The transition from granite to banded aplite-pegmatite sheet complexes: an example from Megiliggar Rocks, Tregonning topaz granite, Cornwall

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Abstract

The genetic relationship between a granite pluton and adjacent complex of rare-metal pegmatite-aplite-banded sheets (Megiliggar Sheet Complex) has been studied at the border of the Tregonning topaz granite at Megiliggar Rocks, Cornwall, SW England. The compositions and textures of the different rock types and constituent minerals were determined using wet chemical techniques for whole-rock major and trace element analysis, automated mineralogy for textural characterisation and electron microprobe and laser-ablation ICP-MS for measuring major and trace element concentrations in minerals. Similarities in whole-rock chemical and mineralogical compositions, together with a gradual change in textures away from the granite margin, provide strong evidence for a genetic link between the Tregonning Granite and Megiliggar Sheet Complex. The sheets are likely to represent apophyses of residual melt which escaped from the largely crystallised roof of the granite pluton. The escaping melt was peraluminous, had a composition near the F, B, Li (slightly enriched) granite minima, and, in comparison with other Cornish granites, was enriched in F, Li, Rb, Cs, Sn, W, Nb, Ta, and U, and depleted in Fe, Mg, Ca, Sr, Th, Zr, and REE. With increasing distance from the
Tregonning Granite, the silicate melt crystallized as homogeneous leucogranite sheets and banded complex sheets (i.e. combinations of bands with granitic, aplite and pegmatitic textures), and layered aplopegmatites; this sequence becoming progressively more depleted in the fluxing and volatile elements F, Li, Rb, and Cs, but showing no change in Zr/Hf ratios. The fixed Zr/Hf ratio is interpreted as indicating a direct genetic link between all rock types, however the melts progressively lost fluxing and volatile elements with distance from the granite pluton, probably due to wall-rock reaction or fluid exsolution and migration via fractures.

Differentiation of the primary melt into Na-Li-F-rich and separate K-B-rich domains was the dominant chemical process responsible for the textural and mineral diversity of the sheet complex. On a large (cliff-section) scale, the proximal Na-Li-F-rich leucogranite passes through complex sheets into K-B-rich aplopegmatites, whilst at a smaller (< 1 m) scale, the K-B-rich bands are interspersed (largely overlain) by Na-Li-F-rich segregations. The grain size differences between the aplite and pegmatite could be related to pressure fluctuations and following undercooling.

Key words: granite; aplite; pegmatite; magmatic layering; Megiliggar Rocks; Cornwall

1. Introduction

The genetic relationship between granitic pegmatites and the adjacent or enclosing granites has long been debated; particularly whether such pegmatites form from residual, volatile-rich melts sourced from the granites (London, 2008, chapter 5). In the case of pericontact pegmatites, e.g. stockscheider in tin granites in the Erzgebirge (Breiter et al., 2005), and intragranitic pegmatites, e.g. Black Hills, South Dakota (Norton, 1994) or Pikes Peak, Colorado (Simmons and Heinrich, 1975), a direct genetic link is generally accepted. Stockscheider represent an early product of volatile enrichment at the upper or lateral contacts of a granite melt with non-granite host rocks or a previously emplaced melt batch (Breiter et al., 2005). Intragranitic pegmatites represent late segregations of residual water-rich melt (Shearer et al., 1992). These pegmatite types are commonly found in both strongly peraluminous and subaluminous (S- and A-type) granite plutons.
In the case of typical “true pegmatites”, i.e. large dykes or bodies with strong internal zoning and enrichment of rare minerals/elements, typically intruded into metamorphic rocks distal from granite plutons of appropriate composition, the source of the pegmatitic melt is often inferred (London 2008, chapter 10). Goad and Černý (1981) introduced the term “fertile granite” for the mainly leucocratic granitic plutons which lie proximal to pegmatite fields (mainly of LCT-type). These fulfil the theoretical expectations for fertile starting compositions coupled with long fractionation processes, forming bodies of complex pegmatites (Černý, 1991; Breaks and Moore, 1992). Nevertheless, despite an intensive search, localities enabling the direct study of the transition from a granite pluton to rare-element pegmatite dykes in the host rock are scarce (Neiva and Ramos, 2010; Autunes et al., 2013).

We describe here a superb example from Megiliggar Rocks in Cornwall, SW England. A subhorizontal sheet complex, showing the transition from leucogranites to aplites and pegmatites, is spectacularly displayed over 500 m of coastal cliff exposures at the SE margin of the Tregonning Granite. Although the locality is well-known, published mineralogical investigations and data are relatively sparse (Hall, 1930; Hosking, 1952; Stone, 1969, 1975, 1992; Stone and George, 1978; Badham, 1980; George et al., 1981; Exley and Stone, 1982; Stone et al., 1988; Henderson et al., 1989; Bromley, 1989; Floyd et al., 1993; Breiter et al., 2016; Duchoslav et al., 2017; Simons et al., 2017); the most comprehensive study of aplitic–pegmatitic banding is that of Stone (1969). The aims of this study are to describe the mineralogy, mineral chemistry and whole-rock geochemistry of the entire range of granitic rocks within the Megiliggar sheets (granites, aplites, pegmatites) and ascertain their relationship(s) with each other and the adjacent Tregonning Granite.

2. Geological setting

The Early Permian Cornubian Batholith of SW England is a classic location for the study of rare-metal granites (e.g. Manning and Exley, 1984; Stone and Exley, 1985; Charoy, 1986; Willis-Richards and Jackson, 1989; Chappell and Hine, 2006; Müller et al., 2006; Simons et al., 2016). These Variscan post-collisional peraluminous granites can be subdivided into five major types (Fig. 1a): two mica (G1), muscovite (G2), biotite (G3), tourmaline (G4) and topaz (G5) granites. The topaz granites are typically medium-grained, equigranular and aphyric alkali feldspar granites (<An3), and are
characterized by lithium-rich micas and up to 3 vol.% topaz (Manning and Hill, 1990; Manning et al., 1996; Stone, 1992; Simons et al., 2016). Topaz granites occur principally in the Tregonning Granite and the Nanpean and Hensbarrow stocks within the composite St Austell Granite; the Meldon Dyke, north of the Dartmoor Granite, is a topaz aplite (Simons et al., 2016).

The Tregonning-Godolphin Granite (Stone, 1975, 1992) comprises the fine- to medium-grained porphyritic two mica Godolphin Granite in the north, and the Tregonning Granite in the central and southern parts of the pluton which is exposed on the coast. Hall (1930) attributed these coastal exposures to the Godolphin Granite, following early Geological Survey usage (Reid and Flett, 1907), but the composite nature of the pluton was recognised by Stone (1960) and the Tregonning Granite has been distinguished separately in most subsequent work (e.g. Stone, 1975, 1990; Floyd et al., 1993; Simmons et al., 2016).

The host rocks to the Tregonning Granite are low-grade regionally- and contact-metamorphosed metasedimentary rocks of the Mylor Slate Formation (Goode and Taylor, 1988; Leveridge and Shail, 2011). Field relations indicate that granite emplacement and contact-metamorphism post-dated the development of folds and cleavages related to both Variscan thrusting (D1 and D2) and post-Variscan extension (D3) (Stone, 1966, 1975; Alexander and Shail, 1996; Pownall et al., 2012). The dominant fabric in the host rocks is a gently SE-dipping S3 crenulation cleavage (S2 of Stone, 1996) that commonly transposes earlier fabrics and locally contains variably boudinaged veins of metamorphic quartz (Alexander and Shail, 1996). The history of pre- and post-granite vein development and the associated fluid characteristics has been described by Wilkinson (1990, 1991) and Gleeson et al. (2000).

A series of leucocratic, partly layered granites, termed the “roof complex” (Stone, 1975), lies along the horizontal upper contact of the Tregonning Granite with the Mylor Slate Formation. At the SE margin of the Tregonning Granite, the roof complex is represented by gently SE-dipping leucogranite and aplite-pegmatite sheets within the Mylor Slate Formation that are continuously exposed in a 30-50 m high cliff section over a distance of c. 500 m between Legereath Zawn and Tremearne Par (“Megiliggar Rocks” 50°04′26.4″ N, 5°24′42.6″ W) (Fig. 2a). We hereafter refer collectively to these sheets as the “Megiliggar Sheet Complex” (MSC). The geometrical relations of these sheets, and
their relations to the Tregonning Granite, have been variably represented in sketch cross-sections (Hall, 1930; Stone, 1975; Badham, 1980; Exley and Stone, 1982; Bromley, 1989; Floyed et al., 1993; Fig. 1b in this work).

The easternmost exposure of the Tregonning Granite occurs around Legereath Zawn where it post-dates an earlier biotite granite porphyry (‘elvan’) dyke (Hall, 1930), the ‘Legereath granite porphyry’ of Stone (1975) or ‘Legereath Zawn Elvan’ of Breiter et al. (2016). The uppermost part of the Tregonning Granite is exposed in the western, northern and eastern walls of Legereath Zawn. In the northern wall it occupies the full cliff height (50 m) but moving eastwards passes, at an elevation of c. 15 m, into the lowermost sheet of the MSC within the Mylor Slate Formation. We concur with Hall (1930, Fig. 8B) that there is also a magmatic linkage, via a short sheet segment, between this lowermost sheet and the uppermost part of the Tregonning Granite towards the base of the cliff on the eastern side of Legereath Zawn. Although the contacts between the more easterly MSC sheets and the Tregonning Granite are not exposed, we infer that all the MSC was sourced in a comparable manner from the upper parts of the Tregonning Granite.

3. Analytical methods

The whole-rock (WR) major element oxide determinations (using wet techniques, for detail see http://www.geology.cz/extranet-eng/services/laboratories/inorganic-analysis) were carried out at the Czech Geological Survey, Praha. Replicate analyses of an international reference material (JG-3; Geological Survey of Japan) yielded an average error (1 sigma) of ± 1 % with respect to the recommended values (Govindaraju, 1994). Trace elements were determined by ICP mass spectrometry following lithium metaborate/tetraborate fusion or nitric acid digestion in the laboratories of the Bureau Veritas, Vancouver, Canada (For details see http://acmelab.com/).

A TESCAN Integrated Mineral Analyzer (TIMA) was used for automated mineralogical, modal and textural analysis employing Liberation analysis mode (Gottlieb et al., 2000). Liberation analysis mode, with ‘high-resolution mapping’, includes the collection of backscattered electron (BSE) and EDS data on a regular grid (10 μm point spacing in our case). At each point, the BSE level is determined. If the BSE level is above a certain threshold, the beam is kept directed on this spot until a predefined number...
of counts (1000 in our case) from the spectrometer are collected. The individual points are grouped
based on a similarity search algorithm and areas of coherent BSE and EDS data merged to produce
segments (i.e. mineral grains). Individual spectra from points within each segment are summed. The
average BSE value is also calculated. Data from each segment are then compared against a
classification scheme to identify the mineral and assign its chemistry and density (Hrstka et al., in
prep.). The results are plotted as a map showing the distribution of minerals within the sample.

Minerals were chemically analysed using a Cameca SX 100 electron microprobe, in wavelength-
dispersive mode, at the Institute of Geology CAS. Analytical conditions for silicates were:
accelerating voltage 15 kV, beam current 10 nA, beam diameter 2 µm. The following calibration
standards were used: Na, Al – jadeite, Mg, Si, Ca – diopside, K – leucite, Ti – rutile, P – apatite, Mn –
MnCr₂O₄, Fe – magnetite, F – fluorite, and Rb – RbCl. The matrix correction procedure X-Phi
(Merlet, 1994) was applied. The empirical formulae of the feldspars were calculated based on 8
oxygen atoms per formula unit (8 O apfu); the empirical formulae of the micas were calculated based
on 44 negative charges. The empirical formulae of the tourmaline were calculated based on 24.5
oxygen atoms per formula unit (boron excluded).
The Sn, W, Nb, Ta-oxide minerals and zircon were analyzed at an accelerating voltage and beam
current of 15 kV and 7 nA, and 15 kV and 10 nA, respectively, with a beam diameter of 1 to 3 µm.
The counting times on each peak were optimized for individual elements according to their expected
concentrations (10–60 s), and half that time was used to obtain background counts. X-ray lines and
background offsets were selected to minimize interference.

Lithium and trace elements in micas and tourmalines were determined using LA-ICP-MS at the
Masaryk University, Brno. Micas were analyzed using a Nd:YAG-based laser ablation system at a
wavelength of 213 nm (New Wave Research, Inc., Fremont, CA, USA), which was coupled to a ICP-
QMS instrument with quadrupole mass spectrometer (Agilent 7500ce, Agilent Technologies, Santa
Clara, CA, USA). Tourmalines were analyzed with an ArF* excimer-based laser ablation system
Analyte G2 (Teledyne CETAC Technologies) at a wavelength of 193 nm, which was coupled to an
Element2 (Thermo Fischer Scientific) ICP-MS instrument with double focusing provided by
electrostatic and magnetic sectors. Operating conditions of both the LA-ICP-QMS and LA-ICP-SFMS
were optimized with the aim of obtaining maximum signal-to-background ratios and sensitivity, minimum spectral and non-spectral interferences and best signal stability, and then kept constant throughout the analyses. Micas were ablated under optimal conditions of: fluence (13 J·cm$^{-2}$), frequency (10 Hz), ablation dwell time (40 s), duration of Ar-He gas blank measurement (40 s) and laser beam spot diameter (80 μm). For tourmaline, a spot diameter 30 μm, fluence 3 J·cm$^{-2}$, frequency of 10 Hz, 60s ablation dwell time and 60s Ar-He gas blank measurement were applied. Silica was employed as the internal reference element having been previously determined in samples by electron microprobe. The systems were calibrated using artificial glass NIST610 and NIST612 to quantify the concentrations of Li, Al, Sc, Ga, Ge, Nb, In, Sn, Cs, Ta, W and Tl in mica, and Li, Be, B, Al, Sc, Zn, Ga, Ge, Rb, Nb, In, Sn, Cs, W, and Tl in tourmaline. Trace element concentrations (Al, B, Be, Fe, Ge, Li, Mn, P, Rb, Sn, Sr, and Ti) in quartz were determined by LA-ICP-MS at the Institute of Geology CAS. This utilized a Thermo-Finnigan Element 2 sector field mass spectrometer coupled to an Analyte Excite 193 nm excimer laser (Photon Machines). Analyses were conducted using a repetition rate of 10-20 Hz, laser fluence of 3–5 J/cm$^2$, beam size of 40-80 μm; all parameters were optimized against the intensity of signals. The ablated material was transported by high purity He gas from the laser ablation cell. Time-resolved signal data were processed using Glitter software (http://www.glitter-gemoc.com/). The isotopes $^{29}$Si and $^{30}$Si were used as internal standards based on the assumption that the analyzed quartz contains 99.95 wt% SiO$_2$. The data were calibrated using artificial glass NIST612. For more details see Breiter et al. (2013).

4. Petrology of the Megiliggar Sheet Complex (MSC)

4.1 Textural varieties of the MSC, studied samples

The Tregonning Granite is a medium-grained equigranular granite, light in colour and composed of quartz, albite, perthitic K-feldspar, zinnwaldite/lepidolite micas, and Li-F-rich schorl. Apatite is minor, while rutile, Fe-columbite, and zircon are accessory (typical sample #5303, Fig. 3a).

A small body of fine-grained equigranular granite with macroscopically black mica, termed a biotite granite dyke, was found within the faulted zone at Legereath Zawn, in association with a typical
granite-porphyry (‘elvan’) dyke. The biotite granite is composed of quartz, albite, K-feldspar, strongly muscovitized Li-Fe-mica (primarily siderophyllite–zinnwaldite in composition) and schorl. Apatite is minor; rutile, zircon and monazite are accessory minerals (sample #4962).

SE from Legereath Zawn, the following principal types (facies) can be defined within the sheets of the MSC (Fig. 1b):

- Homogeneous leucogranite which forms three major sheets, each up to 3 m thick and 200 m long (Fig. 2a). This rock is fine- to medium grained, equigranular and nearly white in colour. It is composed of quartz, albite>K-feldspar, zinnwaldite-trilithionite mica, and Li-enriched fluoroschorl. Sub-parallel dark layers up to 3 cm thick that are enriched in mica are sometimes conspicuous (Fig. 2b, c). Amblygonite and apatite are minor; zircon, Mn-columbite, and uraninite are accessory (typical sample #4963).

- These fine-to medium grained leucogranite sheets also contain a fine-layered aplitic facies and minor pods and laminae of pegmatite facies. Further SE, the proportions of granitic, aplitic and pegmatitic facies became nearly equal forming “complex sheets” (Fig. 2d, e). Some aplitic and pegmatitic layers form rhythmic structures; textural borders are smooth and gradational. The direction of crystallization, i.e. relative age of layers, may be inferred from orientation of feldspar crystals in unidirectional solidification textures (UST) (London, 2008). In some cases, the layering is a product of repeated injection (compare Bromley, 1989) with symmetrical zoning. These sheets are enriched in Li and F; they contain pinkish Li-bearing zinnwaldite–trilithionite micas and Li-enriched (deep green) tourmaline in some laminae, but muscovite and black schorl in others. Albite dominates over K-feldspar. Manganese-rich apatite is minor; fluorite, monazite, xenotime, zircon, columbite, rutile, cassiterite, wolframite, uraninite, pyrite, arsenopyrite, molybdenite and native Bi are accessory minerals. Typical samples are #2015 (fine layered aplitie), 4964 (fine-grained granite with pegmatitic laminae), 5304 (fine-grained granite rich in tourmaline), 5305 (layered combination of granite, pegmatite and aplitie, Fig. 3b).

- Major bodies of aplitie/coarse-grained granite/pegmatite and abundant thinner aplitie/pegmatite sheets with very different textures and scales of layering appear mainly in flat outcrops on the beach, and are subordinate in the cliff. They are composed of irregular and sometimes
interpenetrative domains (layers, nests, dykes) of <1 mm-sized (aplitic), 1–2 cm-sized (granitic) and coarser (pegmatitic) matter. Contacts are both sharp and gradational; in-situ fractionation is combined here with repeated injection of similar magma (thin laminas crystallizing from both contacts inwards cross an older layering with upwards oriented crystallization). All textural varieties within these sheets contain more K-feldspar than albite, and are rich in tourmaline (schorl to foitite). Mica is in all cases muscovite/phengite in composition. Apatite is minor, and zircon, monazite, xenotime, uraninite, sphalerite, pyrite, molybdenite, and native Bi are accessory. Rocks are Li- and F-poor. Typical samples are #4965 (layered aplite from centre of a thicksheet), #5306 (aplite at the border of a sheet), and #5307 (granitopegmatite, centre of the sheet next to #5306, Fig. 3c). Quartz-cored tourmaline is also present (very coarse-grained granite, #5302).

- Thin pegmatite or aplite/pegmatite dykes (usually <20 cm, Figs. 3b, c) occur in the eastern part of the cliff. These dykes often change orientation (horizontal vs. vertical), diverge and coalesce. The pegmatite-like textures appear mainly along the contacts (Fig. 3d), but sometimes change laterally to pericontact and central positions (Fig. 2f). These dykes are tourmaline and muscovite-dominant, and Li- and F-poor. Occasionally, texturally similar, but steeply-inclined sheets occur (Fig. 2g).

- Quartz veins, variably developed throughout the study area, but conspicuous in the easternmost part around Tremearne Par (Hosking, 1952; Badham, 1980; Bromley, 1989). These are deformed (folded and/or boudinaged) within the S3 cleavage and pre-date granite emplacement; they were sourced from Variscan metamorphic fluids and are not part of the MSC.

For further description and interpretation, samples have been classified into three principal groups, based on a combination of textures, whole-rock chemistry, and mineral abundances and compositions: (i) granites, i.e. fine- to medium-grained homogeneous rocks (Tregonning Granite #5303, leucogranite sheet #4963), (ii) Li-mica-dominated complex sheets (#2015, 4964, 5305, 5304), and (iii) muscovite-tourmaline-dominated aplopegmatites (#4965, 5302, 5306, 5307). This classification is somewhat simplistic, as combinations of textural types and transitional facies are common, but is necessary to allow further description, interpretation, and discussion.
4.2 Detail zoning of the sheets

Two samples of fine-layered rock were chosen for a detailed study of mineralogical and geochemical zoning: a Li-mica dominated sample from a complex sheet (#2015, Fig. 4), and a muscovite-tourmaline-dominated aplitic domain of an aplopegmatite sheet (#4965, Fig. 5). Mineral maps across the zoning were constructed and mineral compositions in texturally differentiable layers (laminae) were computed using TIMA-technology. Approximate chemical compositions of individual layers and WR (Fig. 6, Supplementary tables 1, 2) were computed from modal compositions of layers and chemical composition of rock-forming minerals determined by electron microprobe, with Li by the LA-ICP-MS.

The texture of sample #2015, from a Li, F-enriched complex sheet, is composite and can be divided into three sections. The lower part of the sequence, termed layers #1→7, evolved systematically with a decrease in the modal abundance of K-feldspar (28→6.5 vol.%), quartz (33→25 vol.%), and tourmaline (8→4 vol.%), along with a strong increase in the modal abundance of albite (16→74 vol.%, Fig. 4). In the middle section, lines 8→11, the modal abundance of minerals is much more variable, as it is in the upper part of the sample, layers #12→22, which is also rich in albite (38–74 vol.%), zinnwaldite (mostly 5–6 vol.%) and topaz (up to 11 vol.% in lines 19 and 20), and poor in K-feldspar (mostly <10 vol.%), tourmaline (mostly <1 vol.%) and muscovite (mostly <2 vol.%).

Additionally, the grain size of the albite-dominated layers is significantly finer than that of K-feldspar dominated layers.

Distinctive chemical changes appear between layers #11 and 12: K and B decrease, while F increases (Fig. 6a). Mineralogically, this is due to muscovite and tourmaline giving way to zinnwaldite and topaz. The pairs Na–K and F–B are negatively correlated (Fig. 6b, c) due to mineralogical antagonism of albite vs. K-feldspar and lepidolite vs. tourmaline. Boron and iron show a positive trend (Fig. 6d), both hosted dominantly in tourmaline, and fluorine with manganese, as F-rich micas are relatively enriched in Mn. The relationship between F and B vs. the Ab-Kfs ratio is more complex; nevertheless, F- (resp. B-) enrichment in Ab- (resp. Kfs-) dominated layers is clear.

The tourmaline-muscovite aplopegmatite is dominated by aplite (#4965, Fig. 5) and shows only moderate variability in mineral compositions in layers #1-5, with 23–42 vol.% K-feldspar, 12–26
vol.% albite, 30–47 vol.% quartz, 4–8 vol.% muscovite and 4–10 vol.% schorl. The zoning is visually apparent from a variation in grain size and orientation of tourmaline grains. There is no general trend in composition from layers #1→5. Layer #6 differs remarkably and is rich in topaz and muscovite (22.4 and 32.4 vol.% resp.), representing a vug filled with residual melt/ fluid. Surprisingly, even though sample #4965 contains F-poor tourmaline and mica, the WR content of fluorine is, due to the high topaz vol.% in layer #6, higher than that in sample #2015 (Fig. 6c).

5. Whole-rock chemical compositions

All rock types forming the MSC are chemically similar, being rich in silica (69–76 wt.% SiO₂), leucocratic, and strongly peraluminous (ASI=1.23–1.46, (molar Al₂O₃/CaO+K₂O+Na₂O)) (Tab. 1, Fig. 7). All rock types are, in comparison with other Cornubian granites, rich in alumina (mostly 14–16 wt.% Al₂O₃), phosphorus (0.3–0.7 wt.% P₂O₅), Li, Nb, Ta and Sn, but poor in iron (mostly <1 wt.% FeO₉⁰), magnesium (mostly <0.2 wt.% MgO), calcium (with one exception ≤0.6 wt.% CaO), Zr and REE (Chappell and Hine, 2006; Simons et al., 2016).

Comparing the three main groups of rocks, the granites (comprising the Tregonning Granite and leucogranite sheet) are relatively poor in silica (69.2–71.1 wt.% SiO₂) and potassium (4.2–5.3 wt.% K₂O), but rich in sodium (3.4–4.3 wt.% Na₂O), lithium (ca. 0.40 wt.% Li₂O), fluorine (0.9–1.4 wt.% F), Rb (1400–1800 ppm), and Cs (200–250 ppm). In contrast, the aplite/pegmatite sheets are rich in silica (72.1–76.3 wt.% SiO₂) and potassium (mostly >5 wt.% K₂O), but poor in sodium (1.9–2.9 wt.% Na₂O), lithium (<0.03 wt.% Li₂O), fluorine (0.2–0.64 wt.% F), Rb (356–755 ppm), and Cs (17–33 ppm). High-field strength trace elements (HFSE) are highly variable in their concentrations: Sn (13–80 ppm), W (4–46 ppm), Nb (17–69 ppm), Ta (6–50 ppm), and Zr (9–61 ppm). The chemical composition of the “complex sheets” usually lies between the “granites” and “aplopegmatites”.

Within the WR data, there is a strong positive correlation between Li, Rb, F, and Na (i.e. elements hosted in Li-mica and albite), and among all these elements and the Mn/Fe value. All rock types, excl. biotite granite, have very low contents of all REEs, flat REE distribution pattern, and a distinct tetrad effect (Fig. 7e). The extremely low REE-content of the sample 4963 probably indicates strong interaction with a late- or post-magmatic fluid. The biotite granite has a REE pattern typical for
common granitoids with a relative enrichment of LREE over HREE. The granites and sheets from Megiliggar show an extreme enrichment in Li, Nb, Ta, Sn and W relative to other Cornubian granites, and show significantly lower Zr and REE (e.g. Chappell and Hine, 2006; Müller et al., 2006; Simons et al., 2016, 2017).

6. Minerals

Quartz typically has consistent primary abundances of trace elements and therefore gives reliable information about the composition of the magma from which it crystallized (e.g. Jacamon and Larsen, 2009). The chemical composition of quartz in samples from Megiliggar is characterized both by a relatively large scatter of trace elements in each sample, and, conversely, by similarity in composition across all samples (Fig. 8, Supplementary Table 3). Surprising is the strong positive correlation between Ti and Al, which is very different to the usual negative correlation between these elements in common granites, with Ti decreasing with increasing Al during fractionation (Müller et al., 2010; Breiter et al., 2014). The Al/Ti ratio, usually a good indicator of magma fractionation, has a narrow interval of 10–40. Quartz from all samples is very rich in Li, but poor in Ge. In comparison with a large dataset for Variscan granites and pegmatites (Breiter et al., 2013, 2014), quartz from Megiliggar shows trace element trends which are more like those in granites than pegmatites. Indications of a hydrothermal origin, low contents of Ti (<5 ppm) coupled with very high Al (>1000 ppm) (Rusk et al., 2008) were not found.

K-feldspar (Kfs) is present in two textural varieties: (i) as perthite which appears in rock facies with typical pegmatite textures, usually enriched in schorl, and (ii) as small phenocrysts (<25 mm) in the Tregonning Granite. Homogeneous Kfs, often with abundant inclusions of albite (but not admixtures), prevails in other rock types (groundmass in the Tregonning Granite, leucogranite sheet, aplites). In layered rock, the tourmaline-rich sample #4965 contains only homogeneous Kfs, while sample #2015 contains perthite in the layer #4 and homogeneous Kfs in all other layers.

Chemically, two groups of K-feldspars may be distinguished (Supplementary Table 4): (i) relatively more evolved P-enriched (>0.3 wt.% P$_2$O$_5$) grains with 0.2–0.6 wt.% Rb$_2$O were found in the granites (incl. biotite granite from Legereath Zawn) and complex sheets, and (ii) less evolved crystals, with
$P_2O_5<0.3$ wt.% and $Rb_2O<0.3$ wt.%, in the aplopegmatites. The abundance of P and Rb does not relate to whether the K-feldspar has a homogeneous or perthitic texture.

Albite is the main plagioclase phase containing less than 1.2 wt.% CaO (<0.06 apfu Ca), in line with previous studies (Stone, 1992; Simons et al., 2017). The highest content of Ca was found in albite from the biotite granite dyke (0.47–1.18 wt.% CaO <0.06 apfu Ca), while nearly all grains from the other rock types contain albite with <0.4 wt.% CaO. The Li-mica bearing complex sheets contain P-enriched albite (0.4–0.6 wt.% $P_2O_5$, 0.015–0.022 apfu P), while albite from the Tregonning Granite and from the tourmaline-bearing facies of the sheets usually contains less than 0.1 wt.% $P_2O_5$ (<0.004 apfu P).

Micas usually form small grains (<1 mm across) that are evenly distributed through the samples. Aggregates of larger muscovite flakes were only found in some thin laminae within complex sheets, e.g. layer #9 in sample 2015 (Fig. 4), and layer #6 in sample 4965 (Fig. 5). Three types of mica can be distinguished in the rocks studied: (i) zinnwaldite-trilithionite group (hereafter “lepidolite”), (ii) muscovite-phengite group (hereafter “muscovite”), and (iii) mica slightly enriched in Li within the siderophyllite–muscovite-zinnwaldite space (hereafter “Li-Fe-Al-mica”). This mica subdivision is represented on binary plots of mineral composition (Fig. 9a, b).

Lepidolite dominates in granites (e.g. outcrops of the Tregonning Granite and leucogranite sheets) and has also been found in the complex sheets. It is rich in Li (4–5 wt.% $Li_2O$), Rb (0.8–1.1 wt.% $Rb_2O$) and F (8.5–9 wt.% F) (Supplementary table 5); all these elements show a positive correlation.

Muscovite is present in complex sheets and dominates in aplopegmatites. It is enriched in Fe (typically containing 2 wt.% FeO, occasionally up to 4 wt.%), but poor in Li, Rb and F (<0.1 wt.% $Li_2O$, <0.2 wt.% $Rb_2O$, <0.1 wt.% F). In the fine-layered parts of complex sheets, muscovite and lepidolite micas alternate (Fig. 9c).

“Li-Fe-Al-mica” was found dominantly in the biotite granite dyke and occasionally also in the complex sheets. Macroscopically, this mica is black, resembling common biotite, which strongly differs from the light beige to pink colour of zinnwaldite–trilithionite. In comparison to the Li-micas of the zinnwaldite-trilithionite series, this mica is lower in Li (0.6–1.5 wt.% $Li_2O$), Rb (0.3–0.6 wt.%...
Rb$_2$O) and F (3–3.5 wt.% F) and strongly variable in Al and Fe (26–33 wt.% Al$_2$O$_3$, 3–18 wt.% FeO), with an approximate mean formula of K$_2$Li$_{1.6}$Fe$_1$Al$_{2.5}$((Si$_{6}$Al$_{2}$O$_{20}$)F$_{1.5}$OH)$_{2.5}$. Some crystals are tourmaline (Lon). In the following proportions: c
Anchored
while it does not exceed 100 ppm in muscovite and Li-Fe-Al-mica. Similarly, Ta (Fig. 9d) and W have a positive correlation with Li, reaching 25–75 ppm Ta and 300–600 ppm W in lepidolite from the Tregonning Granite and leucogranite sheet. Conversely, the highest content of Sn was found in muscovite from the complex sheets (180–340 ppm) and the highest Nb in the Li-Fe-Al-mica from the biotite granite dyke (120–350 ppm, Fig. 9e). Micas are the major host of Cs and W in all Megiliggar rocks, while their importance for the Sn-, Nb-, and Ta-budget of the rock is limited, consistent with the findings for topaz granites across the region (Simons et al., 2017).

**Tourmaline** was found, with variable modal abundance, in all examined varieties of granite and sheet rocks. It forms elongate grains less than 1 mm long in granites and aplites, but also up to 5–10 cm long and 1–2 mm thin needles in pegmatites. Higher abundances of tourmaline were found in rock types and laminae relatively rich in K-feldspar and muscovite, while samples relatively enriched in albite and lepidolite are usually tourmaline-poor. The tourmaline is mainly schorl and more rarely foitite (Fig. 10a). The most Li-rich tourmaline, which was found in the leucogranite sheet is dark green in colour, contains up to 0.7 apfu F (Supplementary table 7, Fig. 10b). Li is likely to occupy the Y-site in the following proportions: $\square_{0.1}$Li$_{0.7}$(Fe+Mg+Mn)$_{1.2}$Al$_4$ apfu (Fig. 10c). This tourmaline is alkaline and poor in vacancies; it should be termed Li-rich fluoroschorl. Tourmaline in other rocks is mostly black Li-F-poor schorl up to F-poor foitite. Tourmaline in the Tregonning Granite is usually zoned with relatively F-Na-Al-Mn-rich and Fe-Mg-depleted rims. These data are consistent with previous studies (London and Manning, 1995; Duchoslav et al., 2017).

In the finely banded rock domains (both #2015 and #4965), the contents of Fe, Mn, and Na in tourmaline increase, while Mg, Ca, and vacancies decrease from the oldest to the youngest layers. Some crystals are slightly zoned, often with schorl cores and slightly Li-F-enriched rims. Schorl crystals with quartz cores were found in some aplite/pegmatite sheets in the central part of the MSC. Similar textures have been described from Roche Rock, St. Austell (Müller et al., 2005). This tourmaline is slightly chemically zoned (with relatively Fe-rich and Mg-poor rims), but is generally
low in Li and F. The Li and F contents of tourmaline generally show a positive correlation with those in mica.

Among the trace elements (Supplementary table 8) in the tourmaline, Sn correlates strongly with Li reaching 60–130 ppm in fluoroschorl from the leucogranite sheet (Fig. 10d), and Ta attains 5–8 ppm in the leucogranite sheets. In contrast, the concentrations of W and Nb are generally very low: <0.5 ppm and <5 ppm, respectively, consistent with recent studies by Duchoslav et al. (2017) and Simons et al. (2017). Niobium and Ta in tourmaline, as in micas, are decoupled: Ta is preferentially enriched in fluoroschorl from the leucogranite sheets and in schorl from the youngest layer #6 in the fine-layered aplite #4965, while Nb prevails in tourmaline from all other locations. Levels of Zn in tourmaline vary between 400 and 600 ppm, but with little systematic difference between rock types. Gallium concentrations are highly variable (70–350 ppm), with the highest concentrations (>200 ppm) found in tourmaline from the leucogranite sheets and in the latest layer #6 of the sample #4965. The concentration of Be is usually <10 ppm, except in tourmaline from leucogranite sheets where it reaches 30–50 ppm. Contents of Cs, Ge and In are low in tourmaline from all rock types: <3 ppm, <5 ppm, <1 ppm, respectively.

Fluoroapatite appears to have crystallised relatively late in all rock types as it is interstitial and anhedral. Apatite in the granites is enriched in Mn, reaching 0.2–0.3 apfu, and in the albite-rich laminae of the layered rocks, with up to 0.52 apfu Mn (7.18 wt.% MnO). Amblygonite, which shows limited alteration to montebrasite along cleavage planes, was found occasionally in the leucogranite sheets as aggregates of anhedral grains several mm across. Monazite and xenotime form scarce small grains (usually ~20 μm, occasionally up to 100 μm) in all rock types. They are the major carriers of REE.

Rutile forms small anhedral grains which show irregularly or patchy zonation (in SEM-BSE mode) and contain inclusions of columbite, ixiolite or tantalite (Fig. 11a,b,c). Rarely, intergrowths of rutile and cassiterite were found (Fig. 11d). Rutile enriched in W and slightly in Nb (up to 6.1 wt.% WO$_3$ and 1.6 wt.% Nb$_2$O$_5$) were often found as inclusions in micas in the biotite granite dyke. It is the only Nb, W-bearing mineral in this rock. Rutile, which is strongly enriched in Nb and Ta (up to 17 wt.% Nb$_2$O$_5$, 36 wt.% Ta$_2$O$_5$), appears together with Fe-columbite in the Tregonning Granite, complex sheets.
and aplopegmatites (Fig. 12a). It locally contains up to 0.7 wt.% Sc₂O₃ and 1 wt.% WO₃.

(C)olumbite-group minerals form 100–200 μm long needle-like crystals (Fig. 11e, f) or smaller (<30 μm) anhedral inclusions in rutile (Fig. 11a, c). The Ta/(Nb+Ta) value is typically <0.5, i.e. the mineral is classified as columbite. The Mn/(Fe+Mn) value strongly varies not only among samples, but also within a single grain; generally columbite-Mn is more common in the granites and complex sheets, while columbite-Fe prevails in aplopegmatite sheets (Fig. 12b). Fe-columbite contains 0.5–1 wt.% Sc₂O₃ and 2–10 wt.% WO₃. Columbite-like grains with >10 wt.% WO₃ (up to 30.7 wt.% WO₃) are classified as “ixiolite”, however it is difficult to confirm this without more crystal-chemical information. The W-rich grains (domains in complex grains) are relatively Nb- and Fe-rich (Figs. 12b, c). Tantalite-Mn was found only as one small crystal included in rutile in the Tregonning Granite (Fig. 11b).

Cassiterite occurs as scarce subhedral grains in complex sheets (#5304), sometimes associated with rutile (Fig. 11d). It is poor in minor elements (>97.8 wt.% SnO₂) containing only traces of Nb and Fe. Wolframite forms small (~20 μm) anhedral grains in some samples from complex sheets (#2015, 5304). It is poor in minor elements (usually <1 wt.% Nb₂O₅+Ta₂O₅+Sc₂O₃), only one grain contains 4.3 wt.% Nb₂O₅, 2.6 wt.% Ta₂O₅ and 1 wt.% SnO₂.

Monazite and xenotime (Fig. 11g), major hosts of REE, are scarce, but were found in all rock types.

Uraninite, which forms both euhedral and anhedral grains up to 50 μm across, is quite common and is usually rimmed by pyrite (Fig. 13h, i). Within the finely banded aplite (#4965) it was found as inclusions in columbite and zircon (Fig. 11j).

Zircon is a rare accessory mineral in all rock types, as indicated from low WR Zr values, but rare euhedral grains, 10-20 μm across, were found in all samples (Fig. 11f). Numerous inclusions of uraninite were found in some zircon grains from the fine-layered aplite (Fig.11j, k). Zircon is relatively poor in trace elements (Y₂O₃<0.6 wt.%, Yb₂O₃<0.3 wt.%, ThO₂<0.3 wt.%, Supplementary table 10), with uranium only sometimes exceeding 2 wt.% UO₂ (Fig. 13). Hf contents are highly variable, ranging from 1.5–8.9 wt.% HfO₂ (0.013–0.082 apfu Hf); the highest values were found within the rims of some crystals from the leucogranite sheets (Fig. 11k). Zircon from the
aplopegmatite sheets has generally lower Zr/Hf values and lower contents of trace elements than zircon from the complex sheets (Fig. 13). Zircon from the biotite granite dyke is chemically uniform having middle Zr/Hf values (~50) and low contents of all trace elements. All zircon types are free of the “ore elements” Nb, Ta, W, Bi, and Cu.

Magmatic fluorite was found occasionally in some finely banded rock samples. Sulfides (arsenopyrite (Fig. 11l) > sphalerite, galena, bismuthinite, molybdenite) and native Bi were found in some aplopegmatite sheets.

7. Discussion

The origin of layered albite-pegmatite sheets, which can include finely-banded aplites (line rock, Schaller, 1925), is an intriguing petrogenetic question which has broad implications for the genesis of pegmatites. Sheets containing fine-grained “aplitic” (usually in the lower half) and coarse-grained “pegmatitic” textures (usually in the upper halve) have been explained previously as having both metasomatic (Schaller, 1925; Stone, 1969), and magmatic (Jahns and Tuttle, 1963; Webber et al., 1997; London, 2014) origins. The MSC exposures at Megiliggar Rocks provide an excellent prominent locality for testing these hypotheses. Our discussions focus on the relationship between the sheets and the nearby Tregonning Granite, mainly whether the sheets were formed from relatively evolved melt segregations within the roof of the Tregonning Granite. Differentiation of primarily homogeneous granitic melt to Na-Li-F vs. K-B-enriched portions was the main process determining the diversity of sheet rocks. This Na-Li-F vs. K-B differentiation was manifested at two scales: (i) between the Tregonning Granite and MSC, and (ii) within the banding of individual sheets and the cause of the aplite-pegmatite banding in the sheets.

7.1 MSC rocks as fractionated equivalents of the Tregonning Granite; large-scale Na-Li-F vs. K-B differentiation

All previous authors agree unequivocally that there is a link between the Tregonning Granite and the MSC. Hosking (1952) interpreted the MSC as having a purely magmatic origin, with aplite and pegmatite sheets (layers or laminae in the sheets) forming by repeated injections of the same primary
magma which varied episodically in its water and volatile contents. Later, Stone (1969, 1975, 1992) proposed a combination of magmatic and metasomatic processes, with initial formation of the aplites, by crystallisation of residual melts from the Tregonning Granite, followed by subsolidus metasomatic recrystallization of the aplites to pegmatites and replacement of albite by K-feldspar. This view was based on the observation that the aplitic parts of the sheets were more mineralogically and chemically similar to the Tregonning Granite than the pegmatitic portions. The development of banded aplitic-pegmatite sheets has also been interpreted to be a consequence of repeated melt decompression during fracture propagation accompanying xenolith separation (Bromley and Holl, 1986; Bromley, 1989). During decompression, volatile exsolution drove the residual melt towards solidus, resulting in rapid nucleation and crystallization of aplites; the exsolved hydrous fluid trapped above the aplites contributed to the development of complementary pegmatite layer. From our textural and chemical data we suggest a dominantly magmatic origin for all MSC rock types; however, interpretation of the WR chemical data is not straightforward. Nevertheless, the Na vs. K differentiation, mineralogically expressed in albite vs. K-feldspar enriched domains is well documented. In an eastwards traverse from the margin of the Tregonning Granite, through the leucogranite sheets and complex sheets to the alopepegmatite sheets, there are conspicuous changes in some major and trace element concentrations (Table 1): Na₂O decreases from 3.3–4.3 to 1.9–2.9 wt.%, F decreases from 0.9–1.4 to 0.2–0.6 wt.%, Li₂O decreases from 0.23–0.41 to 0.01–0.03 wt.%, Rb decreases from 530–1830 ppm to 360–760 ppm, and Cs from 88–253 ppm to 17–33 ppm. In contrast, K₂O in the same direction increases from 3.3–4.5 to 3.5–6.1 wt.%. The concentration of B, as evident from the abundance of tourmaline, also increases eastwards, but chemical data for this element are not available. The contents of Si, Al, Fe and P remain fairly constant, and the HFSE are variable but show no obvious trends. According to the K/Rb ratio, the most common index for magmatic fractionation, the leucogranite sheets (K/Rb=19) are more evolved than the Tregonning Granite (K/Rb=31), which is consistent with their interpretation as a product of crystallization of residual melt sourced from the Tregonning Granite roof zone. The lepidolite-bearing complex sheets show K/Rb values only slightly higher than the leucogranites (K/Rb=30–44), and have slightly lower contents of Li, Rb, and F, indicating that
they may also represent fractionated equivalents of the Tregonning Granite melt, notwithstanding fracture-controlled partial escape of Li-F-bearing fluids into the surrounding host rocks. Conversely, the chemical composition of tourmaline-muscovite dominated aplopegmatite sheets is less evolved than the Tregonning Granite having relatively low Rb-contents (high K/Rb=58–94) and extremely low F, Li, and Cs abundances.

The complex sheets and aplopegmatite sheets have highly variable mobile alkalis and fluorine compositions. Lower contents of the rare alkalis in the distal parts of the sheet system may be explained by the variable fluid escape from the crystallizing melt. Enrichment of the Mylor Slate Formation in the exocontact, previously noted by Stone and Awad (1988), may have been controlled by fractures now represented by steeply dipping aplite/pegmatite sheets (Fig. 2g). However, this does not explain the relative B enrichment in the distal aplopegmatite sheets. In the proximal part of the MSC (Fig. 1c), both Li-F-bearing tourmaline and mica crystallized late in the leucogranites, due to low levels of Fe in the melt. In the middle part of the MSC, in the complex sheets, crystallization of tourmaline precedes the crystallization of Li-F-micas. Tourmaline was the first Fe-bearing mineral in which the melt became saturated; this demonstrates a relatively high abundance of B and Fe in the melt at the beginning of the crystallization. Mica crystallized later, when F was sufficiently concentrated in the residual melt. In the distal MSC, within the aplopegmatite sheets, B predominates over F, even though its fluid/melt partition coefficient is distinctly higher than that of fluorine. Thus, the eastwards proximal to distal decrease in F was not a result of its partitioning into a fluid and escape to the slates, but a consequence of its consumption by the relatively late crystallization of F-minerals (topaz?) in the proximal and central parts of the MSC. The last portion of melt, filling the distal parts of sheet system, was F-free, but still had sufficient B for tourmaline saturation, with Fe scavenged from the slates host rocks.

Variations in Nb- and Ta-contents and Nb/Ta ratios are often used as indicators of the degree of granite and pegmatite melt evolution and/or zoning (Ballouard et al., 2016). Tantalite has a higher solubility in peraluminous granite melts at low temperature relative to columbite (e.g. Linnen and Keppler, 1997), which commonly results in the melt evolving from Fe–Nb- to Mn–Ta-enriched end-members of columbite group (Černý et al., 1985; London, 2008). Moreover, the crystallisation of
micas also aids in decoupling of Nb and Ta within a peraluminous melt, Nb partitions into biotite over Ta; the latter is strongly partitioned into residual F-bearing melts (e.g. Stepanov and Hermann, 2013). Nevertheless, changes in the Nb/Ta ratio are also influenced by a succession of coprecipitating minerals (oxides, micas, tourmaline) and the combined effects of Li, Na, B, F, and P in the melt or fluid phase (e.g., Johan and Johan, 1994; Belkasmi et al., 2000; Novák et al., 2003; Van Lichtervelde et al., 2006; Wise et al., 2012). In the MSC, fluorine presumably remains in pockets of residual melt until the crystallisation of topaz (e.g. Figs. 4, 5) with Ta therefore concentrated within the latest crystallized layers, while Nb is more evenly distributed throughout the rocks. However, in examining larger volume WR samples (Figs. 14a, b), the Nb/Ta ratio is scattered between 1–7 independent of rock type and Li- and F-content. In micas and tourmaline (Figs. 14c-f) the Nb and Ta-contents and Nb/Ta are highly variable within individual samples, but the general trend is to relative Ta-enrichment in Li-enriched grains and/or the outer zones of crystals. We conclude that WR Nb/Ta ratios in Megiliggar rocks are controlled by the order of crystallization and relative amounts of oxides vs. silicate carriers and, in this case, can not serve as a marker of melt fractionation. The mineralogy of the different MSC rock types reflects their WR compositions, with the leucogranite sheets and complex sheets containing lepidolite, relatively high P-contents in both feldspars and Rb in K-feldspar, and higher Li and Fe/Mg in tourmaline. These signatures are characteristic of “evolved” or “highly fractionated” rocks, comparable with peraluminous tin granites in the Erzgebirge (Förster et al., 1999; Breiter et al., 2005) and France (Raimbault et al., 1995), and LCT pegmatites (London, 2008). In contrast, the aplopegmatite sheets, which contain Li-F-poor muscovite, and often schorl, are chemically and mineralogically more primitive. However, all rock-types show nearly identical and low (12–21) WR Zr/Hf values, which are generally indicative of high degrees of fractionation (Hanchar and Hoskin, 2003; Breiter and Škoda, 2017). The zircon Zr/Hf value (Fig.13) is consistent with WR Zr/Hf data and zircon from the aplite/pegmatite sheets is at least as strongly differentiated as zircon from the complex sheets and is more fractionated than zircon from the Tregonning Granite. The field relations and geochemical similarity indicate a direct link between the Tregonning Granite and the MSC. The textural and mineral diversity in the sheets, from proximal to distal eastwards across the study area, was caused by Na-Li-F vs. K-B fractionation, where the K-B-rich portion of
melt (fluid) could migrate more effectively to the distal part of the crystallizing magmatic system.

However, the Zr/Hf value, unaffected by this fractionation, is similar across the whole MDC, demonstrating a uniform magmatic source.

The composition of the biotite granite dyke is distinctive and does not follow the aforementioned trends; this lithology is not related to the fractionation of the MSC. Instead, it is likely to be an expression of earlier magmatism petrogenetically linked to the Godolphin Granite (two mica) or biotite granite porphyry (‘elvan’) dykes (see Simons et al., 2016).

The suggestion that the easternmost distal expression of the MSC is represented by quartz veins linked directly to aplopegmatite sheets (Hosking, 1952; Badham, 1980; Bromley, 1989) is refuted; we think that this assertion was based on miscorrelation of the easternmost MSC sheets with pre-granite subhorizontal quartz veins contained within the S3 cleavage. The similar orientation of the MSC sheets and these quartz veins reflects the influence of the mechanical anisotropy imparted by the S3 cleavage on the propagation of fractures controlling emplacement of the MSC.

7.2 Local Na-Li-F vs. K-B fractionation within layered sheets

The complex sheets and aplopegmatite sheets within the MSC differ from the majority of common pegmatite sheets having a more complex structure, often appearing to have formed as a result of multiple melt injections. The banding almost certainly originated via in situ fractionation, as crystals grew upwards, in combination with the emplacement of younger narrow melt injections which crystallized from both contacts inards (compare Hosking, 1952). This feature was encountered in both complex sheets and aplopegmatites. Crystallization within most single sheets (or sheet domains), i.e. formed from a single injection of melt, is comparable with other examples of pegmatite sheets (Weber et al., 1997, London et al., 2012).

Samples #4965 and #2015 represent parts of in situ crystallized layered sequences, at an appropriate scale for a detailed investigation. Sample #4965 (Fig. 5, Supplementary table 2) represents a fine-grained (aplitic) part of an aplopegmatite sheet, albite-poor, dominated by quartz, K-feldspar, muscovite and tourmaline. The composition of individual laminae can be traced effectively from the Qtz–Kfs ratio, but without any general evolutionary trend (Fig. 15a). The abundance of tourmaline
varies between 4.1–9.8 vol.% (ca. 0.4–1.0 wt.% B$_2$O$_3$). The younger laminae #4→6 contain 1–2 vol.% apatite (up to 1 wt.% P$_2$O$_5$). The melt, from which layers #1→5 crystallized, was B- and P-rich, but relatively F-poor (<0.15 wt.%), and only the youngest lamina #6 reaches nearly 5 wt.% F due to crystallization of common topaz from the residual liquid or from a new injection of F-rich melt/fluid. In any case, the crystallised rock composition lies away from the granite minima (Johannes and Holtz, 1996, Fig. 15b).

Sample #2015 (Fig. 4, Supplementary table 1) represents a finely banded portion of a Li-F-bearing complex sheet. Its mineral composition is more complex than in the previous case, with bands dominated by K-feldspar, tourmaline and muscovite alternating with those strongly enriched in albite and zinnwaldite. The oldest portion of the layered sequence, lines #1→7, evolved systematically from a Qtz-Kfs-rich composition towards the Ab-apex of the Qtz-Ab-Kfs diagram (16→72 wt.% Ab, Figs. 4, 15a). The bands have variable compositions, but the general trend towards Ab-enrichment is obvious. The computed volatile content varies between 0→1.6 wt.% B$_2$O$_3$, 0.2→0.8 wt.% P$_2$O$_5$, and 0.1→2.4 wt.% F. Although B generally decreases along this trend, P levels remain unchanged and F, Li and Rb increase (Fig. 9c). Here, it should be noted that the sample does not really represent the mean of the whole banded sheet, but only a partial section; the real composition of the injected melt may be different.

### 7.3 Comparison with similar aplite-pegmatite sheets

The first model for the generation of layered aplopegmatitic sheets was developed by Jahns and Tuttle (1963), which was based on a study of miarolitic pegmatites in San Diego County, California. The authors described a typical arrangement of “sodic aplite” in lower, and “potassic pegmatite” in the upper parts of horizontal sheets with inward crystallization of both facies which finished in the central pocket zone. Later, London et al. (2012) and London (2014) confirmed the common position of (often layered) aplitic domains in the lower part, and pegmatitic domains in the upper part of many horizontal pegmatite sheets, but questioned their dominantly sodic vs. potassic character. Another, rhythmic style of layering, expressed by alternations of 0.5–2 m thick K-feldspar and tourmaline-
dominated pegmatite and albite-dominated aplite layers, has been reported from the B-rich Calamity Peak layered pluton (Duke and Papike, 1992).

The evolution of the banded sequences in the MSC is comparable with the George Ashley Block (GAB) pegmatite, Pala district, California (Weber et al., 1997). The mean composition of the granite sheet and complex sheets from Megiliggar is only slightly Ab-enriched in comparison with the mean of the GAB pegmatite, which may be explained by a higher content of F in the Megiliggar sheets (Fig. 15b). The composition of the oldest band in the sample #2015 and the WR #4965 is nearly identical to the composition of the K-rich portions of the GAB pegmatite, located in its central-upper parts, while the mean of the late fine-layered portion of sample #2015 is equal to the composition of the finely banded aplitic portion of the GAB pegmatite (Webber et al., 1997; Fig. 15b). Therefore, the banded portions of the MSC we have studied experienced the same differentiation as the whole George Ashley Block pegmatite dyke. In both localities, both contrasting rock facies (Na+F+Li vs. K+B-enriched) are adjacent in a single sheet, together having logically expected compositions near the “granitic minima” of a slightly B-, resp. F-enriched melt (Manning, 1981; Pichavant, 1987; Fig. 15b).

Weber et al. (1999) and London et al. (2012) concluded that crystallization of finely banded aplite (“line rock”) to give a water- and fluxes-poor mineral assemblage near the lower contact of the sheets was likely due to undercooling, whereas accumulation of volatiles in the upper parts of the sheet decreased the degree of undercooling and promoted crystallization from a flux-enriched boundary-layer, i.e. crystallization of rare minerals and grain size coarsening. At Megiliggar, this process is expressed in complex sheets which show a transition from muscovite-bearing aplite through to Li-F-mica-bearing aplite to coarse-grained sheet domains bearing Li-F-mica and tourmaline. In the aplogematites, the increase in F and Li during crystallization of the aplitic unit was minimal, but their influence was superseded by increasing abundances of water and boron. Repeated sudden decompression followed by exsolution of fluid driving such grain size changes might be driven by repeated fracture propagation during the lateral growth and inflation of the MSC (Weber et al., 1997; London, 2008) rather than xenolith separation (Bromley and Holl, 1986; Bromley, 1989). In such conditions, the growth rate of K-feldspar is higher than these of quartz and albite (Swanson, 1977):
this is well demonstrated in layers 1→7 of the sample #2015: initial dominance of K-feldspar stepwise changed in dominance of albite. Similar, although not so significant, is the evolution in lines 11→13, 15→17 and 20→22.

8. Conclusions

Chemical and mineralogical data together with a gradual change in prevailing textures suggests a strong genetic link between the Tregonning Granite and MSC. The lithologies within the MSC formed from residual melt escaping from the Tregonning Granite. This melt was strongly peraluminous and, in comparison with other Cornish granites, rich in F, Li, Rb, Cs, Sn, W, Nb, Ta, and U, and poor in Fe, Mg, Ca, Sr, Th, Zr, and REE.

During crystallization, the melt underwent differentiation into Na-Li-F-enriched vs. K-B-enriched domains, which may be traced at two scales: (i) in finely banded sequences where the K-B-enriched layers evolved into more Na-Li-F-enriched ones, and (ii) generally, the Na-Li-F-enriched proximal leucogranite sheets pass gradually into K-B-dominated distal aplopegmatites. The mean-composition of the aplogranite sheets is similar to the eutectic composition of leucocratic granitic melts saturated in water and slightly enriched in F and B. Differentiation to fine-grained (i.e. aplitic) and coarse-grained (i.e. pegmatitic) layers was most probably forced by repeated decompression and undercooling due to fracture propagation during the lateral growth and inflation of the MSC system.

With distance from the contact with the parental Tregonning Granite, the melt became depleted in the fluxing and volatile elements F, Li, Rb, and Cs, probably due to escape of fluid to surrounding slates or in to fractures, but the Zr/Hf value remains in all rock types nearly the same indicating their direct relation.

Knowledge gained at Megiliggar Rocks may help to better understand the chemical and mineralogical evolution of large aplite-pegmatite systems and their relation of parental granite plutons. Mineral and textural zoning, usually evolving from contacts to the core of pegmatite body, is at Megiliggar combined with lateral transition from dominantly granitic to aplopegmatitic textures, chemically
expressed in Na-F-Li vs. K-B differentiation. Just combination of transversal and longitudinal zoning of Megiliggar sheets may provoke similar studies in other well-exposed aplitic-pegmatite systems.

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Geomorphologists working in South West England.


861
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863 Tables only as electronic appendix:
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877
**Explanation to figures**

**Fig. 1**  A- Geological sketch map of granite plutons in Cornwall (acc. to Simons et al., 2016); B- Schematic section through Megiliggarg Rocks showing the location of samples (not to scale). The total length of the section is ca. 600 m.

**Fig. 2** Field photographs: a, cliff at Megiliggarg Rocks, western part of the major leucogranite sheets (up to 2.5 m thick) laterally (to the right) passing into “complex sheets”; b-e, the textural evolution of the sheets with increasing distance from the Tregonning Granite (from West to East):

Close to the granite the sheets are more or less homogeneous (leucocratic sheet granite). About 50 m from the contact the first layered structures can be traced caused by a local enrichment in mica (b). Further on (c. 75 m) grain-size differences between individual layers start to develop, in addition to the local mica enrichments, and about 100 m away the first thin veinlets with pegmatitic textures appear within the sheet (c). Further east the borders between the layers become more distinct; the differences in the grain sizes of the aplitic, granitic and pegmatitic layers increases together with the thickness in particular of the pegmatitic layers (d to e).” f, bifurcation of a thin (~30 cm) aplopegmatite sheet, showing comb K-feldspar crystals along both the contact in the upper sheet vs. central position in the lower sheet; g, steeply inclined, thin (~10–15 cm) aplopegmatite sheet in the eastern part of the cliff.

**Fig. 3** Rock textures: a, Tregonning granite (#5303); b, typical layering in the “complex sheets” composed of granitic (G), pegmatitic (P) and aplitic (A) layers (#5305); c, aplopegmatite sheet with aplitic layer near the contact and coarse-grained granite to pegmatite in the centre (# 5306 resp. #5307); d, aplopegmatite sheet with pegmatitic (stockscheider-like) rim and aplitic centre. Contact plane between sheets and Mylor Slates is highlighted by arrows.

**Fig. 4** Detail investigation of finely-banded portion of a complex sheet (sample 2015): left - photo of an 18 cm wide cut sample face; Central - mineral map determined by TIMA (in the middle, Kfs-red,
Ab-light blue, Qtz-dark blue, Msc-pink, Zin-brown, Tur-green); Right - mineral composition of individual bands (vol.%). Crystallization of the rock proceeded upwards.

**Fig. 5** Detail investigation of a tourmaline aplite (sample 4965): left - photo of a 12.5 cm wide sample cut face; middle - mineral map determined by TIMA (Kfs-red, Ab-light blue, Qtz-dark blue, Msc-pink, Tur-dark green, Toz-black, Ap-yellow-green); Right - mineral composition of individual bands (vol.%). The crystallization proceeded upwards.

**Fig. 6** Approximate chemical composition of individual layers in finely banded rocks computed from modal compositions and chemical analyses of minerals: a, distribution of selected elements across the layering (#2015); b, K₂O vs. Na₂O; c, B₂O₃ vs. F; d, FeO vs. B. Mean values of the whole samples are highlighted by red marks in diagrams b–d.

**Fig. 7** Whole-rock compositions of studied rocks. In diagram f, only typical analyses are shown. Remember the tetrad effect in fig. e! Contents of some of the REE in the sheet leucogranite are below the detection limits of ICP-MS.

**Fig. 8** Trace elements in quartz: a, Al vs. Ti; b, Al/Ti vs. Li; c, Al/Ti vs. Ge. Data from Variscan granites (I, S, A-types, Breiter et al. 2013) and pegmatites (muscovite to lepidolite types, Breiter et al. 2014) from the Bohemian Massif are shown for comparison.

**Fig. 9** Chemical composition of micas: a, Si vs. Fe; b, Si vs. F; c, composition of micas (means of 4–5 EMPA analyses) across the finely banded portion of a complex sheet (sample#2015); d, Li vs. Ta; e, Li vs. Nb. In diagrams a–b, three groups of micas are highlighted: I, zinnwaldite–trilithionite series; II, muscovite–phengite series; III, altered (?) Li-Fe-Al mica.

**Fig. 10** Chemical composition of tourmaline: a, Fe/(Mg+Fe) vs. □/(□+Na+K) (apfu); b, F vs. □/(□+Na+K) (apfu); c, occupation of the Y-site (apfu); d, Li vs. Sn (ppm).
Fig. 11 BSE-images of minerals: a, Nb-Ta-rich rutile (grey) with inclusions of W-rich Fe-columbite (bright), #2015, in banded rock; b, patchy zoned Nb-Ta-enriched rutile (grey) with small crystals of tantalite (bright), #5303, in Tregonning granite; c, rutile with inclusions of columbite and ixiolite, #4964, in composite granite/pegmatite sheet; d, intergrowth of cassiterite (bright) and rutile (dark grey), #5304, in granitic part of the composite granite/pegmatite sheet; e, needle-like crystals of Mn-columbite with Ta-enriched rims in Li-mica, #4963, in leucocratic sheet granite; f, crystals of Fe-columbite (light grey with bright zones) in association with two colander-like zircon crystals, #5302, in coarse grained tourmaline-bearing sheet granite; g, monazite (Mnz) associated with xenotime (Xen), zircon (Zrn), Mn-rich apatite (Ap), pyrite (Py) and tourmaline (T) in quartz, #2015, in banded rock; h, crystal of uraninite (bright) rimmed by pyrite in quartz, #2015, in banded rock; i, grain of uraninite (bright) with thin rim of pyrite associated with a Nb, Y-phase, #5307, in pegmatitic core of composite aplite/pegmatite sheet; j, altered zircon with numerous inclusions of uraninite, #4965, in tourmaline-rich banded rock; k, zoned zircon with Hf-enriched rim, in leucocratic sheet granite, #4963; l, zoned crystal of arsenopyrite, #2015, in banded rock. White scale bars in all cases 50μm.

Fig. 12 Nb-Ta-Sn-W-oxide cross plots: a, Nb vs. Ta in rutile; b, columbite classification diagram; c, W vs. Mn/(Fe+Mn) in columbite and “ixiolite”. Coloured symbols = columbite, empty symbols = ixiolite.

Fig. 13 Relation between the Zr/Hf ratios and U concentrations in zircon (using data also from Breiter et al., 2016).

Fig. 14 Variation in the Nb/Ta ratio in Megiliggar Rocks: a, Nb/Ta vs. F in whole rocks; b, Nb/Ta vs. Li₂O in whole rocks; c, Nb vs. Ta in micas; d, Li vs. Nb/Ta in micas; e, Nb vs. Ta in tourmaline; f, Li vs. Nb/Ta in tourmaline.
Fig. 15a Composition of whole rocks and individual bands in banded rocks in the Qtz-Ab-Kfs triangle. Note systematic evolution of the lower (older) part of the sample #2015: systematic shift to the Ab-apex from line 1 to 7 (red arrow). Later zones, poorer in Kfs, scatter along the Qtz-Ab join. Sample #4965 represents the aplopegmatite melt with rather chaotic zoning; b Composition of proposed starting melt (Tregonning granite) and the Megiliggar sheet rocks computed according to whole-rock chemical data and EMPA of rock-forming minerals (sample 2015 acc. to modal analyse by TIMA). Three typical compositions of the George Ashley pegmatite (layered aplite rich in Ab, whole dyke, granular pegmatite rich in Kfs) acc. to Webber et al. (1997) and water-saturated leucogranitic solidus with 1 wt.% added F, resp. B (Manning, 1981 resp. Pichavant, 1987) are also shown for comparison.
Figure 1

Click here to download high resolution image
Figure 14
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Table 1 Chemical composition of studied rocks

<table>
<thead>
<tr>
<th>Granites</th>
<th>Composite sheets (Li-mica bearing)</th>
<th>Aplompogmatites (tourmaline dominated)</th>
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Rem.: major elements in wt.%, trace elements in ppm, elemental ratios by weight.