TESI DI LAUREA MAGISTRALE IN GEOLOGIA E GEOLOGIA TECNICA

TERTIARY PEGMATITE DIKES IN THE CODERA AND BODENGO AREAS OF THE CENTRAL ALPS

Relatore: Prof. Giorgio Pennacchioni
Correlatori: Dott. Alessandro Guastoni
Dott. Anna Maria Fioretti

Laureando: Giacomo Pozzi

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Previous page: the “Altare”, upper Cadera valley
**Abstract**

The tertiary pegmatite field of the Central Alps extends for about 100 km in an E–W direction from the Bergell pluton (to the east) to the Ossola valley (to the west). It intrudes the steepened roots of the Alpine nappes (Souther Steep Belt) north of the Periadriatic Fault and gradually fades within 15 km toward north. The pegmatite field geographically overlaps (1) the highest temperature domain of the Lepontine Barrovian metamorphic dome and (2) the zone of Alpine migmatization. In this thesis is attempted a first multidisciplinary study on these pegmatites over a limited surface of the whole extension of the pegmatite field. Pegmatites were studied in two different areas: (1) the Codera area, located on the western border of the Bergell Pluton, and (2) the Bodengo area, located between the Mera and the Mesolcina valleys. Results show that Codera and Bodengo pegmatites differ under many aspects including structural, geochemical and radiometric data. The main set of pegmatite dikes of Codera area is steeply dipping and strikes WSW-ENE. Crosscutting relationships suggest the presence of at least two generations. All dikes were involved in ductile deformation and in some cases localize mylonitic shear zones. Codera pegmatites were emplaced at relatively high temperature of at least 500°C, which is constrained by the mineral assemblage along the mylonites and the strong CPO of recrystallized quartz (with c-axis maximum in the direction of the Y kinematic axis of the mylonite). The main set of pegmatites of Bodengo area trends approximately N-S to NNE-SSW and crosscuts the ductile deformation structures of the SSB. Most of these dikes are undeformed but some show ductile reactivation at the borders. Bodengo area also includes an earlier generation of boudinaged and folded pegmatite dikes oriented at a small angle to the host rock foliation. Miarolitic pockets are contained only in some undeformed dikes of Bodengo area. The mineralogical content of pegmatites of the two areas does not differ substantially. Most pegmatites have a simple mineral assemblage consisting of K-feldspar, quartz, and muscovite ± biotite, and only a minor percentage of the dikes contain rare accessories including almandine-spessartine garnet, pale blue beryl and schorl tourmaline. On the other hand chemical analyses on minerals, especially on garnets, allow distinguishing further the two selected areas. Codera garnets are systematically richer in spessartine than Bodengo ones and some Codera tourmalines show higher degrees of evolution (toward elbaite compositions) than Bodengo schorls. Radiometric data of monazite crystals yielded different \(^{208}\text{Pb}/^{232}\text{Th}\) ages for Codera and Bodengo pegmatites, which do not overlap and are respectively older and younger than 24 Ma. We concluded that pegmatites of Codera area and Bodengo area belong to different intrusion events.
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1. **Introduction**

The Central Alps host the largest field of Oligocene-Miocene pegmatite dikes, which intrude the stack of the Alpine nappes (Guastoni et al., 2014). Previous studies on pegmatites have mainly dealt with specific characteristics of pegmatite dikes, e.g. their mineralogy and geochronology (e.g. Guastoni, 2012; Romer et al., 1996; Rubatto et al., 2009) but a comprehensive multidisciplinary study integrating the mineralogical, petrographic, structural and geological data is still missing. This multidisciplinary study is attempted in the current thesis for two selected areas in the central part of the Tertiary pegmatite field: namely the Codera area and the Bodengo area. The first area is located at the western contact between the Bergell intrusion and the Gruf complex migmatitic host rock, and includes two main study localities in the upper Codera Valley (COD) and in the Rossaccio (ROS) alp (*fig. 1*). The second area extends over a wider region between the Mera and the Mesolcina valleys within the heterogeneous metamorphic rocks of the southern Adula nappe. It includes the upper portions of several valleys: Garzelli valley (VG), Leggia valley (VLG), Del Dosso valley (VDD) and Darengo valley (VLD). As will be shown in this thesis, these two areas are dominated by different sets of pegmatites that record two main distinct phases of pegmatite intrusion in the Central Alps. Localities are reported with their codes in *fig. 1*.

2. **Overview on the Central Alps in the area of study**

2.1. Tectono-metamorphic history of the Central Alps

Central Alps are a subject that boasts of many years of study, which led to the formulation of a complex polyphasic tectono-metamorphic history. For this brief summary I manly refer to recent works of several authors that provided nice
Figure 1. (a) Simplified structural map of the Central Alps with the field of the Alpine (Oligocene–Miocene?) pegmatites as reported by Wenk (1970) and Burri et al. (2005) outlined by dashed and dotted lines, respectively. The map also shows the two major Tertiary batholiths of Adamello (Ada) and Bergell (Br), in grey, and the smaller and younger Novate stockwork intrusion, in black. The thick black lines represent the Periadriatic Fault (PF), the Giudicarie Fault (GF), and the Engadine Fault (EF). The light grey areas represent quaternary deposits along major valleys. (b) Structural map of the Bergell batholith and the region on the west showing the locations of the Codera and the Bodengo areas. The Codera area includes the upper Codera valley (COD) and the Rossaccio locality (ROS) indicated with black stars. The Bodengo area includes the Garzelli valley (VG), the Darengo valley (VLD), the Del Dosso valley (VDD), and the Leggia valley (VLG) indicated by empty stars. The map also shows the main boundaries (thin black lines) of the Penninic tectonic units: \textit{Lv} = Leventina; \textit{Sm} = Simano; \textit{Ad} = Adula; \textit{Ta} = Tambò; \textit{Su} = Suretta; \textit{Av} = Avers; \textit{BD} = Bellinzona-Dascio; \textit{MF} = Malenco-Forno. The thick black line labeled \textit{FF} is the Forcola Fault. Figure by Guastoni et al. (2014).
reviews concerning our area of interest (see Nagel, 2008; Beltrando et al., 2010; Galli et al., 2013).

The building of the Alpine orogen starts with the closure of the Piedmont-Ligurian and Valais oceanic basins due to the convergence between the Europe and the Adria microplate paleo-margins (Schmid et al., 1996). During this phase, south-dipping consumption by subduction of the oceanic lithosphere beneath the Adriatic margin induced an early staking of the Alpine nappes in an accretionary wedge and finally led to continent-continent collision.

The Central Alps mainly expose tectonic units referred to the lower Penninic domain which includes: (1) the Middle Penninic Zone (composed of the Maggia, Tambo, Suretta and Schams nappes), (2) the Lower Penninic Zone (Antigorio, Lebendun, Monte Leone and Adula nappes) and (3) the Sub-Penninic Zone (Lucomagno, Leventina and Simano nappes) (fig. 1). The Middle Penninic Zone has been interpreted as a domain restored in the Jurassic paleogeography between the Valais and the Piedmont oceans. During subduction, the nappe stacking within the accretion wedge occurred under high to ultra-high pressure (3 GPa in the southern part of Adula nappe) metamorphic conditions. This stage has been dated between 38 and 34 Ma. The age of the high-P metamorphism becomes progressively younger from top to the base of the nappe pile suggesting a sequential accretion during the closure of the ocean (Beltrando et al., 2010). According to Nagel et al. (2002) and Nagel (2008) in the the Adula nappe the oldest pervasive D1 deformation phase of the Central Alps postdates the eclogitic event and is referred as the local Zapport phase (<40Ma). The main foliation S1 is associated to top to N shearing and isoclinal folding. During D1 phase the Adula nappe was thrusted onto the Simano nappe with a substantial exhumation from eclogite to amphibolite facies conditions.

The D2 phase (local Claro for the Adula nappe and Niemet Beverin for the Tambo and Suretta nappes) followed D1 phase with a brief episode of E-W extension between 34 and 30 Ma. Top to SE shearing and folding developed a foliation parallel to the orientation of the fold axes. Extension may have been
achieved in different ways: passive re-equilibration after slab breakoff (45 Ma according to Von Blanckenburg and Davies, 1995) or episodic retreat of the subduction zone hinge by slab rollback (Beltrando et al., 2010). According to Beltrando et al. (2010) D2 deformation of the Central Alps, which formed during E-W extension, is well explained by the rollback of one of the oceanic slabs located west or south-west of the Alps. The collapse of the orogen led to rapid exhumation of the nappes and episodic magmatism such as the Bergell intrusion (Beltrando et al., 2010). The instauration of a medium-P and high-T Barrovian metamorphism in the Central Alps is coeval with the D2 ductile deformation phase (i.e. the Lepontine Dome). Peak conditions of 720–740 °C at 6.5–7.5 kbar produced sapphire-bearing granulites in the Gruf Complex (Galli et al. 2011). The dominant phase of the associated migmatisation in the Gruf Complex occurred between 34 and 29 Ma with the highest grade at about 32.7 Ma (Liati and Gebauer, 2003). According to Galli et al. (2012), the intrusion of the Bergell pluton is coupled with the ductile deformation of the migmatitic Gruf Complex (see also Davidson et al. 1996 and Berger et al. 1996) and their contemporaneous emplacement at higher structural levels was promoted by isostatic uplift due to slab breakoff.

The re-instauration of shortening and crustal thickening took place while the Bergell granodiorite was not completely crystallized (Davidson et al., 1996). D3 ductile deformation phase (local Cressim, 30-25 Ma) is associated to dextral backthrusting and backfolding by up to 20 km relative vertical displacement along the Insbruc mylonites (Rosenberg et al. 1995, Schmid et al. 1996). It led to the formation of large antiforms, like the Cressim antiform (which folded the base of the Bergell pluton) and the Paglia antiform, and the formation of the Southern Steep Belt (SSB) in the south. The SSB developed high-temperature mylonites (~700°C and 6-7 kbar, Burri et al., 2005) with subvertical stretching lineations and common migmatisation due to white-mica breakdown (water-assisted Alpine migmatisation continued up to 22 Ma, Burri et al. 2005). Some authors (Nagel et al. 2002, Maxelon & Mancketelow 2005) suggest that the SSB might be an older south-dipping shear zone with normal sense related to the Claro phase and
refolded during the Cressim phase. First Alpine pegmatite and aplite dikes are
dated by Romer et al. (1996) who individuated two generations of pegmatites
intruding the Symplon ductile shear zone between 29 and 26 Ma. The former is
slightly deformed thus concordant to the syn-kinematic emplacement while the
latter is undeformed. According to Romer et al. (1996) this would provide a
minimum age to the backthrusting along the Simplon shear zone (see also
Gebauer, 1996).
The D4 deformation phase is related to late continental collision and associated
magmatism. Dextral backthrusting was replaced by a pure dextral strike-slip
regime. Sin-collisional orogen-parallel extension at the Forcola mylonites drove
the emplacement of the Novate granite (~24.2 Ma, Liati et al. 2000), which
intrudes discordantly the D3-related structures as well as the associated
leucocratic dikes (Ciancaleoni and Marquer 2006). Maxelon and Mancktelow
(2005) individuated a late stage of ductile deformation that produced similar
structures to those of D3, but prominent only in the Northern and Southern Steep
Belts. These folds deep toward the NNW with fold axes oriented (E)NE-(W)SW.
Chevron type and kink folds are the most common geometries.

2.2. Pegmatites of the Central Alps

The Tertiary pegmatite field of the Central Alps extends in an E-W direction for
about 100 km from the Bergell (East) pluton to the Ossola valley (West) and for
about 15 km north of the Periadriatic Fault. Pegmatites are abundant in the
steepened roots of the Alpine nappes (Southern Steep Belt) and progressively
decrease in number towards north, where the nappes are flat-lying (Burri et al.,
2005). The area, mapped by Wenk (1970), Burri et al. (2005) and Ghizzoni and
Mazzoleni (2005), geographically coincides with the domain of the highest
metamorphic grade of the Alpine metamorphism (the Lepontine Barrovian
metamorphic dome) and with the zone of Alpine migmatization (Guastoni et al.,
2014). Burri et al. (2005) observed that only a minor part of the pegmatite dikes
developed rare accessory minerals such as beryl and tourmaline. Given the low
degree of differentiation of the pegmatites and their depletion in RRE-elements, Von Blanckenburg (1992) referred the pegmatites of the Central Alps to partial melting of the host rocks. However, pegmatites commonly cut and are therefore younger than the hosting migmatites (Wenk, 1973). Radiometric dating of pegmatites by several authors indicate a protracted time of intrusion. These geochronological data also indicate the occurrence of pre-alpine leucocratic dikes within the Central Alps (Romer et al. 1996, Galli et al. 2012, 2013). U-Pb dating of xenotime and monazite from pegmatites intruding the SSB at Malesco indicates the presence of two distinct generations of dikes with ages ranging from 29.2±0.2 and 25.5±0.2 Ma (Romer et al., 1996). An exception is the aplite dike at Lavertezzo yielding an age of ~ 20 Ma. The oldest dikes are deformed and are characterized by high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (>0.71); the geochemistry suggests an origin by melting of old crustal rocks. The youngest dikes are mainly undeformed and have lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (<0.71) suggesting a derivation from melting of a depleted crust. Despite the overlapping of ages of pegmatites from the two sets, in the field there is a clear overprinting relationship with the younger dikes always crosscutting the older. The youngest dike at Malesco has a consistent age to the one (25.1 ± 0.6 Ma) dated by Gebauer et al. (1996) north of San Vittore in the SSB, which is more than 50 km far away. Liati et al. (2000) highlighted the similar age of intrusion of leucocratic dikes and the Novate granite as well as the similarity in the geochemical signature.

2.3. The Lepontine Dome

Wenk (1970) gave the name of “Lepontine Dome” to the area of the Central Alps affected by the Tertiary Barrovian metamorphism (fig. 2). The metamorphic conditions within the Lepontine Dome range from greenschist to the upper amphibolite facies. The dome is asymmetric and extends from the Simplon Line in the west to the Bergell area in the east, confined between the Northern Steep Belt (south of the Gotthard massif) and the Southern Steep Belt, where it is truncated by the Insubric Line. The mineral isograds indicate an increase in
temperature from north to south with a peak of 675°C near Bellinzona (fig. 2, Todd and Engi, 1997). Temperature and pressure isograds indicate the maximum metamorphic conditions experienced during the whole tectonometamorphic history of the Central Alps, which means that contour patterns represent a diachronous field (also note the absence of the peak metamorphism recorded in
the Gruf complex due to lack of data). Todd and Engi (1997) observed that pressure and temperature maximum do not geographically overlap (fig. 2 a and b). This is in contrast with a single event of crustal thickening and thermal relaxation and request at least two major events: the first affecting the northern part and the second affecting only the south-eastern part, at lower pressure conditions. A support to this interpretation is given by the radiometric ages that suggest differential uplift rates i.e. different peak metamorphism ages.

Several authors speculated about the origin of the high temperature Barrovian metamorphism of the Lepontine Dome. Hypothesis range from the classical radiogenic heating in thickened lithospheric crust to the more recent models of tectonic accretion channel (Engi et al., 2001) or viscous shear heating (Burg et al., 2005). According to Beltrando et al. (2010) the models that involve continuous shortening and lithospheric thickening are incompatible with the Central Alps scenario. Well-documented extension along regional scale shear zones with generalized E-W stretching is consistent with the fast nappe exhumation and lithospheric thinning. Consequent relaxation of isotherms produced steep geothermal gradients resulted in Barrovian metamorphism and migmatisation while the short-lived generation of mantle melts is related to the rapid advection of mantle material to shallower levels.

2.4. Adula and Simano nappes

Adula and Simano nappes belong to the lower Penninic units of the Central Alps. These rocks represent the distal portion of the European continental margin subducted beneath the Adria microplate between Palaeogene and late Eocene (Schmid et al., 1996).

The Adula nappe, in contrast with the other Pennic basement nappes, is generally referred to as a lithospheric melange, formed within a tectonic accretion channel (Engi et al. 2001), consisting of Varisican metagranitoids and paragneisses, and Mesozoic sediments. Small to large (up to 2 km of the Arami body) ultramafic bodies are scattered within the nappe. In contrast to the Adula nappe, the Simano
nappe is a rather coherent thrust sheet, mainly composed by pre-Alpine metagranitoids.

Nagel et al. (2002) distinguished two main metamorphic events during the Alpine metamorphism of the Adula nappe: (1) an early stage of eclogite facies metamorphism during the nappe stacking, and (2) a later Barrovian overprint coeval with the D2 deformation and with the backfolding stage. More or less retrogressed eclogites are found mainly in boudins within metapelitic rocks and yielded peak conditions of 12 kbar (and 500–600°C) in the north and 25–30 kbar (and 750–850°C) in the south. Adula recorded decompression to amphibolite facies conditions during top-to-N thrusting on the lower units (D1 phase), which consequently yield younger ages for the H-P peak. The high-T event reaches in the southwestern part the peak of 10 kbar/700-650°C. The D3 phase of backfolding, well developed in the southern part of Adula nappe, is associated to the high-T thermal event and migmatisation.

2.5. Gruf complex

The Gruf complex is a composite unit mainly represented by amphibolite facies ortho-gneisses and migmatitic metasediments (Galli et al., 2012), which are isoclinally folded. Metagranitoids have Permian age (290-260 Ma) and formed during post-Variscan extension and break-up of Pangea. This complex also contains Permian granulite-charnockite rocks (Galli et al. 2013) and ultramafics similar to the ophiolites of the Chiavenna unit and Bellinzona-Dascio zone. Though several authors referred the Gruf complex to the SE continuation of the Adula nappe, Galli et al. (2013) pointed out important differences. High-pressure metamorphism, typical of the Adula nappe, is not found in the Gruf complex and the granulite-charnockite associations of the Gruf complex are not present in the Adula nappe. These characteristics, along with other structural and lithological evidences (Berger et al. 1996; Davidson et al. 1996; Schmid et al. 1996), distinguish the Gruf complex from the other Penninic units.
Metamorphic peak conditions in the Gruf Complex are referable to two main events: (1) an ultrahigh-temperature Permian event (282-260 Ma, Galli et al., 2012) and (2) the Alpine Barrovian metamorphism of the Lepontine Dome. Charnockitic magmatism and sapphirine-bearing granulites are the product of the former event. Metamorphic conditions in excess of 900 °C and pressures of 8.5–9.5 kbar were estimated for the Permian event. Due to the extremely refractory bulk-rock composition of the Gruf granulites, the Alpine upper-amphibolite facies re-equilibration (720–740°C and 7–7.5 kbar) was only partial (Galli et al., 2011). Oligocene Barrovian metamorphism produced widespread migmatisation (the dominant phase was between 34 and 29 Ma) with production of a 10-30% volume of anatectic melt.

2.6. The Bergell Pluton

The Bergell pluton is one of the most studied among the Tertiary Periadriatic intrusions. The Bergell intrusive rocks belong to a calc-alkaline suite and mainly include (1) tonalite forming the outer rim of the pluton (“Serizzo” Auct.) and the “root zone” (“Iorio tonalite”), and (2) granodiorite (“Ghiandone”), forming the main body of the batholith, characterized by pluricentimetric megacrysts of K-feldspar. The shape of the pluton resembles that of a nappe (Wenk, 1973). The main body of the batholith is emplaced at the same structural level of the Suretta and Tambo nappes (Rosenberg et al. 1995, Davidson et al. 1996, Schmid et al. 1996) and extends into an elongated and relatively thin “root” concordant in the main foliation of the SSB mylonites. North of the SSB the Bergell pluton overlap the Gruf complex and the Adula nappe, divided by the remnant of the “North-Penninic suture zone”, strictly related to the Misox zone, the Chiavenna ophiolite and the Bellinzona-Däscio zone (Davidson et al., 1996). In an E-W profile the Bergell pluton is assumed to expose a fossil crustal section of approximately 20 km of thickness from the deepest portions deformed ductilely (to the west and along the root zone) to the shallowest portions intruded into the brittle crust.
The calc-alkaline rocks of the bergell are referred to low degrees of partial melting of the continental lithosphere, caused by astenospheric counterflow (Von Blanckenburg and Davies, 1995; Beltrando et al., 2010). The Bergell tonalite and granodiorite have been dated at 31.88 ± 0.09 Ma and 30.03 ± 0.17, respectively (Von Blanckenburg et al. 1992). The emplacement of the Bergell pluton took place between the final stages of the mesoalpine tectonic extension at the end of the Niemet Beverin deformation phase of Berger et al. (1996) and the initial stages of backthrusting. The N-S shortening during the Cressim (D3) phase produced synmagmatic folding at the base of the intrusion (Rosenberg et al., 1994; Davidson et al., 1996). According to Rosenberg et al. (1994, 1995) the shortening along the feeder root zone is responsible for the upward extrusion and final emplacement of the Bergell pluton. This induced ballooning in the country rocks along the eastern border. In the east, the intrusion of tonalite produced a contact metamorphic aureole, within country rocks originally at a temperature 350°C. The temperature rise due to contact metamorphism was in the order of 450°C after 0.5 Ma from tonalite emplacement (Trommsdorff and Connolly, 1996). The Bergell pluton intruded at a considerable depth with respect to other Periadriatic intrusions (Adaamello, Biella and Traversella). Emplacement pressures of 6-7 kbar have been estimated for the main body (hornblende geobarometry on samples from Val Dei Ratti and upper Codera valley). Davidson et al. (1996) suggested that the intrusion and cooling of the tonalite occurred at about the same depth of 22-26 km. The pressure increase from northeast to southwest suggests a regional tilting due to differential uplift during backthrusting along the Insubric Line (Davidson et al. 1996). Assuming a simple model with a N-S axis perpendicular to the SSB mylonites, the estimated tilt angle of the pluton is between 7° (root zone) and 11° (main body). The real total tilt angle is more likely to be of about 20° considering that part of the rotation was accomplished before the complete solidification of the pluton (Davidson et al. 1996).
2.7. The Novate granite

The Novate granite (San Fedelino) is a S-type leucocratic two-mica and locally garnet-bearing granite. The Novate intrusion intrudes discordantly the base of the Bergell batholith (Wenk 1973, Von Blanckenburg *et al.* 1992, Liati *et al.* 2000). Geochemical data indicate that the Novate and the Bergell batholith are not co-genetic. The Novate granite is exposed at the Monte Peschiera in the western side of the lower Val Mera where it intrudes the D3 structures of the Cressim antiform (Berger *et al.*, 1996, and references therein). Ciancaleoni and Marquer (2006) proposed that the emplacement of the Novate granite occurred during syn-collisional extension along the Forcola shear zone. Space for magma ascent was provided by opening of an extensional jog along the shear zone. Host rock structures are essentially not deflected by the intrusion and local stoping occurs at the southern intrusive contact (Ciancaleoni and Marquer, 2006). U-Pb dating of magmatic zircons form the Novate yielded an age of 24.0 ± 1.2 Ma (Liati *et al.*, 2000). Syn-intrusive fast isobaric cooling occurred at the host rock conditions of 0.2 GPa and 400 °C (Ciancaleoni and Marquer, 2006). A stockwork of leucocratic dikes (microgranites, pegmatites and aplites) radiate from and cut through the intrusion. Liati *et al.* (2000) suggested that these dikes may be genetically related to the Novate granite and possibly to other non-outcropping associated intrusive bodies. This conclusion is supported by the 25.1 ± 0.6 Ma age obtained for pegmatites of the SSB (Gebauer, 1996). Both the Novate intrusion and the pegmatites also share a similar geochemistry with a strongly depleted RRE-pattern and a large Eu anomaly with respect to the Bergell tonalites (Von Blanckenburg *et al.*, 1992).
3. **Field Data**

3.1. **Areas and localities**

The Codera domain is located at the eastern contact of the Bergell pluton. Two areas from this domain were studied: the Upper Codera valley (COD) and the Rossaccio (ROS) (*fig. 1*). The COD area is located in the eastern side of the upper part of the Codera valley at about 2500-2700 m. The area extends between the Pedroni Dal Prà hut and the crest (named “Altare”) at the Italian–Switzerland border, and includes the glacial cirque south of Pizzo Trubinasca. The outcrops include the contact between the intrusives of the Bergell batholith (including the “Ghiandone” granodiorite and the peripheral “Serizzo” tonalite) and the host rock migmatites of the Gruf Complex. The ROS area is located west of the Cima Codera, east of the Aurosina valley and northeast of the Val Piana line. This locality is a few kilometers west from the COD area and is within the Gruf unit. The Bodengo area extends over a wide region between the Mesolcina (in the west) and the Mera (in the east) valleys. The study of this area was conducted in different localities in the upper parts of the valleys cutting through the region: Garzelli valley (VG), Leggia valley (VLG), Del Dosso valley (VDD) and Darengo valley (VLD) (*fig. 1*).

3.2. **Codera area**

Leucocratic dikes and quartz veins are abundant in the Codera area. The dikes are present within both the Gruf migmatites and the Bergell pluton crosscutting the intrusive contact. Within the Bergell, the pegmatites intrude both the tonalite rim (which in the study area is up to 200 m in width) and the granodiorite core (*fig. 3 and 4a*). The leucocratic dikes include pegmatites (barren-type or differentiated dikes with garnet, beryl and tourmaline), aplites and microgranitic dikes. The latter are lithologically very similar to the Novate microgranites.
These dikes are generally up to 1 m thick with the noteworthy exception one of the large dike outcropping just north of the Pedroni Dal Prà hut (fig. 4f). This dike reaches 6-7 m in width and consists of a dominant microgranite at the dike core, rimmed by selvages of pegmatite. The microgranite contains scattered phenoocrystals of K-feldspar. This dike outcrops for several hundred meters, cutting across the contact between the Gruf and the Bergell pluton.

The microgranitic dikes cut and locally even exploit the main set of pegmatite dikes intruding their cores or salbands and achieving the pegmatite orientation (fig. 4c and 7a). The large dike described in upper Codera valley is a striking example. In fig. 4g large K-feldspar crystals and fragments of graphic texture are deflected by the ascent of microgranite intruding the core of a pegmatite. The main set of pegmatite dikes has an average strike of 70°N and dips steeply (75° mean) both toward north and south (as visible in the upper Codera valley structural map, Fig. 3, and stereoplots on figure 8). From the orientation it is
possible to distinguish two different sets: (1) a set (less common) striking E-W, and (2) a set striking ENE-WSW. Pegmatites locally show crosscutting relationships (fig. 4b) suggesting poliphasic intrusion. Most pegmatites are less than a meter in thickness and are barren (for a definition see the “Pegmatites” chapter) while only a minor number of dikes show a more “evolved” mineralogy with abundant local garnet, tourmaline and beryl. Although dikes commonly preserve their pristine texture (including graphic K-feldspar and quartz intergrowth and comb texture) it is present an incipient ductile overprint locally evidenced by microboudinage of tourmalines and beryl or healed bent crystals. A weak tilting of feldspar comb texture also locally indicate a shear overprint. Locally the ductile deformation becomes pervasive even in pegmatite dikes and localizes in discrete shear zones (fig. 4d and 11e). In the Bergell intrusive rocks, ductile shear zones exploited high-temperature joints and compositional boundaries including pegmatite dikes (fig. 4d). Some dikes were simply dragged along crosscutting shear zones but more commonly leucocratic dikes localize deformation and develop mylonites at their boundaries or internally (especially the quartz-rich cores) with transpressive kinematic. Ductile deformation is also pervasive in the quartz veins oriented parallel to the main set of pegmatites. A strong mylonitic overprint is also observed in the pegmatite dikes within the Gruf units of the Rossaccio locality (fig. 4e).

3.3. Bodengo area

The country rocks of this area are the high-grade heterogeneous and migmatitic rocks of the Adula and Simano nappes. These units host an extensive swarm of sub-parallel pegmatite dikes, spaced on the order of tens of meters. These dikes generally do not reach one meter in thickness. As in the case of the Codera area, most dikes are barren and consist basically of quartz, feldspar and muscovite (with minor biotite). The dominant set of pegmatites intrudes discordantly the D3 structures and the steepened regional foliation of the SSB and are basically undeformed.
In rare cases sheared boundaries of the dikes (with strike-slip kinematic) were observed with the development of S-C foliations delineated by white mica (Garzelli valley, fig. 6e and 11d). In the Garzelli valley some deformed dikes of the main set show a sharp internal plane at the dike centre (roughly parallel to the C-planes), which appear to have been formed by reactivation of the dike under brittle conditions. This plane is in some cases weakly reactivated under brittle conditions, allowing late hydrothermal quartz to crystallize within small opened fractures. Pegmatites dip mainly toward W or WNW with an average inclination of 45°-50° (fig. 4 and 7). In Garzelli valley they are steeper with an average dip of 70°. This main set of pegmatite crosscuts an earlier one striking NW-SE (fig. 6b), which is sub parallel to the host-rock foliation (but still discordant). These earlier dikes show are boudinaged, buckled and sheared (fig. 6c and d). They steeply dip toward NE with a mean orientation of 44°N/68°. Most pegmatites exposed in the eastern flank of Garzelli valley belong to this older set.

Except for the degree of ductile overprint the pegmatites of the Bodengo area have the same mineralogy and textures of those of Codera area.
Locally dikes developed a layered structure that can be symmetric (most common) or asymmetric (with a fine-grained layer at the bottom wall zone). Rare miarolitic cavities (fig 6g) occur in the upper part of the core zone as isolated large pockets (up to 1m in size) or smaller pockets (pluridecimetric). Usually they contain brownish to smoky vitreous quartz, aquamarine beryl, schorl tourmaline, garnet and rare accessories. Miarolitic dikes do not develop comb textures.

In Garzelli valley a large pull-apart structure filled with foliated aplite was found. Foliation, which is marked by thin trails of garnet (up to 10 cm in length, fig. 10f) developed parallel to the feeders, which are roughly parallel to the foliation of the host rock. Aplite texture and foliation is probably genetically linked to the syn-intrusion opening of the pull-apart structure.

Quartz veins discordant to the main set of pegmatites are also common in the area. Most of these veins predate the pegmatite intrusion and are affected by the D3 deformation event. However, some undeformed quartz veins are oriented parallel to the pegmatite dikes and could belong to the same event of intrusion. The largest undeformed quartz vein (up to a few meters thick) was found in the Del Dosso valley.
Figure 6  (Page 19) Outcropping dikes of the Bodengo area. (a) Gorge set on a NW-SE striking subvertical pegmatite dike on the eastern flank of upper Garzelli valley. (b) Block of migmatitic gneisses intruded by two pegmatite dikes showing crosscutting relationship. The older dike (horizontal one in the photo) is sub-parallel to the host rock foliation and cuts a discordant dike (vertical) showing a more preserved internal texture. Codera valley. (c) Pegmatite dike displaced left-laterally and thinned along a crosscutting ductile shear zone discordant to the foliation. Pencil (14.5 cm) for scale. (d) Pinch-and-swell boudinage of a pegmatite oriented at a small angle to the main foliation of the SSB. Del Dosso valley, 1 euro for scale. (e) Ductilely deformed dike of the younger set showing internal S-C foliation. Garzelli valley, 50 euro cent for scale (24.25 mm). (f) Foliated aplite dike intruding a pull apart structure and oriented at a small angle to the host rock foliation. The dike is cut by a younger set of pegmatite dikes. Garzelli valley, G. Caviola for scale. (g) Miarolitic cavity in a pegmatite dike. The presence of the cavity is associated with a swelling of the pegmatite dike. Leggia valley; camera lens cap (6 cm in diameter) for scale.

Figure 7  (Page 21) Photomosaics assembled by photogrammetry of glacier-polished outcrops in the upper Codera valley (a) and the Garzelli valley (b). (a) Codera photomosaic shows a set of pegmatite dikes (p) and a younger set of microgranite dikes (g) within the Bergell granitoids. The microgranite dikes crosscut, and locally exploit, the pegmatite dikes. (b) Garzelli photomosaic shows two intersecting sets of pegmatites with the older thin dikes (p1) deformed along ductile shear bands (indicated by black arrows in the lower left part of the outcrop); the younger dikes (p2) crosscut at a high angle the host-rock foliation and appear mainly undeformed except for showing locally a ductile overprint (as indicated by the white arrow in the upper right part of the outcrop).
Figure 8  Stereographic plots (lower hemisphere, equal area) of the orientations of pegmatite dikes from different localities (see fig. 1 for location) of the upper eastern Codera and Bodengo area. On Codera valley – A stereoplot are plotted the orientations of pegmatite dikes. On Codera valley – B stereoplot are plotted the orientations of deformed dikes and veins where the thin lines represent pegmatites, thick lines are leucocratic (microgranite) dikes, and dashed lines indicate quartz veins.
4. **Pegmatites**

4.1. **General appearance of pegmatites**

Most pegmatites occur as dikes that to a first approximation have a tabular shape. In some cases the pegmatite terminations pinch out in the host rock and make transition to quartz veins (as observed in Upper Codera and Rossaccio, see also Ghizzoni and Mazzoleni, 2005). In both the Codera and Bodengo areas the pegmatites generally are less than 1 metre thick with a few exceptions of dikes of as much as a few metre thick. Thin dikes commonly thicken at pull-apart structure, at the intersection with other dikes or where miarolitic pockets are developed. Most pegmatites preserve the pristine structure, which include comb structures (*fig. 9b and c*) of K-feldspar, graphic intergrowth between quartz and feldspar or graphic garnet and tourmaline intergrown with quartz (*fig. 9 fand g*). However, to a close inspection the dyke can show a weak ductile overprint and in the Codera area many dikes are clearly mylonitized (*fig. 4d and e*). The pegmatite structure and mineralogy can abruptly change along strike. According to the nomenclature adopted by London (2008), the following structures can be recognized in the layered pegmatites of the study areas: (1) border zone with fine-grained to aplitic texture; (2) wall zone with centimetric K-feldspar, albite, muscovite or biotite and quartz, often with longated crystals arranged in comb structures (*fig. 9b and c*); (3) intermediate zone with coarser (a few cm to dm) graphic quartz and K-feldspar intergrowth, albite, muscovite and local accessory minerals (mm-sized garnets, graphic black schorl and pale blue beryl, *fig. 9g*); (4) core zone developing giant texture (up to metric perthitic K-feldspar) and eventually grey quartz masses; (5) miarolitic cavities in the core zone (only in Bodengo, *fig. 6g*).
4.2. General mineralogy of pegmatites

Most pegmatites have a simple mineral assemblage consisting in K-feldspar, albite, quartz and biotite and/or muscovite (barren pegmatite). A very minor number of dikes locally contain accessory minerals that include: Sn-Nb-Ta-Y-REE-U oxides, Y-REE phosphates, Mn-Fe-phosphates, Ti-Zr-silicates, Be-Y-REE-U-silicates and oxide minerals (beryl, chrysoberyl, bertrandite, bavenite, and milarite), garnet (almandine-spessartine), tourmaline (schorl to rare elbaite), bismutinite, magnetite, and rarely dumortierite and helvite (Guastoni et al., 2014).

Figure 9 (a) Thin barren pegmatite dike displaying simple mineralogy (K-feldspar, quartz and biotite flakes). Pluricentimetric K-feldspar crystals point toward the core of the dike and in this rare case achieved a pinkish colour. The colour is probably due to the interaction with the more mafic tonalite host rock. Upper Codera valley, 1 euro for scale. (b) Exposed comb texture on a broken opened barren pegmatite. On the broken surface are visible the K-feldspar crystals and the biotite flakes pointing outward. Upper Codera valley, 1 euro for scale. (c) Pegmatite of the main set of dikes crosscutting the main foliation of the country leucocratic gneisses (lower part of the photograph) showing elongated K-feldspar crystals oriented approximately orthogonal to the dike boundary (comb structure). Garzelli valley; compass for scale. (d) Section of the upper half of an evolved pegmatite dike showing biotite and K-feldspar comb texture, decimetric K-feldspar crystals and an inner zone containing graphic garnets characterised by a finer grained texture and ductile deformation. Rossaccio locality, 1 euro for scale. (e) Large flake of muscovite in the evolved Codera Phosphate dike (CODp). 1 euro for scale. (f) Non-graphic garnet surrounded by graphic intergrowth of garnet and quartz. Upper Codera valley, 2 euros for scale (25,75 mm). (g) Characteristic paragenesis of evolved pockets in pegmatite dikes of the Codera area: graphic black schorl tourmaline, graphic and non-graphic garnet and elongated bent crystals of pale blue beryl. Upper Codera valley, 1 euro for scale. (h) Mn-Fluorelbaite broken crystals of the CODp dike. 1 euro for scale.
Accessories normally are found only in discrete portions of a pegmatite dike and “mineralized” portion commonly make transition to barren portions. The occurrence of rare accessories is commonly localized to pockets, thin local layers, thickened portions or convergence of multiple dikes. It is possible to correlate the presence of evolved paragenesis to the type of host rock to: for example, in the upper Codera valley, dikes containing garnet, beryl and tourmaline that intrude the Gruf units and the bergell intrusive close to the contact turn to barren types more inside the pluton. For the classification of Codera and Bodengo pegmatites we remand to the work of Guastoni et al. (2014).

4.3. Sampled dikes

Pegmatites are heterogeneous rocks both chemically and texturally. Since grain size can exceed the meter and the chemical behaviour can vary substantially in all directions, representative bulk geochemical analyses are difficult to obtain. Geochemical characterization of pegmatites is based on the study of single mineral phases and fine-grained portions (London, 2008), whose composition can be used as a proxy for the pegmatite changing chemistry during crystallisation and for pegmatite classification. Minerals of several evolved dikes were sampled for chemical and isotopical analysis. A brief description of each sampled dike is reported below in the text. Most information comes from the valuable knowledge of the areas and hosted pegmatites of A. Guastoni (2012 and personal communications).

Since rare accessory minerals of pegmatites may occur only as rare scattered occurrences, rarely we can offer a list that includes the whole paragenesis. Nevertheless a list of recognized phases is reported.

CODs zircon sample and VCA monazite and zircon samples were provided by A. Guastoni. CODs (Silvana dike of upper Codera valley) and VCA (dike of Cama valley, which is near Leggia valley) dikes will not be described in this section. For information regarding CODs we remand to De Michele and Zezza (1979).
4.3.1. Codera garnet dike – CODg

This dike outcrops for more than 30m in length in the glacial circle of the upper Codera valley. It reaches up to 3m in width in the lower portion where it merges to another pegmatite dike. It is discordant with the foliation of both Bergell tonalite and granodiorite. Ductile deformation of the dike is observed at the dike boundaries where it shows incipient boudinage. The dike is symmetrically layered and includes: (i) border zone of dm-sized K-feldspar, quartz and biotite (arranged in a comb texture); (ii) intermediate zone of K-feldspar; graphic K-feldspar and quartz including layers of millimetric red garnet; (iii) core zone with vitreous smoky quartz and decimetric perthitic K-feldspar. Gemmy aquamarine beryl and trapezohedral red garnet are relatively common. Other subordinate minerals are: schorl tourmaline; rare crystals of columbite-(Fe), euxenite-(Y), monazite-(Ce), xenotime-(Y), uraninite, zircon, magnetite. Monazite crystals were found in the intermediate zone together with garnet. The dike was classified as Rare Elements Pegmatite and belongs to the mixed LCT-NYF family (Guastoni, 2012).

4.3.2. Codera phosphate-bearing dike – CODp

This phosphate-bearing dike outcrops 100 m east of the CODg dike in the upper Codera valley. It cuts discordantly through the foliation and shows a complex internal structure. It is the most evolved dike found in the area as reflected by its peculiar mineralogy. It belongs to the LCT family, rare elements-Li (REL-Li) subclass (Guastoni, 2012). CODp extends for more than for 30 meters in length and reaches up 3 meters in width. As well as the other Codera dikes is deformed and shows lobated boundaries. The sample 12-CODp1 from the dike shows the effect of solid-state ductile deformation at the dike boundary. The dike is texturally and mineralogically zoned and includes: (i) a border zone (30 cm wide) composed by pluricentimetric quartz and albite and containing Mn-rich dark greenish fluorelbaite (fig 9 h), black centimetric masses of end-member F-rich triplite, Mn-hydroxides and pale pink prismatic beryl; (ii) a wall zone of medium-
coarse grained (up to decimetric) assemblage of graphic K-feldspar and quartz, black schorl and red to orange garnet, triplite masses and colorless to pale pink beryl; (iii) an intermediate zone of medium-coarse grained graphic intergrowth of quartz and K-feldspar, white to yellowish and pale green perthitic Cs-rich K-feldspar, colourless to brownish quartz, large muscovite and biotite flakes. The upper end of the dike developed fine-grained bands of graphic intergrowth of quartz and K-feldspar associated with muscovite flakes. These bands are bordered by a coarse-grained zone (pluridecimetric) of K-feldspar, albite, quartz and muscovite flakes, probably related to the coalescence with a lateral pegmatite dike (Guastoni, 2012).

4.3.3. Codera Mary dike - CODm

This dike occurs within the Gruf migmatites in the eastern flank of the upper Codera valley under the Pizzo Porcellizzo peak. The dike, which reaches 150 cm in thickness, is discordant to the foliation and has similar zoning as the CODg dike including: (i) top wall-border zone with poorly-developed comb texture K-feldspar and muscovite, (ii) intermediate zone with graphic intergrowth of K-feldspar and quartz, biotite and muscovite flakes, (iii) core zone with giant perthitic K-feldspar and smoky masses of quartz at the core. Garnet crystals larger than 1 cm in diameter occur between the graphic layer and the core zone. The presence of pale blue beryl has been reported from this dike.

4.3.4. Codera Trubinasca dike- CODt

The dike outcrops on the north-western flank of the glacial circus under the Pizzo Trubinasca in the upper Codera valley. It is hosted within the Bergell intrusives and cuts discordantly the solid-state foliation. The symmetric zoning of the dike includes: (i) a border zone composed of K-feldspar, quartz and biotite developing minor comb textures; (ii) an intermediate zone with abundant graphic K-feldspar and quartz, and a narrower core of K-feldspar and quartz (which
locally occurs as smoky masses). Accessories minerals are garnet, beryl, tourmaline, greenish U-rich monazite-(Ce), zircon and uraninite.

4.3.5. Rossaccio Garnet dike - ROSg

This dike outcrops near the Bocchetta Teggiola within the foliated Gruf mylonitic migmatites. This dike is similar to the CODg dike both texturally and mineralogically. The dike thickness is of as much as 5 m with strong variations along strike. Most segments of the dike are of a barren type, but locally it develops pokets with large garnets (up to 3 cm). At one end this dike transforms makes transition to a massive quartz vein. The dike boundaries are sheared with a mylonitic fabric.

4.3.6. Rossaccio Beryl dike - ROSb

ROSb has a thickness of 2-3 m and outcrops for several tens of meters though partially covered by debris. The internal structure is locally complicated by a strong ductile overprint. The wall zone consists of a medium-grained (up to decimetric) assemblage of K-feldspar, quartz and biotite crystals with a comb texture. The intermediate zone shows a graphic texture of K-feldspar and quartz and contains muscovite and rare zircon. The core zone has pluridecimetric grain size of perthitic K-feldspar, quartz and contain pale blue deformed beryl and graphic to large prismatic (up to 20 cm in length) crystals of shorl tourmaline.

4.3.7. Val Garzelli Lower dike - VGb

This dike outcrops in the western side of the upper Garzelli valley near the Alpe Campo, within migmatitic paragneisses. The dike is up to 50 cm in thickness, and cut discordantly across the host rock foliation without showing any deformation structures. It has a simple zoning: (i) medium-fine grained border zone composed of K-feldspar and muscovite; (ii) intermediate zone with graphic intergrowth of
K-feldspar and quartz, muscovite and nice trapezohedral red garnets up to 1-2 cm in diameter; (iii) core zone of coarser perthitic K-feldspar and local masses of dark quartz.

4.3.8. Val Garzelli Upper dike - VGa

VGa is from the same location as VGb but outcrops slightly to the west. The dike is up to 2 m in thickness and has up to decimetric grain size. The border zone is composed by large K-feldspar and muscovite crystals; the intermediate zone has graphic intergrowth of K-feldspar and quartz, muscovite and red garnet crystals with euhedral trapezohedral habit of as much as 1-2 cm in size; the core zone has decimetric perthitic K-feldspar crystals and quartz masses.

4.3.9. Val Del Dosso dike - VDD

This is a quite huge dike (reaching up to 4-5 m in thickness) from the upper part of the Del Dosso valley. VDD has an asymmetric texture including: (i) border zone with giant (up to 50 cm) biotite crystals and K-feldspar forming a comb texture; (ii) intermediate zone with a finer grainsize of K-feldspar, quartz and muscovite; (iii) a layer of garnets (crystals of as much as 2-3 cm in diameter); (iv) core zone with giant (pluridecimetric) texture of K-feldspar, quartz and large silvery mica flakes containing centimetric euhedral garnets. The dike makes transition at the termination to a thick (up to 50 cm) layer of massive quartz of a smoky variety in the core. The dike is intruded by schorl tourmaline-bearing injections that form large hollow pockets within the pegmatite. The dike contains aquamarine, schorl and garnet.

4.3.10. Upper Val Leggia dike - VLGa

This dike extends for a length of ca. 20 m in the upper Leggia valley. It is hosted within the amphibolites and migmatitic gneisses of the Bellinzona-Dascio zone of
the SSB, and is concordant to the foliation in its lower end. The dike reaches up to 3-4 m in thickness at this termination where it coalescence with a lateral pegmatite dike. The border zone is coarse-grained (decimetric), composed of idiomorphic white perthitic K-feldspar, albite, large aggregates of muscovite and subordinate brownish-vitreous quartz masses. The intermediate zone contains decimetric euhedral K-feldspar crystals, quartz, albite, black shorl and centimetric trapezohedral crystals of red garnet. The dike contains zircon.

4.3.11. Medium Val Leggia dike - VLGm.

This discordant dike is hosted within the migmatite gneiss of the Southern Steep in the upper Leggia valley. It outcrops for a length of 15 meters and is up to 1.5m in width. The zoned structure is asymmetric including: (i) border zone in the lower part showing a fine-grained layering of K-feldspar, albite, quartz and muscovite; (ii) border zone in the upper part composed of medium coarse grained K-feldspar, albite, quartz and abundant flakes of muscovite; (iii) wall zone composed of centimetric white perthite K-feldspar, albite, flakes of muscovite and quartz; (iv) intermediate with medium to coarse grained texture (pluricentimetric) composed of graphic K-feldspar and quartz, albite, muscovite, red millimetric garnets, centimetric prisms of pale blue beryl and graphic black schorl; core zone developing miarolitic pockets.

One of these pockets reaches one meter in width and hosts brownish-smoky quartz crystals (also with sceptre terminations) up to 15cm in length aquamarine beryl, pluridecimetric idiomorphic white perthite K-feldspars, laminar albite var. clevelandite, rare black schorl and lithiowodginite (Guastoni, 2012). Within the smoky quartz were found several millimetric crystals of yellow subhedral monazite.
4.3.12. Lower Val Leggia (Colonnello) dike - VLGb

VLGb cuts discordantly across the foliation of the migmatitic gneisses of the SSB in the lower part of the Leggia valley. It extends for 15 m in length and reaches up to 1.5 m in width. The dike is zoned and includes: (i) a fine-grained lower boundary composed of K-feldspar, albite, quartz and muscovite; (ii) a wall zone of medium grained (centimetric) assemblage of perthitic K-feldspar, albite, muscovite flakes, quartz and millimetric red garnets, centimetric prisms of pale blue beryl and graphic black schorl; (iii) a core zone of coarse grained K-feldspar and quartz with local miarolitic pockets. A large pocket (1 x 0.6 x 0.5 m) provided (Guastoni, 2012): large brownish-smoky quartz crystals (also with sceptre terminations) up to 15 centimeters in length, beryl aquamarine up to 9 x 4 x 4 centimeters, pluridecimetric idiomorphic white perthite K-feldspars, albite var. clevelandite as laminar centimetric crystals, rare black schorl prism up to 5-6 centimeters and lithiowodginite crystals up to 1.6 centimeters in length.

5. Deformation

5.1. Macroscopic evidence of deformation on hand specimens

As described in the chapter 3, pegmatites were locally exploited by ductile deformation especially in the Codera area. Ductile deformation is particularly evident in the quartz veins, associated with the pegmatite swarm, and within the quartz-rich portions of the pegmatite. However, to a close investigation the whole fabric of the pegmatite has been commonly affected even in the case where the pristine pegmatite structure is well preserved (fig. 9d and fig. 10a). Evidence of this deformation overprint are: (i) the presence of trails of fragmented garnet (see thin section 13-VG-Grt-1 description); (ii) microboudinage and bending of tourmaline and beryl (fig. 10c and d). The relatively high temperature condition of the deformation overprint is suggested by the common healing of the fragmented crystals (fig. 10e and fig. 11f).
Garnets have cubic habit and behave differently from elongated crystals. Euhedral garnets of Codera area commonly show a pervasive net of fractures (fig. 13a and b, fig. 14e), which in most case have a preferential trend of sub-parallel planes defining a deformation direction. Although the 12-CODp001 thin section did not intercept garnet crystals, an euhedral one is present on the hand sample surface and displays a short tail of fine-grained garnet (fig. 11b).

5.2. Evidence of deformation in thin sections

This session reports the microstructural observations made under the optical microscope of thin sections that include solid-state ductile fabrics of pegmatites. The code of the thin section is reported before each description.

(1) 12-177: (fig. 11a) Mylonites of Codera area affect the tonalites and the pegmatites. The tonalite mylonites contain as a synkinematic assemblage: quartz, biotite, plagioclase (oligoclase), epidote, ±K-feldspar. Quartz and biotite underwent dynamic recrystallization. The recrystallized biotite in the mylonitic foliation is lighter coloured than the magmatic biotite, reflecting the decrease in Ti of this relatively lower temperature biotite. K-feldspar is replaced along the boundaries by myrmekites that recrystallized along the foliation to fine (a few microns in size) polygonal aggregates of quartz-oligoclase. Plagioclase and K-feldspar persist up to the mylonitic stage as rounded porphyroclasts immersed in the matrix locally forming d- and s-shaped porphyroclasts systems. These microstructures are similar to those described in granitoid plutons deformed during postmagmatic cooling (Pennacchioni, 2005; Pennacchioni and Zucchi, 2012).

(2) 12-144: (fig. 11b) Codera quartz mylonites consist of recrystallized aggregates of small quartz grains (<50µm) of equant or slightly elongated shape, which define a shape preferred orientation oblique to the main foliation.
Under crossed polars light the recrystallized aggregates have a dominant dark color or show an extinction banding. The insertion of the gypsum plate under crossed polars indicate a strong crystallographic preferred orientation (CPO) of the recrystallized quartz. The dark overall colour of the recrystallized quartz aggregate under crossed polars suggests a CPO characterized by a c-axis maximum in the direction of the Y kinematic axis of the mylonite (i.e. parallel to the foliation and orthogonal to the lineation). This CPO has been confirmed by x-ray texture goniometry (Guastoni et al., 2014)(fig. 12).
(3) 12-CODp001: (fig. 11c) This sample of CODp dike dike was taken from an internal mylonitized portion. On hand sample the graphic texture of K-feldspar and quartz is gradually deformed toward a discrete surface decorated by white mica and bearing a well-developed lineation. The ductile shearing likely exploited the planar border of graphic schorl. The deformed tourmaline has the c-axis oriented roughly orthogonal to the lineation. Thin section was cut parallel to the lineation of mica and perpendicularly to the shear zone plane. The monocrystalline quartz of the graphic texture has recrystallized to aggregates of $<100\mu m$ grainsize by subgrain rotation and high temperature grain boundary migration. K-feldspar crystals are microboudinaged and show elongated optical subgrain with fan-like extinction. The boudin gaps of the K-feldspar are filled with quartz and locally white mica. White mica is dragged in the shear zones eventually producing nice mica-fishes (group-1 mica fish). Maximum reduction of grainsize is achieved near the surface with the graphic schorl, in correspondence of a layer of equant grains of albite and the local complete destruction of the large K-feldspar crystals. Under crossed polars the high strained
zone is dark colored suggesting isoorientation of the quartz with the c-axis perpendicular to the thin section plane (i.e. with a strong Y-maximum of c-axis as described above for the quartz-mylonites). Noteworthy is the orientation of schorl tourmaline whose c-axis is parallel to that of quartz. Fast grain boundary migration and the hypothetical CPO of quartz suggest ductile deformation under high temperature and wet conditions (Vernon, 2004).

(4) GAR-1: (fig. 11d) Deformed pegmatites of Garzelli valley display locally a S-C foliation delineated by white mica. Rock in thin section was sampled near the contact with the host rock of a muscovite-rich pegmatite. Deformation mechanism in quartz includes grain boundary migration recrystallization.

(5) 13-VG-Grt-1: (fig. 11e) The aplite intruding a pull-apart structure in Garzelli valley was sampled for the study of the garnet trails. The rock is a fine-grained aplite made essentially by equant grains of dominant albite and K-feldspar. Garnets occur as aggregates of rounded (small ones) to angular crystals (large ones) reaching 1-2 mm in size, locally growing close to or in contact with dark brown pleochroic biotite. Aggregates are arranged along parallel trails defining a foliation and, locally, trails seem asymmetrically folded. Despite this the rock

Figure 11 Thin sections of deformed rocks. (a) 12-177: Ultramylonite in tonalite flanking the border of a pegmatite dike of upper Codera valley. Sense of shear is dextral. Plane polarized light. (b) 12-144: Dynamically recrystallized aggregate in a quartz mylonite showing extinction banding under crossed polars. Shear sense is dextral. (c) 12-CODp001: Trail of small garnet crystal (<2 mm and possibly recrystallized) with pleochroic biotite in aplite matrix. The trail seems asymmetrically folded. Plane polarized light. (d) GAR-1: S-C foliation decorated by white mica. The shear sense is dextral. Crossed polars. (e) 12-CODp001: Mylonitic shear zone of CODp dike. Well visible the boudinage (vertical cracks) and extinction pattern on K-feldspar. Graphic intergrowth of K-feldspar and quartz is gradually obliterated toward the top of the section where it is the strongest reduction of grain size of quartz (dark band on the top right). Crossed polars on a thicker thin section (>30µm). (f) 13-ROSb001: Different extinction patterns in a bended crystal of beryl under crossed polars. Fragments are partially sutured showing indentation of lobes and cusps boundaries.
seems to preserve the pristine magmatic texture, with well-defined grain boundaries and no evidence of ductile deformation. Trails of garnet may be generated during syn-intrusion opening of the dextral pull-apart structure. The mechanism of formation however is not yet clear. EMPA analysis might be useful for the study of an eventual compositional zoning developed during growth.

(6) 13-ROSb001: (fig. 11f) The pale blue, elongated beryl crystal of fig. 10e comes from the ROSb dike of the Rossaccio locality. In the hand specimen the beryl prism is deformed to a faint S-shape with the transparent central part and an “iced” turbid aspect towards the tips. The crystal was cut parallel to the bending plane. Under crossed polars it reveals an internal subtle polygonized extinction pattern, possibly indicating subgrains. The contact between bended fragments of the beryl is sutured (boundaries show indentation of lobes and cusps geometries). The beryl contains widespread healed cracks, decorated by fluid inclusions and forming different sets.

The microstructural observations in the pegmatites and associated mylonites indicate that the dikes were affected by ductile deformation. The mineral assemblage along the mylonites, the type of CPO of recrystallized quartz and the quartz recrystallization mechanisms by subgrain rotation and GBM are all consistent with deformation temperatures in the order of ≥ 500°C. Similar microstructures are typically developed during postmagmatic cooling of granitoid pluton as described, for example in the Adamello periadiatic pluton (Pennacchioni, 2005).
Figure 12 Plots (upper hemisphere, equal area) of (001) (c axis), (110) (<a> axis), (112), and (201) axes of quartz mylonites of the Codera area determined by texture goniometry. The plots are cumulative and the total investigated area in each sample is 2cm. Samples are described by Guastoni et al. (2014).
6. Mineral samples

6.1. Samples and codes

Minerals sampled for chemical analysis are garnet, tourmaline, monazite and zircon. Main accidental findings include Sn-Nb-Ta-Y-REE-U oxides, xenotime, thorite, REE-bearing epidote and apatite. However significant and systematic analysis made so far, which are presented in this thesis, are limited to garnet, tourmaline and monazite. Anyway zircons were sampled for further future characterizations and here are only described.

In the tab. 1 are reported the codes of samples for each dike. The identification code is composed by the dike code ("a" field) followed by the mineral code ("b" field with g=garnet, gg=graphic garnet, t=tourmaline, gt=graphic tourmaline, m=monazite, z=zircon, th=thorite) and a number. This number ("c" field) is used to indicate the group of crystals (minimum 1) of the same phase extracted from the same handsample. Single handsamples commonly provided more than one crystal (see monazites and zircons). If there is more than a crystal in a group or the crystal was fragmented for analysis, an additional number ("e" field) is added after a dash to identify the single crystals or fragments. Monazite and zircon codes may contain the “P” letter ("d" field, eventually followed by a letter in case of multiple samples). These “P” samples are representative (selected mainly for the shape) crystals photographed and used for accurate description. The “f” field is used to indicate an analysis point or a profile (e.g. 1-xxx), it is separated from the sample code by an underscore.

Example of complete code. The first number of "f" field indicate a line of points. This number, "d" and "e" fields are optional.
6.2. Samples description

For each dike here are reported the descriptions of sampled crystals. Note that the accurate identification of the phase for garnets and tourmaline is omitted since it will be discussed in the following chapter. Dimensions of single crystals are attached to the photographic tables.

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Table 1 Handsample codes

6.2.1. Garnets

Garnets of pegmatite dikes of the Central Alps are already described by Guastoni (2012) as solid solutions of almandine-spessartine. Samples collected display the same described morphology with dominant {211} trapezohedron (fig. 14e, g and h). Crystals with dominant romb-dodecahedron {110} faces (fig. 14f and i) are far subordinate. Crystals with different habit can be found in the same dike as well as graphical intergrowth of garnet and quartz (fig. 14a). Garnets are commonly broken by brittle deformation and Codera area ones seem to develop a preferential set of sub-parallel cracks (fig. 13a and b). Following descriptions refer to fig. 14.
(CODp, CODg) Sampled garnets from both dikes of Codera area are anhedral to subhedral, also with graphic texture, embedded in white perthitic and graphic K-feldspar along with muscovite flakes. Although nice trapezohedral, centimetric dark red garnets in CODg dike are not rare. Euhedral ones are up to 2-3 cm large while graphic aggregates reach several centimetres in width. Generally garnets are dark red coloured and non-graphic ones are opaque. An exception are the CODp(g)2 crystals, which have a light red to orange colour and are translucent. Commonly garnet crystals are found with a hybrid habit, composed by a single anhedral large crystal surrounded by graphic intergrowth with quartz. All garnet crystals from COD dikes are pervasively fractured with a distinguishable dominant set of subparallel fractures (fig. 13a and b).

(ROSg) Similarly to CODg, the Rossaccio garnet dike provided nice euhedral garnet crystals of up to 2-3 cm. They have trapezohedral habit and a dark red colour, poorly translucent. It is pervasively fractured and displays a dominant set of parallel fractures. Fine-grained white mica grows within the gaps. Crystals are embedded within perthitic white K-feldspar.

(ROSb) Garnets of this dike are less developed and do not reach 1 cm in width. Sampled ones exhibit euhedral romb-dodecahedron habit and are dark red coloured. Crystals are embedded in white perthitic K-feldspar.

(VGa, VGb) Both dikes of Garzelli valley provided nice centimetric euhedral granets, which have trapezohedral habit, bright to dark red colour and are translucent. Best crystals for shape, which reach 1-2 cm in width, are found embedded within large muscovite flakes and quartz.

(VDD) This dike provided two types of garnet that come respectively from the giant-textured core (VDD(g)1 and 2) and from the miarolitic pockets (VDD(g)3). Crystals of the first type grow with large flakes of muscovite and quartz. They exhibit euhedral trapezohedral habit and a bright red to dark red translucent colour. VDD(g)1 hosts a zircon crystal visible in thin section (fig. 13c). Volume expansion of zircon caused radial cracks in the garnet (fig. 13d). The second type
of garnet grows on the free surface of K-feldspar crystals. They are bright red and
gemmy, with a good trapezohedral habit.

(VLGa) These garnets are found growing with muscovite on large prisms of
black schorl. The habit is euhedral trapezohedral and partially rounded. The
colour is dark opaque red.

(VLGm) The crystal sampled in this dike differs substantially from the other
ones described so far. It has a dark red colour, almost black, and shows locally
pristine faces interrupted by irregular areas. Since it is possible to recognize
discrete faces in those parts, it reasonable to impute the garnet shape to
competitive growth against other crystals, maybe complicated by a latter stage of
corrosion (rough and rounded surfaces).

Figure 13 Garnet sections. (a) CODp(g)1: Non-graphic garnet surrounded by a
graphic aggregate (gg). The crystal shows a set of vertical fractures. (b) CODg(gg)1: Graphic
garnet with a pervasive set of subparallel fractures trending NW-SE in the photo. (c)
VDD(g)1: Zoned garnet with lighter thin rim (r) and included zircon. (d) Zircon crystal
included in VDD(g)1 that caused radial cracks in the host due to volume expansion.
Despite this it is possible to determine the habit by the visible faces that are the rombododecahedron, which is dominant, and the trapezohedron. Note that almost all Bodengo area garnets show a dominant trapezohedral habit.

6.2.2. Tourmalines

All tourmalines are black schorl with very rare exceptions. They occur as elongated prisms with common parallel growth. Tourmalines of deformed dikes show pervasive microboudinage perpendicular to the c-axis and some are bended. Greenish Mn-rich fluorelbaite with schorl core is described by Guastoni (2012) in the CODp dike (fig. 9 h).
Graphic tourmalines are typical evolved parts of Codera pegmatites and commonly occur with beryl. The black schorl tourmaline sampled in the CODp dike is a composite one, made of an inner prismatic crystal surrounded by a graphic intergrowth with mainly quartz. The aggregate is 4 cm in width.

5 cm long, black prismatic schorl tourmaline found in an aggregate of deformed quartz. As for the other tourmalines from the Codera area, the crystal was extracted broken, without termination, and showed an evident microboudinage with cracks perpendicular to the c-axis. These planes act as a pseudo-cleavage since microboudinaged crystals are easily broken into small slices. Some fragments are dislocated and separated by the same recrystallized quartz matrix.

3 cm, black prismatic schorl crystal grown with K-feldspar, muscovite and quartz.

Black prismatic schorl crystal of 2 cm in width and 6 cm in length associated to red garnet crystals, which grew on the prismatic faces, muscovite, K-feldspar and quartz.

Small prismatic, terminated crystals of dark olive green tourmaline up to 6 mm in width. These crystals were found within a miarolitic pocket, growing with large quartz crystals, albite var. clevelandite and K-feldspar perthitic crystals.

6.2.3. Monazites

Monazite crystals were sampled in three different dikes of Codera area (CODg, CODt and CODm) and two different dikes of Bodengo area (VLGm and VCA). Morphology of sampled crystals reflects that described by Catlos (2013) for Th-rich monazites: most crystals are flattened on \{100\} and show small or absent \{101\} faces. Most crystals are stubby while elongation occur commonly on the c-direction, with the exception of CODm(m) samples that is probably strongly elongated on the b-direction (fig. 15f). The non-conventional habit of CODg(m)3 might be an example of competitive growth in pegmatites that imposed the form
of adjacent growing crystals (fig 16d and 16b). Following descriptions mainly refer to samples in fig. 15 and 16.

(CODg) Yellow prismatic crystals found in paragenesis with K-feldspar, quartz and Nb-Ta-REE oxides. Most of them are translucent but appear turbid under the stereoscope. Crystals are elongated on the c-direction with a euhedral to subhedral shape. Prismatic and pinacoidal faces are well developed and some crystals are twinned. Some of these crystals are the largest found among sampled monazites, exceeding 5 mm in length (CODg(m)3P, fig. 15d and 16d). Each crystal shows a well-developed parting on \{001\}. CODg(m)1 hosted at its nucleus small green prismatic crystals of thorite (fig. 15a), surrounded by black lamellar Nb-Ta-U elements-oxide. This crystal contains numerous small inclusions of monazite (<10 µm, fig. 18i).

(CODm) These crystals are the clearest monazites among all samples. Crystals are gemmy, euhedral and strongly elongated, showing well developed sharp faces. They reach several millimetres in length and less than 1 mm in width. Parting on \{001\} is not macroscopically visible, though BSE imaging shows sector zoning parallel to elongation that suggests b-direction elongation. These monazite crystals are hosted in massive white cloudy quartz, in association with black euhedral crystals of euxenite.

(CODt) Single crystal of green monazite. This specimen was found at the core of a deformed (microboudinaged) and recrystallized yellow beryl embedded in quartz. On the same sample two crystals of pale brown zircon and one crystal of

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Table 2 Analysed monazites.

Tot. indicates the number of extracted crystals and fragments. P crystals are the codes of samples that were photographed and described.
black uraninite are growing in contact with the beryl. Beryl colour is commonly turned to yellow by the local presence of metamictic minerals, which sometimes are hosted or grow in contact with the former. In this case the whole crystal achieved a uniform bright yellow colour. The green monazite crystal was pre-fractured and post-extraction was impossible to determine the habit. Anyway the crystal appear euhedral and with no appreciable elongation. C. M. Gramaccioli (1986) reports the finding of green U-rich monazites in the Piona pegmatites of the Como Lake.

(VLGm) Clear, yellow, millimetric crystals of monazite hosted in smoky quartz. This samples come from the central large pocket of the VLGm dyke. VLGm(m)1 crystals are scattered on a clear surface of a fragment of quartz, probably a face, with small red crystals of garnet (fig. 15k). VLGm(m)2 appear as a group of broken orange-yellow crystals in association with flat wodginite crystals, hosted in massive quartz (fig. 15l).
(VCA) This specimen was a large flake of silvery muscovite hosting several crystals of greenish monazites and a group of twinned zircons. The latter have rounded anhedral shape with a greenish core and a partial brown to pinkish coating with cribrous aspect. These crystals are composed by a green monazite core and a rim of riprecipitated poikilitic monazite, which contains small uraninites (fig. 18e), or xenotime (containing also zircon crystals, fig. 18f) on VCA(m)1Pa and VCA(m)1Pb, respectively.

6.2.4. Zircons

All zircons sampled display the same morphology of those described by Corfù et al. (2003) from pegmatite rocks and compared on the “Pupin diagram”. Dominant faces are the \{110\} prism and the \{101\} tetragonal bipiramid. Some samples developed flattening and curious pseudo-symmetries probably due to competitive growth in pegmatite.

(CODg) Zircons found are CODg(z)1 and CODg(z)2. The latter is a subhedral partially altered crystal, little elongated on c-direction. The color varies from light brown to greenish where it is compenetrated by black lamellae of Nb-Ta-U oxides. CODg(z)1 is composed by two flat, light brown coloured, crystals elongated on the c-direction. The hypothetical prism face displays a peculiar, flat pyramidal shape, with concentric stripes (we remand to the CODs(z) for an hypothesis). Crystals produced pink halo in the hosting feldspar.

(CODs) These two crystals are the largest and most intriguing samples among zircons. Both were found within a parallel growth of light blue beryl. The small one CODs(z)1Pb is flat with a hexagonal shape. It displays a curious pseudo-hexagonal (six faces) symmetry on one side (fig. 16n) and a pseudo-ternary (three faces) symmetry on the other side (fig. 16o). The large one CODs(z)1Pa, which is 5,2 mm in length, has a deformed euhedral prismatic habit with one nice termination (four bipyramid faces) and the other pinching out as a wedge. It also displays the pseudo-exagonal symmetry, but less evident, on both two of opposite
hypothetical faces of the prism, which are inclined at a small angle. The other two hypothetical prisms have a little pronounced wedge shape. Each irregular face has a sort of resonant striped texture, which is concentric on the pseudo-hexagonal side. Since all these crystals were found growing at the interface between the beryl prisms, an explanation for the strange habit may come from the competitive growth between the beryl crystal and the zircon crystal. Commonly in pegmatites crystals grow against each other competing for space (London 2008), an example is the graphic intergrowth of quartz and K-feldspar. London (2008) reported the image of a columbite-tantalite that competed successfully against another crystal. Accessories that compete for space are forced to assume a particular shape depending on the surrounding crystals (see also the description of monazite CODg(m)3). If we assume that zircon nucleated on the prism of one beryl crystal, the successive steps of growth may have forced the crystal to assume a complex habit related to the geometry of beryl. A hint comes from the evidence of steps on such surfaces, which represent discrete phases of growth (grow-steps are evident in quartz, feldspars, beryl and in some cases other minerals in pegmatites; London 2008). The free surface pointing out of the beryl was allowed to develop the real habit of zircon (see the termination with bipyramid faces on CODs(z)1Pa). In the case of CODs(z)1Pb, the free surface might be the pseudo-trigonal one. Assuming that the crystal nucleated with the c-axis emerging at a small angle to the beryl c-axis and one prism of the zircon facing the beryl, the pseudo-trigonal arrangement may be the area of the confluence of two bipyramids and a prism (for example (101), (010) and (110)). The crystallographical angles on the faces of bipyramid-prism-bipyramid and prism-bipiramid-bipiramid are respectively 95.63° and 116.80°. Accurate measuring on the existing sample is yet to be done but this hypothesis seems reasonable. CODs(z)1Pa crystal has two opposite surfaces displaying pseudo-hexagonal symmetry and has one regular termination with the \{101\} bipyramids (fig. 16p). This may be explained with the growth against two flanked beryl crystals. Further analysis are needed to confirm this hypothesis.

CODs(z)1Pa after cutting revealed a dominant black core surrounded by a thin light brown rim (fig. 16w), which gives the exterior aspect of the crystal. The rim
shows radial cracks suggesting a major content in radioactive elements of the internal one that caused differential volume expansion (Corfu et al., 2003). The black core seems vitrified and shows (1) an internal oblique band (which follows probably a crack) of a feather-shaped recrystallized phase, similar to the rim one, and (2) needle-like light-coloured longitudinal bands. It is likely that CODs(z)1Pb posses the same core-rim structure.

(CODt) Four different samples come from the Trubinasca Codera dike: CODt(z)1, 2, 3 and 4. CODt(z)1 includes many little, light brown crystals (up to 640 µm) growing on a yellow altered beryl crystal. They developed a bipyramidal habit with no prism faces. CODt(z)2 is an altered subhedral crystal with colours ranging from bluish to greenish and brown, grown within a beryl crystal. The habit is complex and it is probably twinned. It is associated to a dark crystal of probably a Nb-Ta-REE oxide. The beryl crystal colour is altered to yellow and show radial cracks surrounding the zircon (fig. 15f). CODt(z)3 crystals are euhedral light brown colored. They grew at the contact of a yellow beril (see CODt monazite description) with uraninite and monazite. CODt(z)4 zircons are light brown, perfectly euhedral, prismatic and with c-elongation. They grew both in contact with yellow beryl and quartz. The CODt(z)Pb broken crystal displays a black dominant core with conchoidal fracture (fig. 16t).

(ROSb) Several samples were collected from this dike within the intermediate and core zones of the dike. ROSb(z)1 zircons found on muscovite are light brown coloured and developed faces only on the side not in contact with muscovite ROSb(z)2 is a single subhedral, light brown elongated crystal. It grew on a muscovite flake within K-feldspar, which developed a pink halo surrounding the zircon. ROSb(z)3 is an aggregate of several twinned crystals surrounding a black uraninite core. Differently from all other specimens these are translucent and dark orange coloured (fig. 16u). Although they seem perfectly euhedral is not easy to recognize a definite habit due to the intergrowth of several individuals. ROSb(z)4 is an euhedral, light brown crystal grown within quartz and K-feldspar. It is flattened perpendicularly to two of the prisms. ROSb(z)5 was lost during extraction.
Monazite crystals description:

(a) CODg(m)1P: Stubby prismatic sub-euhedral crystal of honey yellow monazite. Figure was taken with the crystal c-axis oriented N-S and the binary axis of monocline symmetry E-W. Parting on {001} is visible on the E-W direction. (b) CODg(m)2Pa: Prismatic euhedral crystal of monazite. It displays c-direction elongation and flattening on {100}. Other smaller crystals grow at the contact with the matrix. Visible the parting {001}, the prism {110} and the pinacoid {100}. The termination faces are not well preserved but is possible to recognise the small (10-1) pinacoidal face. See fig. 17a. (c) CODg(m)2Pb: Stubby prismatic, euhedral crystal of monazite. Traces of parting and cleavage are clearly visible on the fractured surfaces. (d) CODg(m)3P: Euhedral prismatic crystal of clear yellow monazite. The habit is curious since it developed large faces apparently corresponding to the {100}, {010} and {001} pinacoids (see model). This may be imputed to competitive growth against other crystals, which impose the shape. Parting {001} parallel to the termination face and the cleavage {100} are clearly visible. See fig. 17b. (e) CODm(m)1P: Fragment of monazite showing conchoidal fracture. The colour is clear yellow with local orange inclusions. (f) CODt(m)1P: Largest fragment of the green U-rich monazite crystal of CODt dike. Parting and faces are not easily distinguishable so the habit couldn’t be described. (g) VLGm(m)1P: Elongated (c-direction) crystal of clear yellow monazite. Parting {100} is visible on the prism face along the N-S direction of the picture. (h) VLGm(m)2P: Fragment of euhedral prismatic crystal of clear yellow monazite. The parting is clear and faces of the crystal resembles those of CODg(m)3P. (i) VCA(m)1Pa: Rounded subhedral crystal of greenish and pinkish monazite. A tentative to recognise some faces is made with the drawing (fig. 17c). This seem to find some resemblance with the model Monazite no.1 by Goldschmid (1913-1926) of fig. 17d (source: www.mindat.org). (j) VCA(m)1Pb: Large anhedral complex crystal of greenish monazite and pinkish xenotime growing with REE-bearing epidote and prismatic apatite.

Thorite and Zircon crystals (single zircon crystals are already described in the text):

(k) CODg(th)1P: Fragment of prismatic euhedral crystal of dark green thorite. It is twinned with another smaller crystal on a prism face. (l) CODg(z)1P. (m) CODg(z)2P. (n and o) CODs(z)2Pb both sides. (p) CODs(z)1Pa. (q) CODt(z)2. (r) CODt(z)3P. (s) CODt(z)4Pa. (t) CODt(z)4Pb. (u) ROSb(z)3P. (v) ROSb(z)6P.

Polished sections of zircons:

(w) Polished section of CODs(z)1Pa. (x) Polished section of ROSb(z)6P.
ROSb(z)6 is an aggregate of small zircons and a large one (420 µm) growing on feldspar. These crystals are dark coloured displaying an altered surface, the habit is prismatic euhedral but complicated by the coalescence. The internal structure of the largest one (ROSb(z)6P) is complex, composed by a thin outer rim and a large complex core (fig. 16x). It resembles that of CODs(z)1Pa and is composed by a glassy internal mass, which in this case is dark green, fractured and pervasively replaced by vermicular riprecipitated rusty to light-coloured zircon. Another feature of the core is the presence of a (skeletal?) swarm of small isooriented bipyramidal crystals. It was proofed that all these phases are zircon with some rapid EMP analysis not reported in this thesis.

Figure 17 Graphic study on monazite crystals:
Recognizable faces are confronted with Goldschmidt models (1913-1926) and indicized. (a) Drawing of sample CODg(m)2Pa. (b) Drawing of sample CODg(m)3P. (c) Drawing of sample VCA(m)1Pa and (d) model no.1 by Goldschmid (1913-1926) confronted (source: www.mindat.org).
As described for the monazite samples, this pale brown zircon was found within a large flake of muscovite. It is a spray-like aggregate of twinned individuals, which have euhedral prismatic habit. The whole aggregate measures 1.4 mm in length.

6.2.5. Thorite

Dark green thorite crystals (fig. 15a and 16k) were found at the core of one monazite crystal of the CODg(m)1 sample, embedded in lamellar Nb-Ta-REE oxides. The crystals have elongated prismatic habit with flat pinacoidal termination and some are twinned. The largest one reaches 1.5 mm in length.

7. Chemical Analyses

7.1. SEM BSE imaging

Backscattered electrons (BSE) images of polished monazite, xenotime and thorite were taken in order to have a qualitative control on internal chemical variation. These images were useful to plan the successive EMPA and LA-ICP-MS analyses. Since dating was planned for monazite samples it was of primary importance to discriminate different chemical internal domains: growth and sector zoning, riprecipitated or different phases like inclusions and alteration. Rapid qualitative analyses on chemistry allowed a first qualitative identification of the included phases. Images were acquired with the scanning electron microscope (SEM) at the SEM laboratory of Dipartimento di Geoscienze of Padova. Analytic conditions and further information are reported in the appendix I.A.

Most of sampled monazites are chemically quite homogeneous and only highly contrasted BSE images help to recognize the faint primary zoning. Among zoned fragments of sampled monazites two types of zoning are recognisable: primary zoning and secondary zoning. Primary sector zoning is imputed to: (1) selective adsorption on the crystal surface, or (2) different attachment kinetics on different
facets (Catlos, 2013, and references therein). It can be distinguished from secondary zoning by the regular geometries of the chemical variations, which follow precise crystallographic directions. The spectacular concentric zoning on CODg(m)3 (fig. 18b) clearly highlights the growth steps of the crystal.
Figure 18  Highly contrasted BSE images of monazite, xenotime and thorite:
(a) CODg(m)1P: Large unzoned crystal with cribriform (c) areas. Bright spots are small uraninite grains. (b) CODg(m)3P: Spectacular concentric zoning showing asymmetrical growth of the crystal (c=core of the crystal). (c) VLG(m)2-8: Fragment displaying primary sector zoning (p) parallel to the parting and secondary less brighter patchy zoning (s) at the border. (d) CODm(m)1-5: Fragment showing secondary brighter vein zoning (v). (e) VCA(m)1Pa: This monazite crystal is composed by a cribrous, poikiloblastic phase and a homogeneous one (bottom left). The cribrous phase is probably reprecipitated. (f) VCA(m)1Pb-3: Cribrous xenotime including zircon crystals. (g) CODg(th)1-2: Thorite fragment displaying the pervasive alteration to thorogummite and numerous inclusions. (h) Close up of the white frame of fig. 18g. Crystals growing in contact with thorite (t), which is partially altered to thorogummite (tg), are: xenotime (x), REE-epidote (e) and Nb-Ta-REE oxides, probably euxenite (o). (i) Close up of monazites (m), allotriomorphic phosphates (dark areas signed with p) and REE-epidote (e) included in CODg(th)1. The alteration to thorogummite is signed with tg.
As it is evident in the image, the monazite nucleated against another crystal since zoning is strongly asymmetrical. On VLGm(m)2-8 it is visible another type of sector zoning, probably oscillatory zoning, consisting in bands with different brightness parallel to the parting (fig. 18c). Secondary, irregular zoning includes patchy (regions marked by smaller, irregular regions of different brightness and composition) (fig. 18c, signed with s) and vein (differences in composition or brightness near cracks or veins) zoning (fig. 18d). Secondary zoning is common in sampled crystals and in most cases develops in correspondence of cracks or other discontinuities. Most secondary chemical variations in monazites occur with reduction of brightness in BSE images, which suggests depletion in heavy elements. An exception is CODm(m)1 samples that are locally penetrated by brighter thin veins with cloudy aspect (fig. 18d). CODg(m)1 samples don’t show primary zoning but have broad volumes with cribriform aspect (fig. 18a). Polished areas show swarms of small irregular holes (most are less than 10 μm in length) gathered especially near the borders. Those are filled with allotriomorphic phosphates (including REE-phosphates and apatite), quartz and commonly contain rounded grains of xenotime, uraninite, REE-bearing epidote and Nb-Ta-REE oxides. Less bright patchy zoning is visible in these areas.

VCA(m)1Pa and Pb polished crystals confirm their complexity with BSE imaging. VCA(m)1Pa is composed of two different monazite phases: one is clear and homogeneous, the other is cribriform and hosts numerous grains (cribriform themselves) of REE-phosphates and uraninite. VCA(m)1Pb monazite is similar to the clear one of VCA(m)1Pa, but it is intergrown with a large crystal of xenotime and spongiform crystals of zircon. Xenotime locally displays cribriform zones. Areas not affected by cribriform zones display sector zoning (following crystallographical directions) and altered areas with irregular borders. Cribriform areas in xenotime and zircons show patchy zoning suggesting pervasive alteration. The irregular cavities contain the same phases seen in VCA(m)1Pa. Cribriform aspect of inclusions-rich monazite are associated to mottled zoning (Catlos, 2013, and reference therein), which is typical of dissolution and riprecipitation processes.
on monazite. Similar processes are likely to have been affecting xenotime and zircon crystals too.

CODg(th) thorite samples display a pervasive internal alteration to thorogummite (fig. 8g). It appear as less bright vermicular to dendritic volumes that follow major fractures and penetrate in the crystal. Thorite contains numerous inclusions: rounded monazite and REE-rich epidote grains, xenotime and Nb-Ta-REE oxides (fig. 18h and i). Fractures and related alteration commonly exploit grain boundaries of inclusions like monazites. Dark phases filling the fractures are mainly REE-phosphates and apatite.

7.2. EMP analysis

Electron-microprobe analysis (EMPA) was performed on garnet, tourmaline, monazite, thorite and xenotime samples (also for some inclusions) at the laboratory of microanalysis of the Istituto di Geoscienze e Georisorse - CNR (Padova). Complete tables with chemical analysis results are attached in the appendix II, including those of thorite, thorogummite, xenotime and inclusions. Since analysis on inclusions are insufficient for a complete characterization and EMP- was calibrated only for elements expected in monazites, they won’t be discussed in this thesis. Analytic conditions and further information are reported in the appendix I.A.

7.2.1. Garnet

Garnet is used as a useful indicator of fractionation trends in pegmatites (London, 2008). Core-rim or rim-rim chemical profiles were provided with punctual measures, separated by 50 to 200 μm steps depending on chemical variation and size of the crystal, on each garnet. Spessartine (mole %) vs distance (core = 0 μm) profiles of representative samples are reported in fig. 19. Crystal Sps-content profiles of each garnet were plotted on the same diagram and showed that samples separate in two different groups with strong concordance of core
composition and few exceptions. Representative garnets profiles are plotted in fig. 19.

The first group includes all garnets characterised by dominant spessartine content at the core with values ranging between $\text{SpS}_{61}$ and $\text{SpS}_{65}$. CODp(g)1 garnet is fairly homogeneous with compositions ranging from $\text{Alm}_{32}\text{SpS}_{64}\text{Pyr}_{2}$ (core) to $\text{Alm}_{36}\text{SpS}_{61}\text{Pyr}_{2}$ (rim). CODp dike also hosts nearly pure spessartine garnet with composition $\text{Alm}_{7-17}\text{SpS}_{92-82}\text{Pyr}_{0.5-0.3}$ (CODp(g)2). CODg(g)1 is moderately zoned with core composition similar to CODp(g)1 and $\text{Alm}_{44}\text{SpS}_{55}\text{Pyr}_{2}$ rim. ROSg(g)1 has a well-developed bell-shaped zoning with core overlapping COD compositions ($\text{Alm}_{33}\text{SpS}_{64}\text{Pyr}_{3}$) and minimum $\text{Alm}_{53}\text{SpS}_{39}\text{Pyr}_{6}$ rim. ROSb(g)1, which has rhomb-dodecahedron habit, has slightly lesser spessartine component $\text{Alm}_{40}\text{SpS}_{56}\text{Pyr}_{3}$ at the rim, $\text{Alm}_{46}\text{SpS}_{49}\text{Pyr}_{3}$ in the inner rim and a thin outer rim of $\text{Alm}_{39}\text{SpS}_{59}\text{Pyr}_{2}$.

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Table 3 Garnet from the Codera area.
Codera graphic garnets, even if the core of the intergrowth is individuated, are unzoned and have group-1 core composition. VLGm(g)1 garnet is the only one from Bodengo area whose core composition overlaps those of Codera. It has Alm$_{29}$Sps$_{65}$Pyr$_{4}$ core and Alm$_{40}$Sps$_{51}$Pyr$_{5}$ rim, but has higher TiO$_2$ values. It should be noted that unlike other Bodengo area garnets it has an extremely dark red colour and rhomb-dodecahedron habit.

Group-two includes all other garnets, which are exclusively from Bodengo area and all display a well-developed bell-shaped zoning. With the exception of VGa(g)1 and VGb(g)1, all group-two garnets have rather coherent core composition of medium Alm$_{57}$Sps$_{41}$Pyr$_1$ (within the range of Sps$_{39-42}$). VGb(g)1 is richer in Alm with Alm$_{63}$Sps$_{43}$Pyr$_2$ core and Alm$_{73}$Sps$_{57}$Pyr$_5$ rim while VGa(g)1 has higher Sps with Alm$_{48}$Sps$_{47}$Pyr$_4$ core and Alm$_{59}$Sps$_{53}$Pyr$_7$ rim. Since VGb(g)1 core composition is lower in Sps but overlaps the compositions range of other Bodengo garnets, the difference can be imputed to different time of nucleation during pegmatite liquid evolution. On the other hand VLGa(g)1 higher Sps core

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| Table 4 | Garnet from the Bodengo area. |
| Renamed after Guastoni et al. (2014). Structural formula based on 12 oxygen atoms. * (Fe$^{3+}$/Fe$^{2+}$) calculated (Droop 1987). |
values exceed the mean value of group-2 (Bodengo) core compositions and represents an exception.

Results show that Codera and Bodengo garnets (with the exception of VLGm(g)1) form two separate groups with different Sps content. However all non-graphic garnets show the same trend of inverse zoning with Sps-rich core and Alm-rich rim. Pyr (Mg end member) component generally is less than 3 mol % but dark red VLGm(g)1, VGa(g)1 and ROSg(g)1 garnets exceed Pyr values at the rim. Grossular, andradite, and uvarovite components sum always less than 5 mol.%. Despite the relative variance in Sps content, all non-graphic samples display the same trend, more or less pronounced, of depletion in spessartine (Sps) component toward the rim and coupled enrichment in almandine (Alm).

Figure 19 Zoning patterns of Sps content in selected garnets from Codera and Bodengo areas. Renamed after Guastoni et al. (2014).
7.2.2. Tourmaline

Like garnets, tourmalines are important minerals for the mineral-based classification and study fractionation trend of pegmatites. All analysed tourmalines are prismatic and were cut perpendicular to the c-axis. On most crystals composition was measured along core-rim profiles.

All Bodengo tourmalines are schorl with rather low variation in Li content and $2\text{Li/(2Li+Mg+Fe}^{2+})$ ratio ranging between 0.05 and 0.25 (fig. 20c). The most homogeneous one is the miarolitic VLGb(t)1 tourmaline, which, despite the greenish colour, is a schorl and has the lowest Mg number ($\text{Mg/(Mg+Fe}^{2+})$<0.1). Other Bodengo tourmalines show rim-core variations in Mg content. VDD(t)1 miarolitic tourmaline has similar Mg number (~0.1) to VLGb(t)1 but has a thin rim (60µm) showing enrichment in Mg (up to 0.25). VLGa(t)1 shows internal zoning with (1) a foititic (vacant X site >0.5) core with rather constant Mg number of 0.21, (2) a thin transition non-foititic zone with lower Mg number and (3) a non-foititic thicker rim with gradual increase in Mg number (up to 0.35). Both VLGa and VDD dikes intrude amphibolites, which may explain the relatively higher Mg number of hosted tourmalines (Guastoni et al. 2014).

Most Codera tourmalines are prismatic and graphic schorls with composition similar to the cores of Bodengo ones. They don’t show comparable Mg-number variations but some have higher grade of evolution with local enrichment in Li (fig 20 a). The most fractionated dike of Codera CODp hosts tourmaline crystals with yellow-green Mn-rich fluorelbaite rim (CODp Elb. in fig. 20a, Guastoni, 2012, and references therein). CODp(gt)1 portion of graphic tourmaline has thin rims evolving toward elbaite. Guastoni et al. (2014) report the composition of a tourmaline grown in the host rock gneiss of a pegmatite (sample PP), which is identical to that of tourmaline from the VLGb sample.

<table>
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<th>Table 5</th>
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### a

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### Notes
- The table a shows the oxide wt.% for different samples: RO88(t), CO80p(t), and CO80p Elbate.
- The table b shows the oxide wt.% for different samples: VG(41), VG(51), VG(50), VDG(51), and bulk.
- The data is presented in columns for each oxide, followed by the wt.% and standard deviation (st.dev).
7.2.3. Monazite

Monazites were preliminary chemically analysed before LA-ICP-MS U-Th–Pb dating. The composition is typical of pegmatitic Th-rich monazite-(Ce), with an average Ce$_2$O$_3$ of 27.5 mol. % for Codera crystals and 25 mol. % for Bodengo ones. Monazites have medium-high ThO$_2$ content (6-7 mol. %), which is coherent with the habit of most crystals (Catlos, 2013), and subordinate UO$_2$ (<1 mol.%). Other components (REE elements oxides) exceeding the 1 mol. % are (with decreasing relevance) Nd$_2$O$_3$, La$_2$O$_3$, Pr$_2$O$_3$, Sm$_2$O$_3$ and Y$_2$O$_3$, which sum up to

![Classification diagram of tourmaline from the Codera (a) and the Bodengo (c) areas. The complete classification scheme is reported in the inset (b). The compositional profile of a zoned tourmaline crystal from the VLGa dike is shown in (d). Renamed after Guastoni et al. (2014).](image)
an average of 30.5 mol. %. Exceptions are the green monazites from both Codera and Bodengo areas. One is a dark green monazite from CODt dyke of the upper Codera valley that has lower Ce$_2$O$_3$ (~22.7 mol. %) and very high UO$_2$ (~10.5 mol. %). VCA(m)1 greenish monazites have higher ThO$_2$ (10-11 mol. %), slightly higher UO$_2$ (1-2 mol. %) and lower Ce$_2$O$_3$ (~25 mol. %), Pr$_2$O$_3$ and Nd$_2$O$_3$. Greenish U-rich monazites have higher CaO content. CaO values of 3.5 and 2.1 mol. % are measured respectively on CODt(m)1 and VCA(m)1.

VLGm(m) monazites have higher Nd$_2$O$_3$ (as much as 17.5 mol. %), Sm$_2$O$_3$ (as much as 11 mol. %) and lower Y$_2$O$_3$ (<2 mol. %).

Primary zoning of monazites reflect low oscillation of mainly U, Th and Ce content. Secondary zoning occurs generally as darker irregular zones depleted in Th, Pb and U (fig. 18c). In these areas the UO$_2$ value is more than halved. Vein zoning found in CODm(m) samples has higher content in REE and appear as brighter veins in BSE images (fig. 18d). Veins are filled by a secondary monazite phase with higher Ce$_2$O$_3$ (as much as 30 mol. %), high ThO$_2$ (as much as 11 mol. %) and low UO$_2$ (<0.2 mol. %). The high Th phase seems more suitable with chemical instability during magmatism since hydrothermal monazite commonly has lower Th content than magmatic monazite (Catlos, 2013).

Monazites included in the CODg(th)1 thorite crystal are similar to Codera ones but have higher Ce$_2$O$_3$ (30 mol. %) and slightly lower ThO$_2$ (5.5 mol. %).

7.3. **LA-ICP-MS U-Th–Pb Monazite dating**

Isotopic analyses on monazite were obtained with the Laser Ablation and Induced Coupled Plasma Mass Spectrometry (LA-ICP-MS) technique performed at the Istituto di Geoscienze e Georisorse (IGG) of CNR (Pavia). Technique description and analytical conditions are reported in the appendix I.A.

Ages are obtained from monazite samples from three dikes of Codera area (CODg, CODt CODm) and two dikes of Bodengo area (VLGm, VCA). Virtually the three obtained isotope ratios ($^{206}$Pb/$^{238}$U, $^{207}$Pb/$^{235}$U and $^{208}$Pb/$^{232}$Th) would
yield the same age if the crystal system is considered close. However analysis results show a drastic systematic difference in age between the Pb/U ratios and the Pb/Th ratio. This can be explained by the decoupling of the systems caused by alteration. It is noteworthy that monazites sampled show both altered and riprecipitated areas. Major age discordance between Pb/U and Pb/Th ratios are found in the analysis spots of monazites from the VLGm dike of Bodengo area: VLGm(m)1-12_036, VLGm(m)2-4_014, VLGm(m)2-8_019, VLGm(m)2-12_027 and _030 (see age table for correct spots). Each of these analyses comes from darker areas (on SEM BSE images) with irregular borders (e.g. fig. 18c). Correspondent EMPA analyses highlight that those areas are depleted in Th, Pb and U. However ages obtained with the $^{208}\text{Pb}/^{232}\text{Th}$ ratio on the same crystal are comparable both in the altered volume and in the pristine one. Therefore, as for the work of Bosse et al. (2009), accepted ages are those of the $^{208}\text{Pb}/^{232}\text{Th}$ ratio since:

- Monazites contain more Th than U thus the signal of $^{208}\text{Pb}/^{232}\text{Th}$ is better in accuracy.
- $^{208}\text{Pb}$ originating from common Pb is negligible thanks to the abundance of Th.
- Ages obtained with the Pb/U ratios for Codera samples yielded unrealistic older ages than those of emplacement of the Bergell tonalite.
- Altered areas show a strong decrease in U and lesser for Th suggesting circulation of U-aggressive fluids. Loss of U results in age sovrastimation (M. Tiepolo personal communication).

$^{208}\text{Pb}/^{232}\text{Th}$ ages yielded by monazites show significant variations even in the same crystal (>2 Ma on different analysis spots). Since dating work is yet preliminary and lacks of more accurate data discussion it won’t be examined in depth in this thesis and only rough data are presented. Even though dating of dikes actually wouldn’t provide a representative mean age, ages of Codera and Bodengo dikes plot in two rather distinguishable groups of points (including the 2σ error bars, fig. 21).
Codera monazites yielded ages ranging from 28 and 25 Ma. Bodengo monazites are younger and ages range from 23 and 19 Ma. Even if the higher and lower ages of each group are included, pegmatites from Codera area are all older than 24 Ma and vice versa for the Bodengo pegmatites. Only one fragment included in the VLGm(m) samples yielded discordant age of ~26 Ma. EMP analysis on this fragment plot on those of CODm(m)1, whose fragments also share similar appearance and age. Since it is reasonable to consider this as a case of contamination, it was renamed temporarily CODm(m)1-C and added to Codera monazites but not included in the plot.

The same dating was carried on the thorite sample CODg(th) and the xenotime intergrown with VCAm(m)1Pb monazite. Thorite ages are concordant for each ratio but are 5 to 6 Ma older than those of hosting monazite. On the other hand $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages of xenotime are only 2 and 1 Ma respectively older of the intergrown monazite VCA(m)1Pb ages.

The two age groups of Codera and Bodengo pegmatites are respectively older and younger than 24 Ma. According to Liati et al. (2000) who dated the Novate granite at 24.0 ± 1.2 Ma, the Codera monazite ages of pegmatites would be consistent with the field evidence of younger microgranite dikes crosscutting the main set of pegmatite dikes in the upper Codera valley. Codera pegmatite...
intrusion would be coeval with the late D3 (Cressim) ductile deformation stage, which is consistent with the higher degree of deformation of dikes than the Bodengo ones. On the other hand Bodengo deformed pegmatites would be emplaced during the waning stage of ductile deformation in the southern Adula nappe.

8. **Discussion and Conclusions**

In this work only a minor portion of the large Tertiary pegmatitic field of the Central Alps was investigated in Codera and Bodengo areas. Pegmatites of both areas seem comparable by the similar grade of evolution, since evolved dikes display more or less the same mineralogy. On the other hand structural, textural, chemical and radiometric results tell a more complicated story that allows individuating at least two different intrusion events.

8.1. **Structural data**

Codera pegmatites occur with two main groups with different orientations. The main set strikes WSW-ENE, other dikes are oriented E-W. Crosscutting relationships suggest the existence of at least two different generations.

Pegmatites clearly postdate the emplacement of the Bergell pluton since they cut discordantly (1) the base of the intrusion and (2) its parallel pervasive solid-state foliation, and (3) the main fabric of the Gruf complex. Dikes crosscut migmatitic structures thus syn-intrusion peak conditions of 720–740°C and 6–7 kbar (Galli *et al.*, 2011) clearly exceed those of emplacement of pegmatites.

Microgranitic dikes related to the intrusion of the Novate granite (24.0 ± 1.2 Ma, Liati *et al.*, 2000) seem to postdate pegmatites by crosscutting relationships and radiometric results on monazites. Therefore assumed country rock conditions of 0.2 GPa and 400 °C (Ciancaleoni and Marquer, 2006) represent the lower limit.

All pegmatites from Codera area show solid-state deformation and locally localize well-developed mylonites with transpressive kinematics. On two of the
sampled quartz-mylonites (nucleated at the wall of deformed pegmatites) the measured crystallographic preferred orientation shows a strong, single c-axis maximum parallel to the Y-axis of the mylonite (perpendicular to the lineation and parallel to the foliation). This quartz CPO pattern suggest syn-deformation temperatures of ~500°C and is similar to those studied in Adamello quartz-mylonites (Pennacchioni et al., 2010; Guastoni et al., 2014 and references therein). Temperature is consistent with recrystallized stable biotite and k-feldspar in the foliation.

D3 peak conditions of migmatisation in southern Adula nappe (650–750 °C and 0.4–0.6 GPa, Nagel et al., 2002) are similar to those of Codera and can be used as upper limit to the pegmatite intrusion in the Bodengo area. The main set of Bodengo pegmatites is generally undeformed and cuts discordantly the D3 structures. However some dikes show ductile deformation on boundaries (with an annealed quartz fabric typical of a temperature >500 °C) with strike-slip kinematic. Also in Bodengo area there is evidence of at least two generations of pegmatites: the main set dips toward W and NW and crosscuts a former set of strongly deformed pegmatites striking NW-SE. These may represent the ductile deformed set with Codera affinity that predate the main set.

8.2. Chemical data

Pegmatites of Codera and Bodengo areas show a similar grade of evolution and mineralogy. On the other hand some minerals show a chemical signature that is typical of all crystals of the same phase of the same area.

Garnet is the most evident one with Codera ones displaying Sps-rich cores and Bodengo ones Alm-rich cores. With few exceptions all garnet cores of the same area plot coherently on the same Sps content.

Chemical signature of tourmalines are less evident but Codera ones show the highest grade in fractionation, reaching F-elbaite compositions in the Phosphate dike in the Upper val Codera. Bodengo schorls display minor fractionation but
higher grade of variance in Mg content. This is probably due to interaction with
the host rock (Guastoni et al. 2014).

Monazite samples of Codera area display an higher content in Ce (27.5 mol. %)
than those of Bodengo (25 mol. %). However this last datum is based only on two
dikes from Bodengo area and should be treated critically.

8.3. Radiometric data

As Guastoni et al. (2014) assumed, Pb/Th dating on monazite yielded two
different age groups for pegmatite dikes of the two different areas. Codera
pegmatites are older than 24 Ma, with monazite $^{208}\text{Pb}/^{232}\text{Th}$ ages ranging from 28
to 25 Ma, and Bodengo ones are younger with monazite $^{208}\text{Pb}/^{232}\text{Th}$ ages ranging
from 23 and 19 Ma. Error bars (2$\sigma$) of single age measures of monazites from the
same area do not overlap sufficiently to give an acceptable average age. On the
other hand, the virtual medium age of 20,69±0.24 Ma (2$\sigma$) for Bodengo
pegmatites is coherent with observation of some authors that pegmatite
emplacement was associated with a protracted magmatic activity over a time
range from 32 to 20 Ma (Romer et al. 1996, Schärer et al. 1996, Rubatto et al.
2009).

8.4. Conclusions

- Codera and Bodengo areas represent two small portions of the large
tertiary pegmatite field of the Central Alps. Despite a similar grade of evolution of
the dikes and mineralogy, these two areas show systematic differences after
structural, chemical and radiometric study.

Codera pegmatites are older than 24 Ma (monazite ages) and locally show the
major grade of evolution among all sampled dikes (e.g. CODp dike). The main set
trends WSW-ENE and is affected by solid-state pervasive deformation, which
locally produces high-temperature mylonites, developed under transpressive
conditions. Bodengo Pegmatites are younger than 24 Ma and thus than Codera
ones. The main set is oriented N-S and dikes are mainly undeformed but locally show ductile reactivation of borders with strike slip kinematic. Codera garnets are richer in spessartine than Bodengo ones and Codera schorl tourmalines show locally highest grade of evolution.

Since pegmatites of the two areas have (i) different orientations, (ii) different grade of deformation and (iii) different chemical signature of minerals it is reasonable to individuate two separate intrusion events. This is supported by radiometric dating on monazite, which shows no overlap between the Codera and Bodengo pegmatite ages.

- Pegmatites of Codera area emplaced the host rock at a temperature of at least 500°C, which is constrained by the presence of high-temperature quartz mylonites at their boundaries. Dating of pegmatites well concords with the progressive younging of the radiometric ages of peak metamorphism from E to W along the SSB (Todd and Engi, 1997). It is reasonable that Bodengo pegmatites occurred later at similar T conditions during differential uplift rates along the SSB. The time span of emplacement of pegmatites also overlaps the protracted stage of fluid-assisted migmatisation in the SSB, which occurred up to 20 Ma (Romer et al. 1996, Schärer et al. 1996, Rubatto et al. 2009). However pegmatites and migmatites seem genetically unrelated since pegmatite intrusion always postdates the local leucosomes.

- Many authors individuated different pegmatite generations in the Central Alps with young pegmatites treated as post-kinematic intrusions (e.g. Romer et al. 1996). However monazite ages of pegmatite dikes of Bodengo area, which show sometimes ductile reactivation of the margins, indicate that ductile deformation was still active in the southern Adula nappe after 24 Ma and possibly even up to ~20 Ma if the average age is considered. Waning of such conditions is witnessed by the elder set of Bodengo, which is strongly deformed than the crosscutting younger ones.
REFERENCES


APPENDICES

I. Analytical methods

8.5. Scanning Electron Microscope Backscattered Electrons imaging

The electronic microscope used for BSE imaging is the CamScan MX3000 at the SEM laboratory of the Dipartimento di Geoscienze of Padova. The electron beam source is a LaB6 crystal working at standard conditions of 15-20 kV and a current of ~1 nA on the sample. It is equipped with a solid-state semiconductor BSE detector which has 4 independent sectors. At optimum working conditions (10 mm working distance) the resolution is better than 50 nm for silicates.

8.6. Electron Microprobe Analysis (EMPA)

Electron-microprobe analyses were performed on garnet, tourmaline, monazite, thorite and xenotime samples (also for some inclusions) at the laboratory of microanalysis of the Istituto di Geoscienze e Georisorse (IGG) of CNR (Padova). The instrument used is a CAMECA SX-50 electron microprobe, equipped with four Wavelength Dispersive Spectrometers (WDS) and one Energy Dispersive Spectrometer (EDS). The operating conditions were 20 kV accelerating voltage and 20 nA beam current. Counting times were 10 s at the peak and 5 s at the background for major elements and 20 to 100 s at peak and background for minor elements. X-ray counts were converted into oxide weight percentages using the PAP correction program. Analyses are precise to within 1% for major elements and 3–5% for minor elements. Calibration was carried using natural and synthetic international standards in part supplied by Cameca and in part kindly provided by the Smithsonian National Museum of Natural History (Smithsonian Microbeam Standards).
8.7. Laser Ablation and Induced Coupled Plasma Mass Spectrometry (LA-ICP-MS)

Isotopic analyses on monazite were obtained with the LA-ICP-MS technique at the Istituto di Geoscienze e Georisorse (IGG) of CNR (Pavia). The instrument consists in a laser apparatus coupled with a mass spectrometer. The former is the commercial GeoLas102 from MicroLas (Göttingen, Germany), which works with a wavelength of 193 nm and a maximum output energy of 200 mJ per pulse. Spot size depends on focusing and can be varied from 5 to 120 µm. For monazite samples the spot size choice depends on the concentration of U and Th. In order to increase the signal vs. background ratio in high-U/Th monazites a small spot size is recommended. Highly focused beam can be even used to resolve age domains in zoned crystals. The mass spectrometer consists in a single collector double-focusing sector field ICPMS with reverse geometry (type Element I from ThermoFinnigan, Bremen, Germany).

Isotope dating of monazite with laser ablation ICPMS is operated with an analytical method basically similar to that developed for zircon (Paquette and Tiepolo, 2007). The signal of $^{202}$Hg, $^{204}$Pb+$^{204}$Hg, $^{206}$Pb, $^{207}$Pb, $^{208}$Pb, $^{232}$Th and $^{238}$U masses are acquired, where $^{202}$Hg is used to correct the isobaric interference of $^{204}$Hg on $^{204}$Pb by peak stripping. This allows to monitor the presence of common Pb in the sample. The $^{235}$U signal is calculated from $^{238}$U on the basis of the ratio $^{238}$U/$^{235}$U = 137.88. The high sensitivity and low background allows extremely low limits of detection (down to the ppb level) for the heaviest elements, and between 10 and 100 ppb for the lighter masses. Precision and accuracy in age determinations to better than ~2% were attained on the zircon standard 91500 (Paquette and Tiepolo 2007). Analytical conditions used for monazites are the same reported by Paquette and Tiepolo (2007). Thanks to the large size and quality of monazites a 10 µm spot size was used to get more accurate data. The standard used for monazite dating is the Moacir sample described by Paquette and Tiepolo (2007).
II. EMP and LA-ICP-MS analyses results

Following tables include all EMP and LA-ICP-MS results for each analysis spot (An. Pt.) on sampled crystals. The positions of the spots are reported on photographic tables in the attached CD.

- Pages 86-94 Garnet EMPA
- Pages 95-99 Tourmaline EMPA
- Page 99 Inclusions EMPA
- Pages 100-101 Monazite EMPA
- Page 102 Monazite, Thorite and Xenotime LA-ICP-MS
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**Coda phosphate dike**
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ACKNOWLEDGEMENTS

Since I am not good at acknowledging, here are posted some photos that will do it for me.

Thanks also to:

A. Guastoni
A. M. Fioretti
S. Castelli

The 3rd floor team

And, of course,
Mum, dad and sis