Small pluton construction through sills stacking, amalgamation and differentiation: Insight from the Beauvoir granite (Massif Central, France)

Nicolas Esteves*[1], Lydéric France[1,2], Michel Cuney[3], Pierre Bouilhol[1]

[1]Université de Lorraine, CNRS, CRPG, 54000 Nancy, France

[2]Institut Universitaire de France (IUF), France

[3]Université de Lorraine, CNRS, GeoRessources, 54000 Nancy, France

*Corresponding author e-mail address: nicolas.esteves@univ-lorraine.fr

*Corresponding author telephone number: +33 750258090

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Abstract

The kinematics, modes of assembly, and the processes governing the evolution of magmas shape plutonic intrusions. Granite bodies have been suggested to emplace incrementally, with successive magmatic batches locally solidified as dikes or sills. Yet, the complexity and longevity of large-scale plutons hinders a unified model for their emplacement and concomitant differentiation. This is especially true for highly differentiated granites which usually lack continuous outcrops limiting our understandings of the detailed assembly of these igneous complexes and of the related magmatic processes. To tackle this issue, we focus on the Beauvoir intrusion (Massif Central, France), a small pluton (~800 m thick) of high economic interest (Li-Be-Nb-Ta) whose fully recovered 900 m borehole crosscutting the entire granite bring new insights on plutonic processes. The Beauvoir granite contains early-crystallised euhedral quartz and topaz associated with albite, lepidolite (Li-mica), K-feldspar and late amblygonite (Li-phosphate). Here based on numerous high resolution petrographic data (modal composition, intrusive and layering features, mineral morphologies and textural relations, etc.), and on the variation of lepidolite composition throughout the granite, we demonstrate that the whole intrusion formed through the stacking of at least eighteen decametric crystal-poor sills. Those intrusive bodies form the Beauvoir sub-units that emplaced successively without significant magma mixing with previous injections. Based on structural and geochemical features, we constrain the first relative chronology of a highly-differentiated stacked intrusion with an overall over-accretion mechanism. Once intruded, sill differentiation occurred via fractionation of quartz and topaz producing albite-, lepidolite-, amblygonite-saturated residual liquids, notably enriched in incompatible elements such as Li, Be, F and P. Channel like forming albite-rich segregates, representing escaped residual liquids from the solidifying quartz-rich mush often pounds beneath the overlying subsequently intruded sill, indicating a protracted plutonic construction faster than the solidification of a single sill. Alternatively, such evolved residual melts locally

accumulate to form weakly-viscous potentially eruptible melt lenses, which possibly fed the rhyolitic dikes intruding the surrounding host-rocks.

1. Introduction

Igneous bodies formation is the end result of complex interplays between protracted magmas migration and accumulation in the emplacement site and their crystallisation until their entire solidification. The way in which those magmas are assembled plays a key role in the magmatic processes occurring within the igneous reservoir and consequently, on the composition of derivative liquids and cumulative counterparts and thus on the size and shape of the final intrusion. Plutonic intrusions were originally thought to be the result of the solidification of a large liquid-rich magma chamber (Wager, 1963; Irvine, 1980; Kuritani, 1998; Kamiyama *et al.,* 2007). Such magma "chambers" would rise through the continental crust as diapirs toward their final emplacement site once they had reached neutral buoyancy (Buddington, 1959; Hanmer & Vigneresse, 1980; Marsh, 1982; Vigneresse & Brun, 1983; Bateman, 1984; Guillet *et al.*, 1985; Weinberg & Podladchikov, 1994; Miller & Paterson, 1999; Petford *et al.*, 2000; Del Potro *et al.*, 2013; Copley *et al.*, 2023). However, this trans-crustal ascension might be limited in space and time to specific conditions (e.g., abnormally hot crust, large magma volume, see Del Potro *et al.* 2013) as protracted crystallisation would considerably increases magma viscosity, which in turn inhibits further ascension (Glazner *et al.*, 2004; Annen *et al.*, 2015). Igneous intrusions can also be the result of multiple intrusions, whereby magmas are being emplaced and amalgamated in the final reservoir site from deeper crustal region (Coleman *et al.*, 2004; Schoene *et al.*, 2012; Boulanger *et al.*, 2020; Zhang *et al.*, 2022; Eshima & Owada, 2023; Zhang *et al.*, 2024). When this final reservoir site is fed by a high magmatic flux, the reservoir will have a tendency to be liquid rich, and as such, magma mixing will be operative, and the successive replenishments will be recorded by oscillatory zoning in crystallising mineral phases (Zhang *et al.*, 2024). This is supported by field evidences, such as magma mingling and the presence of enclaves of various composition within many plutons, that indicate that they grew from different magmas batches of various compositions (Barbarin & Jean, 1992; Caroff *et al.*, 2015; Jiang *et al.*, 2018). In those conditions, if the feeding zone localisation does not evolve through time, the whole intrusion inflation will lead to a final ballooning shape (Molyneux & Hutton, 2000; Asrat *et al.*, 2003; Schoene *et al.*, 2012; Bella Nke *et al.*, 2022). On the other hand, if the flux rate is low enough to let the whole intrusion in a crystal-rich state when the new magmatic recharge is arriving, magma mixing will be limited due to viscosity contrast between the host mush and the new coming magma. This specific configuration will lead to a laccolith formation in which different sills (i.e. magma recharge) with various composition can be more or less easily identified (Coleman *et al.*, 2004; Clemens *et al.*, 2009; Boulanger *et al.*, 2020, 2021).

The polyphase nature of plutonic intrusions is further demonstrated by high-resolution geochronology using isotope dilution U/Pb analyses of single zircon crystals (Leuthold *et al.*, 2012; Schoene *et al.*, 2012; Barboni *et al.*, 2015). Those studies clearly indicate that igneous bodies took longer to set up than the time it would take for them to cool down if they were emplaced as a single batch (Glazner *et al.*, 2004; Annen *et al.*, 2015). These results imply that most igneous bodies have been formed via the stacking of smaller magmatic pulses (i.e. sills or dykes; Glazner *et al.*, 2004; Menand, 2011), and are now recognised in various tectonic settings (Brown, 1956; Reyf *et al.,* 2000; Tanani *et al.,* 2001; Westerman *et al.,* 2004; De Saint-Blanquat *et al.,* 2006; Michel *et al.,* 2008; Tibaldi & Pasquarè, 2008; Holness & Winpenny, 2009; Farina *et al.,* 2010; Leuthold *et al.,* 2012; Barboni *et al.,* 2013, 2015; Gaynor *et al.,* 2019; Boulanger *et al.,* 2020). When a new magmatic batch experienced limited magma mixing with the previous injections, each sill can be identified, and the assembly style can be constrained using high-resolution U/Pb analyses (Mattinson, 2005; Schaltegger *et al.*, 2009). Following such results, it appears that the majority of shallow igneous bodies are built-up by under-accretion where the older increment is located on top of the pluton whereas the youngest part emplaced at the bottom part (Coleman *et al.*, 2004; De Saint-Blanquat *et al.*, 2006; Michel *et al.*, 2008; Farina *et al.*, 2010). A distinction can be done for the Torres del Paine laccolith where both a granitic under-accretion and a concomitant gabbroic over-accretion have been observed (Leuthold *et al.*, 2012) as well in extremely differentiated granite (e.g. rare-metal granite). These granites are zoned with the more fractionated part (i.e the more enriched in incompatible elements) located at the top of the intrusion. This general feature have been either interpreted to be the result of the protracted stacking of compositionally different sills (Lin Yin *et al.*, 1995; Černỳ *et al.*, 2005) or to reflect a zoned magmatic chamber involving fractional crystallisation and/or fluid-melt immiscibility (Raimbault *et al.*, 1995; Syritso *et al.*, 2001; Zhu *et al.*, 2001; Zoheir *et al.*, 2020).

The assembly style of given pluton has direct consequences on whether or not the magmatic contacts are preserved as well as the fate of the residual liquids in the system (De Saint-Blanquat *et al.*, 2006; Annen, 2011). Indeed, if the flux rate is sufficiently high to allow magmas homogenisation, magmatic contact are barely preserved (De Saint-Blanquat *et al.*, 2006; Miller *et al.*, 2011) and the residual liquids have a chance to be segregated and accumulated at the top of the crystal-rich pile (Jackson *et al.*, 2018; Chen *et al.*, 2021; Boulanger & France, 2023). In those conditions, the maximum melt volume in the whole body can be higher than the volume of a single injection (Annen, 2011). On the contrary, contacts between various injections can be preserved if the flux rate is sufficiently low (De Saint-Blanquat *et al.*, 2006; Clemens *et al.*, 2009). In this case, residual liquids will be trapped within each intrusion and the maximum melt volume in the whole body will be as high as the volume of a single injection (Annen, 2011). Such dichotomy in magmatic fluxes could also be related to the pluton size, and small igneous bodies may be more inclined to preserve the early intrusive contacts than larger bodies.

In this study, we take advantage of the 800 m thick and fully drilled Beauvoir granite body (part of the Echassieres granitic complex, Massif-central, France) to improve our understandings on the emplacement and differentiation of small plutonic bodies and their implications on the formation of melt lenses that can potentially feed small silica-rich eruptions. Petrographic observations as well as microstructures and mineral chemistry were used to constrain the protracted assemblage of the whole intrusion and to understand the fate of residual liquids in this system. It appears that lepidolite composition can be used as a proxy to distinguish the various magmatic batches that compose the Beauvoir granite (Captions:

Fig. 1). We show that the granite formed through the stacking of decametric crystal-poor sills, defining different sub-units within the granite without significant magma mixing. As each sub-units are compositionally different, the detailed study of mineral composition provides a dynamic record of the pluton assembly. Ultimately, the segregation of residual liquids has led to the formation of ephemeral liquid-rich lenses at the top of the intrusion. Their potential subsequent extraction would have allowed the volcanic-plutonic connection.

2. The Echassières granitic complex

2.1 Geological setting

The Echassières granitic complex outcrops in the northern part of the French Massif Central, intruding the Sioule metamorphic series. Those metamorphic series are composed of several nappes formed in relation with crustal thickening during the European Variscan orogeny (Faure *et al.*, 1993), which are from top to bottom: (i) a cordierite-bearing migmatite belonging to the upper-gneiss unit; (ii) a biotite-sillimanite paragneiss corresponding to the lower-gneiss unit and; (iii) a micaschist belonging to the para-autochthonous unit in which the Echassières complex is intruding (Captions:

Fig. 1). This micaschist experienced a medium pressure-medium temperature metamorphic event (Audren *et al.*, 1987) at ca. 365-350 Ma (Do Couto *et al.*, 2016) on which the Echassières contact aureole is superimposed (Merceron *et al.*, 1992).

The Echassières granitic complex is composed of the Colettes leucogranite (surface exposure ~6 km², Cuney *et al.*, 1992) and the Beauvoir rare-metal granite (~ 0.14 km², Cuney *et al.*, 1992). A third plutonic intrusion (La Bosse) has been inferred to be at the origin of the La Bosse stockwork, a wolframite-bearing ore deposit that is crosscut by the Colettes and Beauvoir intrusions. This early magmatic event has been dated via U-Pb ID-TIMS on wolframite, to 333.4 ± 2.4 Ma (Harlaux *et al.*, 2018), recently challenged by Carr *et al.* (2021) at 316.7 ± 3.3 Ma. The main mineral assemblage of the Colettes leucogranite is quartz, K-feldspar, albite-oligoclase, brown mica (protolithionite-zinnwaldite), white mica (muscovite-trilithionite) and subordinate cordierite ± tourmaline (Aubert, 1969; Jacquot, 1990). White mica is also present as a secondary phase replacing K-feldspar, protolithionite and cordierite (Aubert, 1969; Jacquot, 1990). Early structural studies based on megacrysts orientations (K-feldspar and plagioclase) inferred that the Colettes granite emplaced as a vertical intrusion within a pull-apart along a N60°E senestral shear zone (Gagny & Jacquot, 1987). The emplacement age of Colettes igneous body remains weakly constrained with an estimated age of 317 ± 8 Ma (Rb-Sr, whole rock from Pin, 1991 recalculated by Carr *et al.*, 2021).

Despite its smaller size, the Beauvoir granite has received much more attention, because of its important economic potential. Indeed, it has recently been targeted to potentially develop one of the largest European Li-mine (https://emili.imerys.com/). Rare metal enrichment partly motivated the choice of this granite to be part of a drilling campaign (GPF program, Géologie Profonde de la France), allowing the recovery of a 900 m deep borehole across the granite in 1985 (Cuney & Autran, 1987; Captions:

Fig. 1). Although Jacquot (1990) suggested that both Beauvoir and Colettes may have emplaced contemporaneously, the Colettes metasomatic alteration at the vicinity of Beauvoir body strongly suggest the subsequent nature of Beauvoir (Aubert, 1969; Raimbault *et al.*, 1995). Based on fluid inclusions studies, the Beauvoir intrusion emplaced at 80 MPa corresponding to a depth emplacement of 3 km (Cuney *et al.*, 1992). Several studies have tried to date the timing of Beauvoir emplacement, leading to both 308 ± 2 Ma (^{40}Ar-^{39}Ar on lepidolite, Cheilletz *et al.*, 1992), 317 ± 6 Ma (U-Pb on columbo-tantalite, Melleton *et al.*, 2015) and 323 ± 4 Ma (U-Pb on zircon, Monnier, 2018). The Beauvoir intrusion is a rare-metal granite with significant contents in Li, Sn, Nb and Ta (Aubert, 1969; Rossi *et al.*, 1987). It is highly peraluminous (ASI : 1.3-1.8, Frost *et al.*, 2001) and volatile-rich (melt inclusions containing up to 4.9 wt % F and 6.17 wt % H_2O, Kovalenko *et al.*, 1998), and has a unique mineralogical assemblage dominated by albite (An<2%), quartz, Li-mica (lepidolite), K-feldspar (Or<98%), F-topaz, Li-phosphate (amblygonite) and accessory zircon and apatite (Cuney & Autran, 1988). Oxides minerals as cassiterite, columbo-tantalite and microlite are disseminated across the granite, with a progressive enrichment toward the top of each unit. A detailed petrographic description of the various Beauvoir units is provided in section 4.2. Such high concentrations in volatile and Li are known to strongly reduce both the solidus temperature (Wyllie & Tuttle, 1964; London, 1992; Scaillet *et al.*, 1995) and melt viscosity (Reyf *et al.*, 2000; Bartels *et al.*, 2013, 2015). Melting and crystallisation experiments (Pichavant *et al.*, 1987; Pichavant, 2022) using a Beauvoir sample as starting material estimated a solidus temperature around 550°C, which is 100°C less than the haplogranite solidus (Tuttle & Bowen, 1958). In the Orlovka Li-Ta rare-metal granite, a viscosity of 50 Pa.s has been measured for its melt inclusions (4 wt % F and 6 wt % H_2O) at 660°C (see details in Reyf *et al.*, 2000). Therefore, with an analogous composition, Beauvoir magmas might have a similar low viscosity (comparable with basalt viscosity; Lesher & Spera, 2015).

2.2 Previous Beauvoir nomenclatures and structural studies

Following the early study of GPF-1 drilling cores, the Beauvoir intrusion was first segmented in three magmatic units (Cuney *et al.*, 1985), from bottom to top: B_3 (880-750 m), B_2 (750-450 m) and B_1 (450-100 m). Beauvoir's granite architecture was then refined with the identification of an interval belonging to the B_2 unit at the bottom of the intrusion (Rossi *et al.*, 1987; Fig. 2).

Gagny (1987) proposed another classification based on geochemical variations across the granite using the Na_2O/K_2O ratio (Fig. 2a). He distinguished six different units and interpreted them to represent six different intrusions, with a progressive stacking toward the top of the intrusion. Using the $Al_2O_{3norm}/Al_2O_{3tot}$ ($Al_2O_{3norm} = Al_2O_3$-1.643*Na_2O - 1.083*K_2O in weight percent), he then subdivided the $Unit_{II}$ in seven sub-units (U_{IIa} to U_{IIg}) from bottom to top (Fig. 2b). On the continuity of the Gagny's work, Jacquot (1990) cut the $Unit_I$ in two sub-units (U_I and $U_{I\ bis}$), with a delimitation at 835.95m corresponding to the lower contact between B_2 and B_3 defined by Rossi *et al.* (1987). Contemporaneously, Jacquot (1987) measured the magmatic fabric orientations across the granite, in which he found a dominant N120°E 40°S magmatic foliation, attributed to magmatic flow direction. He observed local changes in the dip of this magmatic flow that he interpreted to be related to the emplacement of six intrusions, corresponding to those described by Gagny (1987). Based on anisotropy of magnetic susceptibility , Bouchez *et al.* (1987) also support the existence of the dominant planar foliation direction (N103°E 39°S) determined by Jacquot (1987), and of those six igneous sub-units. Bouchez *et al.* (1987) also observed a rapid increase of the anisotropy in B_1/B_2 (~480 m) and B_2/B_3 (746 m) boundaries as well as 311 m, leading to the subdivision of the B_1 unit into B_{1-1} and B_{1-2}. They interpreted this sharp increase in anisotropy to be the result of viscous shearing between different magmatic injections. Raimbault *et al.* (1995) then subdivided B_2 unit into two units, labelled B_2 (420-571m) and B'_2 (571-746m) based on lepidolite composition variations, with lepidolite from B_2 facies containing 20% zinnwaldite, and lepidolite from B'_2 facies containing 40%. All previous studies thus suggest that the Beauvoir granite is composed of various units that can be identified by whole rock chemistry, structural and geophysical analyses. Those units have been interpreted to represent different magmatic injections. However, their numbers, size and affiliations are not unanimous, and their relation to melt differentiation and volumes were yet to be quantified.

3. Methods

The 900 m GPF-1 drill core (stored at BRGM, Orléans, France) has been entirely revisited macroscopically. Based on a detailed description (mineralogy, structures) we have identified metric to decametric thick inhomogeneous horizons representing individual magmatic units. From those, we have selected 175 samples that either represent the bulk of the units, or centimetric to decimetric anomalous magmatic patterns such as unit boundaries, monomineralogic aggregates, stripes, cockades, and round shaped like aggregates. From those samples, 230 thin sections were studied microscopically, and were imaged through a systematic cathodoluminescence (CL) light using a Cathodyne platine from NewTec Scientific coupled with a Leica DM2700M microscope at Thin Section Lab (Toul, France). Current and voltage were adjusted to have the higher resolution. These observations were crucial in order to select samples without any sub-solidus alteration marks. 39 thin sections were selected from this sample set for further EPMA investigation (quantitative points and maps). 17 samples (representing either bulk units or specific magmatic patterns) were selected for bulk major and trace element analyses (Fig. 2; supplementary materials S1), complementing the existing dataset (Pichavant et al., 1987; Rossi *et al.,* 1987; Raimbault *et al.*, 1995).

Both point analyses and chemical maps were acquired using a JEOL JXA 8230 probe at the Centre de Recherche Pétrographiques et Géochimiques (CRPG; Vandoeuvre-lès-Nancy, France). Point analyses of mica, feldspar, topaz, amblygonite and apatite have been conducted under 15 keV accelerating voltage and 15 nA current by using a focused beam (see supplementary materials S2 for electron-probe micro-analyses and supplementary materials S3 for analyses conditions). Twelve element oxides were calibrated using natural standards as anorthoclase (Si, Al, Na, K), San Carlos olivine (Mg), F-apatite (P), Andradite (Ca), ilmenite (Ti, Mn), magnetite (Fe), fluorite (F) and a synthetic Rb-Ti phosphate (Rb). Chemical Xray maps were obtained by using a 15 keV accelerating voltage, a 100 nA current, and 50 ms of dwell time; pixel size was usually 3 or 5 µm.

Whole-rock major and trace elements were quantified at the Service d'Analyse des Roches et des Minéraux (CRPG; Vandoeuvre-lès-Nancy, France) using an inductively coupled plasma optical emission spectrometry (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS), respectively. Li, B and F were measured independently through an atomic absorption spectroscopy, absorptiometry and potentiometric analyses, respectively. Analytical details and detection limits are summarised in Carignan *et al.* (2001).

4. results

4.1 Whole-rock chemistry

From bottom to the top, the Beauvoir granite is characterised by an overall diminution in iron (Fig. 2c) and manganese whole rock concentration. Reversely, metal concentrations (e.g., Li, Na, Rb, Cs, Be, Nb and Ta) increase toward the top of the Beauvoir granite (Cuney & Autran, 1987; Rossi *et al.*, 1987; Raimbault *et al.*, 1995; Fig. 2d). In details, these concentrations vary from one unit to the other but also within single units where various geochemical steps can be observed. As an example, from 790 to 500 m corresponding to the Unit$_{II}$ of Gagny (1987), the iron (Fig. 2.c) and cesium (Fig. 2d) evolutions are not linear, highlighting different geochemical steps among this unit. The depth of these geochemical steps is consistent with the sub-unit localisations of Gagny (1987) within Unit II. Across the pluton, numerous petrographic discontinuities (e.g., intrusive contact, modal or grain size sharp variations) have been observed (Fig. 3). Although the location of such discontinuities is not necessarily related to any chemical discontinuity, most of them are located at a position consistent with the geochemical steps observed in the bulk rock chemistry (Fig. 2). The presence of petrographic discontinuities related geochemical steps within a unit calls for the presence of various sub-units within this unit.

In the present study, and based on a re-appraisal of chemical and textural variations, we divided the granite in four different units. U_1 corresponding to the B_3 facies identified by Rossi *et al.* (1987). U_2 is constituted by the following Gagny's sub-units: U_I, U_{IIb}, U_{IIc}, U_{IId}, U_{IIe}, U_{IIf}, U_{IIg}. U_3 contains two different parts where the first is located above U_2 and the second part is located between the lepidolite layering at 379.12m (Fig. 3d) and the boundary between the U_{III} and U_{IV} units of Gagny (1987). U_4 is divided in two parts as well. The first is located between the two U_3 parts whereas the second part starts above the uppermost part of U_3 until the top of the pluton (Fig. 2). The justification of those subdivisions is presented below.

4.2 Petrographic and microstructural observations

Changes in crystal morphology across the Beauvoir pluton provide information on the crystallisation sequence in each Beauvoir unit. U_1 (from 835.1 to 743 m) is characterised by a reddish hand specimens color, mostly due to the K-feldspar coloration. Euhedral to subhedral grains of quartz (grain size up to 3.5 mm), topaz (0.7-2.5 mm) ± albite (0.2 to 1.5 mm) are surrounded by anhedral orthoclase, lepidolite ± amblygonite. Topaz and quartz often form clusters, where grains are stuck together along their growth faces (Fig. 4a). Some zones are locally dominated by long albite grains (Ab_I up to 2.5 mm) with interstitial orthoclase, quartz, lepidolite and a second albite generation (Ab_{II} ~ 100-200 µm; Fig. 4b). Locally within U_1, sub-solidus alteration is documented by partial replacement of lepidolite by muscovite (Fig. 4c), as well as by specific light blue to red colors of orthoclase in CL light images (Fig. 4b). This coloration change is ascribed to the partial replacement of orthoclase by secondary brown micas (Kempe *et al.*, 1999). Such alteration stage requires the addition of Fe-Mg that could derive from the surrounding micaschist through the progressive transformation of biotite to zinnwaldite close to the Beauvoir granite contact (Monier *et al.*, 1987). This is consistent with the location of the sample presented in Fig. 4b (789.68 m), which is located just below the 28 m tick micaschist slab, a major discontinuity within U_1 (Captions:

Fig. 1, Fig. 2).

U_2 (from 883.3 to 835.1 m, and from 743.26 to ~490 m) is the least homogeneous unit among the pluton. Its overall color in hand specimens is whitish. Based on a similar whitish color, the lower section of the hole (from 875 to 836 m) below U_1 was initially ascribed to U_2 rather to the reddish colored U_1 (Rossi *et al.*, 1987). In this lower section, the granite is constituted by euhedral to subhedral quartz (~1-3 mm), orthoclase (~0.5-1.7 mm) ± topaz (0.5-2 mm) and are surrounded by late-formed albite (Ab_I, size ~0.4-0.5 mm) as well as anhedral lepidolite ± amblygonite (Fig. 4d). Above 743 m, orthoclase is anhedral and mainly interstitial, thus no longer an early phase, in contrast to quartz (Fig. 4e) and topaz (Fig. 4f). At that depth, lepidolite (up to 2.3 mm) displays euhedral cores and is thus part of the early mineral assemblage (Fig. 4e). Such euhedral cores overgrown by interstitial rims also highlight that lepidolite initially grown from a liquid-rich stage prior to be locked in the quartz-cumulate, and pseudomorphing the interstitial melt. Above 571 m (the boundary B_2-B'_2 made by Raimbault *et al.*, 1995), euhedral topaz form clusters likely via synneusis, attesting its early crystallisation in a liquid-rich environment (Fig. 4g). Albite crystals can be divided in two generations where the first refers to large albite primocrysts (Ab_I) up to 2 mm (Fig. 4h, i) whereas the second generation refers to the small and interstitial albite (Ab_{II}; size ~100 µm; Fig. 4g). Lepidolite forms euhedral thick tablets with a low aspect ratio (Fig. 4g, h), and commonly contains partly resorbed core attesting of a partial dissolution stage during its solidification history (Fig. 4h). Those observation eventually highlight the opposite behaviour of orthoclase and lepidolite along the crystallisation sequence of U_2, with interstitial lepidolite (and euhedral orthoclase) in the deepest sections of U_2, becoming euhedral (and orthoclase anhedral) in the shallowest levels of U_2. Locally in the upper part of U_2 (above 520 m), lepidolite displays skeletal morphologies (Fig. 4i). U_2 is also hosting several porphyritic microgranites (from 861.9 to 860.15 and from

706.6 to 700.2 m). Contacts with the surrounding granite is sutured and strongly greisenised. The microgranite is constituted by centimeter-sized euhedral quartz and feldspar (both orthoclase and albite) inside a devitrified matrix composed of the same Beauvoir mineralogical assemblage. Brown micas inclusions in quartz are present, which is a unique occurrence in the whole 900m drilled core, excluding the host micaschist.

U_3 (from ~490 to ~400 m and from 379 to 354 m) is a whitish granite similar to U_2. It is medium grain sized and characterised by euhedral quartz (up to 3 mm), topaz (~1.5 mm), subhedral orthoclase (0.7-1.8 mm) and by subhedral to anhedral lepidolite (0.4-2 mm; Fig. 5a-c). As in the U_2 upper part, two generations of albite can be observed (Ab_I ~ 1.5 mm and Ab_{II} ~ 0.3 mm). A late albite nucleation episode is inferred as euhedral minerals are surrounded by the second small albite generation (Ab_{II}; Fig. 5a-c). Amblygonite is mostly anhedral attesting its late crystallisation. U_3 differs from the top of U_2 by the presence of euhedral orthoclase in U_3 (Fig. 5a) instead of xenomorphic orthoclase at the top of U_2 (Fig. 4i). Similarly to U_2, lepidolite from U_3 often displays partially resorbed cores attesting of a previous partial dissolution stage (Fig. 5c).

U_4 (from ~400 to 379 m and from 354 to 98 m) is the uppermost unit in the Beauvoir granite. Macroscopically, hand specimens are white with disseminated black dots corresponding to metallic oxides (mostly cassiterite and columbo-tantalite). U_4 is composed of euhedral quartz (up to 4 mm), albite (Ab_I up to 2.5 mm) and topaz (0.5 to 2 mm). Lepidolite (0.5 to 2.5 mm) is euhedral to anhedral attesting of its continuous crystallisation whereas orthoclase is exclusively anhedral (Fig. 5d). Amblygonite is most of the time found in replacement of topaz primocrysts (Fig. 5e), indicating that topaz was no longer in equilibrium in late magmatic stage. Small albite (Ab_{II} ~ 50-250 µm) has also been observed (Fig. 5d, f), attesting of its continuous crystallisation. The modal proportion of albite and lepidolite is increasing from the bottom to the top of the unit while the modal proportion of quartz, topaz and orthoclase is decreasing.

Compared to those in U_1-U_2 and U_3 (Fig. 4c, e, g, h, i and Fig. 5c), lepidolite from U_4 are generally more elongated with a higher aspect ratio (Fig. 5f, g, i). Oxides are commonly enclosed in lepidolite (Fig. 5f). Lepidolite displaying skeletal morphology has only been observed at 393.24 m (Fig. 5d). As mentioned by Rossi *et al.* (1987), lepidolite in U_4 sometimes occurs as rosette, growing from an early-formed nuclei (Fig. 5g). U_4 also host specific lepidolite with a brown aureole between their core and rim (Fig. 5h), attesting a destabilisation event during its crystallisation. The upper part of U_4 (from ~120 m to 100 m) is dominated by thick and euhedral albite (Ab_I) tablets with highly elongated lepidolite (up to 3 mm; Fig. 5i) between them. In those zones, quartz is anhedral and displays typical melt-pseudomorphing textures.

U_4 also host albite-lepidolite ± amblygonite-rich segregates displaying sutured, linear to lobate contacts with the surrounding granite (Fig. 6a-d). Albite size in those segregates its on average smaller compared to the ones in the surrounding granite (50 to 500 µm vs up to 2.5 mm respectively) and are dominated by the second albite generation (Ab_{II}). The mineralogical assemblage of these segregates corresponds to the interstitial phase in U_4 granite (anhedral amblygonite and lepidolite, Ab_{II}; Fig. 5d, e, f). Thus, those segregates likely represent the crystallised product of an albite-lepidolite ± amblygonite-saturated magma. Hence, those magmas percolated through the granite before its entire solidification (Fig. 6a, b). Those albite-rich segregates are locally zoned, with an inner part enriched in lepidolite and amblygonite whereas the outer part is dominated by albite and lepidolite (Fig. 6c). Albite-lepidolite ± amblygonite segregates have been observed from 283 to 202 m whereas albite ± lepidolite segregates are ubiquitous across the granite. Between 230 to 189 m the granite contains large quantity of lepidolite-rich granite (Fig. 6d, e). Those specific facies are mostly constituted by euhedral albite (Ab_I and Ab_{II}) and euhedral to subhedral lepidolite whereas quartz and orthoclase are anhedral (Fig. 6e). Those lepidolite-rich granites can be spatially connected to the albite-lepidolite-rich segregate (Fig. 6d). Compared to the overlying lepidolite-rich granite, the lepidolite modal proportion is lower in the albite-lepidolite-rich segregate (Fig. 6f).

4.3 Interpretation of textures

The different crystal morphologies observed in the various Beauvoir unit's indicate different liquid lines of descent of magmas forming the pluton. In all Beauvoir unit's, quartz and topaz present euhedral morphologies (e.g., Fig. 4f and Fig. 5b, e). These observations imply that those minerals started to crystallise just below the liquidus.

After the crystallisation of the early-formed quartz and topaz, U_1 magmas continued their solidification through albite crystallisation, leading to the formation of K-feldspar and lepidolite-saturated residual liquids. In turn, residual liquids crystallised anhedral K-feldspar and lepidolite pseudomorphing the interstitial melt (Fig. 4b).

In U_2, K-felspar started to crystallise directly after the early-formed quartz and topaz, followed by albite, lepidolite and amblygonite in the lower section of U_2 (Fig. 4a) whereas the presence of anhedral K-feldspar above 743 m indicates its late crystallisation (Fig. 4i).

The presence of subhedral lepidolite, large albite (Ab_I) and K-feldspar in U_3 magmas indicates that the magma became saturated in these mineral phases directly after the crystallisation of quartz and topaz whereas the crystallisation of small albite (Ab_{II}), anhedral lepidolite and amblygonite was predominant in the late magmatic stage (Fig. 5a-c).

The presence of large euhedral albite grains in U_4 as well as albite inclusions in quartz attests that albite and quartz crystallisation were concomitant (Fig. 5d, i). Lepidolite crystallisation followed just after as shown by their mostly subhedral morphology. In addition to albite and lepidolite, the U_4 residual liquids were saturated in K-feldspar and amblygonite components, triggering their crystallisation in interstitial position. However, the weak K-feldspar modal concentration in U_4 indicate that the late crystallisation of K-felspar was limited, which can be explained by the fact that most of the potassium was consumed by lepidolite crystallisation. The U_4 interstitial phase and the albite-lepidolite ± amblygonite present a similar mineralogical assemblage which is dominated by late small albite (Ab_{II}) and lepidolite. This similarity likely indicates that the albite-lepidolite ± amblygonite-rich segregates correspond to the crystallised products of U_4 residual liquids, which have been extracted and channelised in order to form those segregates.

Quartz and topaz are often displaying crystal clusters of several grains (Fig. 4a, g and Fig. 5b). Those grains clusters likely formed via synneusis, a process involving random grain collisions in a liquid-rich magma (Dyck & Holness, 2022; Dyck, 2023). The occurrence of a liquid-rich stage at the beginning of the magma solidification is also indicated by the presence of quartz and topaz-rich cumulate (Fig. 4e and Fig. 6a). Indeed, efficient segregation of these early-formed minerals from the magma cannot be done in a mush (i.e. crystal-rich magma). Skeletal and star-like lepidolite morphologies (Fig. 4i and Fig. 5d, g) are also consistent with a crystallisation in crystal-poor magmas, inducing a nucleation delay, undercooling, and a concomitant rapid crystal growth (Shea & Hammer, 2013; Colle *et al.*, 2023).

4.4 Mineral compositions

4.3.1 Micas

According to the nomenclature of Foster (1960), the Beauvoir white micas are lepidolite straddling between muscovite {$KAl_2Si_3AlO_{10}(OH,F)_2$}, zinnwaldite {$KFeLiAlSi_3AlO_{10}(OH,F)_2$}, trilithionite {$KLi_{1.5}Al_{1.5}Si_3AlO_{10}(OH,F)_2$} and polylithionite: {$KLi_2AlSi_4O_{10}(OH,F)_2$} (Fig. 7a). From U_1 to U_4, a compositional shift in micas from the zinnwaldite-polylithionite toward the trilithionite-polylithionite solid-solution is observed, corresponding to depletion in bivalent ions (e.g. Fe and Mn). This compositional shift is also observed within each unit (Fig. 7b-e). Micas from U_2 show a more pronounced shift from 860.24 m to 518.25 m, with a progressive enrichment in the trilithionite component in comparison to the zinnwaldite one (Fig. 7c), reflecting the substitution $2(Mg - Fe - Mn)^{VI}$ $\Leftrightarrow Al^{VI} + Li^{VI}$ (Foster, 1960; Monier, 1987). From core to rim, micas are progressively enriched in lithium and silica compared to alumina (see also chemical maps in Fig. 6f and Fig. 9a-d) and become closer to the polylithionite end-member (Fig. 7c), involving the substitution $2Al^{IV} + Al^{VI} + \Leftrightarrow 2Si^{IV} + Li^{VI}$ (Foster, 1960; Monier, 1987). Micas from the Beauvoir microgranite and the Colettes leucogranite differ from those of the Beauvoir granite with two distinct clusters corresponding to brown and white micas (Fig. 7a). Their brown micas compositions evolve towards the zinnwalditic component along the miscibility gap between di- and trioctahedral mica (Monier, 1987) whereas white micas are much more enriched in the muscovite component. Although lepidolites composition from equilibrium experiments led by Pichavant (2022) at various temperatures (from 640 to 580°C) fall within the same field than natural Beauvoir lepidolites (Fig. 7), their compositions evolve along the zinnwaldite-trilithionite solid solution with an enrichment in the trilithionite component at decreasing temperature. This evolution perfectly fits the compositional shift observed within each Beauvoir unit, but fail in reproducing the global enrichment in lithium toward the polylithionite component (Fig. 7a-e).

The micas chemical composition from the various Beauvoir horizons can be used to identify four units (U_1, U_2, U_3, U_4) and their various sub-units. When their manganese concentration is plotted against their FeO/MnO ration (Fig. 8), the four Beauvoir units can be distinguished based on their initial and maximal manganese concentration: $1.6 < U_1 < 1.8$ – $1.2 < U_2 < 1.6$ – $0.9 < U_3 < 0.8$ and $0.35 < U_4 < 0.5$.

Within each unit, variations of the mica's FeO/MnO allows to identifying the various sub-units: as an example, the two samples analysed in U_1 (824.20 and 789.68m; U_{1a} and U_{1b}, respectively) can be distinguished by their different lepidolite FeO/MnO ratio for a fixed MnO content (Fig. 8), and so two different trends can be observed. As the manganese concentration in lepidolite decreases during magmatic differentiation (due to lepidolite, columbo-tantalite and apatite crystallisation), the lepidolite with the highest manganese concentration is in equilibrium with the parental melt that formed each sub-unit. As such, it appears that the parental melt of each sub-unit is distinct from each other. Among the two samples belonging to U_1, the shallowest is the one with the lowest initial FeO/MnO ratio (Fig. 8). The second Beauvoir unit (U_2) is constituted by at least nine different sub-units (from U_{2a} to U_{2i}). Within this unit, the initial FeO/MnO ratio is decreasing from 8 to 1.8, and from 860.24 m to 518.25 m respectively (Fig. 8). Within each of these sub-units, the diminution of the MnO content is associated with a moderate increase of the FeO/MnO ratio. Overall, the initial FeO/MnO of micas in each sub-units correlates with their structural position along the drill core, with an increase of the FeO/MnO ratio with depth (Fig. 8). Three samples have been analysed in the third unit (U_3) documenting two distinct trends, and thus sub-units. For U_3, the shallowest sample is the one with the highest micas FeO/MnO ratio. The fourth unit has the less manganiferous micas, with an initial MnO value around 0.35 wt % and can be divided in five different sub-units in which micas chemical variations show a global diminution of MnO associated with a large increase in the FeO/MnO ratio (from 1 to 15, Fig. 8). Lepidolites from 393.24 m are those with the highest initial FeO/MnO whereas lepidolites from 170.53 m are those with the lowest initial FeO/MnO ratio.

Lepidolite are often strongly zoned (Fig. 9a-d) with locally some reverse zoning (Jacquot, 1990). From core to rim, normally zoned lepidolites are characterised by a decrease in alumina, manganese and iron with an increase in silica, lithium and their FeO/MnO ratio (Fig. 8,Fig. 9). Also, they commonly display oscillatory zoning (Fig. 6f and Fig. 9c) which is characteristics of a crystallisation in an open-system where successive magma batches with various composition are recharging the reservoir. As the composition of each lepidolite growth zones are aligned, each recharges shared the same parental melt which corresponds to the U_4b parental melt for the lepidolite presented in Fig. 9c-e. Ultimately, lepidolite crystallised alumina-poor and Li-rich rims (Fig. 6f and Fig. 9a-d) during the porosity closure. Lepidolite core to rim transitions can be sharp (Fig. 5h, Fig. 6f and Fig. 9a, b). The mica represented in Fig. 5h corresponds to one of these cores displaying an abrupt passage to its mantle, resulting to a reactional aureole. Skeletal lepidolite has been observed in three sub-units: U_2h (Fig. 9a) – U_2i (**Erreur ! Source du renvoi introuvable.**i) and U_4a (Fig. 9b). In those samples, the skeletal inherited lepidolite cores are characterised by a high concentration in Al_2O_3 and FeO, and reversely, a low proportion in SiO_2, Li and F.

4.3.2 Quartz

Quartz grains are notably zoned in Al_2O_3 (Fig. 10a, b). They contain a patchy Al-rich core sealed by an Al-poor growth zone (Fig. 10b). They can also be oscillatory zoned with the alternation of alumina-rich and alumina-poor growth zones. These alumina-rich growth zones are characterised by a larger number of inclusions, essentially albite (Fig. 10b). Those quartz containing albite inclusions in the same growth zone are characteristic to the “snow ball” texture, which is commonly observed in rare-metal granite (Wang et al., 2019). Often, CL images of quartz clusters shown individual grains accolated via synneusis, each displaying oscillatory zonation (Fig. 10d). Those zonations are not visible under the alumina-chemical map except one alumina-rich growth zone indicated by white arrows on Fig. 10c. In quartz, silica can be substituted by alumina via the coupled substitution $Si^{4+} = Al^{3+} + Li^{+}$ (Stavrov *et al.*, 1978; Götze *et al.*, 2004). The nature of the oscillatory zoning in Fig. 10d could be the result of trace elements incorporation such as Na, Rb, Ge or Ti (Monnier *et al.*, 2018).

4.3.3 Topaz

Topaz grains are usually euhedral and often grouped in clusters of several grains (Fig. 4a, g) indicating their early crystallisation in a liquid-rich environment. Compositional changes in Beauvoir topaz essentially correspond to variations in their phosphorus content (Fig. 10e, f).

Phosphorus chemical maps as well as Cl light (Fig. 10g, h), show oscillatory zoning corresponding to alternating P-rich and P-poor bands. Variations in phosphorus content are not correlated with fluorine concentration (Fig. 11a). Incorporation of phosphorus in topaz is thought to be the result of berlinite-type substitution: Al^{3+} +P^{5+} = 2 Si^{4+} (London *et al.*, 1990; Breiter & Kronz, 2004). For a given band, concentration of P is variable, and depends on the crystallographic face (Fig. 10f), highlighting sector zoning, which is interpreted to be the result of differences in kinetic behavior of growth steps during topaz crystallisation (see Northrup & Reeder, 1994 for more details). The early stages of topaz growth are dominated by P-rich bands, and crystal rims are relatively P-poor (Fig. 10e, f). The transition from internal P-rich domains to depleted ones is sharp and locally postdates a partial dissolution event (Fig. 10e, g, h).

4.3.4 Albite

Plagioclases are almost pure albite (Fig. 11b). Albite size varies from a few microns to several millimeters and can develop different aspect ratio. They are either prismatic or blocky, and always show a euhedral to subhedral morphology. As for topaz, phosphorus chemical maps are useful to track chemical zonation in albite (Fig. 10e, f and Fig. 11c). Albite grains are characterised by a P-rich core and a P-poor rim, similar to what is observed in topaz. Those P-rich cores are also enriched in Ca compared to their rim (up to 0.43 wt % CaO), and a positive correlation exists between the phosphorus and calcium concentration (Fig. 11b, c, d). Phosphorus concentration in albite is also correlated with their CL intensity (Fig. 11e).

5. Discussion

5.1 Mineral compositions document numerous magma batches

5.1.1. Fractionation trends and sub-unit identification (Trends 3)

Lepidolite is a ubiquitous mineral in the granite and show textural and compositional variations akin to the melt from which they crystallised. As such, variations in lepidolite composition allow tracking melt evolution during pluton construction. To do so, we performed mass-balance calculation in the MnO and FeO chemical space in order to model the melt concentration during fractional crystallisation. The fractionation of the mineralogical assemblage corresponding to the Beauvoir granite (modal and phases compositions; see supplementary material S4), and more specifically the presence of a high proportion of lepidolite in the cumulative assemblage from various initial melt compositions (red and yellow stars in Fig. 12a) triggers melts depletion in both iron and manganese and an increase of their FeO/MnO ratio. Two different modal proportions have been considered for those models to account for the Beauvoir sub-units variability (solid and dashed lines in Fig. 12a). Such models reproduce well the trends highlighted by lepidolites within each sub-unit (Fig. 12a). The main difference between the tested models (solid and dashed lines in Fig. 12a) is that the fractionation degree required to reproduce natural data is variable (between 40 and 99 % of fractionation).

In this MnO-FeO chemical space, protracted differentiation could also potentially explain the alignment of various sub-units (e.g. U_1b, U_2f, U_4a, U_4b or U_4c or U_2i, U_3b and U_4e; Fig. 12b). Nevertheless, when considering those data in another chemical space like the Al_2O_3/SiO_2 vs FeO in lepidolite (Fig. 12c), no geochemical continuity exists between these various sub-units, meaning that they are not related by an extended crystallisation process from the same parental melt. Therefore, in the MnO-FeO chemical space, although the modelled fractionation reproduces the various chemical trends formed by the Beauvoir lepidolites (Trend 3, Fig. 12a), several parental melts (i.e., distinct magma batches) are required to account for the various trends defining sub-units (Fig. 8). In other words, each of the four main units of Beauvoir pluton (i.e., U_1 to U_4) are composed of several sub-units that are defined by variable MnO initial magma composition (Fig. 8 and Trend 2 in Fig. 12d), and by similar fractionation trends (Trend 3; Fig. 12a).

5.1.2 Sub-unit characteristics

As a direct consequence of this model, each unit (U_1-U_4) can be divided into various sub-units that are fed by different parental melts. U_1 would be composed by two different sub-units (U_1a and U_1b), where U_1a contains lepidolites with higher initial FeO/MnO ratio at a given MnO (wt%) content than lepidolite from U_1b (Fig. 8). Although no direct contact has been observed between these two sub-units, the presence of a 28 m thick micaschiste panel (from 790.36 to 817.44 m with decimeter-sized aplites interspersed) likely represents such a limit. U_2 can be subdivided into nine different sub-units (Fig. 8), from U_2a to U_2i. The contact between U_1 and U_2 at 743.26m is marked by a drastic change in albite modal proportion, from an albite-rich zone (U_1b) to an albite-poor and quartz-topaz-rich zone (U_2c) (this modal contact was already identified by Jacquot, 1990). Similar transitions from albite-rich domains to overlying quartz and topaz-rich ones were also reported by Jacquot (1990) for some of the transitions between the various units defined by Gagny (1987). Those are common in U_2 like at 625.48 m (contact U_2b/U_2d) and 546.29 m corresponding to Fig. 3f. Sometimes both modal and grain size variations define the sub-unit discontinuity like at 518.2 m meter (Fig. 3e) where the transition from U_2i to U_2h is corresponding to the sutured contact between a fine-grained, albite and topaz-rich granite, and a medium-grained lepidolite and orthoclase-rich granite. However, there is no systematic in the meaning of modal and grain size variations across discontinuities. Indeed, the discontinuity observed at 546.29 m (Fig. 3f) does not represent a contact between two sub-units as lepidolites analysed on both side of this contact display similar composition (U_2f trend in Fig. 8), meaning that they crystallised from a similar parental magma. U_3 defined herein is subdivided into two sub-units (U_3a to U_3b, Fig. 8). U_3a and U_3b are not stratigraphically connected because U_4a intruded between these two sub-units. The transition between U_3a and U_4a sub-units corresponds to the strong modal heterogeneity observed at 379.12m (Fig. 3d). This lepidolite layering (belonging to U_3a) was likely formed by a viscous shearing during the U_4a emplacement. U_4 is composed of five sub-units (U_4a to U_4e), with clear modal contacts defining some of the sub-units. As an example, quartz accumulations are locally present above albite-rich zones and mark the contact observed at 290.15 m (Fig. 3a) that corresponds to the boundary between U_4c and U_4d. Sub-unit boundaries are sometimes not discernible macroscopically as the U_4b-U_4c transition, which might be located at 311 m where Bouchez et al. (1987) identified a rapid change in the granite anisotropy. Nevertheless numerous petrographic discontinuities characterised by differences in quartz and albite modal proportions have been observed (e.g., within U_4b, Fig. 3c; and within U_4c, Fig. 3b) but, similarly to some of the transitions observed in U_2, they do not correspond to sub-unit contacts as lepidolites have the same composition on both side of the modal contacts (U_4b trend in Fig. 8). A summary of the depth range of each Beauvoir sub-units is provided in supplementary material S4.

5.1.2. Nature of the parental melt (Trends 2 & Trend 1), and origin of Beauvoir rare-metal granite

Textural, modal and chemical discontinuities provide evidences for a pluton construction via multiple melt-dominated injections. At least eighteen intrusions of magmas with variable compositions were involved in the Beauvoir pluton construction (U_1a-b, U_2a-I, U_3a-b, U_4a-e). The thickness of these intrusions is variable, varying from ~130 m (U_4e) to a decametric size for U_2i, with an average of 41 m per sub-unit. We note here that although we studied the Beauvoir pluton at the highest spatial resolution ever conducted, we potentially missed some additional sub-units. Thus, the intrusion number determined herein is yet a minimum.

As highlighted in Fig. 12a, the Beauvoir's minerals fractionation model reproduces the sub-unit chemical trends defined by lepidolite (Trends 3), but fails in reproducing the transition from one sub-unit to the other (Trends 2, Fig. 12d). Thus, there is a need to invoke an up-stream magmatic process sourcing the pluton parental melts (i.e. Trends 2 in Fig. 12d). This process could either be related to source processes (source type variations or melting regime), or to a precursory differentiation event during melt transfer of an intermediate magma. Here we explore those two possibilities.

Source processes play a key role in the evolution of melt composition and could therefore be at the origin of the observed Trends 2. Recently, Ballouard *et al.* (2023) emphasised the role of pressure during crustal anatexis on the genesis of lithium and fluorine-rich magmas. They have shown that during the biotite-breakdown reaction of a leucogneiss (at 790°C), the peritectic/restitic assemblage contains cordierite < 5 kbar, and garnet > 3 kbar. Elements like Li, F, Be and Cs being compatible in cordierite (and incompatible in garnet; Bea *et al.*, 1994; Evensen & London, 2002; Ballouard *et al.*, 2023), rare-metal magma genesis has to take place at > 5 kbar where the peritectic/restitic assemblage contains garnet rather than cordierite. Furthermore, Mn being a major component in garnet (spessartine end-member), a protracted partial melting stage with garnet as part of the peritectic/restitic assemblage would considerably deplete the Mn content in the anatectic melt, thus failing in reproducing Trends 2 that eventually cannot be explained by source processes.

Alternatively an up-stream differentiation process can likely explain such a chemical trend. Indeed iron and manganese evolution of Trends 3 is mostly controlled by lepidolite and columbo-tantalite crystallisation. The presence of columbo-tantalite in the Beauvoir assemblage attests of its saturation in the melt. According to experimental constraints led by Linnen & Keppler (1997), this saturation is reached at 55 ppm Nb and 43 ppm Ta for a 600°C melt containing 500 ppm Mn and 2000 ppm Fe (Pichavant, 2022). For a less enriched magmas such as the nearby Colettes leucogranite (maximum values: 28.6 ppm Nb and 10.1 ppm Ta; Raimbault *et al.*, 1995), columbo-tantalite saturation was not reached, and the resulting liquid line of descent was eventually different from that characterising Beauvoir system. The fractionation of a mineral assemblage similar to the Colettes leucogranite induces melt depletion in iron at relatively constant manganese content (Fig. 12d; modal and phase compositions; see supplementary material S4). Such a differentiation process (20 to 90 % of fractional crystallisation) from various theoretical starting compositions (brown stars in Fig. 12d) produces residual liquids depleted in iron compared to manganese (i.e., diminution of the FeO/MnO in melt), and can explain the observed Trends 2 sourcing the Beauvoir parental melts of each sub-unit. In this perspective, within a given unit (U_1, U_2, U_3, U_4) the parental melt of each sub-unit corresponds to successive residual liquids extracted from a deeper reservoir in which a Colettes-like differentiation trend proceeded.

The Beauvoir units can be distinguished based on their initial manganese content in lepidolite (brown stars in Fig. 12d representing the source of Trends 2 differentiation). Those manganese variations linking the starting points of the various Trends 2 define the Trend 1. From U_4 to U_1, an increase of the initial manganese content could have been explained by episodic Mn-rich magma replenishments (i.e. more mafic magmas). However, those replenishments should have led to a global increase from U_4 to U_1 in other more compatible elements such as Mg, Ti, Cr or Ni which is not observed. Consequently, the evolution along Trend 1 is rather characterised by an evolution toward Mn-poor magmas (from U_1 to U_4). This manganese decrease could either be related to garnet fractionation (Fig. 12d) in a deep reservoir, or be related to source processes involving garnet as peritectic/restitic mineral during rare-metal magma genesis (as discussed earlier for Trends 2). Although the origin of this Trend 1 is not well constrained, Ballouard *et al. (*2023) have shown that a partial melting event under garnet stability field (in the absence of cordierite) is required to form rare metal magmas, eventually explaining the identified Trend 1. There is therefore no need to invoke an additional reservoir where garnet fractionation would occur to explain Trend 1. Thus, the passage from U_1 to U_2, U_2 to U_3 and U_3 to U_4 highlights an increase in the melting degree during the biotite-breakdown reaction (with progressive manganese depletion), and likely documents an increasing thermal regime.

The combined effect of a progressive partial melting of a slightly pre-enriched protolith (e.g., leucogneiss, Ballouard *et al.,* 2023) accounting for Trend 1, together with a two-stage differentiation (Trends 2 & 3) are likely at the origin of the metal-rich nature of Beauvoir magmas. As these metals are concentrated in unaltered igneous minerals (e.g., Li in lepidolite) that are also the mineral phases targeted by mining industries (Demeusy et al., 2023; Korbel et al., 2023), the metal-rich nature of Beauvoir granite has a primary magmatic origin rather than a secondary one related to hydrothermal fluids. Although the role of hydrothermal fluids have been recognised in some specific examples (Hien-Dinh et al., 2017), our model for rare metal granite formation via protracted magmatic differentiation is consistent with previous studies at Beauvoir (Raimbault et al., 1995) or elsewhere (e.g., the Zhengchong deposit in China, Liu et al., 2022).

5.2 Pluton construction through sill stacking

5.2.1 Sill stacks, and magma flux variations

Following our interpretations of Trend 1 origin, U_1 emplaced before U_2, followed by U_3, and then U_4 during an overall increasing melting regime. Assuming that each Beauvoir sub-unit has a different parental melt that derives from a precursory differentiation process (Trends 2; Fig. 12d, evolution from brown stars), the relative chronology of Beauvoir intrusions can be reconstructed within and between each Beauvoir units. Within a given unit, Trend 2 is sourcing each sub-unit parental melt with a protracted decrease in their initial FeO/MnO ratio (Fig. 12d). As such, a sub-unit with a low initial FeO/MnO ratio is more evolved and likely emplaced after one with a higher initial FeO/MnO ratio (e.g., U_1b after U_1a, U_2i after U_2a …). This interpretation is also supported by the progressive increase in micas trilithionite component that is observed from the first to last emplaced sub-unit within each Beauvoir unit (e.g., U_2a to U_2i or U_4a to U_4e; Fig. 7a-e), which is directly related to a magma temperature decrease (Fig. 7; Pichavant 2022) and thus to differentiation along Trend 2. We thus use a nomenclature for sub-unit names using "U_x", with U_xa intruded before U_xb.

The relative emplacement chronology of the various Beauvoir Units and sub-units is summarised in Fig. 13, according to the chronology defined by the lepidolite chemical compositions and the present-day Beauvoir sub-units position. Overall, the Beauvoir granite was built via over-accretion of pluri-decametric sills. U_1a was the first batch to intrude within the micaschist series, followed by the over-accretion of U_1b. U_2a is the first intrusion associated to the second Beauvoir unit and intruded below U_1a via an under-accretion while U_2b over-accreted at the top of the magmatic body (above U_1b at that time) followed by U_2c under-accreted below U_2b. Then, the stacking occurred via over-accretion from U_2d to U_2g and switched another time to under-accretion with the emplacement of U_2h below U_2g and the intrusion of U_2i between U_2h and U_2f (Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig.). U_3a intruded at the top of the Beauvoir body whereas U_3b intruded below U_3a. The first sub-unit of U_4 (U_4a) intruded between U_3b and U_3a, triggering the formation of the lepidolite-rich layer between U_4a and U_3a (Fig. 3d). Ultimately, the stacking from U_4b to U_4e occurred via over-accretion (Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig.).

Parameters that control the relative intrusion level of magma batches is still poorly constrained, but a key role of rheological heterogeneities and thermal gradients are clearly at stake during over- and under-accretion of melt batches. In the Torres del Paine bimodal laccolith (Patagonia), both over- and under-accretion have been observed (Leuthold *et al.*, 2012). The continuous under-accretion of felsic sills was interpreted to be the result of the faster solidification of the previous sill on its roof compared to its base. The base (lower part of the sill) was thus the weakest horizon in which the new-coming felsic sill intruded. After the emplacement of an early mafic body below the felsic sill complex, the subsequent mafic intrusion emplaced within and above the previous one. This final mafic over-accretion would then be the result of a rheological contrast between the underlying mafic magmas and the overlying stiff felsic sill complex (Leuthold *et al.*, 2012). Those interpretation are in line with analogue models predicting dyke flattening into sills when they cross an upper more rigid layer

(Kavanagh *et al.*, 2006). A similar result has been proposed by Fiannacca *et al.* 2017 where they observed an overall over-accretion of the Serre batholith (Calabria, Italy) of compositionally different batches. They emphasised the role of the crystal load of preexisting felsic bodies on the emplacement depth of the new magmatic injections, where new magma batches would have risen under the form of dykes through the crystal-rich preexisting felsic bodies (> 60 % crystals), before spreading out at the top of the batholith.

Recently, Chen *et al.* (2022) explored the relationships between the emplacement depth of mafic melt lenses in slow and ultraslow spreading ridges, and their associated thermal regime. They showed that during a stage governed by high magmatic fluxes (waxing phase), the whole thermal regime of the system is modified, leading to shallower ductile-brittle transition depths. This rheological transition likely governs the emplacement depth of igneous intrusions and so, a waxing phase likely leads to a magmatic over-accretion. On another hand, during a waning phase (low magmatic rate), the thermal regime decreases, leading to a magmatic under-accretion.

Considering the parameters mentioned above, the sill injection level within the Beauvoir pluton could be controlled by melt flux variations, inducing both waning and waxing phases. During waxing phases (i.e. over-accretion), the high injection rate allows sill emplacement before the entire solidification of the previous injection. In this configuration, the new-coming sill intrudes between the stiff overlying host micaschist and the underlying partly solidified magma (Kavanagh *et al.*, 2006; Menand, 2008). On the contrary, during a waning phase, a decrease of the whole thermal regime of the system is expected, and potentially associated with a lower host rock temperature (Chen *et al.*, 2022). In this configuration, a stronger thermal gradient is expected in the upper part of the sill (with the host micaschist) compared to its lower part (with the underlying magmatic pile). Thus, the new-coming magma emplaces below the upper solidification front (Miller *et al.*, 2011; Leuthold *et al.*, 2012), leading to an under-accretion.

This under-accretion within a partially-solidified magma can eventually trigger the formation of viscous layering (Jacquot, 1987; Barbey, 2009) as the one observed between U_4a and U_3a (Fig. 3d). As U_4 sub-units mainly over-accreted (except U_4a), a global increase on the magma flux is inferred (corresponding to a waxing stage) until the end of the Beauvoir magmatism. Such a magma flux increase during late magmatic stages has recently been interpreted at the shallow Takidani pluton (Japan) based on zircon petrochronology (Farina *et al.,* 2024) and thus, could potentially be a common observation for shallow intrusions. Overall and importantly, the results presented in Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig. based on minerals analyses, represent to our knowledge the first attempt to document magma flux variations during the emplacement of a small plutonic body.

5.2.3 Composite decameter-sized sills: evidence for local crystal settling in a granitic body

The Beauvoir pluton emplaced via the stacking of at least eighteen compositionally different intrusions (Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig.). Each of those intrusions was fed by a relatively homogeneous parental melt, but the injection mode remains to be clarified: was each of those decametric intrusions emplaced as a single batch, or build-up incrementally? Cumulative textures linked to lepidolite composition highlight the incremental nature of the sub-units.

From 355 m to 300 m, numerous petrographic discontinuities are characterised by sharp changes in quartz-feldspar proportions (Fig. 3b, c and Fig. 6a). According to experimental data the fractionation of a F-bearing magma produces liquids progressively enriched in albite component at the expense of quartz and K-felspar (Manning, 1981). These experimental results are consistent with our observations showing quartz as a liquidus phase, whereas the interstitial porosity is mostly filled by small albite grains. However, the quartz-rich and albite-poor horizons observed ubiquitously across the pluton (Fig. 3a, Fig. 4b, Fig. 6a and Fig. 14a) present typical cumulative textures (Fig. 4e and Fig. 14a), and bulk compositions that are clearly not representative of a melt composition (e.g., 719.71m: 94.51 % SiO_2, see supplementary material S1). The albite-rich and quartz-poor domains represented either under the form of segregates (Fig. 6a-d) or of local accumulations (Fig. 3a-c and Fig. 4b) could then correspond to the counterpart segregated or accumulated residual liquid. The sutured contact between quartz- and albite-rich zones, in which lepidolite share the same chemical composition, thus correspond to the intrusive contact between two different melt batches that share a similar parental melt (and are thus part of the same sub-unit in the classification presented herein). A specific 7 m thick profile belonging to U_4b (from 352.19 to 345.30m) displaying an upward modal evolution from quartz-rich to quartz-poor and albite-rich zone (Fig. 14a-d) has been selected to detail the process at stake during amalgamation of a sub- unit. As before, lepidolites from the quartz-rich and the albite-rich are used to track melt composition evolution along this 7 m thick profile (Fig. 14f). Those display homogeneous compositions from core to rim, and from one sample to the other indicating that those samples crystallised from a similar melt composition. The quartz-rich layer at the bottom of the 7 m thick section thus corresponds to a quartz and topaz accumulation zone whose tightly packed clusters indicate aggregation in a liquid-rich magma prior to their settling (Fig. 15b, c). The fact that this quartz and topaz-rich cumulate displays a sutured intrusive contact with an underlying albite-rich assemblage (Fig. 6a, b) highlights that the underlying evolved assemblage was partially solidified at the time of intrusion (Fig. 15a-c). This observation reinforces our conclusion that the U_4b sub-unit emplaced during a waxing phase (Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig.). The progressive accumulation of denser minerals (e.g. quartz and topaz mainly) at the bottom of this section was balanced by the progressive accumulation of buoyant residual liquid at the top of the section (Fig. 15d, e). To summarise, this 7 m thick belonging to U_4b formed by the settling of quartz and topaz aggregates and concomitant accumulation of buoyant residual melt at the top of the section. The concentration of such an evolved melt, enriched in incompatible elements at the top of the section is attested by bulk rock enrichments in Li and Be in the upper albite-rich part of the section compared to the bottom quartz-rich part. Although melt fraction was variable along this profile, melt composition was homogeneous as it crystallised lepidolite with similar composition all along the section. This 7 m thick profile is not unique in U_4b sub-unit and several other sutured intrusive contacts between albite-rich and quartz-rich domains have been observed (e.g., Fig. 3c). Those various discontinuities attest for the juxtaposition of several magma batches sharing similar compositions, whose stacking has led to their partial amalgamation eventually forming U_4b sub-unit.

5.2.4 Evidence for an open system crystallisation

Our results demonstrate that Beauvoir pluton emplaced incrementally by the stacking of at least eighteen decameter sized sills, representing the various sub-units. As we demonstrated for U_4b (Fig. 3c and Fig. *15*), although magmatic contacts could have been erased (e.g., sub-solidus textural modification), other Beauvoir sub-units can potentially be formed by the stacking of multiple meter-sized melt-rich injections. The preservation of the injection features (e.g., modal phase variations between two injections) is only possible if the injection rate was sufficiently low to allow the magma to be in a mushy state before the next injection (Fig. 15). For a higher injection rate, the sub-unit inflation likely rather occurred through magma mixing between the different recharges, erasing any potential contact. In this case, magmatic recharges are visible through the mineral record under the form of oscillatory zonation. Indeed, oscillatory zonation in lepidolite clusters is widespread and support crystallisation in an open system in which several melt batches were injected (Fig. 6f and Fig. *9*c). The composition of the various crystal growth zones in the oscillatory zoned lepidolite cluster presented in Fig. 9c-d are characterised by a linear trend in a the Al_2O_3/SiO_2 vs FeO chemical space (Fig. 9e), implying that each magmatic recharges shared similar initial melt composition. This crystallisation in an open system, and the general occurrence of melt recharge in the Beauvoir granite is also attested by the widespread oscillatory zonation observed in quartz (Fig. 10a-d) and topaz (Fig. 10e, h) as well as by the resorption features observed in some micas (Fig. 4h and Fig. 5c, h) and topaz (Fig. 10e, h). Those continuous replenishments likely triggered sill inflation and the progressive build-up of the sub-unit. Once replenishments stopped, the solidification of the intrusion occurred via the progressive porosity closure, associated with the crystallisation of the evolved interstitial melt, producing the differentiated external rims of the various minerals (Fig. 4e, Fig. 6f, Fig. 9a-d and Fig. 10). Thus, although some sub-units (e.g., U_4b; Fig. 14) were formed via the stacking of meter-sized melt-rich injections without significant magma mixing, the wide occurrence of magma recharge in the Beauvoir intrusion would rather attest that most of the sub-units have been formed through multiple melt recharges triggering sill inflation.

5.2.5 The Beauvoir granite as a fractal assemblage

As a result, it appears that the Beauvoir granite build-up incrementally via a fractal scale arrangement of sill stacks. Based on the initial composition of each magmatic injection, the whole intrusion can be divided into four major units (U_1 to U_4), themselves divided into several sub-units (Fig. 8 and Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig.). At an even smaller scale those sub-units appear to result, at least locally, from the amalgamation of several smaller magmatic injections (Fig. 15). The widespread occurrence of resorption features (Fig. 3, Fig. 4 and Fig. 10) and of oscillatory zoning in topaz, quartz, and lepidolite (Fig. 6, Fig. 9 and Fig. 10) all along the Beauvoir intrusion, highlights that the solidification of each sub-unit occurred as an open system. Despite the incremental and fractal accretion of the studied pluton, only few petrographic discontinuities have been observed across the granite, either corresponding to intrusive contacts between sub-unit (section 5.1, Fig. 3a, d, e) or to contacts resulting in the juxtaposition of two magmas batches belonging to same sub-unit (i.e., same parental melt; Fig. 3). However, those contacts can be easily obscured by the rapid continuous nature of magmatic injections (De Saint-Blanquat *et al*., 2006; Miller *et al.*, 2011; Leuthold *et al.*, 2014) or potentially via sub-solidus textural re-equilibration related to the heat brought by the subsequent magma injections (Annen et al., 2015). Also, the intrusion size likely plays a key role on whether or not magmatic contacts between each pulses are preserved, incremental process likely governs in small plutons emplacement whereas injections cycle at different timescale play a major role in larger plutons (De Saint Blanquat *et al.*, 2011). Such fractal increments could easily apply to other similar systems like the Torres del Paine laccolith which is composed of several "complexes", themselves constituted by units formed via the accumulation and of various compositionally similar sills (Leuthold *et al.*, 2013).

5.2.6 Space accommodation and magma emplacement

Space creation in host-rocks is fundamental for the growth of a magmatic reservoir (e.g. Molyneux & Hutton, 2000; Glazner & Bartley, 2006; Paterson *et al.*, 2008). For the Beauvoir granite, the stacking occurred step by step with the intrusion of successive decametric intrusions. For this reason, the magma emplacement did not require a single 800 m opening space, but rather jerky decametric openings. From their structural study, Jacquot & Gagny (1987) proposed that the Beauvoir intrusion emplaced via a cauldron-like subsidence, directly related to the Colettes pull-apart mechanism (Gagny & Jacquot, 1987). In this model, each newly metric-size injection was related to a displacement along the pull-apart shear zone, ultimately leading to an overall vertical displacement of 800m. If the whole Beauvoir intrusion emplaced within 20 to 100 ky (estimation based from de Beauvoir volume and the Fig.4 of De Saint Blanquat *et al.*, 2011), the corresponding slip rate would be comprised between 4 and 0.8 cm per year. Such slip rates are in the order of magnitude of the average velocities on active faults (Annen *et al.*, 2022) and can be enhanced by melt lubrication processes (Cruden, 1998; Annen *et al.*, 2022).

5.3 Melt-rich bodies & their potential relation to surface eruptions

The presence of mineral clusters formed via synneusis (Fig. 4a, g and Fig. 9c), the occurrence of crystal settling forming quartz-rich cumulates (Fig. 6a and Fig. 14a), as well as the occurrence of skeletal lepidolite grains (Fig. 4i and Fig. 9a, b) altogether indicate that most of sill injections were crystal-poor when they intruded the Beauvoir reservoir. As the building scheme of Beauvoir mainly occurred through an over-accretion (Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig.), it is most likely that a new liquid-rich magmatic lens was present at the top of the Beauvoir body each time that a new magma batch emplaced into the reservoir. Thus, several ephemeral stages of melt-rich lenses have occurred during the Beauvoir granite build-up.

Once emplaced, those liquid-rich injections started to crystallise following a F-rich felsic magma liquid line of descent which is characterised by a progressive shift toward the albite component (Manning, 1981). Associated with this sodium and fluorine enrichment, residual liquids are also strongly enriched in incompatible elements such as Li, Be and P compared to their associated cumulates (e.g., quartz-granite). It follows that corresponding magmas have a very low viscosity despite their low equilibration temperature (50 Pa.s at 660°C; Reyf *et al.*, 2000; Bartels *et al.*, 2013, 2015). The albite-rich segregates observed herein highlight that those buoyant residual liquids can be segregated from the host crystallising granitic magma and channelised (Fig. 6a, b). This segregation is potentially assisted by mush deformation (e.g., viscous shearing; Jacquot, 1987; Grocolas & Müntener, 2024). The ascent of such buoyant residual liquids likely stopped when they met a rheological boundary (e.g., the former intrusive contact between quartz-topaz cumulate, and the granite in Fig. 6a). The solidification of such evolved melts eventually formed the observed albite-rich ± lepidolite ± amblygonite segregates (Fig. 6a-d, f). As contacts between those segregates and the surrounding granite are sutured (Fig. 6a-d), the ascent of those channelised residual liquids occurred at the magmatic stage through a partially-solidified magma (e.g., mushy state). A large amount of those segregates is present in the lower part of U_4e between 230 and 198m (Fig. 8). Lepidolite from these segregates follow the same differentiation trend than those in the U_4e quartz-granite (Fig. 8Fig. 16a), indicating that they crystallised from the same parental magma. Moreover, their evolution degree is similar to that of the U_4e quartz-granite, highlighting that they crystallised from the same melt composition (Fig. 8Fig. 16a). Once segregated, residuals liquids percolated through the U_4e sub-unit and ponded around 198 m (no Ab-rich segregate was observed above this level). They potentially ponded below the U_4e upper solidification front, forming a shallow liquid-rich magmatic lens (Fig. 16b).

Results presented above thus highlight that melt-rich bodies were present at various stages of the Beauvoir granite emplacement (first during the emplacement of each sub-unit, and second during the last stages of evolution with the segregation of evolved melts). As the emplacement depth of the pluton was relatively shallow (around 3 km; Cuney *et al.*, 1992), the mobilisation of such lenses could have produced small silicic surface eruptions (Fig. 16b). The rhyolitic dykes connected to the Beauvoir granite observed within the surrounding micaschist (Captions:

Fig. 1) thus potentially represent the volcanic-plutonic connection. Those two models of liquid-rich lens formation eventually provide more constraints on the formation of eruptible silica-rich magmas without the involvement of any compaction processes (Holness, 2018). These mechanisms leading to a felsic and volatile-rich magma ponding at sub-volcanic depths is potentially not endemic to the Beauvoir system. Pegmatites and rare-metal rhyolites are thought to derive from extended crystallisation of granitic magmas (Černỳ *et al.*, 2005; London, 2018) as their compositions often show a continuum with spatially related plutons (e.g., Silverleaf pegmatite with the Greer Lake leucogranite; Černý *et al.*, 2005, Richemont rhyolite with the Blond granite; Raimbault & Burnol, 1998 or Mongolian ongonites with contemporaneous F-rich granites; Kovalenko, 1976; Dostal *et al.*, 2015). Melt extraction from parental bodies has therefore occurred elsewhere in similar systems, and the model presented herein could potentially partially extend to such systems.

6. Conclusion

The petrographic and geochemical study of the Beauvoir rare-metal granite record the protracted emplacement of magmatic batches involved during the formation of the pluton. Through distinct lepidolite composition, eighteen decametric sills (sub-units) grouped in four distinct unit (U_1 to U_4) have been distinguished, each on them corresponding to a compositionally different magmatic intrusion. As lepidolite composition can be used as a proxy for the magmatic differentiation, it appears that each of these sills differentiated through a fractional crystallisation process involving notably the formation of quartz and topaz-rich cumulate. Associated residuals liquids are considerably depleted in MnO + FeO, and reversely are enriched in metals such as Li and Be.

Although all the Beauvoir sub-units followed a similar liquid line of descent, the evolution of their composition were different as their parental melt composition were also different (Trend 3). Within a unit, the various sub-units parental melt compositions can be explained by a protracted fractional crystallisation of a reservoir at depth, in which residual liquids were extracted step by step before intruding the Beauvoir reservoir (Trend 2). The various parental melt composition of each Trend 2 corresponding to the transition between the various units would be the result of source processes under garnet stability field (progressive melting of the protolith; Trend 1). Altogether, these multi-stages of fractional crystallisation and residual liquids extraction are expected to be at the origin of the uncommon and metal-rich nature of the Beauvoir parental magmas.

Thus, by constraining the first relative chronology of emplacement within a small rare-metal granite, we show that the granite mainly formed through the over-accretion of liquid-rich decametric sills, with the youngest increment located at the top of the plutonic body. Although contacts between the various sub-units (i.e., sills) are sutured, the lack of mixing features between various sub-units suggests that each of the new sills emplaced when the previous sub-unit was already partially solidified. Locally, the presence of quartz and topaz cumulate overlying albite-saturated liquid accumulation belonging to the same sub-unit across the granite indicate that some of these decametric sub-units are themselves formed by several meter-sized injections. More generally, the ubiquitous presence of oscillatory zoned lepidolites reflecting various replenishments of similar parental melt composition suggests that most of the Beauvoir sub-units were built trough sill inflation, which ultimately have led to the formation of amalgamated sub-units. The Beauvoir building scheme was thus fractal, with the identification of units, containing several sub-units, themselves constituted by smaller meter-sized injections. Once emplaced, the protracted crystallisation has led to the formation of albite ± lepidolite ± amblygonite-saturated residual liquids. Due to their low viscosity, those residual melts also enriched in incompatible elements (e.g., Li, Be, P, F, Ta) percolated through their parental sub-unit, forming extraction channels. Their crystallisation corresponds now to albite-lepidolite ± amblygonite-rich segregates. During the late magmatic stage (last sub-unit solidification), those channels have ponded to form a volatile and liquid-rich magmatic lens within the sub-unit.

The fact that most of the sub-units formed through the over-accretion of liquid-rich magma sills, together with the extraction and accumulation of residual liquids during the late magmatic stage of each sub-units, suggest that several ephemeral shallow (~3 km) liquid-rich lenses were present at the top of the Beauvoir granite during its construction. The destabilisation of those lenses could have led to small eruptions via notably the formation of the Beauvoir-connected rhyolitic dyke. More generally, these two ways of liquid-rich lenses formation at shallow depth can have significant implications on the generation of felsic sub-volcanic intrusions (e.g., rhyolite and pegmatite) which in turn, allow the volcanic-plutonic connection.

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Data availability statement:

The full dataset used in this study is available for free download on the EarthChem Library. New Beauvoir whole-rock compositions under the reference doi: 10.60520/IEDA/113419 and new EPMA analyses under the reference doi: 10.60520/IEDA/113420.

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Captions:

Fig. 1 – Interpretative sketch of the Beauvoir granite structure. Each magmatic units that constitute the granite are represented. See the section 4.3.1 Micasfor explanations on unit's identification. Modified from Cuney *et al.,* (1985a).

Fig. 2 – Downhole evolution of the Beauvoir bulk rock concentration for: a) Na_2O/K_2O, b) $Al_2O_{3norm}/Al_2O_{3tot}$ (with $Al_2O_{3norm} = Al_2O_3 - 1.643*Na_2O - 1.083*K_2O$ in weight percent), c) Fe_2O_3 (wt %) and d) Cs (ppm). The re-appraised Beauvoir units determined in this study (U_1 to U_4) are indicated as well as the position of the units defined by (Gagny, 1987; Jacquot, 1990; Rossi et al., 1987). Dashed lines correspond to the position of petrographic discontinuities presented in Fig. 3. Beauvoir bulk rock data are from Rossi et al. (1987), Raimbault et al. (1995), Pichavant (2022) and this study (Supplementary material S1).

Fig. 3 – Macrophotographs of representative petrographic discontinuities observed along the GPF-1 drill core. a) 290.15m: Contact characterised by an accumulation of albite-rich material (U_4c) below a quartz-rich zone belonging to U_4d. b) 303.89 m: Intra-sub-unit contact inside U_4c between albite-rich zone and normal granitic facies. f) 338.05 m: Intra-sub-unit contact inside U_4b between albite and lepidolite-rich zone above normal granitic facies. d) 379.12m: Contact between a well-oriented lepidolite layering (U_3a) above granitic facies (U_4a). Lepidolites from these two parts do not share the same composition. e) 518.20 m: Contact between the two sub-unit U_2g and U_2i. For the same mineralogy, the grain size in U_2h is smaller than the one in U_2i. f) 546m: Abrupt passage from a fined-grain and pinkish granite to another fined-grain whitish granite. The altered transition zone is characterised a high quartz and mica modal proportion. From the lepidolite composition analysis, this contact does not represent a contact between two different sub-units but rather an intra-sub-unit contact (U_2f).

Fig. 4 – Microphotographs presenting typical textures observed in Beauvoir unit 1 (a-c) and 2 (d-i). All the microphotographs are in crossed polarised light except (b) and (i). a) 824.01 m (U_1a): Quartz and topaz cluster in the granite. Those grains forms clusters along their growth face. b) 789.68 m (U_1b): Interstitial quartz, lepidolite and K-feldspar inside an albite-network (Ab_I). Note the reddish color of K-feldspar under CL, characteristics of its alteration. Cathodoluminescence image. c) 754.61 m (U_1b): Highly muscovitised lepidolite primocryst. Note the presence of lepidolite remnant. d) 872.41 m (U_2a): Quartz and K-feldspar primocrysts sealed by interstitial albite (Ab_{II}) and lepidolite. Included albite in quartz denotes its early crystallisation. e) 719.95 m (U_2c): Interstitial lepidolite in a quartz-cumulate. f) 630.01 m (U_2b): Large euhedral topaz primocrysts surrounded by small albites (Ab_{II}) and lepidolite as well as interstitial quartz. g) 553.59 m (U_2f): Topaz cluster surrounded by small euhedral albite and lepidolite as well as interstitial quartz. h) 495.38 m (U_2g): Partially resorbed lepidolite visible thanks to its patchy purple zone inside its blue core. i) 518.25 m (U_2i): Lepidolite displaying a dark skeletal texture, filled by reddish lepidolite. Note the difference between lepidolite and muscovite (alteration) under CL light. Cathodoluminescence image. Abbreviations: Ab, albite; Qz, quartz; Lpd, lepidolite; Tpz, topaz; FK, K-feldspar; Ms, muscovite; Ap, apatite; Amb, amblygonite.

Fig. 5 – Microphotographs presenting typical textures observed in Beauvoir Unit 3 (a-c) and 4 (d-i). All the photomicrographs have been taken under crossed-polarised light. a) 368.71 m (U_3a): Euhedral orthoclase containing albite inclusions. Small euhedral albite (Ab_{II}) filled the space between quartz and orthoclase grains. b) 368.71 m (U_3a): quartz and topaz Cluster enclosing small and euhedral albite (Ab_{II}) grains. c) 368.71 m (U_3a): Large and twinned lepidolite grain. Note the difference between its partially dissolved core and its homogeneous rim. d) 393.24 m (U_4a): Lepidolite crystal containing a darker skeletal texture indicated by black

arrows. e) 346.40 m (U_4b): Topaz primocrysts partially replaced by amblygonite. The whole grain is surrounded by euhedral albite (Ab_I). f) 352.30 m (U_4b): Lepidolite cluster enclosing a columbo-tantalite crystal. Note the larger albite size compared to quartz. g) 303.79 m (U_4c): Star-like lepidolite using a topaz grain as nuclei. Note the presence of small cassiterites. h) 199.87 (U_4e): Small lepidolite containing a brownish aureole between its core and rim. i) 118.15 m (U_4e): Highly elongated lepidolite between thick albite tablets. Quartz is interstitial.

Fig. 6 – Macro- and microphotographs of albite- lepidolite ± amblygonite-rich segregates in U_4. a) 352 m (U_4b): Trace of the percolation of an albite-rich segregate through the granite before being blocked by the overlying quartz and topaz-rich cumulate. b) 352.30 m (U_4b): Cross-polarised photomicrograph showing the relationship between albite-rich segregate and the host granite. Note the lobate and pervasive contact between the segregate and the host granite. c) 246.95 m (U_4d): Macrophotograph of a zoned segregate intruding the host granite. The inner part of the segregate is dominated by lepidolite and amblygonite whereas the outer zone is constituted by albite ± lepidolite. d) 218.15 m (U_4e): Macrophotograph showing the connection between the lepidolite-rich granite and the albite-lepidolite-rich segregate. e) Cross-polarised photomicrograph of the lepidolite-rich granite of (d). Albite and lepidolite are the main phases of this facies, associated with minor interstitial topaz, quartz and K-feldspar. Note the partly resorbed rim of lepidolites. f) Cross-polarised photomicrograph coupled with alumina chemical map of one lepidolite in the albite-lepidolite-rich segregate of (d). Albite (Ab_I and Ab_{II}) are aligned and seems to have been hindered by the lepidolite. An oscillatory zoning around an alumina-rich core can be observed on the chemical map. The porosity is filled by the alumina-poor rim of the lepidolite. Note the interstitial position of quartz and the partially dissolved topaz.

Fig. 7- a) Micas compositions from the Echassières granitic complex in the Li-R^{2+}-R^{3+} (a.p.f.u : atom per formula unit) classification diagram of Foster (1960), where R^{2+}: Fe+Mn+Mg and R^{3+}: Al+Ti. B-e) Positions of lepidolites belonging to the U_1(b), U_2 (c), U_3 (d) and U_4 (e) in the zoomed zinnwaldite-polylithionite and trilithionite solid-solution. Li* has been recalculated from the silica content from the following formula: $Li_2O^*=(0.289*SiO_2)-9.658$ (Tischendorf et al., 1997). Micas composition of the Colettes granite are from Jacquot (1990) whereas the immiscibility field between di- and trioctahedral micas is from Monier (1987). Lepidolites obtained during the crystallisation experiments (composition corresponding to U_4d sub-unit) of Pichavant (2022) are also represented.

Fig. 8 – MnO (wt %) vs FeO/MnO in Beauvoir lepidolites. Lepidolites are represented according to their associated sample, where their localisation across the GPF-1 drill core is given by the schematic log. From the maximum lepidolite concentration in MnO of each sample, for different units can be distinguished: U_1-U_2-U_3 and U_4. Inside each unit, two distinct sub-units contain lepidolite that are characterised by a different FeO/MnO ratio for the same MnO content. Lepidolites composition of albite +lepidolite ± amblygonite-rich segregates observed between 230 and 198m (U_4e) is represented by the orange field. These lepidolites share the same composition than those belonging to U_4e sub-unit. The position of each sub-units is indicating on GPF-1 drill log.

Fig. 9 – a-d) Quantitative chemical maps processed with XMpatTools 3.4.1 (Lanari et al., 2014, 2019). a) 504.17m (U_2h): Al_2O_3 (wt %) chemical map in lepidolite in which three skeletal cores can be observed. b) 393.24m (U_4a): Al_2O_3 (wt %) chemical map on the lepidolite in **Erreur ! Source du renvoi introuvable.**d, in which three skeletal cores can be observed. Two of them are stuck together along their planar growth face via synneusis. c and d) 315.98m (U_4b): Al_2O_3

(wt %) and Li_2O (wt %) chemical maps on lepidolite cluster in which three cores are surrounding by oscillatory zoning. These three grains were sealed together during the porosity closure with the crystallisation of the alumina-poor and lithium rich rim. e) Position of those cores, oscillatory zonation and rim composition in the Al_2O_3/SiO_2 vs FeO (wt %) diagram. For comparison, lepidolite analysed in U_4 are also represented. Positions of these analyses are represented in purple in (c) and (d). Note that the composition of this mica cannot be explained by magma mixing between different sub-units and rather follow the U_4b differentiation trend.

Fig. 10 – a) Al_2O_3 qualitative chemical map in quartz from 265.87 m (U_4d). Note the presence of an alumina-rich core and alumina-poor rim. B) Al_2O_3 qualitative chemical map in three quartz from 368.71 m (U_3a). Note the presence of an alumina-rich core enveloped by an alumina-poor zone. These quartz also contain another external alumina-rich growth zone containing a large number of small albite inclusions, prior to the crystallisation of the final alumina-poor rim. c and d) 828.76 m: Respectively the qualitative alumina chemical map and the CL image of a quartz cluster belonging to the Beauvoir microgranite (µG). The oscillatory zonation observed under CL light are not marked in Al_2O_3, except a slight alumina-rich growth zone indicated by the white arrows in (c). e and f) P_2O_5 qualitative chemical maps respectively at 630.01 m (U_2b) and 553.59 m (U_2f). Phosphorus oscillatory zonations are observed in topaz as well as dissolution texture. Albites are ubiquitously zoned with a P_2O_5-rich core and a P_2O_5-poor rim. g and h) CL image on the topaz in (e) and it's representative scheme. CL image in topaz is strongly correlated with its phosphorus concentration and reveal sector zoning in topaz.

Fig. 11 – a) F vs P_2O_5 (wt %) in Beauvoir topaz. Note that the variations in phosphorus is not correlated with their fluorine concentration. b) P_2O_5 (wt %) vs anorthite content

(An/(An+Ab))*100) in Beauvoir plagioclases. Phosphorus concentration is anticorrelated with the anorthite content. c, d and e) Respectively the P_2O_5 , CaO qualitative chemical maps and CL image of plagioclases grain at 630.01 m (U_2b). Note the correlation between the phosphorus and calcium signal with the CL intensity.

Fig. 12 – a) Mass balance calculations showing the theorical evolution of MnO and FeO/MnO in melt through fractional crystallisation from two distinct initial melt compositions. The red star has a high FeO/MnO potentially reflecting U_2a parental melt whereas the yellow has a small FeO/MnO potentially reflecting U_2i parental melt. White-filled circles represent the liquid fraction remaining in the system. b) MnO vs FeO/MnO in Beauvoir lepidolites in which an apparent continuity between U_1b, U_2f, U_4a, U_4b and U_4c is shown. c) U_1b, U_2f, U_4a, U_4b and U_4c lepidolites composition in the Al_2O_3/SiO_2 vs FeO diagram, in which any continuity is observed between these samples. d) Mass balance calculations in the MnO vs FeO/MnO chemical space showing the evolution of melt composition through the fractionation of a Colettes-like mineralogical assemblage (from brown stars initial composition) and the effect of garnet fractionation on liquid composition (from blue star initial composition). Same color code as Fig. 7.

Fig. 13 – Structural position of each sub-unit along the GPF-1 drill core versus the order in which they intruded the Beauvoir reservoir. See text for details. Same color code as Fig. 7.

Fig. 14 – a-d) Crossed polarised photomicrographs from a quartz and topaz cumulate (352.19 m, U_4b) to albite and lepidolite-rich facies (345.47 m, U_4b). B and C represent two intermediate sample from (a) to (d), respectively 349.47 (U_4b) and 345.92 (U_4b). E) Coupled quartz modal proportion and whole rock Be concentration (ppm) from the quartz and topaz cumulate (a) to

the albite and lepidolite-rich facies (d). f) Probability histogram of FeO/MnO ratio in lepidolite from 346.40 m to 345.47 m.

Fig. 15 - Sketches explaining the protracted formation of a sub-unit via the stacking of metric to decametric magmatic intrusions. a) The last intruded magma started to crystallise at the top of the Beauvoir intrusion, allowing the presence of a liquid-rich lens at the top on the magmatic pile. b) Another liquid-rich sill took place over the last partly solidified intrusion, with a similar initial melt composition. c) Stochastic collision in the upper liquid-rich sill allows the formation of quartz and topaz clusters, prior to their deposition above the previous mushy intrusion. The last differentiation stage of the first intrusion produced residual liquids, which formed the albite and lepidolite-rich vein. The ascent of this vein is stopped by the quartz and topaz cumulate of the overlying sill, forming an accumulation of albite-rich material just beneath this cumulate. e) The crystallisation continued in the upper sill, resulting to the settling of quartz and topaz and the accumulation of evolved liquids at the top of the intrusion.

Fig. 16 – a) Al_2O_3/SiO_2 vs FeO (wt %) of lepidolites from U_4e albite + lepidolite ± amblygonite-rich segregates in comparison with the analysed lepidolite from U_4e, U_4d and U_4c granite. Lepidolite in albite + lepidolite ± amblygonite-rich segregates are not necessary more differentiated than those in the U_4e granitic facies. b) Sketch of the potential construction of the last Beauvoir sub-unit. The liquid-rich U_4e sub-unit emplaced above the probably mushy U_4d sub-unit. Crystallisation of U_4e magma started on its edges due to thermal gradient, triggering the formation of residual liquids channels, corresponding to the albite + lepidolite ± amblygonite-rich segregates. The accumulation of residual liquids in the center of the sill led to an accumulation of weakly-viscous magmas that can easily be erupted to form a sub-volcanic intrusion (rhyolite, pegmatite or ongonite).