone-Simplon Fault system (Grand

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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 formation of a new cleft generation with a different orientation associated with strong hydrothermal fluid activity (Bergemannet al., 2017, 2019; Janotset al.,2019). Since in the study area clefts outside the Gotthard Nappe, where they are horizontal, are vertical whether they formed during extension or later strike-slip deformation, such a switch in deformation style cannot be proven. But it might

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Figure 7.Overview maps of the study area showing the monazite-(Ce) age record over time and space. Note the shift over time from the southern and eastern regions of the Lepontine Dome to the central and western areas and finally to the areas close to the shear zones bounding its western limit. Weighted mean ages, quoted near the stars representing the corresponding sample locations, indicate individual deformation events that could be identified for a grain within a given time interval. Published hydrothermal monazite-(Ce) locations (grey stars) of the areas adjacent to the Lepontine Dome are from Janotset al.(2012), Bergeret al.(2013) and Ricchiet al.(2019).

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6 Conclusions

Hydrothermal fissure monazite-(Ce) always dates crystallization and not cooling due to system closure and often shows com-plex recrystallization features. It provides an important record of the shifting tectonic activity associated with the regions exhumation history within the monazite stability field. A comparison between hydrothermal monazite-(Ce) samples from dif-ferent parts of the Lepontine metamorphic dome shows that age clusters within individual crystals from a simply exhuming area5 have a less clear age distribution than samples from fault zone areas, or fast exhuming areas. Monazite-(Ce) (re)crystallization/ 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 homogenous crystal zones that are easier to date.

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explain the progressive restriction of the monazite-(Ce) age record areas to samples from the vicinity of major fault zones in 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-Simplon Fault (southern region, Fig. 1) which had continued since~16.8 Ma, largely parallel to that in the eastern region (Figs. 7a-d).

At the same time, 11-10 Ma also marks the beginning of monazite-(Ce) crystallization in the foot wall of the Rhone-Simplon5 Fault ((Figs. 1, 7d). The primary monazite-(Ce) crystallization ages of the western area tend to postdate, but are still in close agreement with zircon fission track ages (Fig. 6). Samples of the western region often yield well constrained weighted mean ages (Fig. 5), which might suggest a dominance of strong individual tectonic events. This in mind, weighted mean ages in the western zone (Fig. 4) may suggest deformation during brittle tectonics along the extended Rhone-Simplon Fault system.

The mean age group around 12 Ma, found in the eastern part of the western zone (Figs. 4, 7c) is related to the exhumed deeper part of the Simplon Fault (Hartel and Herwegh 2012), whereas the younger ages are more close to the localized and late Simplon Fault. The 12 Ma age also falls together with the switch in deformational style elsewhere in the Western Alps discussed above, and is followed by a group from~10-7 Ma (Figs. 4, 7d). These two age groups are also recorded in the central Lepontine (sample DUTH 6; Fig. 5e). After 10 Ma, the weighted mean ages show a spread down toca.7 Ma but are progressively restricted to the westernmost areas close to the fault zones (Figs. 4, 7e, f). The ages likely mark phases of tectonic activity and corroborate evidence of continuing deformation along the Rhone-Simplon Fault (e.g. Zwingmann and Mancktelow, 2004; Campaniet al., 2010; Suraceet al., 2011). Only one sample in this group (VANI 5; Fig. 7f) yields ages younger thanca.7 Ma, with a weighted mean age around 5.5 Ma and a spot age of~2.7 Ma (Fig. 5m). The sample comes from an area where strong late-stage hydrothermal activity occurred, and the~5.5 Ma age coincides with ZFT ages of 6.4-5.4 Ma that are younger than those found in most of the region (Kelleret al., 2006). This coincidence of ages younger than in the surrounding areas may indicate a resetting of the ZFT ages through the hydrothermal activity. These phases of strike-slip deformation are not local to the western Lepontine Dome, but seem to have affected the extended Rhone-Simplon Fault system in much of the Western Alps (Bergeret al., 2013; Grand ' Hommeet al., 2016; Bergemannet al., 2017, 2019; Ricchiet al., 2019).

7 Summary

Hydrothermal fissure monazite-(Ce) offers the possibility to date tectonic activity in the brittle domain for extended time periods, as it could be shown to provide a record of the shifting tectonic activity within the Lepontine Dome associated with the regional exhumation history. A comparison between hydrothermal monazite-(Ce) samples from different parts of the Lepontine Dome and thermo-chronometric data suggest that hydrothermal monazite-(Ce) dating might be used to identify areas of slow exhumation/cooling rates during ongoing tectonic activity. The ^{232}Th-^{208}Pb monazite-(Ce) crystallization data records prolonged hydrothermal activity between 19 and 5 Ma contribute to the understanding of the tectonic evolution of the Central Alps in a temperature range of ca. 350-200

Pb monazite-(Ce) crystallization data records prolonged hydrothermal activity between~19 and 2.7 Ma, and contribute to the understanding of the tectonic evolution of the Central Alps in a temperature range of roughly 350-200 °

C. The oldest ages of 19-17 Ma come from the eastern- and southernmost regions of the study area (Fig. 1), in the hanging wall of the Forcola and Rhone-Simplon faults defining the borders of the metamorphic dome. Within the dome, monazite-(Ce) crystallization started in the northern Ticino dome and eastern Gotthard nappe around 15 Ma and show signs of slow exhumation. Further west, in the Toce dome, primary crystallization occurred in the western Gotthard nappe and the central Aar massif at 12-10 Ma. Younger ages of 9-7 Ma in the west of the study area record the progressive concentration of tectonic activity along the large fault systems of the Rhone-Simplon Fault and the Rhine-Rhone Line.

C. The monazite-(Ce) age record reveals a relatively smooth east-west age trend within the Lepontine Dome. The record starts in the eastern- (and southern) parts of the study area, with

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Figure 8.Backscatter electron image of monazite-(Nd) co-type material sample GRAESER 4 with the ovals representing the two measurement 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 on the large fault systems of the western Lepontine Dome. The oldest ages of~19-17 Ma come from the eastern- and southernmost regions of the study area, in the hanging wall of the Forcola and Rhone-Simplon normal faults. Within the dome, monazite-(Ce) crystallization started in the eastern Lepontine Dome, as well as the eastern Gotthard Nappe around 16-15 Ma. Further west, primary crystallization occurred in the western Gotthard nappe at 13-10 Ma. Younger ages of 9-7 Ma in the west of the study5 area record the progressive restriction of the recorded tectonic activity to the extended Rhone-Simplon Fault system.

Competing interests.No competing interests are present.

Acknowledgements.This work was funded by the Swiss National foundation, projects 200021-143972 and 200020-165513. We greatly appreciate the help of M. Andres, R. Duthaler, M. Flepp, S. Graeser, L. Klemm, B. Hofmann, A. Salzmann, F. Vanini, and M. Walter in20 organizing monazite-(Ce) samples for this study.

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Manuscript under review for journal Solid Earth
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Acknowledgements.Fraukje Brouwer and Meinert Rahn are thanked for their detailed reviews that considerably improved this manuscript. We would also like to thank Anna Wenzel and Bernhard Grasemann for their editorial handling and helpful contact during manuscript revision. We greatly appreciate the help of M. Andres, R. Duthaler, M. Flepp, S. Graeser, L. Klemm, B. Hofmann, A. Salzmann, F. Vanini, and M. Walter by providing monazite-(Ce) samples for this study. This work was funded by the Swiss National Science Foundation, projects 200021-143972 and 200020-165513.5

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