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U–Pb SHRIMP dating of zircon from the Novate granite (Bergell, Central Alps): evidence for Oligocene–Miocene magmatism, Jurassic/Cretaceous continental rifting and opening of the Valais trough

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Abstract

U–Pb SHRIMP-dating assisted by cathodoluminescence imaging was carried out on different types of zircons and zircon domains from the Novate granite (Bergell, Central Alps). The melt-precipitated oscillatory zircon domains yielded an age of 24.0 ± 1.2 Ma for the time of emplacement of the Novate granite. This age is in good agreement with the 25.1 ± 0.6 Ma SHRIMP-ages obtained for pegmatites of the southern steep belt (SSB). It seems probable therefore, that the magmatic activity generating the Novate and possibly also other intracrustal granites (not exposed at the surface) is linked to the formation of the numerous pegmatites and aplites that crosscut the more or less vertical structures of the SSB. The time of backfolding and backthrusting of the Central Alps over the Southern Alps is constrained to be between ca. 30 Ma (age of the Bergell granodiorite) and ca. 24–25 Ma. The numerous published mineral ages of the SSB, yielding ca. 24–25 Ma or scattering between ca. 30–25 Ma, can best be explained with this ca. 24–25 Ma old, magmatically induced static metamorphic overprint, that is probably restricted to the SSB. Therefore, they postdate the regional metamorphic peak, recorded best in the Adula-Cima Lunga nappe system, by up to ca. 8 Ma. Calculated average cooling rates to 280 °C (zircon fission track) for the Novate granite are 89 °C/Ma or 68 °C/Ma (depending on the assumed crystallization temperature).

Caledonian and Hercynian zircon cores occur within the co-magmatic zircons. Granulite-type inherited zircons from the Novate granite were separated and dated. They include sector zoned and slightly oscillatory zoned zircons yielding ages of 142.8 ± 7.0 Ma and 133.5 ± 3.9 Ma, respectively. These inherited zircons are interpreted to have formed within the lower crust, as a result of granulite-facies pulses triggered by rift-related underplating of basic melts. Such episodic rifting processes around the Jurassic/Cretaceous boundary probably caused the break-off of the Briançonnais microcontinent from the European crust and the opening of the Valais ocean. Thus, the source rocks of the Novate granite lie probably within continental crust of the Central Alpine Valais domain on either or both sides of the Valais ocean.

Keywords: SHRIMP, U–Pb zircon, Novate granite, Bergell, Central Alps, Valais domain.

1. Introduction

The Bergell (Bregaglia) in the Central Alps is an area that has attracted the interest of numerous researchers mainly because of its key position between the Penninic and Austroalpine nappes at the eastern margin of the Lepontine (for details see e.g. SCHMID et al., 1996).

The post-nappe deformational history in the Bergell Alps is closely related to the timing of the Bergell intrusions (ages at ca. 30 and ca. 32 Ma for the granodiorite and the tonalite, respectively; e.g. von BLANCKENBURG, 1992) including the Novate granite. The latter is younger than both the synmetamorphic Bergell tonalite and the virtually undeformed and unmetamorphosed granodiorite (e.g. DAVIDSON et al., 1996; BERGER et al., 1996). However, unlike the Bergell intrusions, its age is not well constrained radiometrically as the existing, partly inconsistent radiometric and fission

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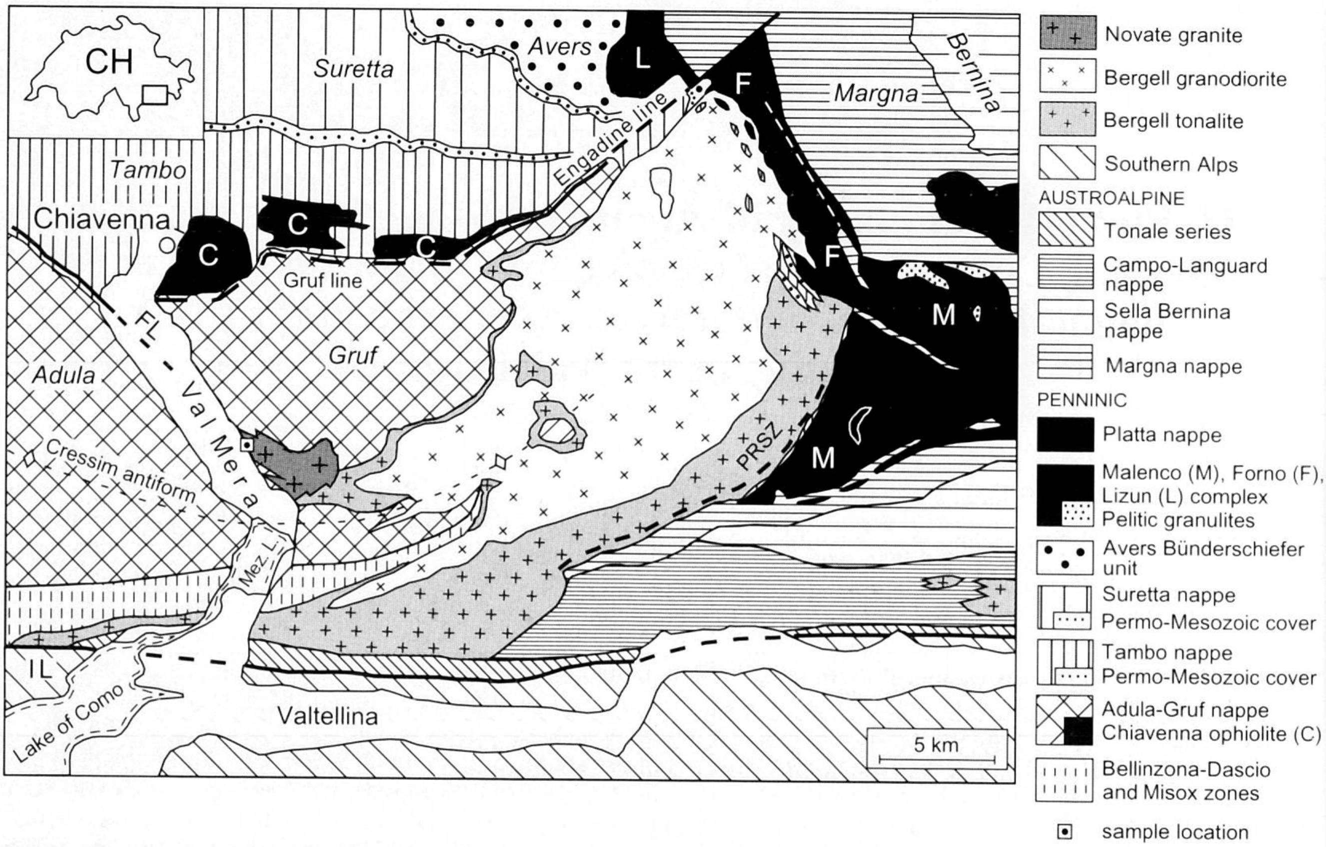

Fig. 1 Tectonic map of the Bergell pluton and surrounding tectonic units, including the Novate granite (from Schmid et al., 1996). FL: Forcola Line; IL: Insubric Line; PRSZ: Preda Rossa Shear Zone.

track mineral data (Tab. 1), give information almost exclusively on its post-emplacement alteration and cooling history.

The aim of this study is to date precisely the age of emplacement of the S-type Novate granite in order to try to answer the following questions: (1) What are the time constraints for the post-nappe deformational stages in the southern steep belt (SSB)? (2) Are the ca. 25 Ma old pegmatites and aplites (Gebauer, 1996; Romer et al., 1996) genetically related to intracrustal granites (of the same type as Novate), not presently exposed at the surface? (3) How does the emplacement of the Novate granite, and possibly also of the numerous pegmatites and aplites of the SSB, affect the cooling history in this area? (4) Are the ca. 25 Ma old extensive fluid activity and reheating, observed in the mafic/ultramafic and felsic rocks at Alpe Arami (SSB) related to the emplacement of intracrustal granites (Novate and others of the same type) and their late magmatic fluids? Furthermore, SHRIMP-dating of zircons from especially S-type granites has the important advantage of dating also zircons inherited from the source rock. In the case of the Novate granite dating of such zircons can provide information on the age and possibly also the palaeogeography of the source from which the magma was produced.

2. Geological setting and description of the dated rocks

The Novate granite, exposed in Val Mera (Fig. 1), is an S-type leucocratic two-mica granite with associated aplite and pegmatite dikes that crosscut the late structures of the SSB. It is generally fine- to medium-grained and consists of quartz, plagioclase, K-feldspar, biotite, muscovite and commonly also garnet. It is often inhomogeneous and locally shows mineral orientation inherited from the source rock. As already mentioned, it crosscuts fabrics of the Bergell tonalite. Based on geochemical criteria, the peraluminous Novate granite is not related genetically to the calc-alcaline Bergell suite. It rather derived by partial melting of crustal rocks during late-Alpine decompression (e.g. Reusser, 1987; Oschidari and Ziegler, 1992; von Blanckenburg et al., 1992). Thus, the intrusion of the Novate granite probably occurred during exhumation of the Bergell pluton in connection with backthrusting along the Insubric line (Schmid et al., 1987, 1989; Heitzmann, 1987). Previous radiometric data of the Novate granite are summarized in table 1 (see also Hansmann, 1996, for a detailed review). They include biotite and muscovite Rb/Sr and K/Ar dating, as well as fission track dating on apatite

Tab. 1 Summary of radiometric data from the Novate intrusion.

Rock type	Locality	Method, Mineral	Age (Ma)	Reference
pegmatite	1	Rb/Sr, mu	22.5±1.6	JÄGER et al., 1967
granite gneiss	1	Rb/Sr, bio	18.3±1.0	JÄGER et al., 1967
granite	2	Rb/Sr, mu	24.5±9.4	JÄGER and HUNZIKER, 1969; PURDY and JÄGER, 1976
granite	2	Rb/Sr, bio	22.1±2.1	JÄGER and HUNZIKER, 1969; PURDY and JÄGER, 1976
granite+aplites	3	Rb/Sr, w.r.	25±80	GULSON, 1973
granite	5	U/Pb, mon	26.0 (n.i.)	KÖPPEL and GRÜNENFELDER, 1975
granite	2	K/Ar, mu	22.9±1.1	PURDY and JÄGER, 1976
granite	2	K/Ar, bio	22.4±1.2	PURDY and JÄGER, 1976
granite	2	FT, ap	13.5±2.7	WAGNER et al., 1977
pegmatite	1	FT, ap	11.2±2.4	WAGNER et al., 1977
leucogranite	3	K/Ar, bio	21.5±0.6	MUNARDI, 1989
leucogranite	4	K/Ar, bio	21.9±1.6	MUNARDI, 1989
leucogranite	5	K/Ar, bio	21.4±1.6	MUNARDI, 1989
leucogranite	3	FT, zrc	18.1±3.2	MUNARDI, 1989; GIGER, 1991
leucogranite	5	FT, zrc	18.1±3.0	MUNARDI, 1989; GIGER, 1991
leucogranite	4	FT, zrc	19.9±3.6	MUNARDI, 1989; GIGER, 1991
leucogranite	3	FT, ap	15.1±2.2	MUNARDI, 1989
leucogranite	5	FT, ap	13.1±4.0	MUNARDI, 1989
leucogranite	4	FT, ap	16.7±2.6	MUNARDI, 1989
leucogranite	3	K/Ar, mu	21.8±0.4	MUNARDI, 1989
granite dyke	6	K/Ar, bio	21.7±3.6	MUNARDI, 1989
granite	5	U/Pb, mon	25.4, 25.0 (n.i.)	KÖPPEL, 1996 (in HANSMANN, 1996)

mu = muscovite; *bio* = biotite; *zrc* = zircon; *ap* = apatite; *w.r.* = whole rock; *mon* = monazite; *FT* = fission track; *n.i.* = not indicated. 1 = Novate-Mezzola; 2 = Codera; 3 = East Novate; 4 = Monticello; 5 = Riva (Novate); 6 = San Fedele.

and zircon. Given the relatively wide range of Rb/Sr, as well as K/Ar biotite and muscovite ages, the inconsistency between muscovite and biotite ages (biotite ages are hardly younger than muscovite ages) and the uncertainty in the U/Pb monazite ages (problematic correction for disequilibrium), precise dating of the Novate granite becomes necessary. Moreover, the necessity of dating the age of crystallization and not the cooling or alteration age, as may be the case for example for mica ages, is obvious.

The sample dated was taken from a homogeneous part of the Novate granite, where no mineral orientation is observed. It was collected in a quarry situated at the main road 1.8 km NNW of the village of Novate-Mezzola. It consists of quartz, K-feldspar, plagioclase, biotite, muscovite and garnet.

3. Analytical procedures

The U–Pb ionprobe data presented in this paper were obtained on SHRIMP II, at the Australian National University in Canberra. The spot size was between 15 and 20 microns in diameter. For data collection, seven scans through the critical mass range were made (further details on the SHRIMP technique are given, e.g., by COMPSTON et al., 1992).

SHRIMP-dating was assisted by cathodoluminescence (CL) imaging of the zircon crystals dated, since CL images allow distinction of different zircon domains, provide useful information on their formation history and, most importantly, help to avoid mixing of ages. In general, weak CL means high amounts of minor and trace elements, strong CL means low amounts of minor and trace elements, including U. Thus, in the pictures included in this paper the darker the colours of the zircon crystals (weaker CL emission) the higher the U content. The relative U contents can therefore be imaged by using CL.

The cathodoluminescence pictures of zircon crystals were produced at the ETH in Zürich from a split screen on a CamScan CS 4 scanning electron microscope (SEM) operating at 13 kV (see GEBAUER, 1996, for a detailed technical description). Secondary electron (SE) pictures were produced simultaneously with the CL pictures using a different detector. The same sample mount was used later for SHRIMP-dating.

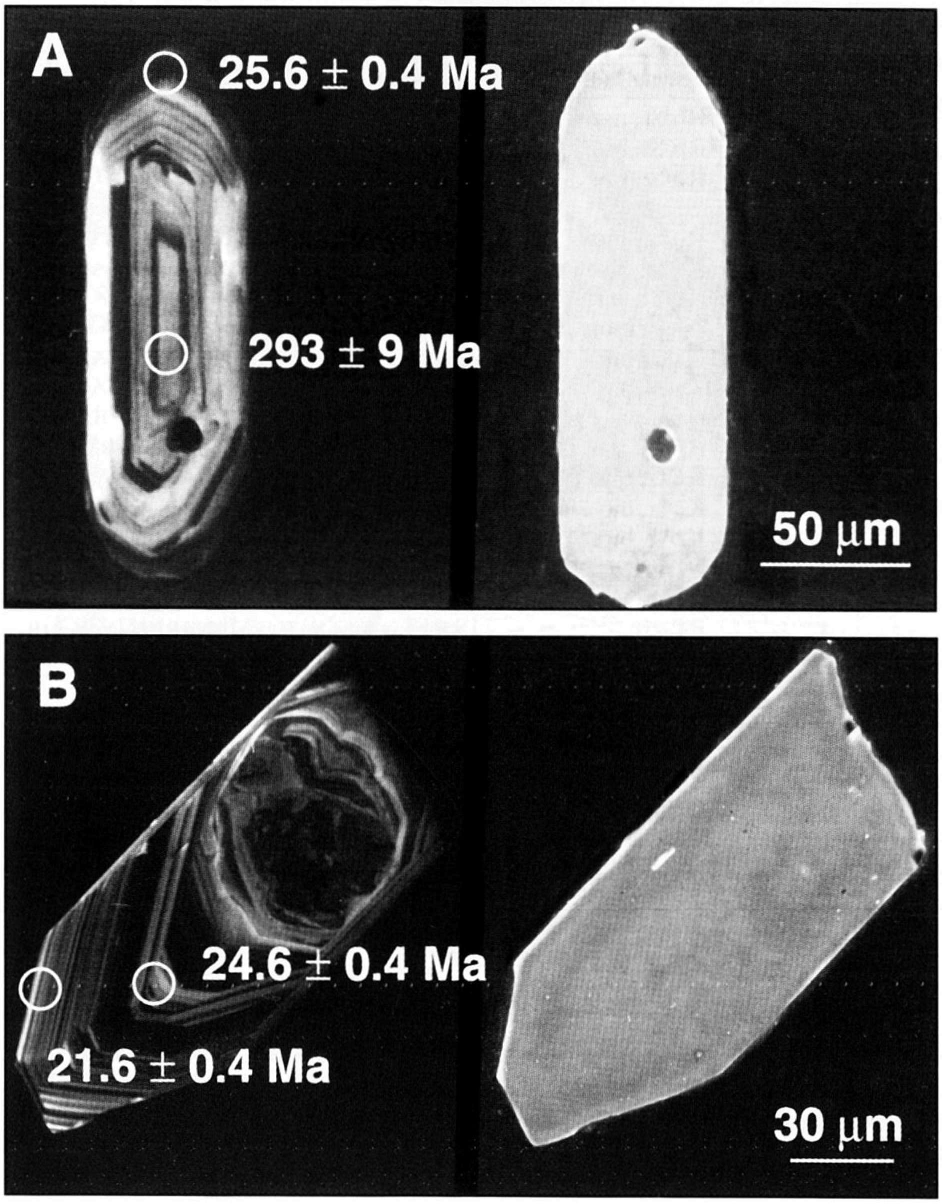

Fig. 2 Cathodoluminescence (CL) pictures (on the left) and secondary electron (SE) pictures (on the right) of co-magmatic zircon crystals from the Novate granite, enclosing older cores. In (A) a Hercynian core occurs within the young, co-magmatic zircon domain. Low luminescence of this domain, which makes oscillatory zoning almost indistinguishable, is due to its relatively high U content (analysis NOV1-8.1 in table 1). The size of the zircon crystal is better outlined by the SE picture. In (B) the oscillatory zoned domain which precipitated from the granite melt is clearly shown. Note the CL-light-coloured thin outermost rim of the crystal (best visible along the upper left rim) that probably formed by interaction with fluids after crystallization of zircon, resulting in some Pb loss (see also text).

4. Data evaluation

For the calculation of the Pb/U ratios, the data were corrected for common Pb using the ^{207}Pb correction method. Since this correction is based on the assumption of concordance, the data are graphically presented on Tera-Wasserburg (TW) diagrams.

The amount of common Pb was calculated using the isotope composition of common Pb obtained from both the model of CUMMING and RICHARDS (1975) and using the Broken Hill common Pb composition. With the exception of samples with very low ^{206}Pb/^{204}Pb ratios, the resulting ages were analytically indistinguishable. The Cumming and Richards model was chosen here, since most analyzed spots plot in the Tera-Wasserburg diagram along a mixing line passing closer through this isotopic composition (^{207}Pb/^{206}Pb = 0.834). The individual data points are plotted with 2σ errors.

For the U–Pb calibration both standards, SL13 (sample nr. with superscript[a] in table 2) and AS3

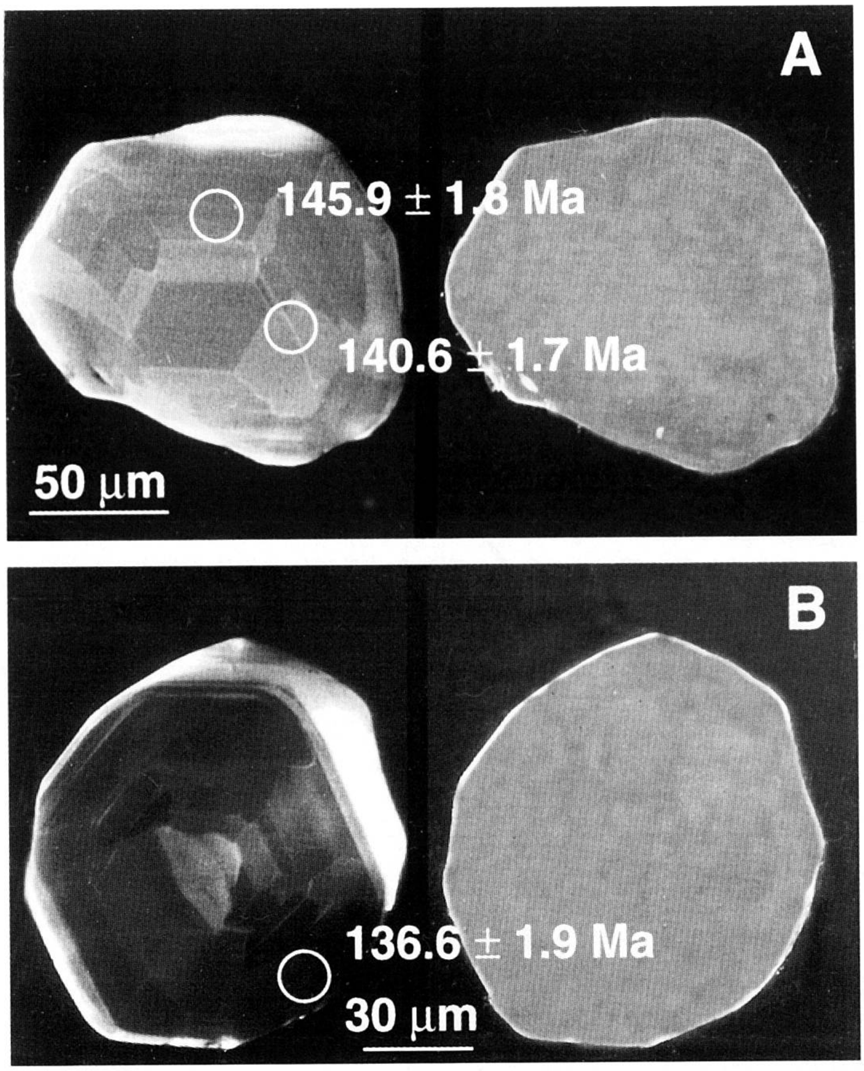

Fig. 3 Cathodoluminescence (CL) pictures (on the left) and secondary electron pictures (on the right) of inherited granulite-type zircon crystals from the Novate granite. Note the rounded shape typical of granulite-type zircons. (A) depicts a sector zoned crystal, (B) a slightly oscillatory zoned crystal (see also text).

were used. U and Th concentrations, however, are listed for all samples relative to SL13 (Tab. 2).

The mean ages were calculated both as normal mean and weighted mean. Although in both cases the resulting ages are identical within analytical error limits, the weighted mean is used here because it is more representative of the analytically best measurements. Mean ages are given at the 95% confidence level. For single analyses 1σ errors are given (Tab. 2).

5. Morphology of the zircon crystals and CL patterns

Two main types of zircons, differing both in their morphology and internal structure, were identified in the granite of Novate:

(1) Co-magmatic zircons: Zircons of this type are elongate, euhedral and consist of an outer oscillatory zoned domain varying in width between 15 and 50 microns and an inner older core (Fig. 2). As can be derived from the CL pictures and the SHRIMP-results (see below), the outer oscillatory domains precipitated from the granitic melt during early crystallization of the Novate granite.

(2) Inherited zircons : Two groups of inherited zircons are distinguished. (i) Zircon crystals with more or less rounded outlines. They are commonly equidimensional, 100–200 microns across but slightly elongate crystals also occur. Some of the zircon crystals show weak oscillatory zoning (Fig. 3B), others show sector zoning (Fig. 3A). Their morphology and CL characteristics are very similar to granulite-type zircons described e.g. in the Ivrea zone (Vavra et al., 1996) or the Rho-

Tab. 2 U, Th, Pb SHRIMP data for zircons from the Novate granite.

Sample	U (ppm)	Th (ppm)	Th/U	rad. Pb (ppm)	f^{206}Pb (%)	^{207}Pb/^{206}Pb (1σ) (uncorrected)	^{238}U/^{206}Pb (1σ) (uncorrected)	^{206}Pb/^{238}U (1σ) (radiogenic)	age (Ma) ^{206}Pb/^{238}U (1σ)
co-magmatic, oscillatory zircon domains									
NOV1-8.1	1587	41	0.026	6	0.37	0.0495 ± 0.0009	250.8 ± 4.8	0.0040 ± 0.0001	25.6 ± 0.4
NOV1-9.1	1136	156	0.137	4	0.84	0.0531 ± 0.0014	295.4 ± 5.9	0.0034 ± 0.0001	21.6 ± 0.4
NOV1-9.2[a]	4485	1418	0.316	17	<0.01	0.0460 ± 0.0007	261.3 ± 3.9	0.0038 ± 0.0001	24.6 ± 0.4
NOV1-11.1	7279	490	0.067	27	0.08	0.0471 ± 0.0005	241.6 ± 3.7	0.0042 ± 0.0001	26.6 ± 0.3
NOV1-11.2[a]	3506	525	0.150	12	0.10	0.0473 ± 0.0011	271.2 ± 3.3	0.0037 ± 0.0001	23.7 ± 0.3
NOV1-13.1	1992	119	0.060	7	0.66	0.0517 ± 0.0011	267.1 ± 4.7	0.0038 ± 0.0001	23.9 ± 0.3
(inherited cores)									
NOV1-1.2[a]	151	70	0.463	11	0.07	0.0560 ± 0.0016	14.5 ± 0.3	0.0688 ± 0.0014	429 ± 9
NOV1-8.3[a]	251	260	1.029	14	<0.01	0.0515 ± 0.0110	21.6 ± 0.7	0.0464 ± 0.0014	293 ± 9
NOV1-10.2[a]	336	180	0.531	16	0.20	0.0537 ± 0.0016	21.9 ± 0.3	0.0456 ± 0.0007	287 ± 4
inherited zircons									
(sector zoned zircons)									
NOV1-4.1	899	4	0.004	18	<0.01	0.0487 ± 0.0006	43.7 ± 0.7	0.0230 ± 0.0003	145.9 ± 1.8
NOV1-4.2	760	3	0.004	15	0.19	0.0504 ± 0.0009	45.3 ± 0.7	0.0221 ± 0.0003	140.6 ± 1.7
NOV1-6.2	174	2	0.010	3	0.40	0.0521 ± 0.0012	44.8 ± 0.8	0.0223 ± 0.0003	141.7 ± 2.1
(weakly oscillatory zircons)									
NOV1-3.1[a]	1138	5	0.005	22	0.10	0.0495 ± 0.0008	46.6 ± 0.6	0.0214 ± 0.0003	136.6 ± 1.9
NOV1-5.1[a]	930	4	0.004	17	0.17	0.0501 ± 0.0008	48.5 ± 0.6	0.0206 ± 0.0002	131.3 ± 1.5
NOV1-7.1	901	5	0.006	17	0.22	0.0503 ± 0.0005	47.4 ± 0.8	0.0211 ± 0.0002	134.3 ± 1.5
NOV1-7.2[a]	187	2	0.010	3	0.58	0.0533 ± 0.0015	48.1 ± 0.9	0.0207 ± 0.0004	131.8 ± 2.4

f^{206}Pb% denotes the percentage of ^{206}Pb that is common Pb.
[a]Analyses are relative to SL13. (The other analyses relative to AS3).

dope zone of northern Greece (GEBAUER and LIATI, 1997). As confirmed by the SHRIMP-data (see below), zircons of this type are probably inherited from the crustal source rock that melted partially to form the granite of Novate. (ii) Irregularly shaped crystals showing oscillatory zoning which occur as cores overgrown either by the granulite-type zircons described above or by co-magmatic zircons (e.g. Fig. 2A).

The granulite-type zircons show no overgrowth by co-magmatic zircon. We comment on this below, in view of the SHRIMP-results.

6. SHRIMP-results and interpretation

The ion microprobe data for the analyzed zircons are given in table 2 and plotted on Tera-Wasserburg (TW) diagrams (Fig. 4). The weighted mean ages and the errors (at the 95% confidence level) are given in figure 4.

(1) Co-magmatic zircons: Six data points were obtained from the outer oscillatory zoned, co-magmatic zircon domains. On a TW diagram three of them plot within analytical error limits on a mixing line with common Pb and radiogenic ^{238}U/^{206}Pb as end members. The ages of these three spots average at 24.0 ± 1.2 Ma (95% c.l.; MSWD: 2.1). One spot analysis plots immediately to the left of the mixing line (Fig. 4A). Careful observations of the corresponding CL picture reveals that the analyzed spot may have just touched an older Hercynian core (spot 8.1, Fig. 2A), which thus may have increased the age by an amount small enough to shift the data point very slightly to the left. If we include this point in our weighted mean calculations, we get an insignificantly older age (24.3 ± 1.3 Ma), while the MSWD value increases from 2.1 to 5.6. Based on the CL characteristics and the form of the zircon crystals as described above, the 24.0 Ma age (or the 24.3 Ma age) reflects the time of precipitation of zircon in the granitic melt of Novate.

The other two data points plot farther away on either side of the mixing line. The one on the left side yields an older age (26.6 ± 0.3 Ma), which is attributed to the very high U content of the zircon (7280 ppm; for this issue see also MC LAREN et al. 1994 or WILLIAMS et al. 1996). The one on the right side yields a younger 'age' (21.6 ± 0.4 Ma). In this case, the analyzed spot lies very near the edge of the crystal (partly on the epoxy) and was probably affected by some Pb loss. Careful examination of the CL picture reveals a very thin (3–4 μm) bright rim forming locally some embayments at the outermost edge of the zircon (upper left part

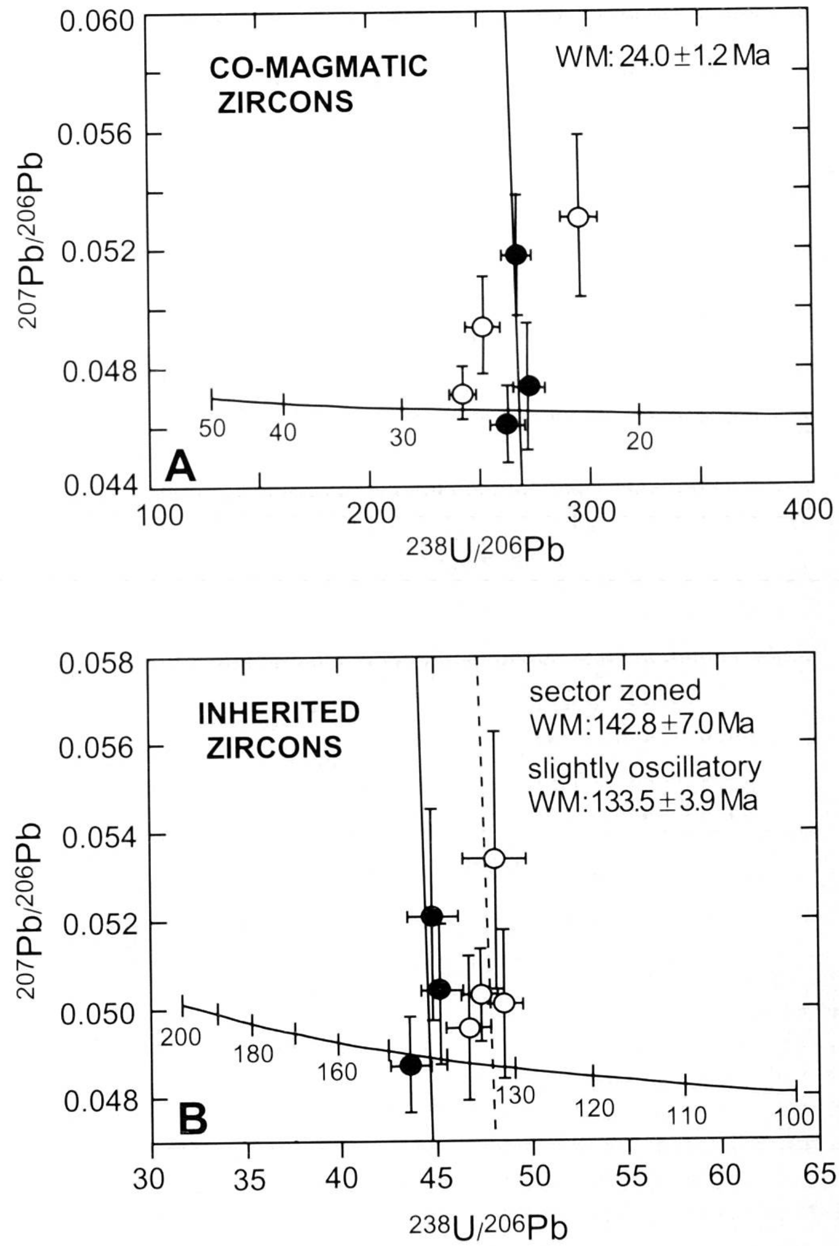

Fig. 4 Tera-Wasserburg (TW) diagrams with data of zircons from: (A) the co-magmatic, oscillatory zoned zircon domains. The analyzed points plot along a mixing line with common Pb (composition according to the model of Cumming and Richards, 1975) and radiogenic $^{238}U/^{206}Pb$ as end members. Three outliers (open circles) are due to: spot slightly touching a Hercynian core (just left of the mixing line), the very high U contents of the analyzed spot (further left off the mixing line) and to lead loss (point on the right side of the mixing line); (B) the inherited granulite-type zircons. The analyzed points plot along two different mixing lines interpreted to reflect two distinct stages of rifting processes (see text): filled circles are data from the sector zoned crystals, open circles from the slightly oscillatory zoned crystals. 'WM': weighted mean; error at the 95% confidence level; error bars of the individual analyses are 2σ errors.

of figure 2B). This may have resulted from the action of fluids after co-magmatic zircon precipitation. This interaction with fluids may explain Pb loss of an initially older zircon (24.0 ± 1.2 Ma) resulting in a younger figure, i.e. 21.6 ± 0.4 Ma. Therefore, the 21.6 ± 0.4 Ma analysis does not reflect a geologically meaningful age, but must be taken as a mixing age between that of co-magmatic zircon precipitation and fluid overprint. It can be considered as a maximum age for a post-magmatic fluid overprint.

(2) Inherited zircons: Seven data points were obtained from the granulite-type inherited zircons. Three of them are from sector zoned zircons (e.g. Fig. 3A) and four from those with slight oscillatory zoning (e.g. Fig. 3B). The SHRIMP-analyses from the sector zoned and the oscillatory zoned zircons plot along two mixing lines on a TW

diagram which intersect the concordia at 142.8 ± 7.0 Ma (MSWD: 1.9) and 133.5 ± 3.9 Ma (MSWD: 2.5), respectively (Fig. 4B). The errors (95% c.l.) of 7.0 Ma and 3.9 Ma for the two zircon types are large due to the few data. Thus, considering the extreme error margins for the two zircon types, the ages overlap by 1.6 Ma, at a calculated weighted mean age difference of 9.3 Ma (142.8–133.5). Nevertheless, it is important to note that the data sets for both zircon types are analytically consistent. This is expressed in the fact that all individual spot ages from the sector zoned domains are systematically older than the ages of the oscillatory domains. In addition, the 2 sigma errors of the individual spot analyses are between 3.0 and 4.7 Ma for the oscillatory zoned zircons and between 3.4 and 4.1 Ma of the sector zoned zircons. On the other hand, the age errors of 2 sigma standard deviation of the mean (= 2 standard errors), are 2.5 Ma and 3.2 Ma, for the oscillatory and sector zoned zircons, respectively. This results in two ages significantly different from each other, at least by 3.6 Ma. Although geologically of no major importance, we feel that it is justified to conclude that the analyzed sector zoned zircons are slightly older than the oscillatory zoned zircons. This is also in line with observations from the Ivrea Zone, Southern Alps (e.g. GEBAUER, 1993 or VAVRA et al., 1996).

As already mentioned, based on their morphology and CL characteristics, the sector zoned and oscillatory zoned inherited zircons are characterized as granulite-type zircons. A prominent interpretation is that they formed within the lower crust during rift related intrusion of basic melts (magmatic underplating). The basic melts caused local heating and intergranular melting of the adjacent continental crust. Under these conditions, zircons could grow newly in the partial melt. Underplating of basic magma may well have occurred in more than one stage thereby causing more than one thermal pulse which would result in melting episodes and therefore zircon growth in the partial melts. During the first stage, at 142.8 ± 7.0 Ma, restricted amounts of partial melt were present, which resulted in the formation of sector zoned zircon crystals (see also VAVRA et al., 1996). During the second stage, at 133.5 ± 3.9 Ma, higher degrees of partial melting and/or faster crystallization of zircon occurred and oscillatory zoned crystals formed. The reason why more melt was present in these crustal rocks during the second stage may be related to intrusion of higher amounts of basic melts into the lower crust and/or the position of the basic melts closer to the partially melted crustal rocks. Magmatic underplating involving abundant basic intrusions is probably related to the initiation of rifting, which should then be placed temporally at around this time.

The lack of 24.0 ± 1.2 Ma magmatic rims around the granulite-type zircons may be interpreted by assuming that these zircons come from xenoliths that were digested at a level of intrusion where undersaturation of zircon occurred in the melt.

An alternative explanation for the ages of the granulite-type zircons would be to consider the data as reflecting a single, long-lasting granulite-facies pulse (between ca. 143 Ma and ca. 131 Ma; youngest and oldest ages of the corresponding five inherited granulite-type grains). We consider this possibility as less likely because in such a case zircon would precipitate during the time of partial melting and therefore one would rather expect a concentration of the ages at the beginning of this granulite-facies pulse (i.e. at around 143 Ma). Instead, as discussed above, we rather see a concentration of the zircon ages at two different times. This infers two partial melting events closely following each other.

Older cores of inherited zircons of the second group (see section 5) yielded Caledonian (429 ± 9 Ma) or Hercynian ages (293 ± 9 Ma; Fig. 2A and 287 ± 4 Ma) reflecting previous (pre-Alpine) magmatic episodes, assuming the individual cores can be shown to give reproducible and concordant ages.

7. Geodynamic implications and conclusions

The melt-precipitated oscillatory zoned zircon domains yield a protolith age of 24.0 ± 1.2 Ma for the granite of Novate. Unlike previous mineral chronometers that were generally interpreted to reflect cooling ages (mainly K/Ar and Rb/Sr on muscovite and biotite; see table 1), the zircon SHRIMP-data rather reveal the time of emplacement of the granite. This is now well constrained to be ca. 2 Ma older than the ages given by the analytically indistinguishable biotite and muscovite ages (Tab. 1).

An important implication arising from the present SHRIMP-results is that the time of emplacement of the Novate granite agrees very well with SHRIMP-ages at 25.1 ± 0.6 Ma (GEBAUER, 1996) obtained for pegmatites of the SSB. These pegmatites were interpreted to reflect a final thermal pulse connected to considerable magmatic and fluid activity after formation of the SSB. It is then very probable that many pegmatites and aplites are genetically related to the Novate granite and possibly also other granites of similar type, not presently exposed at the surface. A direct, previously unrecognized evidence for this relatively local metamorphic overprint under static conditions around 24–25 Ma are many concordant, i.e. analytically identical muscovite and biotite ages (both Rb/Sr and K/Ar). In addition, hornblende-Ar ages also fall within analytical error limits into the same time range. These numerous mineral ages were reported from both the Bergell tonalite and granodiorite, the Gruf migmatites and from different rock types of the southern, generally steeply dipping parts of the Simano, Adula-Cima Lunga, Tambo and Suretta nappe systems (see compilation of HANSMANN, 1996). At Alpe Arami, there are numerous zircon domains, usually forming at the rims of zircon crystals from ultramafic/mafic and felsic rocks, which give ages at ca. 25 Ma and therefore demonstrate the importance of this late, static metamorphic overprint that seems to be limited to the SSB.

There are also some multi-grain monazite ages from the Simano nappe (Calanca valley) and the SSB in the areas of Bellinzona and Locarno (summary by HANSMANN, 1996 and KÖPPEL, pers. comm.) that fit the ca. 24–25 Ma age range. These monazite data are not corrected for radioactive disequilibrium and therefore may represent only maximum ages. Thus, although some may reflect a geological event, they can not be demonstrated a priori to reflect all concordant, geologically meaningful ages. Previously published zircon domain SHRIMP-data from the Cima Lunga nappe system (SSB) gave ages at 32–33 Ma, ca. 30 Ma, 24–25 Ma (GEBAUER, 1994, 1996) and even less than ca. 21 Ma, as deduced in this and other studies (Liati and Gebauer, unpubl.). Thus, the monazites may also contain domains of slightly, but significantly different ages with a similar age spectrum as the zircons. Of course, also very slightly discordant data, caused by Pb-loss, may be expected in the monazites.

The Sm–Nd data on 3 garnet fractions, calcite and whole-rock from the Castione quarry in the SSB (26.7±1.7 Ma; VANCE and O'NIONS, 1992) also fall into this age range given mainly by the SHRIMP-age of the Novate granite. However, as these Sm–Nd data do not strictly define an isochron, both age and error may be misleading.

Naturally, it remains speculative to define the cause(s) for this Oligocene–Miocene heat input that triggered melting of the lower crust to produce S-type granites. Counterflow of hot asthenospheric mantle after delamination of subducted lithosphere (e.g. VON BLANCKENBURG and DAVIES, 1995) has been proposed as a plausible model (GEBAUER, 1999), but clearly more work is necessary to obtain a better constrained answer to this problem.

As the ca. 25 Ma old pegmatites crosscut the steep, partly even overturned S-vergent structures of the SSB, they yield a minimum age for this important episode of backfolding and backthrusting of the Central Alps over the Southern Alps. A maximum time limit for backfolding and backthrusting of the Central Alps over the Southern Alps is put at ca. 30 Ma (age of the Bergell granodiorite).

Furthermore, as some brittle deformation can be seen in the ca. 25 Ma old pegmatites, this very late phase of deformation is constrained to be younger than 25.1 ± 0.6 Ma.

Regarding the cooling history of the Novate granite, previous estimated average rates for initial cooling between presumed temperature of emplacement (> 640 °C; solidus temperature) at 25 Ma and 300 °C at 22 Ma are 140–175 °C/Ma, then 21 °C/Ma, from 300 °C to 120 °C (22 Ma–14 Ma) and finally 6 °C/Ma during the last 14 Ma (see review paper by HANSMANN, 1996, and references therein). These rates are based on the blocking temperature concept, i.e. the K/Ar and Rb/Sr biotite ages, ranging from 21.4 ± 1.6 Ma to 22.4 ± 1.2 Ma (see table 1), are taken as cooling ages. An exception, however, is a 18.3 ± 1.0 Ma Rb–Sr age by JÄGER et al. (1967; Tab. 1). An additional complication for this model is the fact the the K/Ar and Rb/Sr muscovite ages give identical ages at ca. 22 Ma (Tab. 1).

At the time of emplacement of the Novate granite, now reliably fixed at 24.0 ± 1.2 Ma, its country-rocks (Gruf complex and Bergell pluton) were assumed to have cooled down to temperatures of ca. 500 °C (HANSMANN, 1996). Thus, based on the SHRIMP-results and the published biotite ages (Tab. 1; 21.7 ± 0.4 Ma; weighted mean of 6 biotite ages at 95% c.l.), the average regional cooling rates, based on the weighted mean ages, calculated between 500 °C and 300 °C, are 87 °C/Ma. Doing the same type of calculation for cooling of the Novate granite only, cooling rates of ca. 150 °C/Ma apply assuming a solidus temperature of 640 °C (NANEY, 1983), or ca. 200 °C/Ma assuming a relatively high solidus temperature of 750 °C (e.g. WHITNEY, 1988). Applying extreme error values simultaneously (24.0+1.2 = 25.2 Ma and 21.7–0.4 = 21.3 Ma, resp. 24.0–1.2 = 22.8 and 21.7+0.4 = 22.1 Ma), maximum and minimum cooling rates of 285 °C/Ma and 50 °C/Ma arise. It should be noted that since our errors are given at the 95% confidence level, it is rather unlikely that lowermost and uppermost extreme age values apply simultaneously for both dated minerals (biotite and zircon) considered in the calculations.

Ignoring the blocking temperature concept and taking mica and other mineral ages as related to fluid induced recrystallization (e.g. VILLA, 1998), cooling rates for the Novate granite and its country-rocks have to be estimated by fission track ages. For the Novate granite , cooling from 750 °C, resp. 640 °C to 110 °C (apatite) results in average cooling rates of ca. 70 °C/Ma, resp. ca. 60 °C/Ma. Taking the average zircon fission track ages of MUNARDI (1989) and GIGER (1991) for the Novate granite to be 18.7±1.2 Ma and an annealing temperature of 280 °C (assuming cooling rates > 50 °C/Ma, e. g. FOSTER et al., 1996 or YAMADA et al., 1998), initial cooling rates are 89 °C/Ma, resp. 68 °C/Ma. These cooling rates are considerably lower than the extremely high cooling rates of ca. 200 °C/Ma, resp. 150 °C/Ma as derived from the assumption of the cooling age concept. This, together with initial cooling rates of ca. 50–100 °C/Ma found in other parts of the Central and Western Alps (see summary in GEBAUER, 1999) argues here against the blocking temperature concept for isotopic dating of minerals (see also VILLA, 1998). The biotite ages (21.7 ± 0.4 Ma), being ca. 3 Ma older than the zircon fission track ages from Novate, can be taken as further evidence that they are not related to simple cooling to about 300 °C. The biotite age of 18.3 ± 1.0 Ma (JÄGER et al., 1967), however, may reflect some fluid induced recrystallization at temperatures around 280 °C. This event is probably also responsible for minor recrystallization along the outermost margins of the zircon resulting in a geologically meaningless mixed age of 21.6 ± 0.4 Ma (spot Nov 1-9.1; Tab. 2). As described in the previous chapter, this 21.6 ± 0.4 Ma 'age' would reflect a maximum age for this fluid induced event inside the Novate granite.

It is interesting to note that zircons from a garnet peridotite at Alpe Arami (SSB) gave a fission track age of 17.4±0.9 Ma (GEBAUER et al., 1992). This, together with biotite and muscovite ages (both Rb/Sr and K/Ar) being also around 18–20 Ma, argues for similar cooling rates and times of fluid induced recrystallization further to the west within the SSB.

Assuming a geothermal gradient of 30 °C/km for the metamorphism of the country rocks and considering temperatures of the country rocks at 24.0 Ma to have been ca. 500 °C (HANSMANN, 1996), calculated initial exhumation rates of the Novate granite and its country-rocks (24.0 ± 1.2 Ma to 21.7 ± 0.4 Ma) are ca. 2.9 mm/a (or 2.9 km/Ma), slowing down to an average rate of 0.8 mm/a (21.7 Ma to 14 Ma) and 0.3 mm/a over the past 14 Ma. Again, taking into account the rather unlikely case of extreme error values applying simultaneously, minimum and maximum initial exhumation rates of 1.7 mm/a and 9.5 mm/a arise for the time period 24.0 ± 1.2 Ma to 21.7 ± 0.4 Ma.

The inherited zircon domains as cores inside the oscillatory zoned zircon domains give Caledonian and Hercynian ages. This is in agreement with well known ages of pre-Alpine orogenic episodes in the continental crust of the Alps.

The inherited granulite-type zircons are interpreted to have formed within the lower crust during rift-related intrusions of basic melts (underplating), probably in two stages: at 142.8 ± 7.0 Ma and 133.5 ± 3.9 Ma. These basic intrusions caused local intergranular melting of the adjacent lower continental crust, more pronounced at around 133 Ma, and produced the granulite-type zircons. The interpretation of these zircons as reflecting rifting episodes around the Jurassic/Cretaceous boundary, i.e. break-off and separation of the Briançonnais microcontinent from the European crust, fits well with recent SHRIMP-results for the MORB-type protoliths of eclogites from Antrona (ca. 133 Ma; Liati and Gebauer, unpublished data). Thus, the opening of the Valais ocean, as also inferred from sedimentological evidence (e.g. TRÜMPY, 1980), closely follows continental rifting episodes around the Jurassic/Cretaceous boundary.

These rifting episodes around the Jurassic/Cretaceous boundary cannot be related to the opening of the Piemont-Ligurian ocean, because ophiolite members of this ocean have been dated at ca. 164 Ma (e.g. Zermatt: RUBATTO et al., 1998; Platta: DESMURS et al., 1999). Thus, the source of the Novate granite belongs to the Central Alpine Valais domain and lies in continental crust on either or both sides of the Valais ocean.

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