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RARE-ELEMENT PEGMATITES: A MINERAL SYSTEMS ANALYSIS

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Cover image: Packing up the campsite in a claypan about 5 km south of Minilya in the southern Pilbara (photo by Olga Blay)

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Abstract

Rare-element pegmatites are an important host to Li, Cs and Ta mineralization in Western Australia, exemplified by the occurrence of the world-class Greenbushes, Pilgangoora and Wodgina deposits in the Yilgarn and Pilbara Cratons. A mineral systems analysis has been performed to define critical and constituent processes controlling their genesis, as well as mappable proxies for these processes. Critical processes include: i) formation of fertile magmas as a source for fluids and metals; ii) structures and fabrics in country rocks as pathways for fluids; iii) cooling and chemical diffusion in evolved granitic melts that result in the formation of rare-element mineralization in compositionally and texturally distinct pegmatites; iv) preservation of deposits through erosion and uplift of crustal profiles hosting rare-element pegmatites. The constructed Mineral System Tree for rare-element pegmatites demonstrates the link between geological processes and their recommended geographical information systems map layers for exploration.

KEYWORDS: caesium, lithium, pegmatite, rare element, tantalum

Introduction

The **Mineral Systems Atlas** (MSA) is an interactive geological information system (GIS)-based platform that collates and delivers map-based geoscience data layers filtered to be specifically relevant to understanding and exploring for mineral deposits in Western Australia (www.dmirs.wa.gov.au/mineralsystemsatlas). Atlas content is systematically defined by applying the mineral systems concept advocated by Wyborn et al. (1994) and McCuaig et al. (2010). The premise of this concept is that mineral deposits will only form and remain preserved where there has been a spatial and temporal coincidence of critical earth processes (geodynamic setting, lithosphere architecture, fluid, ligand and ore component reservoir(s), fluid flow drivers and pathways, depositional mechanisms, post-depositional processes), and that the occurrence of these critical processes might be recognized from mappable geological features expected to result from them. It is these geological features ('targeting elements' or 'geological proxies') that can be extracted as digital map layers from geoscience datasets, and may be used in GIS-based prospectivity studies.

Mineral systems, as defined by Fraser et al. (2007), are analysed to define the mappable geological proxies for critical mineralizing processes. Such analyses draw on in-house knowledge, existing literature and collaborations with subject-matter experts. Structured queries are then used to extract relevant data from one or more statewide GSWA geoscience databases, for those proxies that can be practicably produced. These queries operate directly on, and are dynamically linked to, primary GSWA geoscience data sources. No new data are acquired or created, although some information may be reformatted to meet the internal requirements of particular map layers. Furthermore, the queries are scheduled to automatically update the derived proxy map layers whenever new data are added to the primary databases. Users may therefore be confident that the data layers portrayed in the MSA are always current.

The rare-element pegmatite mineral system is an important addition to the MSA since several large pegmatite-hosted Li–Cs–Ta deposits are found in Western Australia, including the Greenbushes (3.53 Mt Li_2O), Pilgangoora (2.33 Mt Li_2O), Wodgina (2.32 Mt Li_2O), Mount Holland Earl Grey (1.84 Mt Li_2O), Mount Marion (1.07 Mt Li_2O), Bald Hill (0.22 Mt Li_2O), Mount Cattlin (0.18 Mt Li_2O), and Lynas Find (0.09 Mt Li_2O) (data extracted from the GSWA mines and mineral deposit database [MINEDEX], 2017). Although many published reviews of pegmatites and rare-element pegmatites describe their physical and chemical characteristics, spatial occurrences and ore formation processes (e.g. Cerný, 1991; Cerný et al., 2005; Cerný and Ercit, 2005; London, 2008, 2018; Bradley et al., 2017), fewer studies describe these mineralization occurrences using a mineral systems approach. Dill (2015) describes granites in terms of their key processes controlling rare-element pegmatites, whereas Sweetapple (2017) proposes a mineral systems approach for understanding genetic processes that are critical for the genesis of these deposits and which inform exploration targeting for these deposits. In their studies, both workers outline critical source, pathway and mineralization (i.e. trap) processes, but only briefly describe mappable proxies for these processes in the form of recommended GIS layers.

This contribution documents the steps taken to develop a mineral systems analysis of the rare-element pegmatite mineral system. The outcome of the analysis is a list of mappable proxies that will direct construction of GIS map layers in the GSWA MSA. In this Record, a brief description of the classification of pegmatites and rare-element pegmatites is provided before an evaluation of the mineral systems analysis is presented in graphic form as a Mineral System Tree. Further information about the rare-element pegmatite mineral system is provided in the Guide to the MSA. The information in the Guide and Atlas will be updated based on improvements in our understanding about this mineral system and additions of related geoscience data to the GSWA databases.

Granitic pegmatites and their classification

Granitic pegmatites are coarse-grained igneous rocks that contain abundant crystals with skeletal, graphic or other strongly directional growth habits, or anisotropic layered mineral fabrics (London, 1992, 2008). Giant or megacrystic crystals may also be present. Several classification schemes exist for granitic pegmatites (Cerný and Ercit, 2005; London, 2008; Simmons and Webber, 2008) — the simplest scheme divides them into common pegmatites and rare-element pegmatites. More complex schemes are based on the presence of different rare-metal mineral assemblages. The rare-element pegmatites have anomalous contents of Be, Li, Ta, Sn and Cs. Beryllium is most commonly present as beryl, Li occurs as spodumene or lepidolite, Ta as columbite–tantalite, Sn as cassiterite and Cs as pollucite (Bradley et al., 2017). Pegmatites are also often mined for high-purity quartz, potassium feldspar, albite, kaolinite, white mica, gem beryl, gem tourmaline and museum-quality specimens of many rare minerals.

Rare-element pegmatites

Rare-element pegmatites are divided into two end-member petrogenetic/compositional families (Cerný, 1991; Cerný and Ercit, 2005) as a simple chemical division to emphasize key differences in the geological processes responsible for rare-element mineralization:

- Lithium–caesium–tantalum (LCT) pegmatites are enriched in Li, Cs, Ta, Be, B, F, P, Mn, Ga, Rb, Nb, Sn and Hf. Examples of major LCT pegmatite deposits include the Tin Mountain pegmatite in the US; Tanco pegmatite in Canada; Altai Number 3 pegmatite in China; the Greenbushes, Wodgina and Pilgangoora pegmatites in Western Australia; Bikita pegmatite in Zimbabwe; and the Kenticha pegmatite district in Ethiopia (e.g. see summaries of Cerný et al., 2005; Bradley et al., 2017).

- Niobium–yttrium–fluorine (NYF) pegmatites are enriched in Be, Sn, B, Nb > Ta, Ti, Y, rare earth elements (REE), Zr, Th, U, Sc and F, but are depleted in Li, Cs and Rb. Biotite is more common in NYF pegmatites, whereas muscovite is dominant in LCT pegmatites. Notable NYF pegmatite deposits, as summarized by Ercit (2005), include the South Platte granite and pegmatite system in Colorado (Simmons et al., 1987), the Grötingen granite and Abborselet and other associated pegmatites in Sweden (Kjellman et al., 1999), the Lac du Bonnet biotite granite and Shatford Lake pegmatite group in Canada (Buck et al., 1999), and the Stockholm granite and Ytterby pegmatite group, Sweden (Kjellman et al., 1999).

- Mixed or 'hybrid' rare-element pegmatites have blended rare-element signatures and are considered to be products of contamination of NYF pegmatites at the magmatic or postmagmatic stage. For example, they have been suggested to result from remelting of newly formed NYF pegmatites by metasomatic fluids rich in Li, B, Ca and Mg (Cerný and Ercit, 2005; Martin and De Vito, 2005). Some examples of mixed pegmatites include those at Kimito in Finland (Pehrman, 1945), the Tørdal district of Norway (Bergstøl and Juve, 1988; Cerný, 1991) and the O'Grady batholith in Canada (Ercit et al., 2003).

Mineralization processes

Lithium–caesium–tantalum pegmatites

Lithium–caesium–tantalum pegmatites are present in all continents and span three billion years of Earth history. Their global age distribution mirrors those of orogenic granites and detrital zircons, corresponding to times of supercontinent assembly and major collisional orogenic events (Tkachev, 2016; Bradley et al., 2017).

In Proterozoic–Phanerozoic settings, where collisional tectonic processes are well documented, LCT pegmatites most likely formed in orogenic hinterlands related to plate convergence (Bradley et al., 2017). Arc-related processes that control pegmatite generation include: i) overthickening of continental crust; ii) slab breakoff; iii) slab delamination; iv) extensional collapse occurring late in the collisional event and involving decompression melting. Lithium–caesium–tantalum pegmatites are consequently hosted in metamorphosed supracrustal rocks (e.g. greenstone belts). Intrusions are emplaced at midcrustal levels late during orogeny and are controlled by existing faults, fractures, foliation and bedding in country rocks. Pegmatites exposed to these conditions are tabular, whereas at lower levels of the crust, ductile hydrostatic conditions promote lensoid to irregular pegmatites (Brisbin, 1986). In the Proterozoic and Phanerozoic, LCT pegmatites are products of extreme fractional crystallization of S-type granites, derived from melting of metasedimentary rocks in continental collision zones (Cerný and Ercit, 2005). Specific examples include pegmatite fields in South Norway (Müller et al., 2015), Namibia (Fuchsloch et al., 2018), Maine (Webber et al., 2019), and in the Italian Alps (Konzett et al., 2018). An alternate process proposed for pegmatite generation is by direct melting of rocks with the appropriate composition (e.g. metasedimentary rocks with evaporite sequences: Simmons and Webber, 2008; London, 2008, 2018).

In Archean settings such as the Pilbara and Yilgarn Cratons, S-type granites are scarce and the largest known deposits hosted by LCT pegmatites (e.g. the Wodgina, Pilgangoora and Greenbushes deposits) are associated with highly fractionated I-type granites (Sweetapple and Collins, 2002; Sweetapple, 2017). Although contentious, some form of plate tectonics is generally agreed upon for the Archean (e.g. Cawood et al., 2013). In this context, progressive partial melting of trondhjemite–tonalite–granodiorite precursors is one possible method for the enrichment of rare elements in melts that act as the parental sources of mineralized pegmatites (Sweetapple, 2017). These pegmatites are most commonly emplaced into mafic or ultramafic host rocks within greenstone belts (e.g. the Pilbara Craton, Sweetapple and Collins, 2002; Yilgarn Craton, Witt, 1992). In these Archean settings, regional-scale structures control the distribution of pegmatites, being responsible for focusing and transporting fluids and magmas (e.g. Sweetapple and Collins, 2002; Demartis et al., 2011; Deveaud et al., 2013).

Most LCT pegmatite melts are enriched in fluxing components (H_2O, F, P and B) that depress the solidus temperature, lower the magma density and increase rates of ionic diffusion. Hence, LCT pegmatites form relatively thin dykes with large crystals at lower temperatures (350–550°C) compared to common granitic melts (London, 2008, 2018). Rates of crystallization modelled experimentally are remarkably short (days to years; Webber et al., 1997; London, 2008, 2018).

Pegmatites are located within 10 km of cogenetic peraluminous granites and leucogranites (as modelled experimentally by Baker, 1998). The roof zones of large plutons are the most favourable positions (London, 2018). Proximal pegmatites are the least evolved and are poorly mineralized, containing only general rock-forming minerals (Fig. 1). More distal and evolved pegmatites may include beryl, beryl and columbite, tantalite and Li aluminosilicates, and pollucite in the most evolved pegmatites. The spatial zonation of pegmatites around a common granitic source is a fundamental starting point for exploration models (London, 2018).

Niobium–yttrium–fluorine pegmatites

Niobium–yttrium–fluorine pegmatites are identified in most continents and their crystallization ages correspond to major intervals of global continent assembly from the Archean to the Neogene, with a peak at ~1000 Ma corresponding to the Grenville orogeny in Laurentia (McCauley and Bradley, 2014).

Niobium–yttrium–fluorine pegmatites are products of pronounced differentiation of anorogenic, A-type granites, which are a common product of bimodal gabbro–granite magmatism in rift zones. Geological processes controlling the genesis of A-type granites include: i) fractionation of direct partial melts from the upper mantle; ii) remelting of basalts that accumulate beneath the thinned lithosphere; iii) partial melting of lower crustal gneisses (Eby, 1990; Christiansen and McCurry, 2008). In the advanced rift setting where A-type granites are commonly generated, the mafic and felsic melts are mostly metaluminous. The melts are near or above silica saturation, with the granites notably depleted in Ca and P, and possessing heavy rare earth element (HREE) enrichment (London, 2018).

Like the LCT pegmatites, NYF pegmatites are often controlled by structures, fabrics and bedding in country rocks. However, regional zonation patterns around parental granites do not appear to occur in NYF pegmatite fields (Simmons and Webber, 2008). Rather, the NYF pegmatites are commonly hosted within granites (e.g. in the Pilbara Craton; Sweetapple and Collins, 2002).

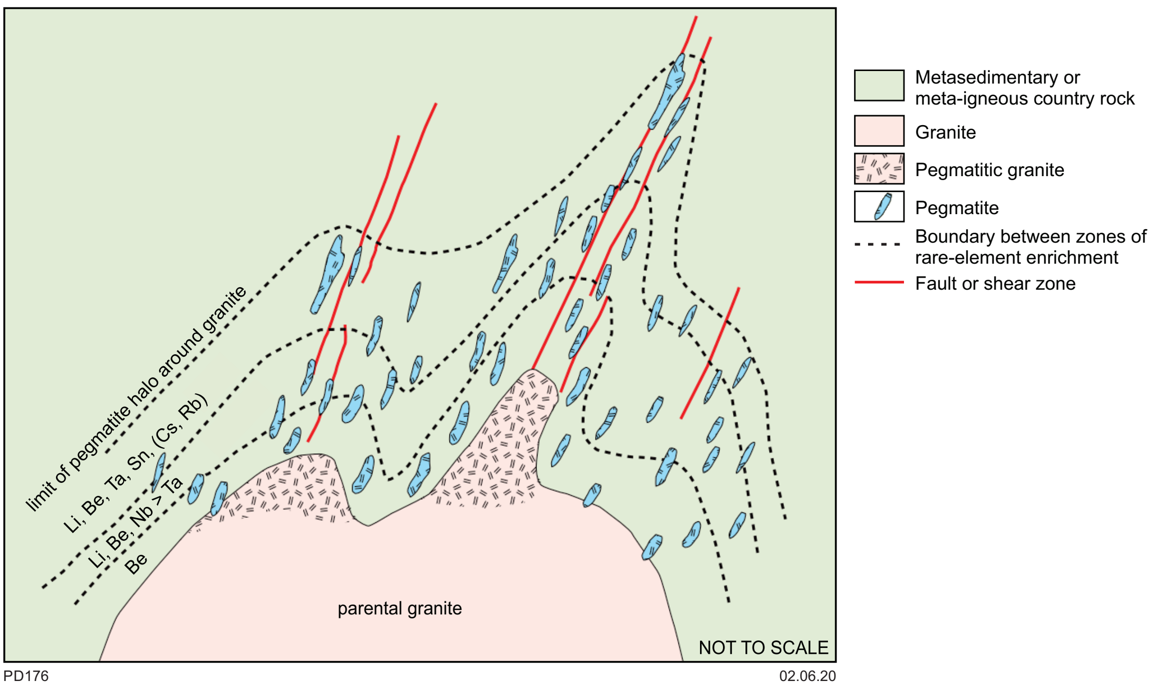

Figure 1. Schematic model in profile that shows regional zoning patterns in a pegmatite field (modified after Trueman and Cerný, 1982; Cerný, 1989; Galeschuk and Vanstone, 2005; Bradley et al., 2017). Characteristic rare-element suites of the most enriched pegmatites in each zone are indicated. The most prospective pegmatites are located in distal areas compared to the parental granite

Mineral systems analysis for rare-element pegmatites

Features of the mineral system for rare-element pegmatites are summarized as a table of critical processes (Table 1) and as a more detailed Mineral System Tree (Fig. 2), which is a graphical representation of all the important components of the mineral systems analysis. Mappable proxies in the lower section of the Mineral System Tree represent recommended GIS map layers that will inform the development of the MSA and future collection of data relevant to exploration for rare-element pegmatites.

Table 1. Critical features of the rare-element pegmatite mineral system

Critical process	*Description*
Source	Formation of fertile magmas
Pathway	Shear zones and faults
Trap	Cooling and chemical diffusion in fractionating melts
Preservation	Erosion and uplift of rare-element pegmatites

Conclusions

This Record summarizes the mineral systems model for rare-element pegmatites, which include LCT, NYF and mixed varieties of mineralized pegmatites. The objective is to demonstrate links between geological processes involved in their genesis and GIS map layers that may be useful for rare-element exploration. Critical processes include: i) formation of fertile magmas as a source for fluids and metals; ii) structures and fabrics in country rocks as pathways for fluids; iii) cooling and chemical diffusion in evolved granitic melts that result in the formation of rare-element mineralization in compositionally and texturally distinct pegmatites; iv) preservation of deposits through erosion and uplift of crustal profiles hosting rare-element pegmatites. The provided Mineral System Tree presents a list of recommended GIS map layers for exploration. Further information about these layers is provided in the Guide to the MSA.

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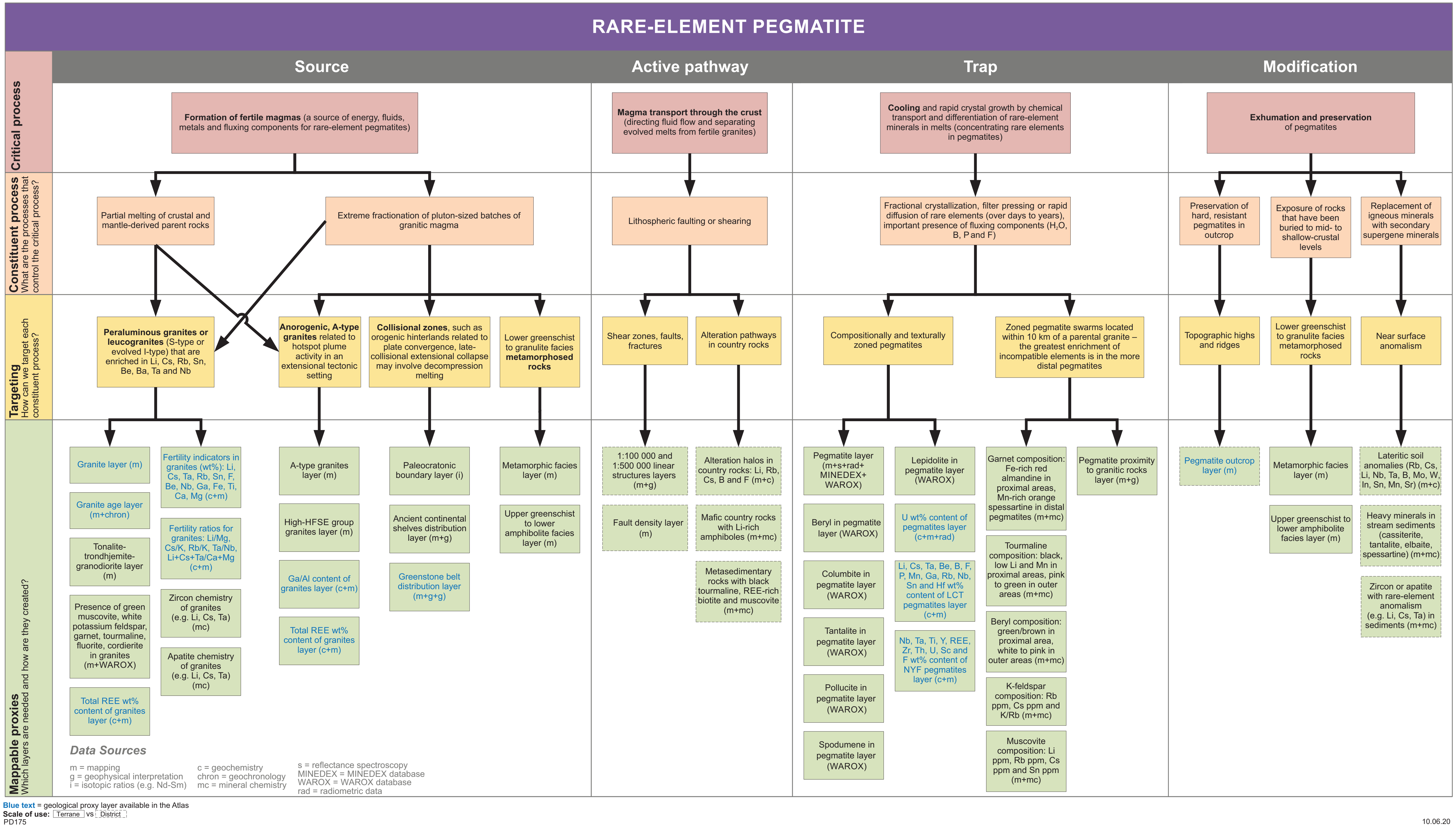

Figure 2. The Mineral System Tree is the graphical display of a mineral systems analysis showing the link between critical/constituent processes and their recommended targeting features and GIS layers. Abbreviations: HSFE, high field strength elements

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