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Lithium Pegmatites in Africa: A Review

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Abstract

Electrification of transport plays a vital role in the energy transition, which is needed to tackle the pressing challenge of climate change. Lithium is a critical raw material for the batteries that are used to power electric vehicles. Currently, about 60% of the world's lithium is sourced from rare metal pegmatites, with the top three producing countries (Australia, Chile, China) accounting for more than 80% of global supply. There is limited legal extraction of lithium on the African continent, with Zimbabwe currently being the only country actively mining lithium at large scale, but Africa is host to significant, untapped lithium resources. This paper provides an overview of lithium pegmatites in Africa, describing the key features (e.g., zonation, mineralogy, and paragenesis) of pegmatites from different tectonic settings and of varying ages. It is notable that each of the key orogenic events on the continent has a distinct lithium pegmatite fingerprint. Archaean pegmatites are typically petalite dominated; unzoned spodumene pegmatites are common in the Paleoproterozoic of the West African craton; Mesoproterozoic pegmatites in Central Africa are typically tin-tantalum rich, which is a function of the high degree of albitization observed in many of these pegmatites; and complex zoned pegmatites are more common in the Neoproterozoic to Paleozoic orogens. Many of these pegmatites have a common paragenesis that can be broadly described in four stages (magmatic crystallization, albitization, greisenization, and low-temperature alteration), but there is a need to understand what controls the wider variation in pegmatite type and economic mineral assemblages. The continent of Africa provides an excellent natural lab for placing pegmatites into their broader geologic context in order to develop better mineral deposit models.

Introduction

Tackling climate change is now a global priority, and a focus for many governments is the transition away from fossil fuels to cleaner sources of energy with lower greenhouse gas emissions. This energy transition will require electrification of transport and a continued shift to renewable energy sources with associated energy storage. It is widely recognized that the energy transition will drive greatly increased demand for a range of raw materials, and that these will need to be sourced in as sustainable a way as possible (Sovacool et al., 2020). In recent years, there has been particular interest in the raw materials required for lithium-ion batteries: nickel, cobalt, manganese, graphite, and lithium (Olivetti et al., 2017). Demand for these raw materials is expected to grow markedly in the coming decades (Maisel et al., 2023), providing a potential economic opportunity for those developing countries with appropriate resources (Hund et al., 2020). There will be a need for geologists, mineralogists, metallurgists, economists, and environmental experts to work together to identify and develop the best resources of all these raw materials (Pell et al., 2021).

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Lithium (Li) is of particular interest to geologists because of its presence in a wide variety of resource types (Bowell et al., 2020). Currently, around 40% of global lithium supply (U.S. Geological Survey, 2024) comes from brines in salars, or salt lakes, chiefly in Argentina and Chile (Munk et al., 2016; López Steinmetz and Salvi, 2021; Al-Jawad et al., 2024). The other 60% comes from hard-rock mines, chiefly in Li-rich granitic pegmatites (Bradley et al., 2017). There is increasing exploration for other lithium deposit types, including Li-rich granites, geothermal brines, and volcano-sedimentary (VS) systems such as Thacker Pass in Nevada (Gourcerol et al., 2019; Bowell et al., 2020; Benson et al., 2023).

This paper focuses on the continent of Africa, which is well endowed with lithium resources, predominantly in lithium pegmatites (Goodenough et al., 2021). We summarize the state of knowledge on the geology, mineralogy, and structure of known lithium pegmatites across Africa, as well as their exploration status and potential to contribute to supply chains. This paper largely represents a review of published literature but also draws on our many years of collective experience working on these rocks with colleagues from across Africa.

Lithium Pegmatites

Pegmatites are very coarse grained igneous rocks, most commonly granitic in composition and characterized by a variety of textures such as directional mineral growth, mineral zonation, and graphic intergrowths (London and Kontak, 2012). The classification of pegmatites is complicated, and there have been many schemes proposed—some based on depth of formation (Ginsburg and Rodionov, 1960; Ginsburg, 1984; Zagorsky et al., 1999), some based on mineralogy (Wise, 1999; Wise et al., 2013), some based on geochemistry (Niggli, 1920; Landes, 1933), and some that utilize geochemistry, mineralogy, and structural setting (Pezzotta, 2001; Černý and Ercit, 2005; Dill, 2016; Müller et al., 2018). A widely used classification is that of Černý and Ercit (2005), which includes five classes, of which the most relevant for economic purposes is the rare element pegmatite class. This can in turn be divided either into a number of types based on mineralogy, or into two main families: the NYF (niobium-yttrium-fluorine) and LCT (lithium-cesium-tantalum) pegmatites. The LCT pegmatites have typically been considered as derived from peraluminous S-type granites formed by melting metasedimentary material, whereas the NYF pegmatites have an affinity with alkaline A-type granites formed by melting of the lower continental crust and/or mantle (Černý et al., 2012). Most recently, this classification has been modified by Wise et al. (2022), who recognized the need to classify pegmatites based on their mineralogy and account for potentially variable methods of formation. Pegmatites containing lithium minerals are considered in this classification as belonging to group 1. It is the LCT or group 1 pegmatites that contain the main lithium resources globally and that will be the focus of this paper; hereafter, for simplicity, they are referred to as lithium pegmatites.

Lithium does not occur as a native element; instead it is found in pegmatites within the matrices of a suite of minerals, and understanding this complex mineralogy is critically important for mining (Linnen et al., 2012). Pegmatites are made up of gangue minerals such as quartz and feldspar, a range of lithium ore minerals (chiefly silicate and phosphate minerals), and other accessory minerals. The most important ore mineral for lithium-ion batteries is spodumene, for which cracking and refining processes are well established (Rioyo et al., 2022; Kundu et al., 2023). Other potential lithium ore minerals found in pegmatites include petalite, lepidolite, amblygonite, and eucryptite (Table 1). Key accessory minerals include pollucite (mined for cesium), beryl, columbite group minerals (CGMs; niobium, tantalum), and cassiterite (tin).

Experimental work has demonstrated that pressure and temperature of formation exert a significant control on which lithium minerals crystallize (Fig. 1) (London, 1984). Where petalite is the original magmatic mineral, it may be replaced by a spodumene-quartz intergrowth (SQI) as the pegmatite cools (London, 1984). Estimates for depth of crystallization, based on mineralogy, did not always match the regional context, and this led to the recognition that pegmatites begin to crystallize at temperatures below the granitic solidus (undercooling) (London, 2005). This lowering of crystallization temperatures is supported by the presence of fluxes such as H_2O, B, F, Cl, and P in the melt. Significant degrees of undercooling are an important factor in the crystallization of economic lithium pegmatites (McCaffrey and Jowitt, 2023).

Table 1. Lithium-Bearing Minerals and Key Accessory Minerals in Lithium Pegmatites

Mineral	Formula	Examples from this study
Spodumene	$LiAlSi_2O_6$	**Ewoyaa,** Ghana; **Goulamina,** Mali; **Manono-Kitotolo,** DRC
Petalite	$LiAlSi_4O_{10}$	**Arcadia,** Zimbabwe; **Uis,** Namibia
Eucryptite	$LiAlSiO_4$	**Arcadia,** Zimbabwe; **Kivu,** DRC
Lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$	**Rubicon-Helicon,** Namibia; **Zulu,** Zimbabwe
Zinnwaldite	$KFe_2Al(Al_2Si_2O_{10})(OH)_2 \rightarrow KLi_2Al(Si_4O_{10})(F,OH)_2$	**Rubicon-Helicon,** Namibia
Bityite	$CaLiAl_2(AlBeSi_2O_{10})(OH)_2$	**Arcadia,** Zimbabwe
Cookeite	$LiAl_4(Si_3Al)O_{10}(OH)_8$	**Kamativi,** Zimbabwe; **Uis,** Namibia
Amblygonite	$(Li,Na)Al(PO_4)(F,OH)$	**Bikita,** Zimbabwe; **Gatumba,** Rwanda
Montebrasite	$LiAl(PO_4)(OH,F)$	**Kamativi,** Zimbabwe; **Musha-Ntunga,** Rwanda
Triphylite	$Li(Fe,Mn)PO_4$	**Gatumba,** Rwanda; **Saraya,** Senegal
Lithiophilite	$Li(Mn,Fe)PO_4$	**Gatumba,** Rwanda; **Saraya,** Senegal
Sicklerite	$Li_{1-x}(Mn^{3+}{}_xMn^{2+}{}_{1-x})PO_4$	**Vredefort,** South Africa
Wavellite	$Al_3(PO_4)_2(OH)_3 \cdot 5H_2O$	**N'dora,** Burundi
Burangaite	$NaFeAl_5(PO_4)_4(OH)_6 \cdot 2H_2O$	**Buranga,** Rwanda
Bertossaite	$(Li,Na)_2(Ca,Fe,Mn)Al_4(PO_4)_4(OH,F)_4$	**Buranga,** Rwanda
Gatumbaite	$CaAl_2(PO_4)_2(OH)_2 \cdot H_2O$	**Buranga,** Rwanda
Columbite-tantalite	$(Fe,Mn)(Nb,Ta)_2O_6 \rightarrow (Fe,Mn)(Ta,Nb)_2O_6$	**All** pegmatites in varying amounts (referred to in text as columbite group minerals)
Microlite	$(Na,Ca)_2Ta_2O_6(O,OH,F)$	**Noumas,** South Africa; **Bikita,** Zimbabwe
Cassiterite	SnO_2	**Kamativi,** Zimbabwe; **Musha-Ntunga,** Rwanda; **Manono-Kitotolo,** DRC
Danalite	$Be_3Fe^{2+}{}_4(SiO_4)_3S$	**Arcadia,** Zimbabwe
Hectorite	$Na(Mg,Li)_3(Si_4O_{10})(F,OH)_2$	**Rubicon-Helicon,** Namibia
Pollucite	$(Cs,Na)_2Al_2Si_4O_{12} \cdot (H_2O)$	**Bikita,** Zimbabwe; **Norabees,** South Africa
Bikitaite	$LiAlSi_2O_6 \cdot H_2O$	**Bikita,** Zimbabwe; **Arcadia,** Zimbabwe
Bismuth minerals	Various; e.g., native bismuth (Bi)	**Noumas,** South Africa; **Arcadia,** Zimbabwe

Note: Bold font indicates the name of the actual locality and is followed by the country name in standard text
Abbreviations: DRC = Democratic Republic of the Congo

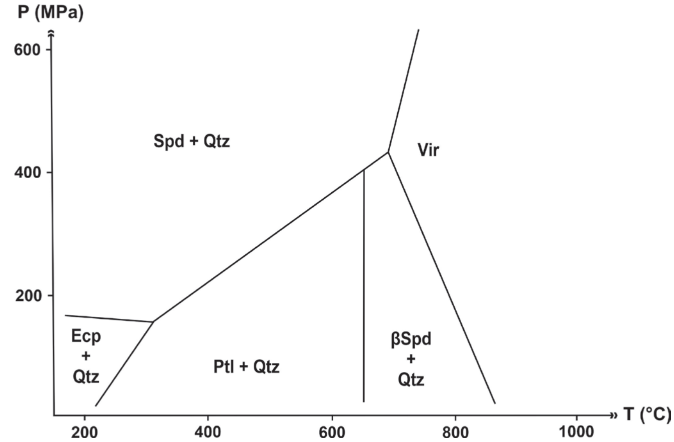

Fig. 1. Phase diagram for lithium minerals in pegmatites after London (1984). Abbreviations: βSpd = beta spodumene, Ecp = eucryptite, P = pressure, Ptl = petalite, Qtz = quartz, Spd = spodumene, T = temperature, Vir = virgilite.

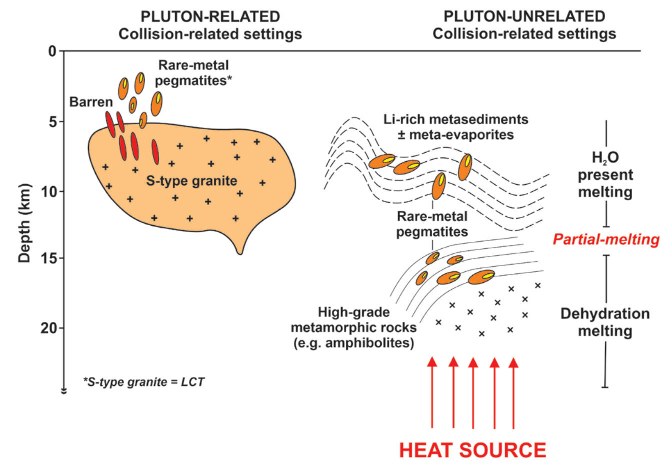

Fig. 2. Two contrasting models for the formation of pegmatites, after Müller et al. (2017). Abbreviation: LCT = lithium-cesium-tantalum.

Internal (variation in texture and mineralogy within an intrusion) and regional (compositional variation between pegmatites in a pegmatite field) zonation are often referred to as key features of rare metal pegmatites (Černý, 1991; London, 1992, 2005, 2014). However, many examples of economic lithium pegmatites, particularly those assigned to the albite-spodumene type (Černý and Ercit, 2005), lack such zonation; several examples occur in Africa and are described below.

It is widely accepted that the formation of rare metal pegmatites involves a complex interplay of both magmatic and hydrothermal processes, and many studies have investigated the point at which the magmatic-hydrothermal transition occurs (London, 1986; Veksler, 2004; Touret et al., 2007; Kaeter et al., 2018; Ballouard et al., 2020; Barros et al., 2020; Michaud and Pichavant, 2020; Shaw et al., 2022). Several key paragenetic stages have been reported, particularly from unzoned spodumene pegmatites: (1) magmatic crystallization, (2) albitization, (3) greisenization, and (4) postsolidus alteration. However, the distribution and intensity of stages 2 to 4 can vary greatly between pegmatites and indeed within a single pegmatite. The terminology used to describe these stages can also be highly variable, which can make large-scale comparisons difficult. It is clear that some apparent zonation in pegmatites is primary, whereas in many cases it is more complex and likely related to these later replacement stages (Černý, 1991; Wise et al., 2022).

There are two models that are currently used to explain the formation of rare metal pegmatites (Fig. 2): (1) prolonged, fractional crystallization of a peraluminous granitic magma at the pluton scale and (2) direct formation by low-degree partial melting of crustal rocks in the presence of a fluid (London, 2005; Martin and De Vito, 2005; Simmons and Webber, 2008). The first model is proposed to generate pegmatite fields with regional zonation, with the most highly evolved LCT pegmatites as the most distal from the parental granite (London, 2018). In reality, these two models represent the simplest end members, with many pegmatites likely forming by a multiphase process, involving crustal anatexis to produce varied melt batches that reflect their crustal sources. These melts were transported upward along structural pathways in the crust and may have undergone evolution through fractional crystallization and/or crystallization and remelting (Plunder et al., 2022; Knoll et al., 2023; Koopmans et al., 2023; Xu et al., 2023). Plutonic-scale magma bodies may be part of this process but are not an essential constituent. What is clear is that lithium-rich magmas typically form in zones where continental collision has taken place, burying (meta)sedimentary source rocks to a depth where they may be partially melted, but the final emplacement of pegmatites typically occurs in a postcollisional regime, where structural pathways can make space for magmas to be emplaced at shallower levels in the crust (Hulsbosch et al., 2017; Silva et al., 2023). Thus, the chemical and mineralogical composition of the pegmatites reflects the sources that were originally melted, the processes by which those melts formed and evolved, and the wider structural setting into which they were emplaced. This broad understanding allows us to place LCT pegmatites into their wider tectonic context across Africa.

The Geology of Africa: An Overview

The continent of Africa has a long and complex geologic history, which we summarize briefly here with a focus on the orogenic events that are particularly associated with pegmatite formation. The oldest parts of the African continent are the Archaean to Paleoproterozoic cratonic cores, represented in the Kalahari, Congo, Tanzania, and West African cratons (Fig. 3), which are dominated by tonalite-trondhjemite-granodiorite (TTG) gneisses with greenstone belts comprising mafic igneous and metasedimentary supracrustal rock types. These are separated by Proterozoic to Paleozoic mobile belts (Begg et al., 2009). Neoproterozoic sedimentary basins cover large areas of the continent, such that the architecture of some of the cratons is not completely known.

In Southern Africa, the Kalahari craton comprises the Kaapvaal and Zimbabwe cratons, together with belts of Paleoproterozoic to Mesoproterozoic crust (Jacobs et al., 2008). The Kaapvaal craton contains some of Africa's oldest crust (>3500 Ma) including ancient supracrustal rocks in the Barberton greenstone belt on the eastern side of the craton (Kröner et al., 2016). This craton was stitched by granitoid intrusions

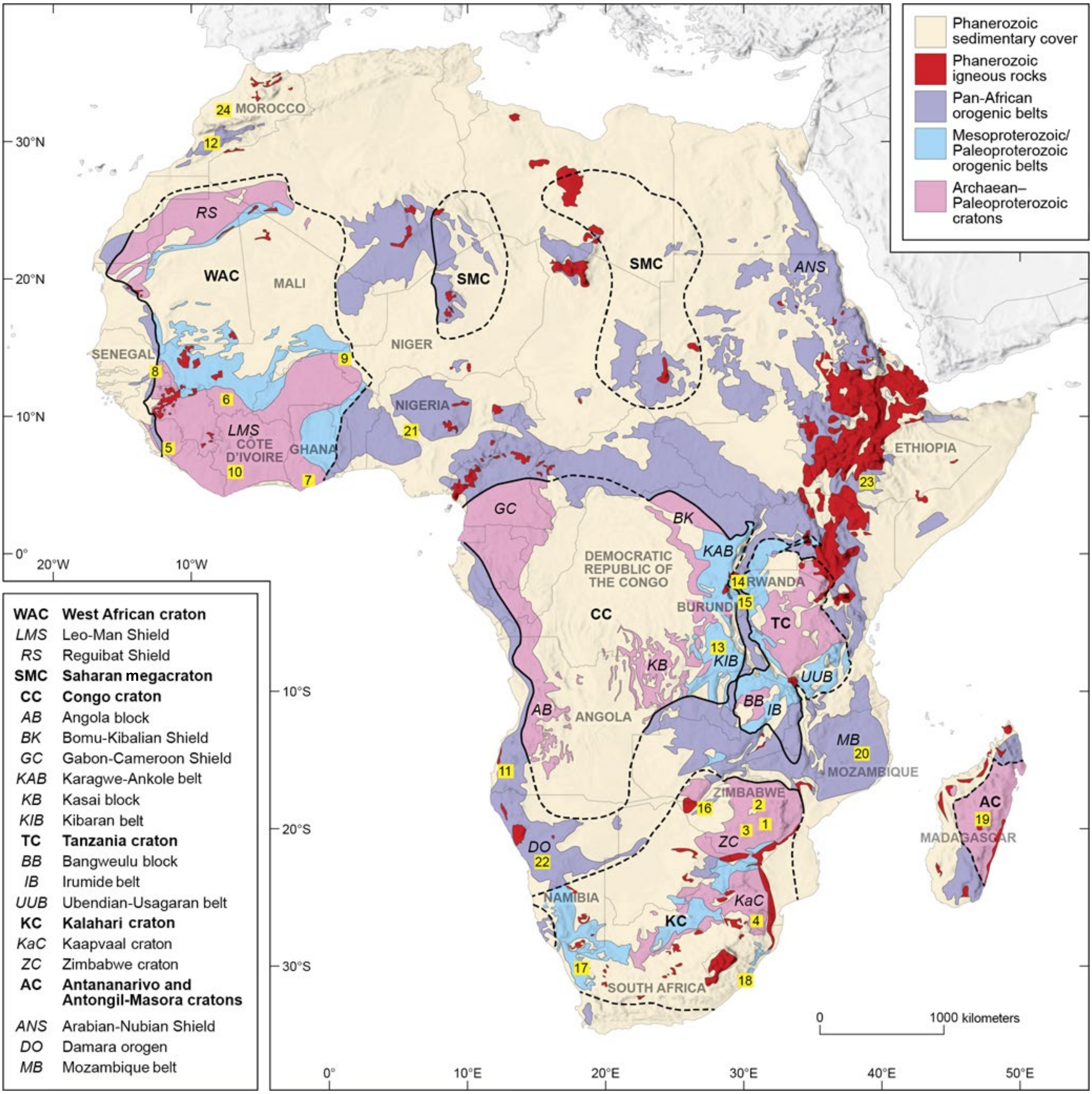

Fig. 3. Simplified geologic map of Africa, showing the major cratons and mobile belts. Numbered localities are pegmatite fields mentioned in the text: 1 = Bikita, 2 = Arcadia, 3 = Zulu, 4 = Archaean pegmatites of South Africa/ Eswatini, 5 = Archaean pegmatites of Sierra Leone, 6 = Goulamina and Bougouni, 7 = Ewoyaa, 8 = Saraya, 9 = Dibilo, 10 = Issia, 11 = Giraúl, 12 = Zenaga, 13 = Manono-Kitotolo, 14 = Gitarama-Gatumba and Musha-Ntunga, 15 = N'dora, 16 = Kamativi, 17 = Orange River, 18 = Highbury, 19 = Madagascar, 20 = Alto Ligonha, 21 = Angwan Doka, 22 = Damara belt, 23 = Kenticha, 24 = Sidi Bou Othmane.

around 3000 Ma (Eglington and Armstrong, 2004) prior to the formation of extensive sedimentary basins, including the Witwatersrand Supergroup. A major event in the Kaapvaal craton was the formation of the Bushveld Complex at 2050 Ma (Scoates and Friedman, 2008). The Zimbabwe craton (Fig. 4) contains TTG gneisses dated at 3565 to 3350 Ma (Horstwood et al., 1999) and supracrustal rocks in greenstone belts formed around 2800 to 2580 Ma (Jelsma and Dirks, 2002). A regional deformation event that affected both gneisses and greenstone belts was followed by intrusion of granitoids in the period 2630 to 2580 Ma (Jelsma and Dirks, 2002). The whole craton is crosscut by the 2575 Ma Great Dyke (Oberthür et

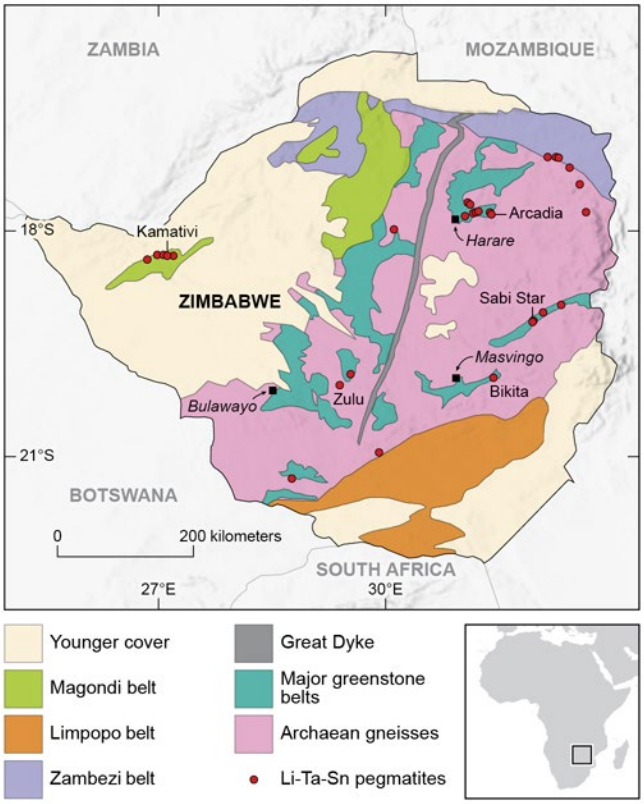

Fig. 4. Simplified geologic map of Zimbabwe after Shaw et al. (2022) with pegmatite locations indicated.

al., 2002). The Kaapvaal and Zimbabwe cratons are separated by the Limpopo belt, a high-grade metamorphic province comprising reworked Archaean and juvenile Paleoproterozoic material (Zeh et al., 2007). The western part of the Kalahari craton is marked by the Magondi belt, comprising a Paleoproterozoic volcano-sedimentary succession that was metamorphosed at 2060 to 1960 Ma (Master et al., 2010).

The West African craton includes two areas of Archaean to Paleoproterozoic rocks—the Leo-Man Shield in the south and the Reguibat Shield in the north—with both shields having a western block of Archaean rocks and an eastern zone of Paleoproterozoic rocks. The Paleoproterozoic rocks comprise a variety of metasedimentary and metavolcanic units with numerous, dominantly granitoid, intrusions; collectively this area of ca. 2270 to 1960 Ma crust is termed the Birimian (Grenholm et al., 2019). The Paleoproterozoic rocks, together with the margins of the Archaean blocks, were affected by polyphase deformation and metamorphism associated with episodic continental collision during the ca. 2150 to 2000 Ma Eburnean orogeny (Schofield et al., 2006; Block et al., 2016; McFarlane et al., 2019). The rocks of the West African craton are well endowed with a variety of mineralization, including iron ore and diamonds in the Archaean block and volcanogenic massive sulfide (VMS) and other syngenetic mineralization styles, as well as extensive orogenic gold, in the Paleoproterozoic zone (Markwitz et al., 2016).

The Congo craton, which occupies much of Central Africa, is made up of several different Archaean to Paleoproterozoic blocks exposed around the margins of the Neoproterozoic to Paleozoic Congo basin (Fig. 3). The Archaean blocks include the Angola block, the Kasai block, the Gabon-Cameroon block, and the Bomu-Kibalian block (De Waele et al., 2008; Begg et al., 2009; Djeutchou et al., 2024). The western parts of the Congo craton, particularly in Angola and Cameroon, comprise Neoarchaean gneisses and greenstone belts that show extensive evidence of metamorphic reworking and emplacement of granitoids in the Eburnean orogeny around 2100 to 2000 Ma (De Waele et al., 2008; Tchakounté et al., 2017). To the east of the Congo craton lies the Archaean Tanzania craton, with the Paleoproterozoic Bangweulu block on its southwestern side (De Waele et al., 2008). The two cratons are separated by Paleoproterozoic mobile belts, including the ca. 2000 to 1900 Ma Usagaran belt on the southern side of the Tanzania craton, and the ca. 2100 to 1850 Ma Ubendian belt between the Tanzania craton and the Bangweulu block (Ganbat et al., 2021).

In Madagascar, the Archaean Antananarivo and Antongil-Masora cratons make up the core of the island (Schofield et al., 2010; Tucker et al., 2014). Finally, Archaean rocks occur in the Uweinat Massif at the border between Egypt, Libya, and Sudan (Bea et al., 2011), leading to the suggestion of a highly reworked Saharan metacraton largely buried beneath younger sedimentary cover (Abdelsalam et al., 2002). The Congo and Zimbabwe cratons are separated by the long-lived Irumide belt, which has a Paleoproterozoic to Mesoproterozoic history (De Waele et al., 2008).

The cratons of southern and central Africa are joined by a complex series of Mesoproterozoic mobile belts, including the Karagwe-Ankole belt between the northern parts of the Tanzania and Congo cratons (Tack et al., 2010; Fernandez-Alonso et al., 2012), the Kibaran belt between the Tanzania craton and the Kasai block (De Waele et al., 2008; Debruyne et al., 2015), and the Namaqua-Natal belt within the Kalahari craton (Eglington, 2006). These belts record multiple phases of sedimentation, deformation, and magmatism between ca. 1400 and 1000 Ma (Villeneuve et al., 2023). These belts are particularly important for granites and pegmatites that have been extensively mined for tin and CGMs (Pohl, 1994).

The final amalgamation of Africa as the continent that we recognize today largely occurred during the Neoproterozoic through the assembly of the supercontinent of Gondwana and the development of the Pan-African orogenic belts. A major feature that formed at this time is the East African orogen, which stretches from the Red Sea in the north to Madagascar and Mozambique in the south (Fritz et al., 2013). The northern part of this orogen constitutes the juvenile crust of the Arabian-Nubian Shield, which was formed by episodic growth and accretion of arc terranes throughout the Neoproterozoic (Johnson, 2021). To the south, the Mozambique belt represents older crust that was reworked, largely between 650 and 500 Ma, extending between the Congo, Tanzania, Kalahari, and Antananarivo cratons (Fritz et al., 2013). In Namibia, the Damara orogen extends between the Congo and Kalahari cratons and comprises largely juvenile Neoproterozoic to Cambrian crust that was metamorphosed in the Cambrian (Miller et al., 2009; Goscombe et al., 2017). The Damara orogen is divided into a NE-trending inland branch that is 400 km wide and 1,000 km long (the Damara belt), the coastal Gariep belt to the south, and the coastal Kaoko belt to the north. Further northwest, the West African craton is surrounded by Neoproterozoic to Cambrian mobile belts that also extend into South America. These belts contain both juvenile crustal material and reworked older crust (Deynoux et al., 2006). All the Neoproterozoic to Cambrian (Pan-African) orogenic belts are characterized by extensive postcollisional granitoid magmatism (Küster and Harms, 1998; Goodenough et al., 2010, 2014).

Before, during, and after these orogenic events, extending from the Neoproterozoic into the Paleozoic, several major sedimentary basins developed. These include the Tindouf, Taoudeni, and Volta basins in West Africa (Deynoux et al., 2006), the Katangan Supergroup of the Central African Copperbelt (Cailteux and De Putter, 2019), and basins within the Damara orogen (Nascimento et al., 2017). Continued continental extension then led to intracontinental magmatism and, finally, opening oceans. In the west, Mesozoic opening of the Atlantic Ocean was associated with the formation of the Central Atlantic magmatic province (Marzoli et al., 2019). In south-central Africa, the Karoo sedimentary basins developed from the Carboniferous, with extensive magmatism of the Karoo large igneous province in the Jurassic (Svensen et al., 2012). In East Africa, opening of the East African rift was accompanied by voluminous magmatism (Michon et al., 2022). Only North Africa was affected by orogenesis at this time, with evidence of the Variscan and Alpine orogenies (Angrand and Mouthereau, 2021; Michard et al., 2023). Overall, this complex geologic history provided the setting for emplacement of several major lithium pegmatite swarms, associated with each of the major orogenic events.

Lithium Pegmatites in Africa

Lithium granites and pegmatites are typically found in zones of collisional orogenesis, and as described above, the continent of Africa has experienced such geologic conditions at many times during the last 3,500 m.y. In this section, we take a chronological approach, summarizing the known lithium granites and pegmatites associated with each major crust-forming or orogenic event in turn. Known lithium deposits that already have openly available mineral resource estimates are summarized in Table 2.

Archaean LCT pegmatites in the Kalahari craton

Zimbabwe: The Zimbabwe craton is known to be extremely rich in lithium pegmatites, with 29 occurrences mentioned by Bartholomew (1990). The majority of these occur within the Archaean cratonic core (Fig. 4) and are considered to be of Archaean age. The most well-known is the Bikita pegmatite field, which intrudes the Masvingo greenstone belt in southeast Zimbabwe and is dated at 2617 ± 1 Ma (Melcher et al., 2015). Mining has taken place at Bikita since tin was discovered in 1910, and mining of petalite started in the 1940s. Petalite has been the main commodity mined at Bikita since then (Fig. 5A), but pollucite and CGMs have also been mined in certain zones of the pegmatite. The mining license area includes several pegmatites, with the main mined pegmatite being 30 to 40 m thick, trending roughly north-northeast and dipping around 30° toward the east (Bartholomew, 1990; Dittrich et al., 2019). Mining is carried out in a series of open pits along the pegmatite. The pegmatite has a rather irregular and complex zonation (Cerny et al., 2003), with marginal unmineralized zones made up largely of quartz, feldspar, and mica, and a more mineralized core zone that shows some variation in lithium ore minerals (Dittrich et al., 2019). The mineralized zone varies from lepidolite- and pollucite-rich zones in the south, to petalite in the main Al Hayat pit and to lower-grade transitional petalite ore with abundant mica at the northern end of the pit. The le-

Table 2. Known Mineral Resource Estimates for Lithium Deposits Across Africa as of July 2024, Based on Publicly Available Data from Company Reports and Websites

Deposit	Company	Country	Lithium minerals	Code	Mineral resource	Tonnage (Mt)	Grade (% Li_2O)	Year
Arcadia	Huayou Cobalt	Zimbabwe	Petalite, spodumene	JORC	Resource (measured + indicated + inferred)	72.7	1.06	2021
Kamativi[1]	Galileo Resources	Zimbabwe	Spodumene	JORC	Resource (indicated)	26.32	0.58	2018
Zulu	Premier African Minerals	Zimbabwe	Spodumene	SAMREC	Resource (indicated + inferred)	24.75	0.43	2024
Bikita[2]	Sinomine Resources	Zimbabwe	Petalite, spodumene		Resource (measured + indicated + inferred)	113.35	1.03	2023
Sabi Star[2]	Chengxin Lithium	Zimbabwe			Resource (measured + indicated + inferred)	Not specified	1.98	2023
Karibib	Lepidico	Namibia	Lepidolite	JORC	Resource (measured + indicated + inferred)	11.85	0.4	2022
Uis (V1V2)	Andrada	Namibia	Petalite	JORC	Total resource estimate	81	0.73	2023
Manono-Kitotolo	AVZ Minerals and others	DRC	Spodumene	JORC	Resource (measured + indicated + inferred)	842	1.61	2024
Manono Tailings	Tantalex	DRC	Spodumene	NI-43-101	Resource (measured + indicated)	5.46	0.72	2023
Goulamina	Leo Lithium	Mali	Spodumene	JORC	Resource (measured + indicated + inferred)	267	1.38	2024
Bougouni	Kodal Minerals	Mali	Spodumene	JORC	Resource (indicated + inferred)	31.9	1.06	2023
Ewoyaa	Atlantic Lithium	Ghana	Spodumene	JORC	Resource (measured + indicated + inferred)	35.3	1.25	2023

Abbreviations: DRC = Democratic Republic of the Congo; JORC = Joint Ore Reserves Committee, SAMREC = South African Code for the Reporting of Exploration Results, Mineral Resources, and Mineral Reserves
[1]Resource at Kamativi is for historical tailings
[2]Reporting code not specified for the Bikita and Sabi Star resources

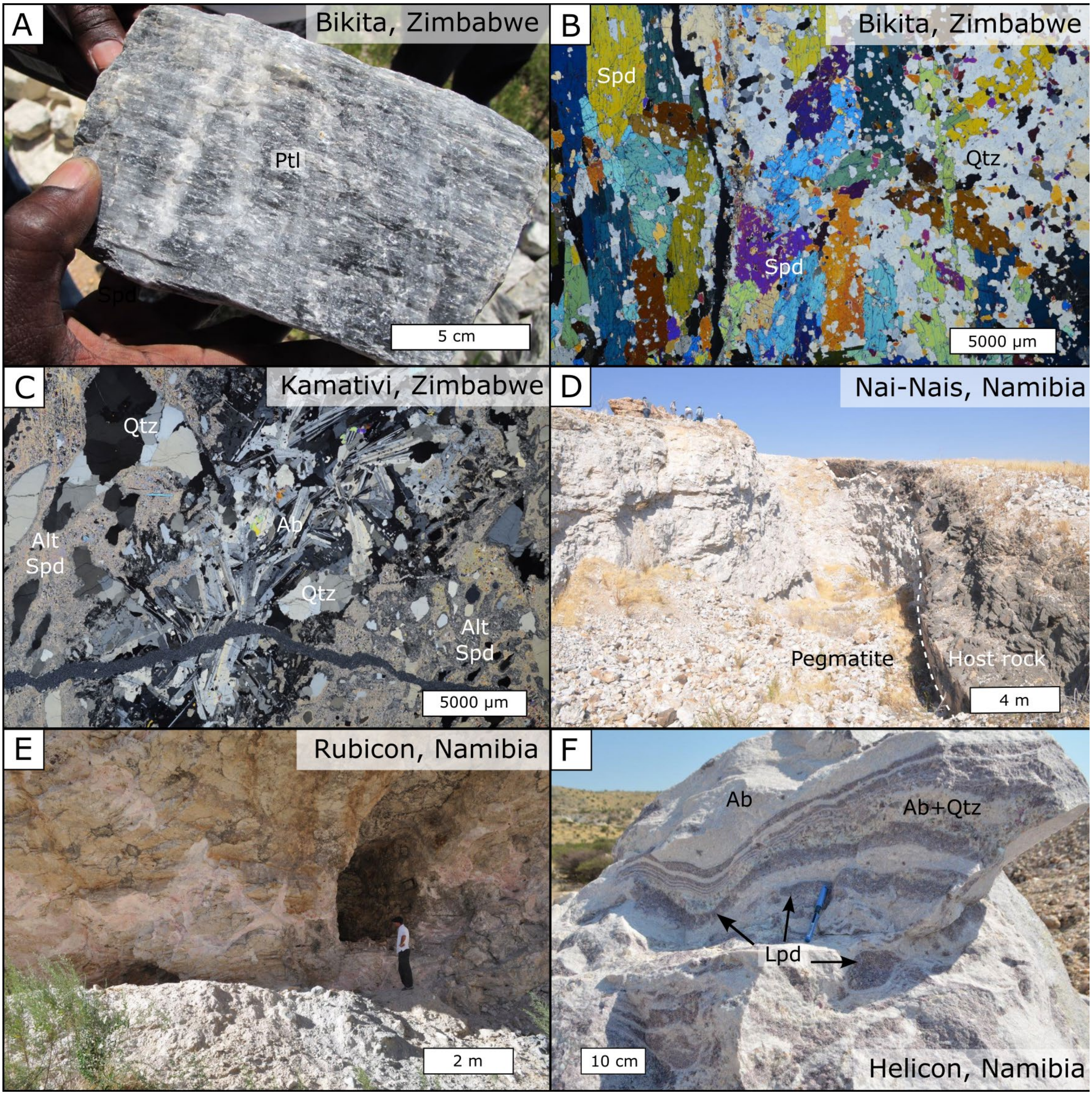

Fig. 5. Images of pegmatites from southern Africa. (A) Hand specimen of massive petalite (Ptl) and (B) spodumene-quartz intergrowths (SQI) from Bikita, Zimbabwe. (C) Replacement of spodumene (Alt Spd) to fine-grained micas, zeolites, and clays in Kamativi, Zimbabwe. (D) Albitized pegmatite showing vertical contact with host rock at Nai-Nais, Namibia. (E) Large pink tabular petalite within the Petalite zone of the Rubicon pegmatite, Namibia; zoned perthite-albite feldspar crystals with muscovite rims are visible in the adjacent Beryl zone above. (F) Layered albite (Ab) and lepidolite (Lpd) from the Lepidolite zone of the Helicon II pegmatite, Namibia. Additional mineral abbreviations: Qtz = quartz, Spd = spodumene. Images A, B, C copyright British Geological Survey; D, E, F Paul Nex.

pidolite zone in the southern part of the pegmatite is associated with high Ta grades (>1,000 ppm), where tantalite is the dominant Ta-bearing phase. A separate limb of the pegmatite to the west has been explored and is rich in spodumene intergrown with quartz (Fig. 5B). Other minerals recorded in the Bikita pegmatite include beryl, amblygonite, microlite, topaz, and garnet (Tyndale-Biscoe, 1951). Bikita is also the type locality of the rare lithium-bearing zeolite bikitaite ($LiAlSi_2O_6 \cdot H_2O$), which was first discovered by Hurlbut (1957).

The Arcadia pegmatite field, northeast of Harare, is currently the largest known lithium deposit in Zimbabwe, and mining has been underway since 2023 (Table 2). Recent exploration has shown that the Arcadia pegmatite field consists primarily of a series of parallel, shallowly dipping (~10°) stacked pegmatites, which attain widths upward of 75 m. The pegmatites at Arcadia typically have very sharp contacts with the metabasaltic country rock, which forms screens a few tens of meters thick between pegmatites. The Arcadia pegmatites have a simple zonation, with an aplitic-layered border zone consisting of albite + quartz + muscovite and a core zone that consists of petalite, quartz, and potassic feldspar. In some areas, the primary magmatic mineralogy is largely preserved, though thin zones of SQI locally replace the outer rims of petalite. Lithium muscovite is uncommon, but where present tends to rim petalite, and there is no substantial Ta or Sn mineralization. Near the main Arcadia suite is a series of steeper-dipping pegmatites (the Step-aside zone), which has a similar mineralogy, though petalite is more pervasively recrystallized to SQI. We have observed evidence of complex, late-stage replacement of early formed magmatic minerals in material from the upper levels of the Arcadia pegmatites. The distribution of the replacement mineral assemblage is highly variable throughout the pegmatites, typically taking the form of pods and lenses. The replacement mineralogy comprises two generations of eucryptite, zeolites (e.g., bikitaite), clays (e.g., kaolinite), danalite (an iron beryllium sulfur-bearing silicate), and suspected bityite (a calcium-lithium mica). The areas of most intense replacement also contain native bismuth and thin, crosscutting veins filled with calcite.

The Zulu pegmatite field, 80 km from Bulawayo, is predominantly hosted in the Fort Rixon-Shangani greenstone belt, and the widest intersections (termed the Main pegmatites) exploit the contact between a serpentinized ultramafic sill and underlying metavolcanic successions (Harrison, 1969). The Main pegmatites are a sheeted set of steeply dipping (~60°) pegmatites that locally attain widths up to ~50 m and extend along strike (NNE-SSW) for ~1 km. The pegmatites are simply zoned, with a fine-grained margin of albite + quartz + muscovite, an intermediate zone of SQI (after petalite) + microcline + quartz, and a poorly developed quartz core. Locally, a pervasive overprint of albite + quartz + lithium muscovite replaces the primary magmatic mineralogy and is associated with CGM. Oblique to the main pegmatites (E-W) are the subordinate river pegmatites, which attain widths up to 5 m and predominantly retain the original magmatic mineralogy with minimal conversion of petalite to SQIs. Other lithium pegmatites also occur within the granitoid basement to the east of the main Zulu pegmatites, though these are not well understood. Ongoing lithium exploration has identified other lithium pegmatite fields of presumed Archaean age across Zimbabwe—for example, the Sabi Star pegmatites (Fig. 4), which have been developed as a mine in recent years, but these have not been described in detail.

South Africa and Eswatini: Archaean pegmatites are less abundant in the Kaapvaal craton than in the Zimbabwe craton. Possibly the oldest LCT pegmatites in Africa are deformed albite-spodumene pegmatites in the vicinity of the New Consort gold mine on the northern edge of the Barberton greenstone belt. They were studied in underground workings of the gold mine and have been dated at ca. 3.1 Ga (Tomkinson et al., 1995). Of similar age are LCT pegmatites associated with the ca. 3.0 Ga Sinceni pluton of northwest Eswatini (formerly Swaziland) regarded by Grew et al. (2018) as one of the earliest examples of LCT pegmatites on Earth. Two generations of pegmatites have been described, with only the younger enriched in rare metals (Trumbull, 1993, 1995). Alluvial and eluvial tin deposits derived from these pegmatites have been mined since the early 1900s, and occasional lithium minerals including lepidolite, elbaite, and spodumene have been noted. Lithium pegmatites also occur within the Vredefort impact structure, where they are emplaced into amphibolites and mafic schists of Archaean age (Bischoff and Bischoff, 1988; Rajesh et al., 2020). The pegmatites can only be studied in isolated outcrops; they comprise quartz, feldspar (largely albite), and lath-shaped, randomly oriented spodumene crystals up to 15 cm long. Accessory minerals include muscovite, Mn-rich garnet, apatite, sicklerite, CGMs, and topaz (Rajesh et al., 2020). Crosscutting relationships show that the pegmatites were emplaced prior to the formation of impact-associated pseudotachylites. Petalite was identified by Rajesh et al. (2020) as an alteration product of spodumene, and this was attributed to a postimpact thermal shock in the area.

Archaean LCT pegmatites in the West African craton

Pegmatite dikes are a common feature in the Archaean migmatitic basement gneisses and greenstone belts of the Leo-Man Shield, but the whole region is understudied and very little is known about the potential for lithium pegmatites. Cassiterite and CGMs have been reported in alluvial sediments from some greenstone belts in Sierra Leone and Liberia (MacFarlane et al., 1981; Gunn et al., 2018) and have been dated as Archaean (Melcher et al., 2015); these are considered likely to be pegmatite derived, but the source pegmatites have rarely been described. We have observed poorly exposed, heavily weathered pegmatites within the Loko Hills greenstone belt of northern Sierra Leone (Fig. 6) (Goodenough et al., 2018). The majority of these pegmatites are unmineralized, between 2 and 5 m wide, and parallel to the foliation in the country rock but can locally be crosscutting. Rarer lithium pegmatites largely comprise coarse-grained plagioclase feldspar, quartz, and spodumene (up to 2 cm in size), with minor tourmaline and CGMs. Some finer-grained material dominantly comprises SQI, likely after petalite, in a quartz- and plagioclase-rich groundmass, with minor garnet and CGMs (Fig. 7A). The spodumene generally shows little evidence of alteration; however, the margins of some grains are altered to fine-grained masses of mica.

Paleoproterozoic pegmatites in the West African craton

The Paleoproterozoic part of the Leo-Man Shield comprises metasedimentary and metavolcanic Birimian rocks intruded by abundant Eburnean granitoids. The granitoids show a geochemical evolution from arc type before 2100 Ma to collisional magmatism after 2100 Ma and include both metaluminous and peraluminous compositions (Parra-Avila et al., 2017, 2019). In recent years, this domain has also been recognized as being of significant interest for LCT pegmatites (Kazapoe, 2023), and the key localities are summarized below and in Figure 6. In some areas, pegmatites have been described but with no evidence of lithium minerals (e.g., the Mangodara area of Burkina Faso; Bonzi et al., 2023); these areas are not discussed in detail here. Lateritic weathering across this domain is intense and can extend down to depths of 75 m, mean-

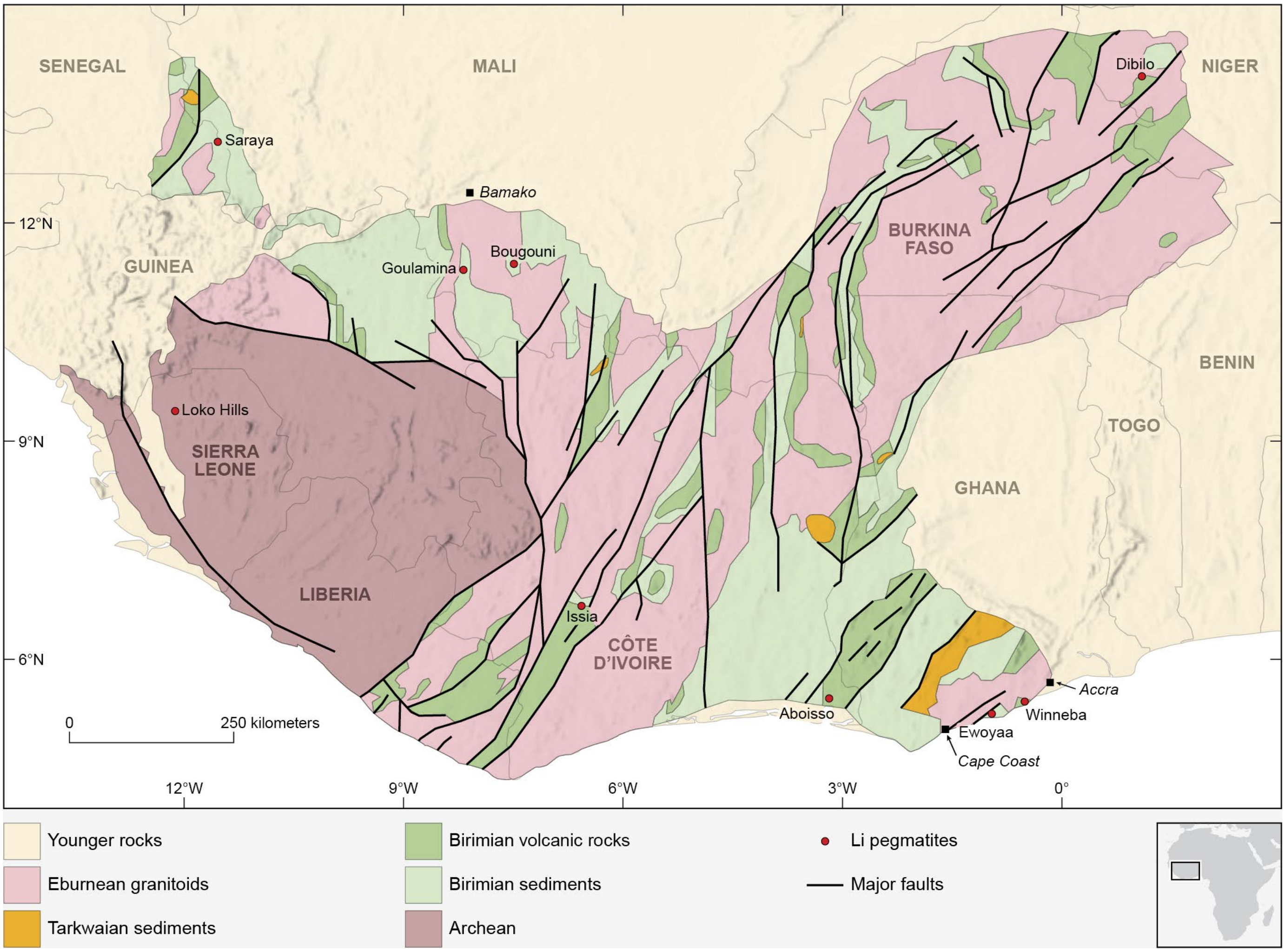

Fig. 6. Simplified geologic map of West Africa after Gunn et al. (2018) with pegmatite locations indicated.

ing that exposure is very poor, and thus there are undoubtedly many more lithium pegmatites to be discovered in the region.

Mali: The Goulamina lithium project is in southern Mali, 150 km from the capital Bamako (Fig. 6; Table 2). The Goulamina pegmatite field is hosted by the peraluminous Goulamina granite, which is a large, elongate intrusion extending for over 20 km in a north-south direction, intruding a series of metapelites, metagraywackes, and metaconglomerates (Wilde et al., 2021). A large proportion (approximately 70%) of the resource at Goulamina is hosted by five pegmatites, namely Main, West, West II, Sangar I, and Sangar II. These pegmatites are steeply dipping and typically trend northwest-southeast. Individual intrusions vary in thickness from 10 to 80 m and have been traced over a strike length of more than 1 km. The Danaya pegmatite swarm accounts for about 30% of the resource at Goulamina; it is approximately 400 m wide and can be traced over >1.5 km. The pegmatites at Danaya are typically thinner than the intrusions at Main, West, and Sangar and are orientated north-south, instead of northwest-southeast (Wilde et al., 2021).

The pegmatites at Goulamina lack both regional and internal zonation. They comprise varying amounts of quartz, sodic and potassic feldspar, muscovite, and spodumene, with spodumene being the main, and often only, lithium-bearing phase encountered (Fig. 7C). Minor amounts of tourmaline, apatite, and CGMs are also present. Spodumene in the pegmatites can be up to 15 cm in length but is typically in the order of a few centimeters and is generally fresh, showing little evidence of alteration. The paragenesis at Goulamina comprises a magmatic stage involving crystallization of coarse-grained quartz, feldspar, spodumene, and mica; an albitization stage; and a weathering stage with complete breakdown of K-feldspar and spodumene to kaolinite and Fe hydroxides in samples from close to the current land surface. Albitization is irregular and complex within the pegmatites, often represented by fine-grained albitic zones that have also been described as aplites (Wilde et al., 2021). Our study of samples from Goulamina shows that where spodumene is in contact with albite, intense alteration can be seen, particularly around grain margins. The albitization observed in the Goulamina pegmatites is clearly late (postmagmatic crystallization), as the albite tends to form radiating masses that are largely confined to veins, void spaces, and grain boundaries between spodumene and quartz. The final stage in the paragenesis has important economic implica-

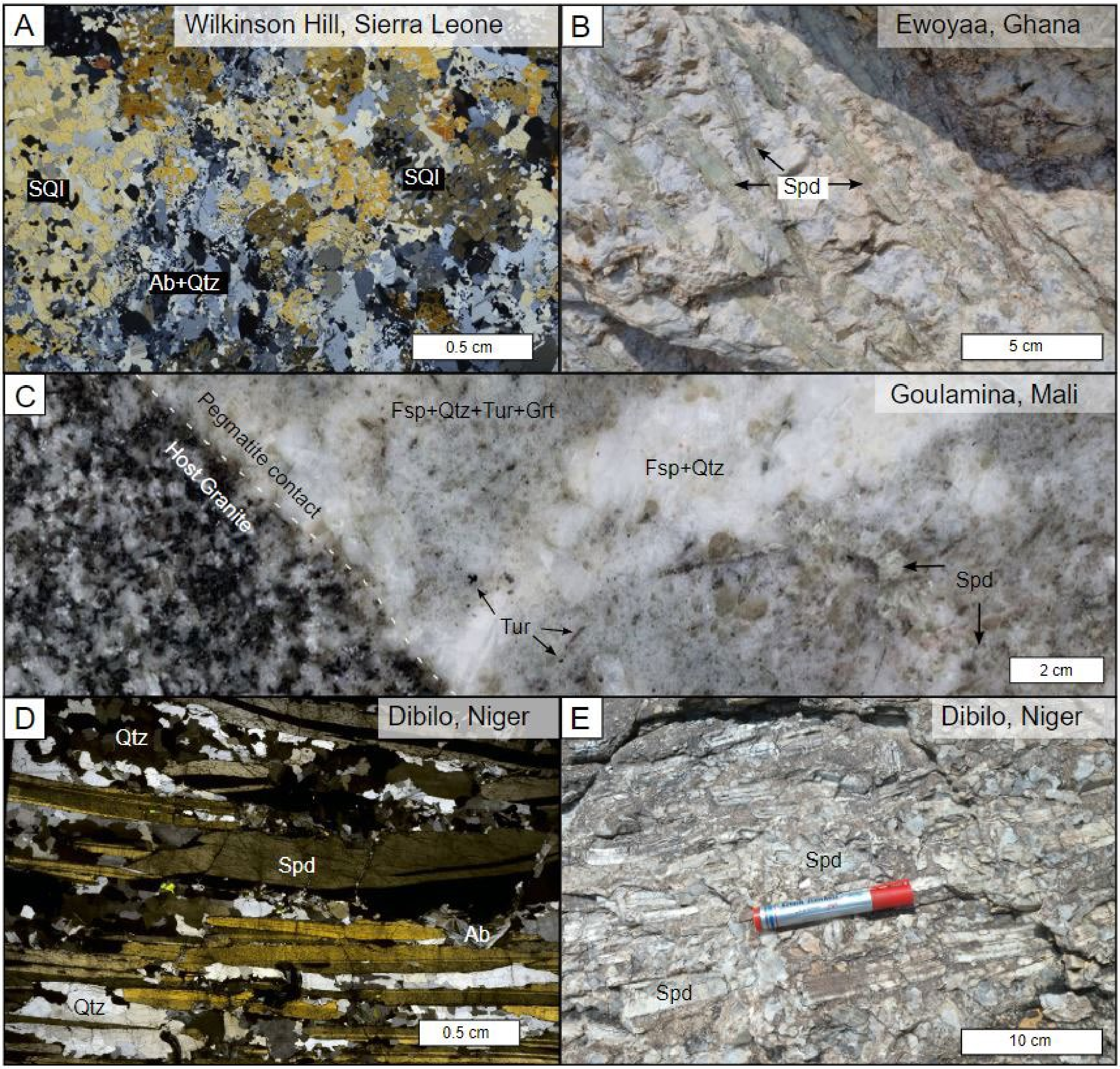

Fig. 7. Images of pegmatites from West Africa. (A) Spodumene-quartz intergrowths (SQI) after petalite from Wilkinson Hill pegmatites in Sierra Leone. (B) Elongated green spodumene (Spd) from Ewoyaa, Ghana. (C) Sharp intrusive contact of garnet (Grt)-tourmaline (Tur)-spodumene (Spd)–bearing pegmatite against host rock at Goulamina, Mali. (D, E) Deformed pegmatite in thin section and outcrop showing preferred orientation of the spodumene (Spd) laths at Dibilo, Niger. Additional mineral abbreviations: Ab = albite, Fsp = feldspar, Qtz = quartz. Images A, B, C copyright British Geological Survey; D, E by Sofiyane Attourabi; used by permission.

tions, as samples of weathered pegmatite are observed to have much lower lithium contents than samples of unweathered pegmatite (Otto and LeGras, 2018; Wilde et al., 2021).

The Bougouni pegmatites in southern Mali are hosted by Birimian metavolcanic and metasedimentary rocks. Sanogo et al. (2021) describe them as steeply dipping (~90°) sheets that predominantly trend in an east-west or southeast-northwest direction and have sharp contacts with the country rock, likely indicating emplacement in a postcollisional brittle regime. The pegmatites comprise spodumene, albite, quartz, K-feldspar, and muscovite; the very high albite content described in some pegmatites indicates the presence of extensive albitization. Minor mineral phases include apatite, garnet, CGMs, tourmaline, beryl, and rutile.

Ghana: A large pegmatite field is well exposed along the coast of southern Ghana between Cape Coast and Winneba, with spodumene-bearing pegmatites known at a number of localities (Adams et al., 2023). The pegmatites are hosted by a suite of Birimian metasedimentary and metavolcanic rocks together with their associated Eburnean granitoids. The country rocks are mostly quartz-mica and/or hornblende schists and have a strong foliation that trends in a northeasterly direction and dips steeply (~85°–90°) to the southeast (Kesse, 1985; Chalokwu et al., 1997).

The easternmost pegmatite exposures are those at Winneba, some 50 km west of Accra. Pegmatites at Winneba are strongly albitized, with spodumene crystals up to a meter in length, blue beryl, apatite, and tourmaline (Adams et al., 2023). There is little or no evidence of internal zonation in these pegmatites. West of Winneba, at Egyasimanku Hill, the country rocks are hornblende schists that are commonly tourmalinized and cut by tourmaline-quartz veins, aplites, and pegmatites (Chalokwu et al., 1997). The pegmatites at Egyasimanku Hill are zoned and flat (~5°–6°) to shallowly dipping (~30°–35°), with a general northwest-southeast trend. Individual intrusions can be traced for hundreds of meters and have average thicknesses of less than 10 m (Kesse, 1985). Mineralogically the pegmatites have been reported to comprise albite, K-feldspar, quartz, spodumene, CGMs, and muscovite, with accessory tourmaline (schorl-dravite), beryl, garnet, apatite, cassiterite, and arsenopyrite (Kesse, 1985; Chalokwu et al., 1997). However, more recent work shows that albitization is widespread, with only one locality hosting spodumene (Adams et al., 2023).

Pegmatites occur at many localities along the coast between Winneba and Cape Coast, but lithium minerals are rare and have not been described in detail. The most distinctive pegmatite in this area is a large (~50 m thick) very coarse pegmatite at Fort Amsterdam, which dips steeply (~60°) to the north and has very sharp contacts with the country rocks. The pegmatite is dominated by tabular K-feldspar (up to 20 cm in length), quartz, and muscovite with accessory blue-green apatite, garnet, CGMs, and dark-brown phosphate minerals.

The most significant lithium pegmatites known in this region are the spodumene pegmatites within the Ewoyaa project license area (Table 2), which are hosted by Birimian mica schists and associated granitoids. The schists are locally tourmalinized and may contain small (2–3 cm) pods rich in tourmaline, garnet, and Fe oxides. The metasedimentary rocks have a NE- trending foliation with a moderate to steep dip to the southeast (Hughes and Farrant, 1963). Pegmatites vary between 2 and 60 m in width and in some cases can be traced for up to 800 m along strike. The pegmatites are generally steeply dipping, and the dominant strike is southeasterly (Hughes and Farrant, 1963). The pegmatites at Ewoyaa typically have a fairly simple mineralogy (dominated by quartz + feldspar + spodumene + apatite + muscovite) and lack any clear zoning; spodumene is typically present from margin to core of the pegmatites, showing clear unidirectional solidification textures (Fig. 7B). Our sample collections (from core material, courtesy of Atlantic Lithium) show that four broad facies can be recognized: (1) coarse pegmatite containing quartz, albite, muscovite, and variable amounts of spodumene with minor sulfides, blue-green apatite, triphylite, lithiophilite, and cassiterite, (2) very coarse grained pegmatite, which has a similar mineralogy to facies 1 but typically contains very abundant spodumene, up to 10 cm in length, (3) rarer aplitic material that dominantly comprises fine-grained albite and quartz with minor sulfides, blue-green apatite, triphylite, lithiophilite, and CGMs, and (4) a localized alteration assemblage that is dominated by K-feldspar, muscovite, and phosphate minerals. Where this alteration is most intense it has led to the almost complete removal of primary spodumene. The spodumene at Ewoyaa is generally fresh, showing little evidence of alteration; however, where the spodumene is in contact with albite the margins are locally characterized by SQIs, which may indicate replacement during albitization. Albite in the pegmatites can be early (magmatic) or late and associated with albitization; the latter typically forms bladed clusters in fractures and void spaces. The lithium phosphates in Ewoyaa show evidence of extensive alteration, with a complex paragenesis including triphylite, lithiophilite, and apatite.

Senegal: In Saraya, eastern Senegal, Paleoproterozoic rocks are exposed within the Kédougou-Kenieba inlier (Lambert-Smith et al., 2016). In this area, hundreds of pegmatites are distributed along a 50-km distance within and at the margins of a granitic complex comprising granodiorite, two-mica monzogranite, and leucogranite (Delor et al., 2010). The granitic batholith shows increasing fractionation (Rb/Cs, Nb/Ta indicators) from the center to the borders of the batholith (van Lichtervelde, unpub. data, 2018). Within the batholith, the pegmatites are mostly barren, having a simple mineralogical assemblage consisting of quartz, K-feldspar, albite, micas (commonly muscovite and rarely biotite), tourmaline, garnet, beryl, and apatite. Close to the batholith margin, along the Faleme River at the border with Mali, lithium pegmatites with pink Li muscovite, spodumene (several cm in size), and triphylite-lithiophilite occur. Niobium-tantalum mineralization is well developed with the presence of columbite and wodginite group minerals and pyrochlore. Preliminary analyses of CGMs indicate a large range of Nb/Ta and Fe/Mn fractionation similar to that observed at Winneba in Ghana (Adams et al., 2023).

Niger: The Dibilo lithium pegmatite field in the Liptako area of Niger (the northeastern end of the Baoulé-Mossi domain) was emplaced into Paleoproterozoic TTG gneisses in contact with a greenstone belt, controlled by shear zones in the host rocks (Ahmed et al., 2023). The field comprises a variety of pegmatites, from barren to spodumene-bearing (Fig. 7D, E), with some pegmatites being enriched in lepidolite and CGMs (Attourabi et al., 2021; Ahmed et al., 2023). The preliminary model of formation of these pegmatites involves direct anatexis of the staurolite and garnet-bearing mica schists intercalated with amphibolites, fractional crystallization of a fertile leucogranite that itself issued from the partial melting of the host tonalitic-dioritic gneisses, and possible mixing of these two types of magma. The formation of the most evolved spodumene-bearing pegmatites has been explained by partial melting of an Li-rich diorite, followed by fractional crystallization of the anatectic Li-rich melt (Attourabi et al., 2024).

Cote d'Ivoire: In central Cote d'Ivoire, in the Issia region, a large peraluminous granite batholith is surrounded by important placer deposits of CGMs. Extensive lateritic weathering means that a small number of altered boulders are the only evidence of a large field of lithium pegmatites, as evidenced by the presence of Li mica (possibly zinnwaldite) compositions with Cs_2O concentrations up to 17 wt %. The presence of spodumene in the Issia region has been demonstrated by Allou et al. (2005), but the region has never been explored for lithium, although it is artisanally exploited for CGMs. Evidence of extreme melt fractionation in the pegmatites is demonstrated by CGM compositions covering the whole columbite quadrilateral from ferrocolumbite to manganotantalite and ferrotapiolite (Brou et al., 2022). Three types of granites are recognized in the batholith, all genetically linked through fractional crystallization and ranging from sterile metaluminous biotite-dominant granites to fertile peraluminous muscovite-dominant granites enriched in rare elements. A genetic model for the LCT pegmatites by fractional crystallization of the granitic batholith was rejected based on the temporal gap between granite ages (2090 ± 30 Ma, U/Pb ages on zircon) and pegmatite ages (2053 ± 2 to 2045 Ma, U/Pb ages on CGMs) (Legros et al., 2019). On the other hand, evidence of melting in apatite- and tourmaline-rich domains of the granitoids supports another genetic model involving partial melting of a fertile granite, 40 m.y. after its complete cooling, during exhumation associated with regional transpression.

Some lepidolite-bearing pegmatites have also been described in the Aboisso region of southeastern Cote d'Ivoire (Adingra et al., 2023).

Angola: In southwestern Angola, the Giraúl pegmatite field is associated with Eburnean granitoids that intrude an Archaean greenstone belt (Gonçalves et al., 2019). No dates have been published for the pegmatites, but they have been described as Paleoproterozoic in age (Gonçalves et al., 2009). The pegmatite field forms a belt exposed over an area 20 × 8 km, with about 600 pegmatite bodies varying from 5 m to 1 km in length. The majority of these pegmatites do not contain lithium minerals, but one pegmatite has been described as containing petalite, spodumene, lepidolite, elbaite, and amblygonite (Gonçalves et al., 2019).

Morocco: Pegmatites of Paleoproterozoic age are not well-known from the northern part of the West African craton but have been described from the Zenaga inlier in Morocco. Here, the pegmatites intrude metasedimentary and metavolcanic rocks that may correlate with the Birimian and are spatially associated with the peraluminous Taznakht granite. The granites have been dated (U-Pb in zircon) at 2032 ± 5 Ma (Thomas et al., 2002). The Zenaga pegmatites form centimetric to decametric zoned lenses and dikes. They are mainly composed of quartz, feldspars, and muscovite, with accessory minerals that include tourmaline, beryl, apatite, garnet, zircon, and Fe, Li, Mn, and Ca phosphates. The main lithium-bearing phosphates are triphylite, tavorite, and ferrisicklerite, with triphylite representing a primary magmatic mineral (Fransolet et al., 1985). The pegmatites are classified as LCT pegmatites and considered to represent fractionation products of the Taznakht granite (Morsli et al., 2022).

Mesoproterozoic of central and southern Africa

The Great Lakes region in central Africa, spanning Rwanda, Burundi, and much of the eastern Democratic Republic of the Congo (Fig. 8), is rich in pegmatite- and quartz vein-hosted tin, tungsten, and tantalum deposits (Varlamoff, 1972; Pohl, 1994; Hulsbosch, 2019). No deposits here are currently mined for lithium, but many of the pegmatites that were historically, or are actively, mined for Sn and Ta host significant lithium-bearing phases such as spodumene, amblygonite-montebrasite, and/or eucryptite, particularly below the weathering zone. Pegmatites have also historically been described in Uganda (Von Knorring and Condliffe, 1987), but little modern information is available. Pegmatites of Mesoproterozoic age also extend into Zimbabwe and Namibia and are described in more detail below.

The pegmatites and quartz veins in central Africa are associated with widespread S-type granitic magmatism emplaced around 1 Ga within Mesoproterozoic metasedimentary sequences (Tack et al., 2010; De Clercq et al., 2021). These tin granites are leucocratic and typically show graphic textures and are themselves emplaced within the cupolas of an older generation of peraluminous granitic batholiths (1375 Ma, Tack et al., 2010). This large Li-Sn-Nb-Ta-W metallogenic province stretches across the Mesoproterozoic Karagwe-Ankole belt (KAB) in the north, and the Kibaran belt (KB) in the southeast (Fernandez-Alonso et al., 2012; Debruyne et al., 2015). The Kibara and Karagwe-Ankole belts share a long history of mining and exploration for tin, tantalum, and tungsten, the 3Ts, which are dominantly extracted by artisanal miners and have also been coined "conflict minerals" given the significant socioeconomic issues involving illegal trade, child labor, and armed conflicts in Eastern Congo (Deberdt and Billon, 2021; Vogel, 2022). Unlike lithium, the 3Ts are amenable to artisanal mining methods because they are resistant to weathering and concentrate within the soft eluvial and alluvial surface deposits.

Democratic Republic of the Congo (DRC): Various lithium occurrences are reported in the DRC, within the Kibara belt and the Congolese side of the Karagwe-Ankole belt (Fig. 8) (Varlamoff, 1961; Safiannikoff and van Wambeke, 1967; Dubois et al., 1972). These include spodumene, eucryptite, lepidolite, montebrasite-amblygonite, and triphylite-lithiophilite–bearing pegmatites in the Kivu and Maniema provinces. Pegmatites mineralized in Nb, Ta, Sn, and Be have been described from the area around Lake Kivu (Kalikone et al., 2023). Because of conflicts and other safety concerns in Eastern Congo, however, many of the pegmatites here remain poorly studied.

In the Kibara belt (KIB), the most prominent lithium pegmatites are the Manono-Kitotolo pegmatites in the Tanganyika province. The Manono-Kitotolo pegmatites represent a large network of gently to steeply dipping, sheet-like pegmatites that stretch southwest-northeast and crop out over a total length of 13.5 km, with a thickness of ~300 m (Dewaele et al., 2016). They intrude a series of Paleoproterozoic schists and amphibolites (metadolerites) and are exposed within two separate districts: the Manono district is exposed directly northeast of Lake Lukushi, and the Kitotolo district lies 2 km southwest of Lake Lukushi. Although there is no direct exposure between the two districts, the pegmatites may be connected at depth. The pegmatite and Nb-Ta-Sn-Li mineralization was dated at 945 to 930 Ma, with muscovite ^{40}Ar-^{39}Ar ages of 938.8 ± 5.1 and 934.0 ± 5.9 Ma (Dewaele et al., 2016) and a columbite-tantalite U-Pb age of 940 ± 5.1 Ma, respectively (Melcher et al., 2015).

In the Manono district, early reports describe the pegmatites as a gentle antiform structure, consisting of one or more stacked and faulted pegmatite sheets with individual thicknesses between 10 and 200 m and with the pegmatites gently dipping to both sides of the axial outcrop zone (Bassot and Morio, 1989; Kokonyangi et al., 2006). In the southern Kitotolo area, the pegmatite dips roughly 30° to 35° toward the southeast. It is not known how far down the pegmatites

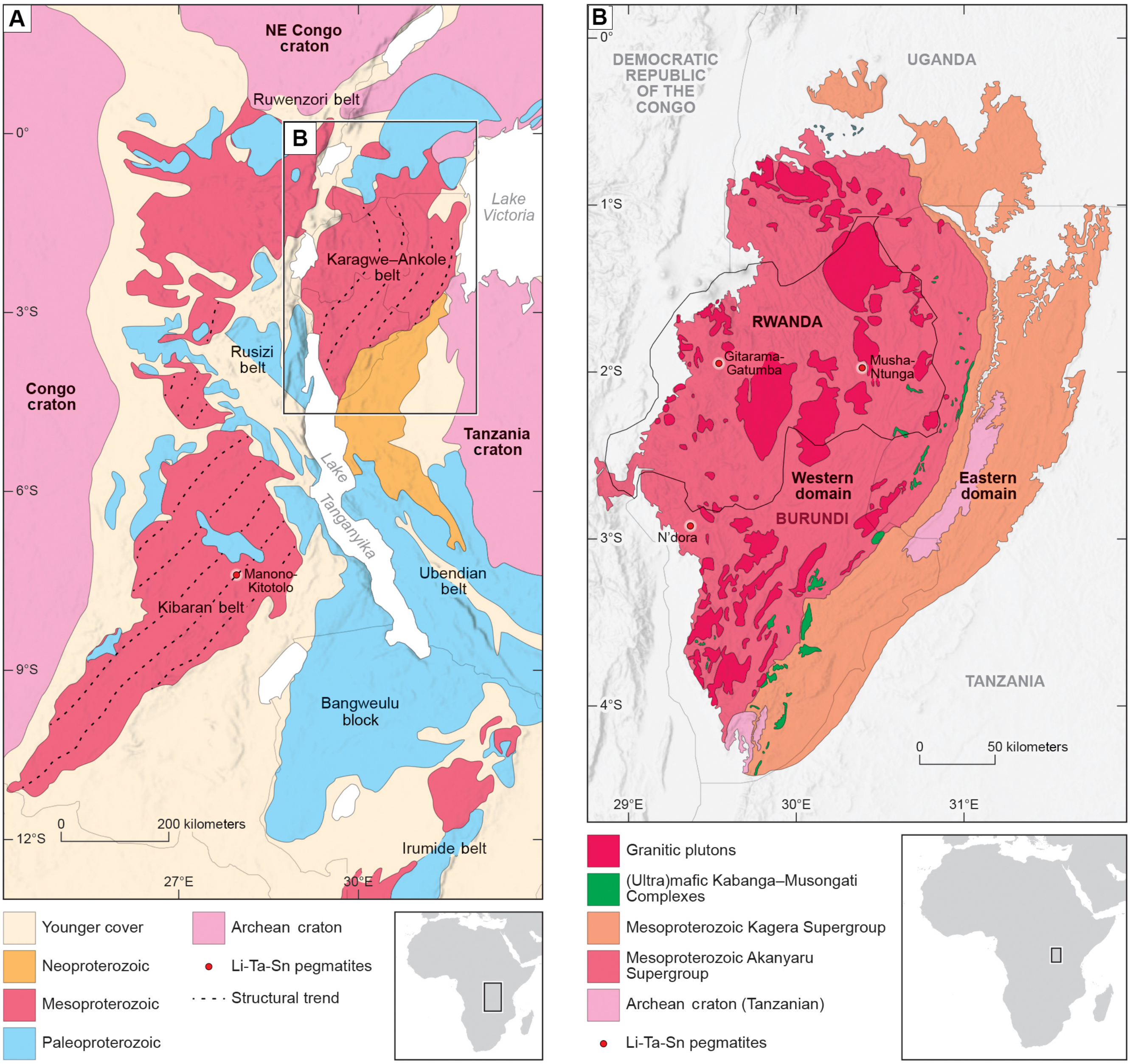

Fig. 8. Simplified geologic maps of Central Africa after Koegelenberg et al. (2015) and Hulsbosch (2019), with main Li pegmatites indicated.

extend beyond the axial outcrop zone, although recent drilling campaigns have shown they continue at depth and that the dip angle, thickness, and structure vary laterally. The pegmatites are also expected to extend further along strike, within a 5-km-wide pegmatite corridor identified in regional aeromagnetic data.

The alluvial and elluvial deposits that overlie the Manono-Kitotolo pegmatites were mined for tin between 1915 and the 1980s (Dewaele et al., 2016). Tailings from industrial mining were accumulated in a dozen large spoil heaps, mostly on the northeastern flanks of the quarries, that are now the subject of artisanal mining and lithium exploration. The southernmost quarry in the Kitotolo district, the Roche Dure pit, was recently drained to allow diamond drilling and resource estimation. Outcrops of the pegmatite along the quarry walls show meter-scale layering, dipping toward the southeast (Fig. 9A). Spodumene is abundant throughout and typically occurs in tabular crystals with a unidirectional growth perpendicular to the pegmatite contacts (Fig. 9B, C). Individual crystals can range up to 40 cm in size. The higher-grade ores contain up to 3.59 wt % Li_2O, typically occurring in decimeter- to meter-thick zones with fine-grained unidirectional spodumene crystals, alternating with lower-grade albite- and/or mica-rich layers. The spodumene is generally white but is locally altered to a green variety (along fracture zones in the drill core) or even red-brown varieties. Spodumene locally has thin margins of SQI, and locally coarse-grained SQI is also observed. Accessory phases include apatite, lithiophilite, and bluish

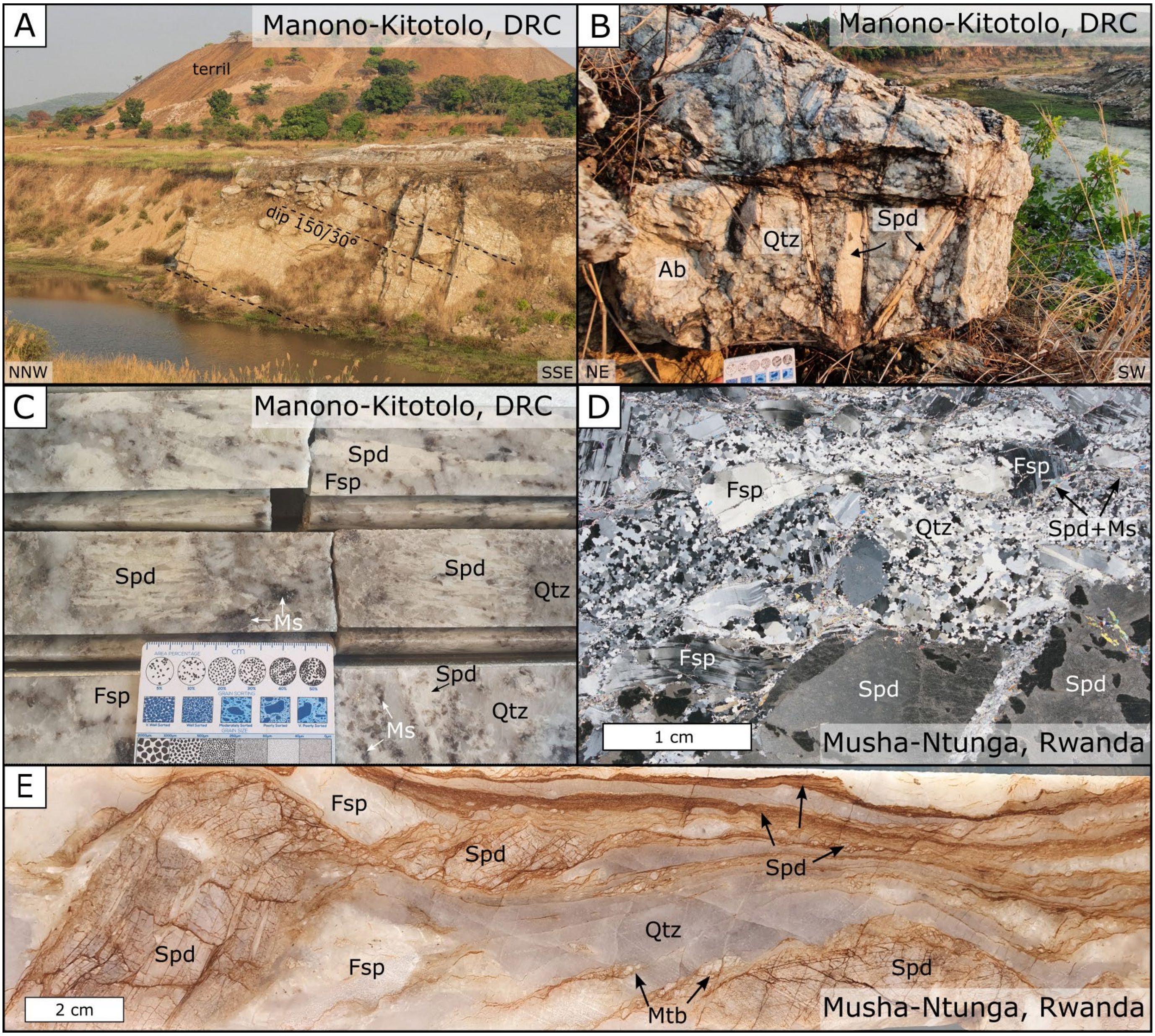

Fig. 9. Images of pegmatites from Central Africa. (A, B) Outcrop photos and (C) drill core photos showing layering and unidirectional growth of spodumene (Spd) at Roche Dure, Manono-Kitotolo, Democratic Republic of the Congo (DRC). (D, E) Thin section and drill core photo of sheared pegmatite with spodumene (Spd) and montebrasite (Mtb) from Musha-Ntunga, Rwanda. Additional mineral abbreviations: Ab = albite, Fsp = feldspar, Ms = muscovite, Qtz = quartz. Images A-C copyright Anouk Borst; D, E Jolan Acke; used by permission.

tourmaline (Borst et al., 2024). In the lower-grade zones, the primary mineralogy has been subjected to intense albitization and later greisenization (Dewaele et al., 2016).

Other pegmatite occurrences in DRC are known but very poorly described in terms of their lithium mineralogy and potential. These include Bukena, Numbi, Mumba, Kalima, Kobokobo (Buyse et al., 2024), and Nanzila.

Rwanda: In Rwanda, lithium-rich pegmatites are known from at least six localities, five of which are pegmatites within the Gitarama-Gatumba pegmatite district and the sixth recently discovered from the Musha-Ntunga pegmatite district (Varlamoff, 1972; Lehmann et al., 2014; Goodship et al., 2019). The Gitarama-Gatumba pegmatite district shows a well-developed regional zonation, starting with (1) biotite pegmatites internal and proximal to the parental granite, to (2) biotite-muscovite pegmatites farther away from the granite, followed by (3) muscovite pegmatites, and then (4) LCT-type pegmatites mineralized in Nb, Ta, Sn, Be, and Li (Hulsbosch et al., 2013, 2014). Chemical trends recorded in micas and tourmaline show progressive magmatic fractionation trends away from the parental leucogranites, where the mineralized pegmatites formed from the most evolved melt fractions that had undergone over 97% fractional crystallization, and whose internal mineral paragenesis records the magmatic-hydrothermal transition (Hulsbosch et al., 2014; Hulsbosch, 2019). The Buranga, Gatumba, Rubindi, Rongi, and Rosorora pegmatites all lie within the mineralized pegmatite zone of the Gitarama-Gatumba district and host spodumene, amblygonite-montebrasite, eucryptite, lepidolite, occasionally triphylite or lithiophilite, CGMs, cassiterite, topaz, beryl, and a wide range of phosphate minerals (Prado Araujo et al., 2023a, b). Although all are exploited for tin and tantalum, none are industrially mined for lithium to date. The spodumene in some of these localities is intensely albitized and/or kaolinized (e.g., Rubindi, Hatert et al., 2005). Petalite has thus far not been reported from any Rwanda pegmatites.

A new lithium occurrence was discovered in drill cores from the Musha-Ntunga pegmatite district, Eastern Rwanda, in 2018. Here, Trinity Metals is extracting tin and tantalum from intensely kaolinized pegmatites crosscut by cassiterite-rich quartz veins in the weathered zone and exploring the deeper unweathered pegmatites for lithium. Kaolinization of the pegmatites extends down to 100 m, below which a prior stage of albitization is prominent. Starting at a depth of 150 m, significant drill core intervals contain fresh to moderately deformed spodumene pegmatites with quartz, albite, and locally microcline up to a depth of 400 m (Acke et al., in press). Lithium grades range between 1 and 3 wt % Li_2O (Goodship et al., 2019). Spodumene is the dominant Li mineral and occurs as tabular, white to light-pink crystals in a quartz-albite matrix, varying in size between 1 and 10 cm (Fig. 9D, E). Minor montebrasite, lithiophilite, eucryptite (late-stage alteration), and local intervals rich in yellow-green mica are also present. Apart from the clear vertical zonation showing progressive albitization and kaolinization toward the surface, the deeper LCT pegmatites appear internally unzoned. The Musha-Ntunga pegmatites show macro- and microscopic evidence of intense shearing and deformation, with boudinaged spodumene crystals, sigma clasts ("spodumene fish"), and quartz grain boundary migration (Acke et al., in press).

Burundi: In Burundi, the only reported spodumene occurrence is at the N'dora pegmatite in Northern Burundi, which was formerly exploited for cassiterite and CGMs. The N'dora pegmatite occurs together with numerous muscovite-tourmaline pegmatites and quartz-muscovite veins (Fransolet and Tack, 1990). Reported lithium minerals include spodumene, lepidolite, and montebrasite-amblygonite. Other minerals reported from this locality include albite (cleavelandite), tourmaline, wavellite, cassiterite, CGMs, fluorapatite, quartz, K-feldspar, and kaolinite.

Zimbabwe: The Kamativi pegmatite, in northwestern Zimbabwe, was mined for tin from 1936 to 1994, but lithium minerals were never extracted. It is one of a number of large tin-bearing pegmatites in western Zimbabwe that are hosted by the Dete-Kamativi inlier (Fig. 4). The inlier is a roughly NE-SW–trending belt of Precambrian metamorphic rocks, surrounded by Mesozoic sedimentary rocks and Cenozoic aeolian sands (Lockett, 1979). It comprises Archaean orthogneisses (ca. 2700 Ma), Paleoproterozoic granitoids (2080–2010 Ma), and a Paleoproterozoic metasedimentary sequence that has been strongly deformed and metamorphosed to amphibolite and granulite facies during the ca. 2000 Ma Magondi orogeny (Master et al., 2010; Glynn et al., 2020). Subsequently, a lower-pressure amphibolite facies metamorphism has been identified at ca. 1060 Ma (Mandingaisa et al., 2022). The pegmatites at Kamativi have been dated at ca. 1030 Ma (Melcher et al., 2015; Glynn et al., 2017).

The pegmatites in the Kamativi region are largely hosted by muscovite and biotite schists and psammites that commonly contain accessory garnet and tourmaline (Lockett, 1979). There are two groups of pegmatites in the Kamativi region: (1) barren tourmaline pegmatites that are up to a few meters thick and typically strike and dip parallel to the country-rock foliation and (2) large (up to 40 m thick), flat-lying cassiterite-pegmatites that crosscut the host-rock fabric, including the main Kamativi pegmatite (Rijks and van der Veen, 1972; Shaw et al., 2022). The Kamativi pegmatite is a thick (~40 m) gently domed sheeted intrusion. It does not show a classic internal zonation, although it has ~50-cm-thick barren border zones that lack lithium minerals. Within the main body of the pegmatite, there is a crude margin-parallel banding defined by grain size; coarser-grained bands are dominated by spodumene, alkali feldspar, and quartz, whereas finer-grained (aplitic) bands are very albite rich (Shaw et al., 2022). The main lithium mineral is spodumene, but montebrasite also occurs in relatively small amounts. Columbite group minerals and cassiterite are typically associated with zones of albitization. Four main paragenetic stages have been identified in the Kamativi pegmatite: (1) a primary assemblage of spodumene, alkali feldspar, quartz, and montebrasite, (2) albitization (Fig. 5C), (3) greisenization and the formation of a quartz-muscovite assemblage, and (4) widespread lower-temperature alteration leading to the formation of cookeite, analcime, sericite, and apatite (Shaw et al., 2022).

Orange River pegmatite belt, South Africa and Namibia: The Orange River pegmatite belt in the Northern Cape of South Africa is an arcuate 50-km-wide belt that extends east-west along the border with Namibia (Fig. 10). The Orange River pegmatite belt comprises more than 30,000 pegmatites intruded into the Mesoproterozoic Namaqua-Natal mobile belt, which was accreted to the Kaapvaal craton between ca. 1.2 and 1 Ga during the formation of the supercontinent Rodinia (Thomas et al., 1994a; Eglington, 2006). Recent studies indicate that the pegmatites were emplaced over an 80 m.y. period between ca. 1040 and 960 Ma, after the peak of metamorphism and granitic magmatism (Doggart, 2019).

The pegmatite belt shows a broad regional zonation with the economically important lithium pegmatites at both the western end in the Steinkopf-Vioolsdrif area and in the eastern extremity of the belt, whereas the central part is dominated by the less economically important complex NYF pegmatites (Hugo, 1970; Schutte, 1972; Minnaar and Theart, 2006). Intermittent mining of the pegmatites of the Orange River pegmatite belt for beryl, CGMs, and lithium minerals dates from the beginning of the 1900s. When industrial minerals such as mica became important, extraction focused on these until more recently when feldspar became the main mined mineral (Minnaar and Theart, 2006). Only recently has lithium become the main priority for exploration (von der Heyden et al., 2023).

Pegmatites within the Orange River pegmatite belt are variably zoned; some have a massive quartz core with perthite, an intermediate zone, a wall zone, and a border zone, whereas homogeneous bodies comprising quartz, feldspar, mica, and accessory minerals are generally much larger than the zoned

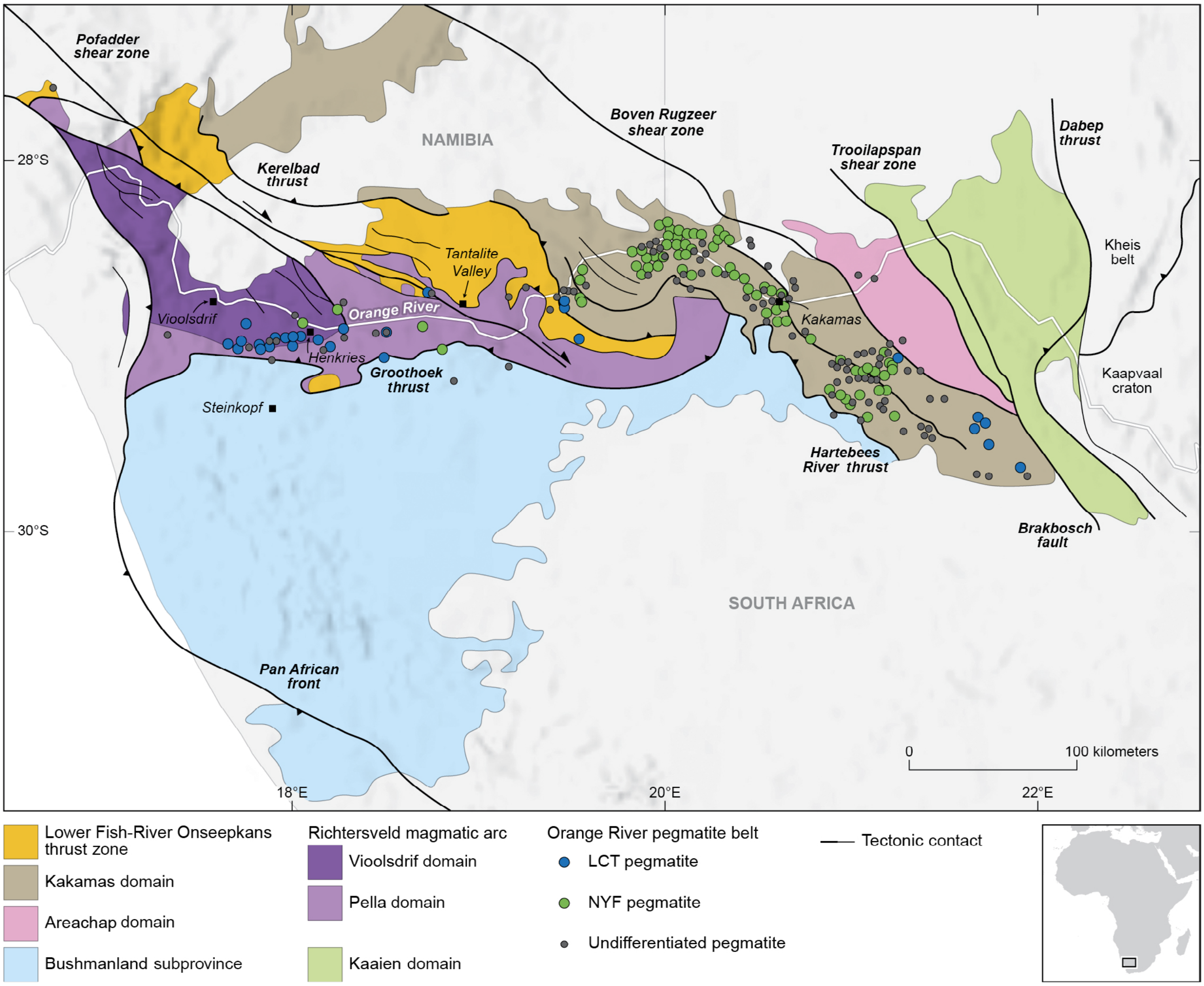

Fig. 10. Map of the Orange River pegmatite belt after Ballouard et al. (2020). Abbreviations: LCT = lithium-cesium-tantalum, NYF = niobium-yttrium-fluorine.

bodies (Thomas et al., 1994b; Minnaar and Theart, 2006). The pegmatites range from only a few centimeters in extent to more than 3 km in length and about 100 m in width. Lithium-bearing minerals are distributed sporadically throughout the pegmatite belt and are dominated by lepidolite and spodumene, with very minor lithiophilite and triphylite, which are typically altered to dark manganese-iron oxides.

The Vioolsdrif-Henkries area in the west of the Orange River pegmatite belt hosts a broadly east-west zone with numerous lithium pegmatites hosted by granitoids. The pegmatites contain abundant lithium minerals (spodumene and/or lepidolite), plus beryl, tourmaline, and rare earth element phosphates and have been producers of feldspar, mica, beryl, spodumene, CGMs, and Bi-bearing minerals in the past. Of these, the Noumas I pegmatite (Blesberg mine) ~15 km south of Vioolsdrif is the largest known heterogeneous complex mineralized pegmatite in the belt (Schutte, 1972). It has been well exposed by previous mining operations, and Marula Mining PLC exported their first spodumene concentrate from the mine in 2024. The dike-like pegmatite body is ~1 km long and up to 40 m wide and strikes northwest and dips 50° to 80° south-southwest. It is discordantly emplaced into foliated granodiorite. It comprises quartz, K-feldspar, and mica, with minor plagioclase and accessory spodumene, apatite, beryl, garnet, CGMs, microlite, gummite, orangite, phosphates such as triplite and lithiophilite, native bismuth, and a variety of bismuth minerals such as bismite, bismutite, and bismuto-sphalerite (Minnaar, 2006). The pegmatite is also the type locality of bismoclite (BiOCl), which was first described from here in 1935 (Mountain, 1935). The pegmatite is variably zoned (Schutte, 1972; Ballouard et al., 2020), with (1) a fine-grained aplitic border zone 1 to 15 cm wide comprising alkali feldspar, saccharoidal plagioclase, quartz, and muscovite with minor CGMs, zircon, garnet, and apatite, (2) a 1- to 6-m-thick wall zone that has muscovite, microcline-perthite, quartz, and cleavelandite, with accessory beryl, bismuth minerals, apatite, garnet, and triplite, (3) an intermediate zone that contains quartz, alkali feldspar, plagioclase, beryl, and CGMs with green, pink, or white spodumene, and (4) a core zone that comprises milky white anhedral quartz and large subhedral crystals of microcline perthite. Locally the distinction of individual zones is unclear, such that the wall zone and intermediate zone merge to form a relatively homogeneous pegmatite. Saccharoidal albite forms irregular lenses, veinlets, and patches within the pegmatite. Fracture-filling lenses close to the contact between the wall zone and intermediate zone comprise garnet and muscovite with subordinate smoky quartz, Bi minerals, and U (Th-, Pb-, Cu-rich) phosphates, such as torbernite and plumbogummite (Ballouard et al., 2020). Secondary greisenization is recognized between the wall and intermediate zones and close to the contact with country rock.

Numerous other pegmatites with lithium mineralization occur in the area (Minnaar, 2006). Many of these show a similar, weakly developed type of internal zonation with a quartzofeldspathic wall zone, an intermediate zone containing quartz, albite, spodumene, beryl, and CGMs, and a quartz-rich core zone. Other lithium minerals that may occur in these pegmatites include amblygonite, lepidolite, and lithiophilite.

In the Norabees area close to Henkries there is a swarm of N-S–striking inhomogeneous pegmatite dikes containing spodumene and beryl that crosscut the foliation of the host metagranodiorite (Ballouard et al., 2020). The most economically important of these is Norrabees I, although pegmatites II, III, IV and VI are all noted to include spodumene (Minnaar, 2006). These pegmatites represent the greatest concentration of lithium minerals in South Africa (Gevers et al., 1937), and most of them have been mined previously for beryl and spodumene. The Norabees I pegmatite varies in width between 7 and 25 m, extends >100 m, strikes north-south, and dips ~60°W. It has a wall zone 2 to 8 m wide dominated by quartz, plagioclase, biotite, muscovite, green spodumene, tourmaline, garnet, and beryl; an intermediate zone consisting of albite, quartz, lepidolite, spodumene, and watermelon tourmaline (Gevers, 1937); and a quartz microcline-perthite core with perthite embedded in massive white quartz (Ballouard et al., 2020).

Farther east, the LCT pegmatites of the Kakamas-Kenhardt area host economic muscovite, feldspar, beryl, spodumene, CGMs, cassiterite, and Bi-bearing minerals (Hugo, 1970). Spodumene has only been documented in three of the many pegmatites, Straussheim 1 and 2 and Angelierspan 3, all of which also carry beryl; the Straussheim pegmatites are also host to cassiterite. In all three, spodumene is associated with albite, quartz, and muscovite in the intermediate zones close to the cores, although some spodumene was found dispersed in the quartz-rich parts of the cores. Fresh spodumene is white, cream, or pale green (Hugo, 1970). It typically forms subhedral, lathlike crystals that are deeply striated and from 5 cm to 2 m in length. Spodumene is locally replaced by albite and by clay minerals (Hugo, 1970).

The Orange River pegmatite belt extends into Namibia, in an area to the north of Henkries known as Tantalite Valley. Here, spodumene-bearing pegmatites up to 1 km long and >10 m thick intrude mafic-ultramafic rocks. The pegmatites contain spodumene, lepidolite, amblygonite, beryl, and CGMs (Melcher et al., 2015). These pegmatites were historically mined, chiefly for tantalum.

On the eastern side of the Namaqua-Natal belt, close to Port Shepstone, the spodumene-bearing Highbury pegmatite was only recognized in the 1990s (Thomas et al., 1994b). The pegmatites form a stack of sills, typically 1 to 15 m thick, and have been emplaced subconcordantly into a klippe of granulite facies mafic rocks. The pegmatites contain quartz, alkali feldspar, spodumene, and some garnet; spodumene typically occurs intergrown with quartz as SQI, and albitization is variable and extensive (Thomas et al., 1994b).

Neoproterozoic-Paleozoic (Pan-African)

Neoproterozoic to Cambrian orogenic belts form a network that extends across much of the African continent (and hence has been referred to as Pan-African). These belts also extend into South America, where they are referred to as Brasiliano orogenic belts. Pegmatites are common in many of these orogenic belts, but the most economic, unzoned, spodumene-rich lithium pegmatites are less well-known in Africa. Pegmatites of this age also occur in the Eastern Brazilian pegmatite province (Pedrosa-Soares et al., 2011), where both gem-bearing and unzoned spodumene pegmatites occur and are currently mined.

Madagascar and Mozambique: Madagascar and Mozambique are well-known for their gem-bearing pegmatites, with a variety of pegmatite fields producing beryl, tourmalines, amazonite, and emeralds, including those intruded into the Paleoproterozoic Itremo Group of central Madagascar (Pezzotta, 2001, 2005). These pegmatites have typically been described as mixed NYF and LCT pegmatites, and they locally do contain some spodumene and lepidolite in patchy and irregular zones (De Vito et al., 2006; Gadas et al., 2023). Pegmatites in this area of Madagascar have been explored for lithium (for example at the Millie's Reward deposit), but classic unzoned spodumene pegmatites of the type that are being developed as mines elsewhere in the world have not been described.

In Mozambique, pegmatites of the Alto Ligonha pegmatite province have been dated at 480 to 440 Ma (Melcher et al., 2015). These pegmatites are not described in detail in recent literature, but the Muiane, Mutala, Morrua, and Marropino pegmatites have been described as highly mineralized in lithium (Von Knorring and Condliffe, 1987) with spodumene and lepidolite in their cores. These are large pegmatites, some up to 100 m thick, typically forming tabular, gently dipping sill- or lens-like bodies with sharp contacts with their host rocks (Hutchinson and Claus, 1956). They are described as having outer zones dominated by quartz, feldspar, and muscovite; a variable intermediate zone that contains quartz, muscovite, spodumene, lepidolite, albite, and rarer amblygonite; and a quartz core (Hutchinson and Claus, 1956). Spodumene is typically highly altered to clays. The pegmatites were historically mined for CGMs (Melcher et al., 2017).

Nigeria: Nigeria lies within a wide Pan-African belt that separates the West African and Congo cratons. The basement of central Nigeria is characterized by extensive Neoproterozoic granitoid plutons, intruded into metasedimentary host rocks, with abundant pegmatites that are exploited by artisanal miners (Goodenough et al., 2014). These are typically complex pegmatites, often only a few meters thick, with a clear zonation, as exemplified by those described from the Angwan Doka area. Unmineralized border and wall zones pass into an intermediate zone that comprises quartz, K-feldspar, muscovite, albite, and patchy areas rich in beryl, lepidolite, spodumene, cassiterite, CGMs, and phosphates (Akoh et al., 2015). Similar pegmatites have been described from several other areas in Nigeria (Küster, 1990; Chukwu and Obiora, 2021), but no unzoned spodumene pegmatites have been identified.

Namibia: A variety of syn- and post-tectonic granitic pegmatites occur within the Northern, Central and Southern zones of the Damara orogen in Namibia (Miller et al., 2009) including NYF and LCT pegmatite types that range from distinctly zoned to completely homogeneous (Keller et al., 1999). Richards (1986) argued that the pegmatites of the Damara belt span the entire syn- to post-tectonic history, whereas others suggest that they are predominantly post-tectonic in age (Kinnaird and Nex, 2007; Ashworth, 2014; Ashworth et al., 2018; Fuchsloch et al., 2018). It is, however, generally accepted that they represent the youngest magmatism in the orogen, being the last phase of granitic magma to crystallize, regardless of when the first pegmatite intrusion occurred. Age dating, albeit limited, suggests intrusion between 520 and 490 Ma (Diehl, 1993a; Longridge, 2013; Melcher et al., 2015). Several major pegmatitic belts have been recognized across the Damara belt (Fig. 11), including a wide variety of pegmatites from barren, NYF, and gem-tourmaline pegmatites that are not discussed further here, to lithium pegmatites. The lithium pegmatites can be broadly divided into two groups: (1) large, unzoned, tin-rich pegmatites with minor tantalum, niobium, and local lithium mineralization in the Cape Cross-Uis, Nainais-Kahero, and Sandamap-Kranzberg pegmatite belts and (2) large, zoned Li-Be pegmatites including those in the Rubicon-Helicon belt, De Rust in the Ugab belt, and the Petalite pegmatite in the Cape Cross-Uis belt.

The northernmost of the pegmatite belts is the Ugab belt, where a number of tin-tantalum–bearing pegmatites (Fig. 11) intrude turbiditic metasedimentary rocks of the Southern Kaoko zone. The pegmatites have a dominantly north-northeasterly strike, which crosscuts the metasedimentary fabric. The belt stretches over a length of 60 km and is 25 km wide. This belt was previously mined for cassiterite and CGMs, but some of the pegmatites in this belt carry substantial amounts of lithium, such as those of the De Rust pegmatite swarm. The pegmatites include several bodies that vary in length up to 470 m. The bodies have undergone late-stage hydrothermal alteration of the original magmatic mineralogy and cassiterite-columbite group mineralization is more concentrated in these replacement zones.

The De Rust pegmatite, which is situated ~2.5 km north of the Ugab River, is a weakly zoned spodumene-amblygonite-cassiterite-CGM body (Diehl, 1993b). An approximately 5-cm-wide border zone grades into an outer intermediate zone dominated by quartz, with microcline-perthite that is partially albitized, gray-green muscovite, and grains of altered petalite. Cassiterite and traces of fine disseminated CGMs are associated with the albitized patches of the pegmatite. The inner intermediate zone is coarse grained and quartzofeldspathic, with large spodumene crystals up to 1 m in length and accessory blue apatite, lepidolite, eucryptite, zircon, and monazite. The alkali feldspars are intensely albitized, and locally patches of pure white albitite host accessory cassiterite and CGMs. Toward the core zone spodumene is symplectically intergrown with quartz and is hosted by rounded nodules of lithium phosphates of the amblygonite-montebrasite series. The elongate lenticular core zone consists mainly of quartz with subordinate perthitic feldspar and muscovite. The De

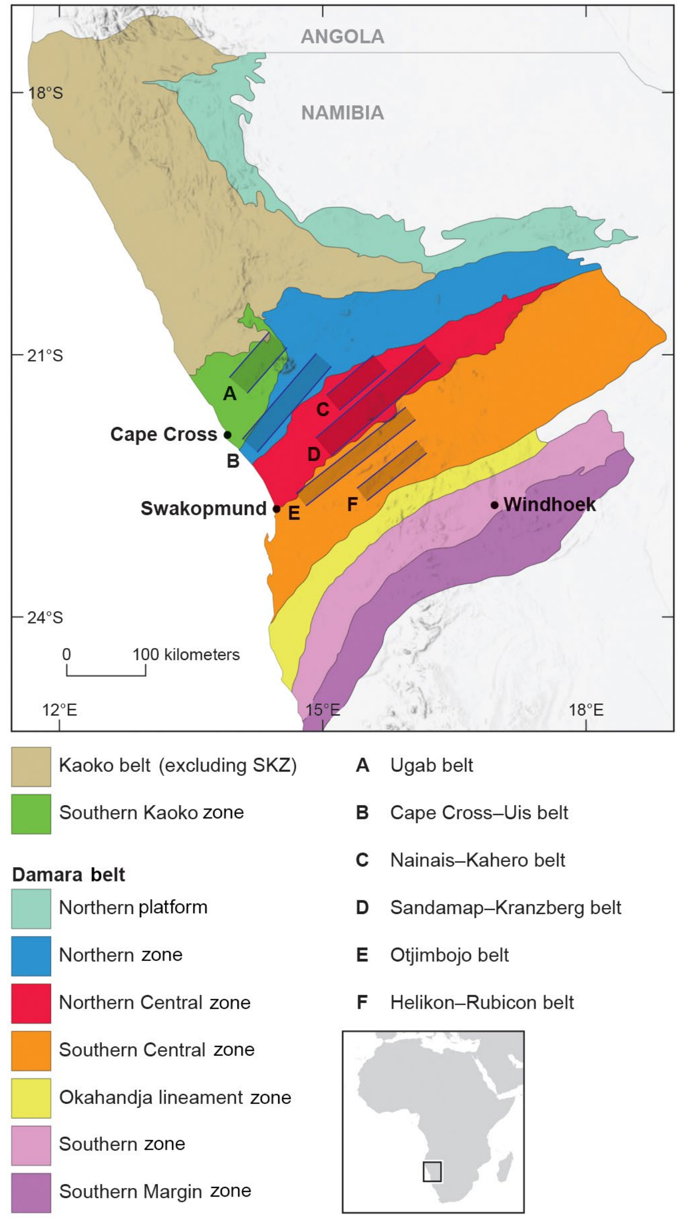

Fig. 11. The main pegmatite belts of the Damara orogen in Namibia after Fuchsloch et al. (2018). Abbreviation: SKZ = Southern Kaoko zone.

Rust pegmatite was mined on a small scale for CGMs and cassiterite from 1960 to 1990.

The Cape Cross-Uis pegmatite belt trends northeast and is 40 km wide and 120 km long (Fig. 11). The pegmatites are postorogenic and cut across the fabric of their host rocks. They may be simple or complexly zoned, barren to rare element bearing, dike-like to lensoidal, and range in width from small stringers to bodies more than 50 m wide. The belt is divided into three pegmatite swarms: (1) the southwest Strathmore with complexly zoned Li-Ta-Nb-Sn-Be petalite-bearing pegmatites, including the Petalite pegmatite, (2) the Li-Nb-Ta–rich Karlowa pegmatites with spodumene as the dominant Li mineral, and (3) the Uis swarms that are more enriched in cassiterite but contain minor lithium minerals (Diehl, 1993a;

Fuchsloch et al., 2018). Some of these pegmatites have been mined for Li, Nb, Sn, and Ta.

The Strathmore swarm is host to more than 180 rare metal pegmatites up to several hundred meters long and 60 m wide, dominantly rich in Nb-Ta-Sn but more rarely Li. The most complex pegmatite in the belt is the Li-Nb-Ta-Sn-B–bearing Petalite pegmatite, which extends several hundred meters in length and is 60 m wide. It has a north-northeast orientation and dips at 65° to the northwest. Historically this pegmatite was mined for lithium, beryllium, tin, and industrial mica. It shows a crude zoning with a ~1- to 2-m wall zone consisting of mica with a unidirectional solidification texture, fine-grained quartz and apatite, tourmaline, and albite; a greisen zone where the original mineralogy has been completely replaced by new or recrystallized quartz and muscovite with centimetric crystals of tapiolite, cassiterite, and apatite (Fuchsloch et al., 2018); an intermediate zone which makes up 60% of the pegmatite volumetrically; and an ~70-m-long core zone. The intermediate zone is thicker in the northwest and comprises variably perthitic alkali feldspar, quartz, beryl, petalite, apatite, tourmaline, hectorite, albite, and eucryptite. Beryl occurs rarely at the contact between the intermediate and wall zone.

The Karlowa swarm is smaller than the other swarms and most of the pegmatites are unzoned or very weakly zoned. Mineralogy is dominated by quartz, albite, and Li-rich muscovite with accessory phases including Li aluminosilicates, CGMs, and cassiterite—the latter most prominently developed in greisens. Pegmatites of this swarm have spodumene as the dominant Li mineral instead of petalite but are typically strongly albitized and greisenized.

The Uis pegmatite swarm covers an area of approximately 650 km^2 and contains several hundred individual unzoned pegmatites cropping out at surface, each with a northeast-east strike and dip of 30° to 70° northwest. Some of the main pegmatites are up to 1 km long and ~60 m wide, although this is not easy to assess at surface, as individual bodies may bifurcate and change orientation with depth and/or along strike. The pegmatites intrude perpendicular to bedding in their host metasedimentary rocks, are all roughly sigmoidal in shape, and lack conspicuous zoning (Richards, 1986; Diehl, 1993a; Fuchsloch et al., 2018). The major minerals are primarily alkali feldspar (perthite/microcline), albite, quartz, and muscovite, with extensive albitization and greisenization (Fuchsloch et al., 2018). Accessory phases include cassiterite, CGMs, garnet, tourmaline, topaz, apatite, beryl, zircon, and monazite plus localized petalite, amblygonite, montebrasite, and cookeite. Andrada Mining (formerly Afritin) operates the Uis mine, where the V1-V2 pegmatite is currently producing tin, lithium, and tantalum. Near-mine exploration at Nai-Nais (Lithium Ridge) and Spodumene Hill has noted the presence of petalite, spodumene, and lepidolite (Fig. 5D).

The most significant Li-Cs-Be-Rb pegmatites in the Rubicon-Helicon belt are those southeast of Karibib—the zoned Rubicon and Helicon pegmatites. From the 1930s they were mined for beryl and then from 1951 for Li, Cs, Be, and Ta. More recently they were worked for quartz but are now being redeveloped for lithium production. These pegmatites have been dated at 505.5 ± 2.6 Ma by U-Pb isotope dilution-thermal ionization mass spectrometry (ID-TIMS) on CGMs (Melcher et al., 2015), whereas the host Okongava monzodiorite (ca. 540 Ma) is significantly older (Jung et al., 2002).

The Rubicon pegmatite consists of two, ellipsoidal, well-zoned, Li-mineralized orebodies developed around two quartz cores that extend along the same strike (Roering, 1966). The two main bodies form a ridge, which strikes northwest and dips between 20° and 65° northeast (Ashworth, 2014). Together, they measure about 700 m in length and each have a width of 25 to 35 m (Roering, 1963). The main lithium orebody measures approximately 320 m in length and 25 to 35 m in width. The pegmatite is asymmetrically zoned (Fig. 5E), and dips vary on either side of the pit: on the east side zones dip 65° to the northeast, whereas in the western wall of the pit the zones dip ~40° to the southwest. The mapped zonation differs slightly between that mapped by Roering (1963), Diehl and Schneider (1990), and Ashworth (2014). The latter recognizes seven zones: (1) a thin fine-grained Border zone a few centimeters thick consisting of quartz, perthite, and garnet, (2) the Wall zone, which is generally a few meters thick and has quartz, muscovite, schörl tourmaline, and spessartine together in an albite-rich matrix, (3) the Intermediate zone comprising quartz, Li muscovite, lepidolite, microcline-perthite, albite, accessory beryl, apatite, and Li phosphates, (4) the Perthite zone, which varies in thickness and may consist of pure perthite with individual crystals up to 1 × 3 m in size or a mix of microcline-perthite, quartz, Li muscovite, lepidolite, and albite, with accessory pale-green to white beryl, apatite, and Li phosphates, (5) the 1- to 2-m-thick Beryl zone, which contains abundant albite, lithian muscovite, quartz, lepidolite, microcline perthite, and apatite, with white to bluish-green beryl aggregates, (6) the Petalite zone, which is 0.2 to 6 m thick with an assemblage of petalite, albite, perthite, lepidolite, amblygonite, beryl, and subordinate quartz, with accessory columbite, apatite, fluorite, amblygonite, bismuth, and Li phosphates, and (7) the Lepidolite zone, which is ≥10 m in width and characterized by pink to purple lepidolite, albite, quartz, amblygonite, and petalite.

The Helicon pegmatite group occurs about 7 km north-northeast of Rubicon. The group comprises a series of outcrops along an east-west strike (Fowler et al., 2018) with a dip between 43° and 89° north, cutting marbles and schists. Helicon I, the largest body, has been mined for lepidolite, amblygonite, petalite, and mica, with beryl, pollucite, quartz, and CGMs as minor by-products. It is elongate, lens shaped, and asymmetrically zoned, about 400 m long and 66 m wide, dipping 60° to 70° north. It cuts schist and marble of the Karibib Formation that strike east-west and dip southward at 45° to 55°. It has a wall zone that is ~4 m thick and is composed predominantly of albite, quartz, and muscovite with accessory perthite, garnet, rare beryl, blue tourmaline, and CGMs. Albite, the major constituent, is larger than other minerals, with some crystals up to 70 cm long. Muscovite crystals are large (>3 cm), forming radiating fans, whereas blue tourmaline crystals have an acicular habit and form radiating blades 2 to 15 cm long. The Intermediate zone is ~4.5 m wide and comprises intergrown quartz and albite and large petalite crystals ≤30 cm long. The Lepidolite zone is ~20 m wide and is characterized by locally banded albite, quartz, lepidolite, and zinnwaldite, with accessory muscovite, CGMs, white beryl, amblygonite, and blue and pink tourmaline (Fig. 5F). A beryl zone, about 40 cm thick, occurs as a footwall on the south side of the quartz core. It comprises albite often as radiating crystals, massive lepidolite, and whitish beryl crystals several centimeters in diameter. According to Roering (1963), crystals of columbite <20 cm in size were extracted from this zone.

Ethiopia: The Kenticha pegmatite field of Ethiopia contains a variety of pegmatites, intruding Neoproterozoic rocks of the Arabian-Nubian Shield. It includes a number of complexly zoned spodumene-bearing pegmatites, with the most well-known being the main Kenticha pegmatite (Küster et al., 2009). This is a flat-lying, moderately E-dipping intrusion, exposed over more than 2 km length and varying from 40 to 100 m in thickness. It has been divided into lower, intermediate, and upper zones, with the most voluminous upper zone composed of a coarse-grained muscovite-quartz-albite-microcline-spodumene pegmatite assemblage (Küster et al., 2009). Spodumene crystals may be up to 4 m in length, and albitization and greisenization are common. The main Kenticha pegmatite thus has many characteristics similar to an unzoned spodumene pegmatite.

Paleozoic (Variscan) pegmatites of North Africa

To the north of the West African craton, the most promising lithium pegmatites are Variscan in age. They crop out in the Moroccan Meseta, which represents the southern prolongation of the European Variscides. They were formed in a post-collisional setting (Essaifi et al., 2014) similar to that of the lithium pegmatites of the Variscan in Europe (Roda-Robles et al., 2018). Hundreds of pegmatite bodies have been identified and mapped by Huvelin (1977) in the Sidi Bou-Othmane region, where they form a subvertical dike swarm intruding Devonian to Carboniferous mica schists that were deformed during the Variscan orogeny. The thickness of the pegmatites ranges from a few centimeters to 4 to 5 m, and their extension can reach several hundreds of meters. The dikes display pegmatitic and aplitic textures, rhythmic layering, and abundant unidirectional solidification textures, including pseudographic intergrowths. Their main minerals are quartz, feldspars, and muscovite, whereas the accessory minerals include schorl, garnet, CGMs, lepidolite, elbaite, cassiterite, fluorapatite, and phosphates of the amblygonite-montebrasite series. Based on the abundance of the accessory minerals, different types of pegmatites are distinguished (Erraji et al., 2024). They show a zonal distribution marked by an evolution from barren pegmatites (schorl and garnet bearing), through intermediate pegmatites characterized by the abundance of Fe-Mn phosphates, and then to fertile pegmatites that contain Li-rich minerals including ferrisicklerite, montebrasite, lepidolite, and elbaite.

Africa's Lithium Pegmatites: Paragenesis and Evolution with Time

As the descriptions above show, the continent of Africa is rich in lithium pegmatites, which were formed in the waning stages of orogenic events during five main time periods: the Neoarchaean, the Paleoproterozoic (in West Africa), the Mesoproterozoic (in Central Africa), the Neoproterozoic to Cambrian, and the Paleozoic (in North Africa). Across all these time periods, lithium pegmatites are most typically hosted by metasedimentary or metavolcanic rocks and sometimes by granitoid intrusions; they are rarely hosted in TTG gneisses. Lithium pegmatites are characterized by coarse grain sizes and form tabular bodies with sharp contacts against their host rocks, indicating that they were emplaced into rocks that were relatively cool and subjected to undercooling before crystallization began. Thus, whatever their source may have been, they were emplaced at a higher level in the crust than where the melt was formed. Many lithium pegmatites occur close to major structural features such as shear zones, which may represent pathways for magma movement through the crust (Plunder et al., 2022; Silva et al., 2023).

Some of Africa's lithium pegmatites are characterized by a classic zonation with border, wall, intermediate, and core zones, but many, including some of the most economic, are unzoned spodumene pegmatites, which are more common than previously thought (London, 2018). The unzoned spodumene pegmatites commonly exhibit at least some, if not all four, of the expected paragenetic stages (magmatic crystallization, albitization, greisenization, and low-temperature alteration; Fig. 12) (Ballouard et al., 2020; Shaw et al., 2022; Acke et al., in press). In many cases, these alteration stages may give a pegmatite an appearance of irregular zoning, and it can sometimes be challenging to distinguish literature descriptions of true zoned pegmatites from those that show irregular albitization and greisenization.

Our firsthand knowledge of these pegmatites has allowed us to recognize that each of the five orogenic events mentioned below has its own lithium pegmatite fingerprint.

1. Archaean pegmatites commonly have petalite as a magmatic mineral (although variably replaced by SQI). This is consistent with pegmatites emplaced at relatively shallow depths but with higher crustal temperatures due to higher geotherms in the Archaean. Archaean pegmatites may show zonation, but this is commonly patchy and irregular.
2. Paleoproterozoic lithium pegmatites in the Birimian of West Africa are most typically variably albitized, unzoned spodumene pegmatites, with spodumene growing from the pegmatite margin. Notably, many of these pegmatites are also relatively phosphate rich but have relatively low contents of boron- and fluorine-rich minerals. However, the region is poorly explored because of extensive lateritization and a predominant exploration focus on gold. This is potentially one of the most prospective regions for lithium pegmatite exploration in Africa.
3. Mesoproterozoic lithium pegmatites extend from Rwanda, Burundi, and DRC to northern Zimbabwe and Namibia. These include some very large intrusions, most notably the Manono-Kitotolo pegmatites. These are typically weakly zoned pegmatites, which may have a thin border zone and a quartz core, but are dominantly made up of a spodumene-bearing intermediate zone. They can be highly albitized and may be rich in columbite and cassiterite group minerals associated with the albitization (Fig. 12), thus being exploited for tin or tantalum rather than lithium.
4. Neoproterozoic to Paleozoic (Pan-African and Variscan) lithium pegmatites are typically much more distinctly zoned (complex pegmatites) than those in older orogens. Many are gem bearing, and a wide range of lithium minerals may occur, including petalite, spodumene, amblygonite, lepidolite, and others. However, these typically only occur

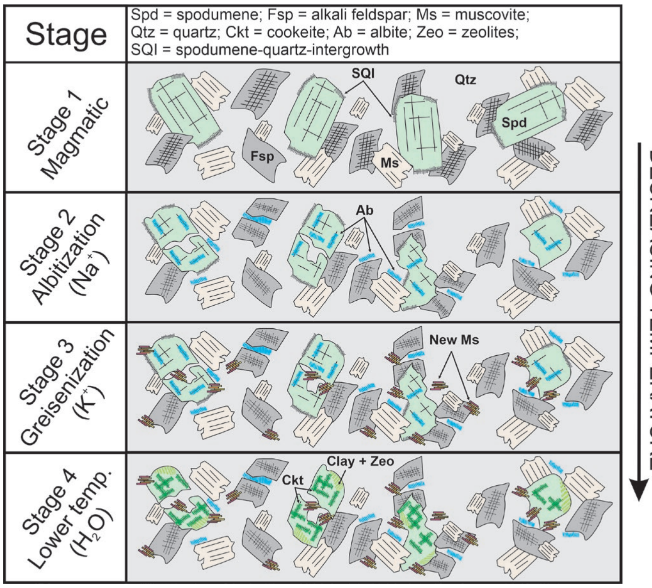

Fig. 12. Schematic illustration of the main stages of lithium pegmatite evolution and paragenesis.

in distinct zones within the pegmatite. Tourmaline is also a common mineral. Thus, these pegmatites have evidence of enrichment in B, F, and P, but are perhaps less enriched in Li than some of the older pegmatites.

The controls on formation of these different pegmatite types remain to be understood. As described in the "Lithium Pegmatites" section, recent research is moving away from simplistic end-member models and demonstrating that lithium pegmatite formation is likely related to a complex crustal magmatic system in which variable degrees of melting of a fertile (likely metasedimentary) source are followed by the accumulation of melts at varying levels in the crust, with further evolution by fractional crystallization or crystallization and remelting (Knoll et al., 2023; Koopmans et al., 2023). Thus, potential controls on pegmatite composition include available sources for melting, conditions and thus degrees of melting, crustal residence time of melts, and conditions of emplacement. These controls will all be interrelated; for example, a source that has higher contents of fluxing elements such as B or F will create more volatile-rich melts, allowing them to travel farther through the crust and be emplaced at shallow levels with high degrees of undercooling, supporting the development of complex pegmatites.

It is interesting to note that elsewhere in the world (Canada, Australia), many of the largest and most economically important lithium pegmatites are Archaean and spodumene dominated (McCauley and Bradley, 2014; Groves et al., 2022). In contrast, the main known Archaean pegmatites in Africa are those of Zimbabwe, where petalite predominated as a magmatic mineral. Features recognized in the Neoproterozoic to Paleozoic pegmatites of Africa can be correlated across those orogens, even into other continents; for example, the Pan-African pegmatites show features similar to those of examples in Brazil, where zoned lithium pegmatites, often gem bearing, and unzoned spodumene pegmatites occur in the same region (Pedrosa-Soares et al., 2011). There are also some features that appear to have a geographical rather than temporal control; for example, all generations of lithium pegmatites in the West African craton are rich in phosphate.

Therefore, our review supports the work of others (Černý et al., 2012) in proposing that the ultimate control on the distribution, and lithium enrichment, of pegmatites lies in the source; but rather than considering a granitic magma, it is necessary to look back to the original (most commonly metasedimentary) material that was melted. The chemistry of this source, and the melts that it produces, may have been affected at the time by climatic and tectonic conditions (Romer and Kroner, 2016), which will in turn affect the development of the magmatic system and the eventual type of pegmatite that forms. Lithium pegmatites are the end point of a complex system, and development of their mineral deposit model requires a full understanding of the wider geologic context in which they were formed.

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REFERENCES

Abdelsalam, M.G., Liégeois, J.-P., and Stern, R.J., 2002, The Saharan metacraton: Journal of African Earth Sciences, v. 34, p. 119–136.
Acke, J., Dewaele, S., Barros, R., et al., in press, Magmatic, magmatic-hydrothermal, and deformational mineral evolution of spodumene pegmatites from the Musha-Ntunga area (Rwanda): Economic Geology.
Adams, S.J., Van Lichtervelde, M., Amponsah, P.O., Nude, P.M., Asiedu, D.K., and Dampare, S.B., 2023, Characterisation and rare-metal potential

of the Winneba-Mankoadze pegmatites, southern Ghana: Evidence of two pegmatite fields: Journal of African Earth Sciences, v. 207, article 105049.

Adingra, M.P.K., Ouattara, Z., Boya, T.K.L.D., Yapo, A.J., Brou, K.J., and Kouassi, B.R., 2023, Petrography and geochemical signatures of pegmatites from the southeastern part Comoé basin (south-east Côte d'Ivoire, North Alépé): Journal of Geography, Environment and Earth Science International, v. 27, p. 51–68.

Ahmed, Y., Attourabi, S.A., Hallarou, M.M., Chamsi, L.I., Noura, G.R., and Sanda Chékaraou, M.M., 2023, Relationship between regional deformation and the emplacement of the Dibilo pegmatites (Liptako, West Niger): Journal of African Earth Sciences, v. 198, article 104814.

Akoh, J.U., Ogunleye, P.O., and Ibrahim, A.A., 2015, Geochemical evolution of micas and Sn-, Nb-, Ta- mineralization associated with the rare metal pegmatite in Angwan Doka, central Nigeria: Journal of African Earth Sciences, v. 112, p. 24–36.

Al-Jawad, J., Ford, J., Petavratzi, E., and Hughes, A., 2024, Understanding the spatial variation in lithium concentration of high Andean Salars using diagnostic factors: Science of the Total Environment, v. 906, article 167647.

Allou, B.A., Lu, H.-Z., Guha, et al., 2005, Une corrélation génétique entre les Roches granitiques, et les Dépôts Éluvionnaires, colluvionnaires et alluvionnaires de columbo-tantalite d'Issia, Centre-Ouest de la Côte d'Ivoire: Exploration and Mining Geology, v. 14, p. 61–77.

Angrand, P., and Mouthereau, F., 2021, Evolution of the Alpine orogenic belts in the Western Mediterranean region as resolved by the kinematics of the Europe-Africa diffuse plate boundary: Bulletin de la Société Géologique de France, v. 192, article 42.

Ashworth, L., 2014, Mineralised pegmatites of the Damara belt, Namibia: Fluid inclusion and geochemical characteristics with implications for post-collisional mineralisation: Ph.D. thesis, Johannesburg, University of the Witwatersrand.

Ashworth, L., Kinnaird, J.A., Nex, P.A.M., Erasmus, R.M., and Przybyłowicz, W.J., 2018, Characterization of fluid inclusions from mineralized pegmatites of the Damara belt, Namibia: Insight into late-stage fluid evolution and implications for mineralization: Mineralogy and Petrology, v. 112, p. 753–765.

Attourabi, S.A., Ahmed, Y., and Hallarou, M.M., 2021, Origin and emplacement conditions of the Dibilo lithiniferous mineralization (Liptako, Western Niger): International Journal of Scientific Research, v. 10, p. 55–71.

Attourabi, S.A., Van Lichtervelde, M., Hallarou, M.M., Ahmed, Y., Sanda Chekaraou, M.M., and Abdourhamane Toure, A., 2024, Petrogenetic relationships between Paleoproterozoic granitoids and rare-element pegmatites from Dibilo (Liptako, West Niger, West African craton): Journal of African Earth Sciences, v. 220, article 105440, https://doi.org/10.1016/j.jafrearsci.2024.105440.

Ballouard, C., Elburg, M.A., Tappe, S., Reinke, C., Ueckermann, H., and Doggart, S., 2020, Magmatic-hydrothermal evolution of rare metal pegmatites from the Mesoproterozoic Orange River pegmatite belt (Namaqualand, South Africa): Ore Geology Reviews, v. 116, article 103252.

Barros, R., Kaeter, D., Menuge, J.F., and Škoda, R., 2020, Controls on chemical evolution and rare element enrichment in crystallising albite-spodumene pegmatite and wallrocks: Constraints from mineral chemistry: Lithos, v. 352–353, article 105289.

Bartholomew, D.S., 1990, Base metal and industrial mineral deposits of Zimbabwe: Zimbabwe Geological Survey, Mineral Resources Series, issue 22, 154 p.

Bassot, J.-P., and Morio, M., 1989, Morphologie et mise en place de la pegmatite Kibarienne a Sn, Nb, Ta, Li de Manonon (Zaïre): Chronique de la Recherche Minière, v. 496, p. 41–56.

Bea, F., Montero, P., Anbar, M.A., and Talavera, C., 2011, SHRIMP dating and Nd isotope geology of the Archean terranes of the Uweinat-Kamil inlier, Egypt-Sudan-Libya: Precambrian Research, v. 189, p. 328–346.

Begg, G.C., Griffin, W.L., Natapov, L.M., et al., 2009, The lithospheric architecture of Africa: Seismic tomography, mantle petrology, and tectonic evolution: Geosphere, v. 5, p. 23–50.

Benson, T.R., Coble, M.A., and Dilles, J.H., 2023, Hydrothermal enrichment of lithium in intracaldera illite-bearing claystones: Science Advances, v. 9, article eadh8183.

Bischoff, I., and Bischoff, A.A., 1988, A lithium-bearing pegmatite from the Vredefort dome: South African Journal of Geology, v. 91, p. 550–552.

Block, S., Jessell, M., Aillères, L., et al., 2016, Lower crust exhumation during Paleoproterozoic (Eburnean) orogeny, NW Ghana, West African craton: Interplay of coeval contractional deformation and extensional gravitational collapse: Precambrian Research, v. 274, p. 82–109.

Bonzi, W.M.-E., Van Lichtervelde, M., Vanderhaeghe, O., André-Mayer, A.-S., Salvi, S., and Wenmenga, U., 2023, Insights from mineral trace chemistry on the origin of NYF and mixed LCT + NYF pegmatites and their mineralization at Mangodara, SW Burkina Faso: Mineralium Deposita, v. 58, p. 75–104.

Borst, A., Rodriguez, J.S., Acke, J., and Dewaele, S., 2024, Incremental emplacement of the giant Manono-Kitotolo spodumene pegmatites, Democratic Republic of the Congo: Geological Association of Canada-Mineralogical Association of Canada 10th International Symposium on Granitic Pegmatites (GAC-MAC-PEG) 2024, May 19–22, 2024, Brandon University, Manitoba, Canada, Abstract, https://event.fourwaves.com/gacmac2024/abstracts/3ff6d01b-797b-4e3e-aeb6-a776163a3618.

Bowell, R.J., Lagos, L., de los Hoyos, C.R., and Declercq, J., 2020, Classification and characteristics of natural lithium resources: Elements, v. 16, p. 259–264.

Bradley, D.C., McCauley, A.D., and Stillings, L.L., 2017, Mineral-deposit model for lithium-cesium-tantalum pegmatites: U.S. Geological Survey, Scientific Investigations Report 2010-5070-O, 58 p.

Brou, J.K., Van Lichtervelde, M., Kouamelan, N.A., Baratoux, D., and Thébaud, N., 2022, Petrogenetic relationships between peraluminous granites and Li- Cs-Ta rich pegmatites in south Issia zone (central-west of Côte d'Ivoire): Petrography, mineralogy, geochemistry and zircon U-Pb geochronology: Mineralogy and Petrology, v. 116, p. 443–471.

Buyse, F., Dewaele, S., Boone, M.N., and Cnudde, V., 2024, Contribution of 3D automated mineralogy in unraveling the formation history of Nb-Ta-Sn mineralized LCT pegmatites in the Karagwe-Ankole belt (Central Africa): Geologica Belgica, v. 27, no. 1–2, p. 1–14, https://doi.org/10.20341/GB.2024.001.

Cailteux, J.L.H., and De Putter, T., 2019, The Neoproterozoic Katanga Supergroup (D.R. Congo): State-of-the-art and revisions of the lithostratigraphy, sedimentary basin and geodynamic evolution: Journal of African Earth Sciences, v. 150, p. 522-–31.

Černý, P., 1991, Rare-element granitic pegmatites. Part I: Anatomy and internal evolution of pegmatite deposits: Geoscience Canada, v. 18, p. 49–67.

Černý, P., and Ercit, T.S., 2005, The classification of granitic pegmatites revisited: The Canadian Mineralogist, v. 43, p. 2005–2026.

Černý, P., Anderson, A.J., Tomascak, P.B., and Chapman, R., 2003, Geochemical and morphological features of beryl from the Bikita granitic pegmatite, Zimbabwe: The Canadian Mineralogist, v. 41, p. 1003–1011.

Černý, P., London, D., and Novák, M., 2012, Granitic pegmatites as reflections of their sources: Elements, v. 8, p. 289–294.

Chalokwu, C.I., Ghazi, M.A., and Foord, E.E., 1997, Geochemical characteristics and K□Ar ages of rare-metal bearing pegmatites from the Birimian of southeastern Ghana: Journal of African Earth Sciences, v. 24, p. 1–9.

Chukwu, A., and Obiora, S.C., 2021, Petrology and geochemistry of pegmatites and associated rocks in Wamba areas, northcentral basement complex, Nigeria: Implications for petrogenesis and rare-metal mineralizations: Arabian Journal of Geosciences, v. 14, article 906.

Deberdt, R., and Billon, P.L., 2021, Conflict minerals and battery materials supply chains: A mapping review of responsible sourcing initiatives: The Extractive Industries and Society, v. 8, article 100935.

Debruyne, D., Hulsbosch, N., Van Wilderode, J., Balcaen, L., Vanhaecke, F., and Muchez, P., 2015, Regional geodynamic context for the Mesoproterozoic Kibara belt (KIB) and the Karagwe-Ankole belt: Evidence from geochemistry and isotopes in the KIB: Precambrian Research, v. 264, p. 82–97.

De Clercq, S., Chew, D., O'Sullivan, G., De Putter, T., De Grave, J., and Dewaele, S., 2021, Characterisation and geodynamic setting of the 1 Ga granitoids of the Karagwe-Ankole belt (KAB), Rwanda: Precambrian Research, v. 356, article 106124.

Delor, C., Coueffe, R., Goujou, J.C., Diallo, D.P., Théveniaut, H., Fullgraf, T., Ndiaye, P.M., Dioh, E., Blein, O., Barry, T.M.M., Le Metour, J., Martelet, G., Sergeev, S., and Wemmer, K., 2010, Notice explicative de la carte géologique à 1/200 000 du Sénégal, feuille Saraya-Kédougou Est: Ministere des Mines, Dakar, Senegal.

De Vito, C., Pezzotta, F., Ferrini, V., and Aurisicchio, C., 2006, Nb-Ti-Ta oxides in the gem-mineralized and "hybrid" Anjanabonoina granitic pegmatite, central Madagascar: A record of magmatic and postmagmatic events: The Canadian Mineralogist, v. 44, p. 87–103.

De Waele, B., Johnson, S.P., and Pisarevsky, S.A., 2008, Palaeoproterozoic to Neoproterozoic growth and evolution of the eastern Congo craton: Its role in the Rodinia puzzle: Precambrian Research, v. 160, p. 127–141.

Dewaele, S., Hulsbosch, N., Cryns, Y., Boyce, A., Burgess, R., and Muchez, P., 2016, Geological setting and timing of the world-class Sn, Nb-Ta and Li mineralization of Manono-Kitotolo (Katanga, Democratic Republic of Congo): Ore Geology Reviews, v. 72, p. 373–390.

Deynoux, M., Affaton, P., Trompette, R., and Villeneuve, M., 2006, Pan-African tectonic evolution and glacial events registered in Neoproterozoic to

Cambrian cratonic and foreland basins of West Africa: Journal of African Earth Sciences, v. 46, p. 397–426.
Diehl, B., and Schneider, G., 1990, Geology and mineralisation of the Rubicon pegmatite, Namibia: Ministry of Mines and Energy, Geological Survey, Economic Geology Series, no. 84.
Diehl, M., 1993a, Rare metal pegmatites of the Cape Cross-Uis pegmatite belt, Namibia: Geology, mineralisation, rubidium-strontium characteristics and petrogenesis: Journal of African Earth Sciences (and the Middle East), v. 17, p. 167–181.
——1993b, Tin: Geological Survey of Namibia, Mineral Resources of Namibia, p. 2.8-1–2.8-30.
Dill, H.G., 2016, The cmS classification scheme (chemical composition-mineral assemblage-structural geology)-linking geology to mineralogy of pegmatitic and aplitic rocks: Neues Jahrbuch für Mineralogie-Abhandlungen/Journal of Mineralogy and Geochemistry, v. 193, p. 231–263.
Dittrich, T., Seifert, T., Schulz, B., Hagemann, S., Gerdes, A., and Pfänder, J., 2019, Geological settings of Archean rare-metal pegmatites, *in* Dittrich, T., Seifert, T., Schulz, B., Hagemann, S., Gerdes, A., and Pfänder, J., eds., Archean rare-metal pegmatites in Zimbabwe and Western Australia: Geology and metallogeny of pollucite mineralisations: Cham, Springer International Publishing, p. 23–59.
Djeutchou, C., de Kock, M., Ernst, R.E., Ossa Ossa, F.G., and Bekker, A., 2024, A review of the intraplate mafic magmatic record of the Greater Congo craton: Earth-Science Reviews, v. 249, article 104649.
Doggart, S.W., 2019, Geochronology and isotopic characterisation of LCT pegmatites from the Orange River pegmatite province: M.Sc. thesis, Stellenbosch, Stellenbosch University, https://scholar.sun.ac.za/items/5a5d7a49-4260-4060-9475-0458885eb300.
Dubois, J., Marchand, J., and Bourguignon, P., 1972, Données minéralogiques sur la série amblygonite-montebrasite: Annales de la Société géologique de Belgique.
Eglington, B.M., 2006, Evolution of the Namaqua-Natal belt, southern Africa—a geochronological and isotope geochemical review: Journal of African Earth Sciences, v. 46, p. 93–111.
Eglington, B.M., and Armstrong, R.A., 2004, The Kaapvaal craton and adjacent orogens, southern Africa: A geochronological database and overview of the geological development of the craton: South African Journal of Geology, v. 107, p. 13–32.
Erraji, I., Essaifi, A., Roda Robles, E., and N'diaye, E., 2024, The Sidi Bou Othmane pegmatite field (Jebilet Massif, Morocco): Geological Association of Canada and Mineralogical Association of Canada, GAC-MAC-PEG 2024, Brandon, Manitoba, 2024, p. 80.
Essaifi, A., Samson, S., and Goodenough, K., 2014, Geochemical and Sr-Nd isotopic constraints on the petrogenesis and geodynamic significance of the Jebilet magmatism (Variscan belt, Morocco): Geological Magazine, v. 151, p. 666–691.
Fernandez-Alonso, M., Cutten, H., De Waele, B., Tack, L., Tahon, A., Baudet, D., and Barritt, S.D., 2012, The Mesoproterozoic Karagwe-Ankole belt (formerly the NE Kibara belt): The result of prolonged extensional intracratonic basin development punctuated by two short-lived far-field compressional events: Precambrian Research, v. 216–219, p. 63–86.
Fowler, G., Utiger, M., Mackenzie, B., Duinker, R., Cronwright, M., Geldenhuys, A., Mwiya, S., and von Welligh, A., 2018, Preliminary economic assessment for Desert Lion Energy Lithium Project: NI-43-101 Technical Report.
Fransolet, A., and Tack, L., 1990, La pegmatite lithique de Ndora, Burundi: Publication occasionnelle, Centre international pour la formation et les échanges géologiques, IGCP 255, Newsletter/Bulletin 3, p. 27–29.
Fransolet, A.-M., Abraham, K., and Speetjens, J.-M., 1985, Evolution génétique et signification des associations de phosphates de la pegmatite d'Angarf-Sud, plaine de Tazenakht, Anti-Atlas, Maroc: Bulletin de Minéralogie, v. 108, p. 551–574.
Fritz, H., Abdelsalam, M., Ali, K.A., et al., 2013, Orogen styles in the East African orogen: A review of the Neoproterozoic to Cambrian tectonic evolution: Journal of African Earth Sciences, v. 86, p. 65–106.
Fuchsloch, W.C., Nex, P.A.M., and Kinnaird, J.A., 2018, Classification, mineralogical and geochemical variations in pegmatites of the Cape Cross-Uis pegmatite belt, Namibia: Lithos, v. 296–299, p. 79–95.
Gadas, P., Novak, M., Galiova, M.V., and Pezzotta, F., 2023, Chemical composition of tourmalines from the Manjaka pegmatite and its exocontact, Sahatany Valley, Madagascar: Journal of Geosciences, v. 68, p. 185–202.
Ganbat, A., Tsujimori, T., Boniface, N., Pastor-Galán, D., Aoki, S., and Aoki, K., 2021, Crustal evolution of the Paleoproterozoic Ubendian belt (SW Tanzania) western margin: A Central African Shield amalgamation tale: Gondwana Research, v. 91, p. 286–306.
Gevers, T., 1937, Phases of mineralisation in Namaqualand pegmatites: South African Journal of Geology, v. 40, p. 331–377.
Gevers, T., Partridge, F., and Joubert, G., 1937, The pegmatite area south of the Orange River in Namaqualand: Memoris of the Geological Survey of South Africa, v. 31, 164 p.
Ginsburg, A., 1984, The geological condition of the location and the formation of granitic pegmatites: International Geological Congress, 27th, Moscow, 1984, Proceedings, p. 245–260.
Ginsburg, A., and Rodionov, G., 1960, On the depths of the granitic pegmatite formation: Geologiya Rudnykh Mestorozhdenyi, Izd, Nauka, Moskva l.
Glynn, S.M., Master, S., Wiedenbeck, M., Davis, D.W., Kramers, J.D., Belyanin, G.A., Frei, D., and Oberthür, T., 2017, The Proterozoic Choma-Kalomo block, SE Zambia: Exotic terrane or a reworked segment of the Zimbabwe craton?: Precambrian Research, v. 298, p. 421–438.
Glynn, S.M., Master, S., Frei, D., and Wiedenbeck, M., 2020, U-Pb zircon geochronology of the Dete-Kamativi inlier, NW Zimbabwe, with implications for the western margin of the Archaean Zimbabwe craton: Precambrian Research, v. 346, article 105824.
Gonçalves, A.O., Melgarejo Draper, J.C., and Alfonso Abella, M.P., 2009, Sequence of crystallisation of pegmatites: The Angola case: Estudos Geológicos, v. 19, p. 35–39.
Gonçalves, A.O., Melgarejo, J.-C., Alfonso, P., Amores, S., Paniagua, A., Neto, A.B., Morais, E.A., and Camprubí, A., 2019, The distribution of rare metals in the LCT pegmatites from the Giraúl field, Angola: Minerals, v. 9, article 580.
Goodenough, K., Jones, D., and Ford, J., 2018, Geological mapping of Sierra Leone: Baseline assessment and next steps: British Geological Survey, Open Report OR/21/037.
Goodenough, K.M., Thomas, R.J., De Waele, B., et al., 2010, Post-collisional magmatism in the central East African orogen: The Maevarano Suite of north Madagascar: Lithos, v. 116, p. 18–34.
Goodenough, K.M., Lusty, P.A.J., Roberts, N.M.W., Key, R.M., and Garba, A., 2014, Post-collisional Pan-African granitoids and rare metal pegmatites in western Nigeria: Age, petrogenesis, and the "pegmatite conundrum": Lithos, v. 200–201, p. 22–34.
Goodenough, K.M., Deady, E.A., and Shaw, R.A., 2021, Lithium resources, and their potential to support battery supply chains, in Africa: Keyworth, Nottingham, British Geological Survey.
Goodship, A., Dace, A., O'Hare, P., Uwiringiyimana, J., Siddle, R., and Moon, C., 2019, Geology and genesis of the Musha-Ntunga Sn-Ta-Li-Nb vein-pegmatite deposit, Rwanda: First results from deep drilling of a coltan mine in Rwanda and first detailed description of Li minerals: Applied Earth Science, v. 128, p. 47–48, https://doi.org/10.1080/25726838.2019.1602953.
Goscombe, B., Foster, D.A., Gray, D., and Wade, B., 2017, Metamorphic response and crustal architecture in a classic collisional orogen: The Damara belt, Namibia: Gondwana Research, v. 52, p. 80–124.
Gourcerol, B., Gloaguen, E., Melleton, J., Tuduri, J., and Galiegue, X., 2019, Re-assessing the European lithium resource potential—a review of hard-rock resources and metallogeny: Ore Geology Reviews, v. 109, p. 494–519.
Grenholm, M., Jessell, M., and Thébaud, N., 2019, A geodynamic model for the sPaleoproterozoic (ca. 2.27–1.96 Ga) Birimian orogen of the southern West African craton—insights into an evolving accretionary-collisional orogenic system: Earth-Science Reviews, v. 192, p. 138–193.
Grew, E.S., Bosi, F., Ros, L., Kristiansson, P., Gunter, M.E., Hålenius, U., Trumbull, R.B., and Yates, M.G., 2018, Fluor-elbaite, lepidolite and Ta-Nb oxides from a pegmatite of the 3000 Ma Sinceni pluton, Swaziland: Evidence for lithium-cesium-tantalum (LCT) pegmatites in the Mesoarchean: European Journal of Mineralogy, v. 30, p. 205–218.
Groves, D., Zhang, L., Groves, I., and Sener, A., 2022, Spodumene: The key lithium mineral in giant lithium-cesium-tantalum pegmatites: Acta Petrologica Sinica, v. 38, p. 1–8.
Gunn, A.G., Dorbor, J.K., Mankelow, J.M., Lusty, P.A.J., Deady, E.A., Shaw, R.A., and Goodenough, K.M., 2018, A review of the mineral potential of Liberia: Ore Geology Reviews, v. 101, p. 413–431.
Harrison, N., 1969, The geology of the country around Fort Rixon and Shangani: Rhodesia Geological Survey, Bulletin 61, 152 p.
Hatert, F.d.r., LeféVre, P., Fransolet, A.-M., Spirlet, M.-R., Rebbouh, L., Fontan, F.o., and Keller, P., 2005, Ferrorosemaryite, $NaFe_2$ + Fe_3 + $Al(PO_4)_3$, a new phosphate mineral from the Rubindi pegmatite, Rwanda: European Journal of Mineralogy, v. 17, p. 749–759.
Horstwood, M.S.A., Nesbitt, R.W., Noble, S.R., and Wilson, J.F., 1999, U-Pb zircon evidence for an extensive early Archean craton in Zimbabwe: A

reassessment of the timing of craton formation, stabilization, and growth: Geology, v. 27, p. 707–710.
Hughes, C.J., and Farrant, J.R., 1963, The geology of 1/4 field sheet no. 26—Cape Coast and Saltpond districts: Accra, Ghana Geological Survey.
Hugo, P., 1970, The pegmatites of the Kenhardt and Gordonia districts: Geological Survey, Department of Mines of South Africa, Pretoria, Memoir, p. 1–94.
Hulsbosch, N., 2019, Nb-Ta-Sn-W distribution in granite-related ore systems: American Geophysical Union, Geophysical Monograph 242, p. 75–107, https://doi.org/10.1002/9781119290544.ch4.
Hulsbosch, N., Hertogen, J., Dewaele, S., Andre, L., and Muchez, P., 2013, Petrographic and mineralogical characterisation of fractionated pegmatites culminating in the Nb-Ta-Sn pegmatites of the Gatumba area (western Rwanda): Geologica Belgica, v. 16, p. 105–117.
Hulsbosch, N., Hertogen, J., Dewaele, S., André, L., and Muchez, P., 2014, Alkali metal and rare earth element evolution of rock-forming minerals from the Gatumba area pegmatites (Rwanda): Quantitative assessment of crystal-melt fractionation in the regional zonation of pegmatite groups: Geochimica et Cosmochimica Acta, v. 132, p. 349–374.
Hulsbosch, N., Van Daele, J., Reinders, N., Dewaele, S., Jacques, D., and Muchez, P., 2017, Structural control on the emplacement of contemporaneous Sn-Ta-Nb mineralized LCT pegmatites and Sn bearing quartz veins: Insights from the Musha and Ntunga deposits of the Karagwe-Ankole belt, Rwanda: Journal of African Earth Sciences, v. 134, p. 24–32.
Hund, K., la Porta, D., Fabregas, T.P., Laing, T., and Drexhage, J.R., 2020, Minerals for climate action: The Mineral Intensity of the Clean Energy Transition: World Bank Group, 112 p., https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099052423172525564/p16627806f5aa400508f8c0bdcba0878a3e.
Hurlbut, C.S., Jr., 1957, Bikitaite, $LiAlSi_2O_6 \cdot H_2O$, A new mineral from southern Rhodesia: American Mineralogist, v. 42, p. 792–797.
Hutchinson, R.W., and Claus, R.J., 1956, Pegmatite deposits, Alto Ligonha, Portuguese East Africa: Economic Geology, v. 51, p. 757–780.
Huvelin, P., 1977, Etude geologique et gitologique du Massif Hercynien Des Jebilet (Maroc Occidental): Memoirs of the Geological Survey of Morocco, v. 232.
Jacobs, J., Pisarevsky, S., Thomas, R.J., and Becker, T., 2008, The Kalahari craton during the assembly and dispersal of Rodinia: Precambrian Research, v. 160, p. 142–158.
Jelsma, H.A., and Dirks, P.H.G.M., 2002, Neoarchaean tectonic evolution of the Zimbabwe craton: Geological Society, London, Special Publications, v. 199, p. 183–211.
Johnson, P.R., 2021, The Arabian-Nubian Shield, an introduction: Historic overview, concepts, interpretations, and future issues, *in* Hamimi, Z., Fowler, A.-R., Liégeois, J.-P., Collins, A., Abdelsalam, M.G., and Abd Ei-Wahed, M., eds., The geology of the Arabian-Nubian Shield: Cham, Springer International Publishing, p. 1–38.
Jung, S., Hoernes, S., and Mezger, K., 2002, Synorogenic melting of mafic lower crust: Constraints from geochronology, petrology and Sr, Nd, Pb and O isotope geochemistry of quartz diorites (Damara orogen, Namibia): Contributions to Mineralogy and Petrology, v. 143, p. 551–566.
Kaeter, D., Barros, R., Menuge, J.F., and Chew, D.M., 2018, The magmatic-hydrothermal transition in rare-element pegmatites from southeast Ireland: LA-ICP-MS chemical mapping of muscovite and columbite-tantalite: Geochimica et Cosmochimica Acta, v. 240, p. 98–130.
Kalikone, C., Borst, A.M., Nahimana, L., et al., 2023, Pegmatite zonation and the use of muscovite as a geochemical indicator for tin-tantalum-tungsten mineralization: Case studies from the Kalehe and Idjwi areas, Democratic Republic of Congo: Journal of African Earth Sciences, v. 207, article 105067.
Kazapoe, R.W., 2023, Assessing the lithium potential of the Paleoproterozoic rocks of the West African craton; the case so far: Geosystem Engineering, v. 26, p. 257–271.
Keller, P., Roda Robles, E., Pesquera Pérez, A., and Fontan, F., 1999, Chemistry, paragenesis and significance of tourmaline in pegmatites of the Southern tin belt, central Namibia: Chemical Geology, v. 158, p. 203–225.
Kesse, G.O., 1985, The mineral and rock resources of Ghana: Netherlands, A.A. Balkema, 610 p.
Kinnaird, J.A., and Nex, P.A.M., 2007, A review of geological controls on uranium mineralisation in sheeted leucogranites within the Damara orogen, Namibia: Applied Earth Science, v. 116, p. 68–85.
Knoll, T., Huet, B., Schuster, R., Mali, H., Ntaflos, T., and Hauzenberger, C., 2023, Lithium pegmatite of anatectic origin—a case study from the Austroalpine Unit pegmatite province (eastern European Alps): Geological data and geochemical modeling: Ore Geology Reviews, v. 154, article 105298.
Koegelenberg, C., Kisters, A.F.M., Kramers, J.D., and Frei, D., 2015, U-Pb detrital zircon and ^{39}Ar-^{40}Ar muscovite ages from the eastern parts of the Karagwe-Ankole belt: Tracking Paleoproterozoic basin formation and Mesoproterozoic crustal amalgamation along the western margin of the Tanzania craton: Precambrian Research, v. 269, p. 147–161.
Kokonyangi, J.W., Kampunzu, A.B., Armstrong, R., Yoshida, M., Okudaira, T., Arima, M., and Ngulube, D.A., 2006, The Mesoproterozoic Kibaride belt (Katanga, SE D.R. Congo): Journal of African Earth Sciences, v. 46, p. 1–35.
Koopmans, L., Martins, T., Linnen, R., Gardiner, N.J., Breasley, C.M., Palin, R.M., Groat, L.A., Silva, D., and Robb, L.J., 2023, The formation of lithium-rich pegmatites through multi-stage melting: Geology, v. 52, p. 7–11.
Kröner, A., Anhaeusser, C.R., Hoffmann, J.E., Wong, J., Geng, H., Hegner, E., Xie, H., Yang, J., and Liu, D., 2016, Chronology of the oldest supracrustal sequences in the Palaeoarchaean Barberton greenstone belt, South Africa and Swaziland: Precambrian Research, v. 279, p. 123–143.
Kundu, T., Rath, S.S., Das, S.K., Parhi, P.K., and Angadi, S.I., 2023, Recovery of lithium from spodumene-bearing pegmatites: A comprehensive review on geological reserves, beneficiation, and extraction: Powder Technology, v. 415, article 118142.
Küster, D., 1990, Rare-metal pegmatites of Wamba, central Nigeria—their formation in relationship to late Pan-African granites: Mineralium Deposita, v. 25, p. 25–33.
Küster, D., and Harms, U., 1998, Post-collisional potassic granitoids from the southern and northwestern parts of the Late Neoproterozoic East African orogen: A review: Lithos, v. 45, p. 177–195.[a]
Küster, D., Romer, R., Tolessa, D., Zerihun, D., Bheemalingeswara, K., Melcher, F., and Oberthür, T., 2009, The Kenticha rare-element pegmatite, Ethiopia: Internal differentiation, U-Pb age and Ta mineralization: Mineralium Deposita, v. 44, p. 723–750.
Lambert-Smith, J.S., Lawrence, D.M., Müller, W., and Treloar, P.J., 2016, Palaeotectonic setting of the south-eastern Kédougou-Kéniéba inlier, West Africa: New insights from igneous trace element geochemistry and U-Pb zircon ages: Precambrian Research, v. 274, p. 110–135.
Landes, K.K., 1933, Origin and classification of pegmatites: American Mineralogist, v. 18, p. 33–56.
Legros, H., Mercadier, J., Villeneuve, J., et al., 2019, U-Pb isotopic dating of columbite-tantalite minerals: Development of reference materials and in situ applications by ion microprobe: Chemical Geology, v. 512, p. 69–84.
Lehmann, B., Halder, S., Munana, J.R., Ngizimana, J.D., and Biryabarema, M., 2014, The geochemical signature of rare-metal pegmatites in Central Africa: Magmatic rocks in the Gatumba tin-tantalum mining district, Rwanda: Journal of Geochemical Exploration, v. 144, p. 528–538.
Linnen, R.L., Van Lichtervelde, M., and Černý, P., 2012, Granitic pegmatites as sources of strategic metals: Elements, v. 8, p. 275–280.
Lockett, N.H., 1979, The geology of the county around Dett: Salisbury, Rhodesia Geological Survey, 198 p.
London, D., 1984, Experimental phase equilibria in the system $LiAlSiO_4^-$ SiO_2-H_2O: A petrogenetic grid for lithiumx-rich pegmatites: American Mineralogist, v. 69, p. 995–1004.
——1986, Magmatic-hydrothermal transition in the Tanco rare-element pegmatite: Evidence from fluid inclusions and phase-equilibrium experiments: American Mineralogist, v. 71, p. 376–395.
——1992, The application of experimental petrology to the genesis and crystallization of granitic pegmatites: The Canadian Mineralogist, v. 30, p. 499–540.
——2005, Granitic pegmatites: An assessment of current concepts and directions for the future: Lithos, v. 80, p. 281–303.
——2014, A petrologic assessment of internal zonation in granitic pegmatites: Lithos, v. 184–187, p. 74–104.
——2018, Ore-forming processes within granitic pegmatites: Ore Geology Reviews, v. 101, p. 349–383.
London, D., and Kontak, D.J., 2012, Granitic pegmatites: Scientific wonders and economic bonanzas: Elements, v. 8, p. 257–261.
Longridge, L., 2013, Tectonothermal evolution of the southwestern Central zone, Damara belt, Namibia: Ph.D. thesis, Johannesburg, University of the Witwatersrand, 524 p.
López Steinmetz, R.L., and Salvi, S., 2021, Brine grades in Andean salars: When basin size matters: A review of the Lithium Triangle: Earth-Science Reviews, v. 217, article 103615.
MacFarlane, A., Crow, M., Arthurs, J., Wilkinson, A., and Aucott, J., 1981, The geology and mineral resources of northern Sierra Leone: HM Stationery Office, 103 pages.

Maisel, F., Neef, C., Marscheider-Weidemann, F., and Nissen, N.F., 2023, A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles: Resources, Conservation and Recycling, v. 192, article 106920.

Mandingaisa, P., Tsunogae, T., Uthup, S., Basupi, T.O., Lydia Meck, M., and Tsutsumi, Y., 2022, Latest Mesoproterozoic (ca. 1.2–1.1 Ga) amphibolite-facies metamorphism from the Dete-Kamativi inlier, NW Zimbabwe: Implications for a Rodinia-related intracratonic orogen in Southern Africa: Precambrian Research, v. 376, article 106688.

Markwitz, V., Hein, K.A.A., and Miller, J., 2016, Compilation of West African mineral deposits: Spatial distribution and mineral endowment: Precambrian Research, v. 274, p. 61–81.

Martin, R.F., and De Vito, C., 2005, The patterns of enrichment in felsic pegmatites ultimately depend on tectonic setting: The Canadian Mineralogist, v. 43, p. 2027–2048.

Marzoli, A., Bertrand, H., Youbi, N., et al., 2019, The Central Atlantic magmatic province (CAMP) in Morocco: Journal of Petrology, v. 60, p. 945–996.

Master, S., Bekker, A., and Hofmann, A., 2010, A review of the stratigraphy and geological setting of the Palaeoproterozoic Magondi Supergroup, Zimbabwe—type locality for the Lomagundi carbon isotope excursion: Precambrian Research, v. 182, p. 254–273.

McCaffrey, D.M., and Jowitt, S.M., 2023, The crystallization temperature of granitic pegmatites: The important relationship between undercooling and critical metal prospectivity: Earth-Science Reviews, v. 244, article 104541.

McCauley, A., and Bradley, D.C., 2014, The global age distribution of granitic pegmatites: The Canadian Mineralogist, v. 52, p. 183–190.

McFarlane, H.B., Ailleres, L., Betts, P., Ganne, J., Baratoux, L., Jessell, M.W., and Block, S., 2019, Episodic collisional orogenesis and lower crust exhumation during the Palaeoproterozoic Eburnean orogeny: Evidence from the Sefwi greenstone belt, West African craton: Precambrian Research, v. 325, p. 88–110.

Melcher, F., Graupner, T., Gäbler, H.-E., Sitnikova, M., Henjes-Kunst, F., Oberthür, T., Gerdes, A., and Dewaele, S., 2015, Tantalum-(niobium-tin) mineralisation in African pegmatites and rare metal granites: Constraints from Ta-Nb oxide mineralogy, geochemistry and U-Pb geochronology: Ore Geology Reviews, v. 64, p. 667–719.

Melcher, F., Graupner, T., Gäbler, H.-E., Sitnikova, M., Oberthür, T., Gerdes, A., Badanina, E., and Chudy, T., 2017, Mineralogical and chemical evolution of tantalum-(niobium-tin) mineralisation in pegmatites and granites. Part 2: Worldwide examples (excluding Africa) and an overview of global metallogenetic patterns: Ore Geology Reviews, v. 89, p. 946–987.

Michard, A., Driouch, Y., Kuiper, Y.D., Caby, R., Farah, A., Ouanaimi, H., Soulaimani, A., Chabou, M.C., and Saddiqi, O., 2023, The Variscan belts of north-west Africa: An African legacy to the Wilson Cycle concept: Journal of African Earth Sciences, v. 208, article 105042.

Michaud, J.A.-S., and Pichavant, M., 2020, Magmatic fractionation and the magmatic-hydrothermal transition in rare metal granites: Evidence from Argemela (central Portugal): Geochimica et Cosmochimica Acta, v. 289, p. 130–157.

Michon, L., Famin, V., and Quidelleur, X., 2022, Evolution of the East African rift system from trap-scale to plate-scale rifting: Earth-Science Reviews, v. 231, article 104089.

Miller, R.M., Frimmel, H.E., and Will, T.M., 2009, Chapter 5.8 Geodynamic synthesis of the Damara orogen sensu lato, *in* Gaucher, C., Sial, A.N., Frimmel, H.E., and Halverson, G.P., eds., Developments in Precambrian geology, v. 16: Elsevier, p. 231–235.

Minnaar, H., 2006, The exploitability of pegmatite deposits in the lower Orange River area (Violsdrif-Henkries-Steinkopf): M.Sc. thesis, University of Pretoria, 64 p.

Minnaar, H., and Theart, H.F.J., 2006, The exploitability of pegmatite deposits in the lower Orange River area (Vioolsdrif-Henkries-Steinkopf): South African Journal of Geology, v. 109, p. 341–352.

Morsli, Y., Zerhouni, Y., Wafik, A., Elouazzani, A., Alikouss, S., Saidi, A., and Baroudi, Z., 2022, Eburneen pegmatites of the Zenaga inlier (Anti-Atlas, Morocco): Petrography, geochemistry, and classification: Journal of African Earth Sciences, v. 186, article 104438.

Mountain, E.D., 1935, Two new bismuth minerals from South Africa: Mineralogical Magazine, v. 24, p. 59–64.

Müller, A., Romer, R.L., and Pedersen, R.-B., 2017, The Sveconorwegian pegmatite province—thousands of pegmatites without parental granites: The Canadian Mineralogist, v. 55, p. 283–315.

Müller, A., Simmons, W., Beurlen, H., et al., 2018, A proposed new mineralogical classification system for granitic pegmatites—part I: History and the need for a new classification: The Canadian Mineralogist, https://doi.org/10.3749/canmin.1700088.

Munk, L.A., Hynek, S.A., Bradley, D.C., Boutt, D., Labay, K., and Jochens, H., 2016, Lithium brines: A global perspective: Reviews in Economic Geology, v. 18, p. 339–365.

Nascimento, D.B., Schmitt, R.S., Ribeiro, A., Trouw, R.A.J., Passchier, C.W., and Basei, M.A.S., 2017, Depositional ages and provenance of the Neoproterozoic Damara Supergroup (northwest Namibia): Implications for the Angola-Congo and Kalahari cratons connection: Gondwana Research, v. 52, p. 153–171.

Niggli, P., 1920, The volatile components in the magma: Preisschriften der Furstlich Jablonowskischen Gesell-schaf, 272 p.

Oberthür, T., Davis, D.W., Blenkinsop, T.G., and Höhndorf, A., 2002, Precise U-Pb mineral ages, Rb-Sr and Sm-Nd systematics for the Great Dyke, Zimbabwe—constraints on late Archean events in the Zimbabwe craton and Limpopo belt: Precambrian Research, v. 113, p. 293–305.

Olivetti, E.A., Ceder, G., Gaustad, G.G., and Fu, X., 2017, Lithium-ion battery supply chain considerations: Analysis of Potential bottlenecks in critical metals: Joule, v. 1, p. 229–243.

Otto, A., and LeGras, M., 2018, Mineralogical characterisation of the Goulamina lithium deposit: Commonwealth Scientific and Industrial Research Organisation (CSIRO) Mineral Resources Report, 49 p.

Parra-Avila, L.A., Kemp, A.I.S., Fiorentini, M.L., et al., The geochronological evolution of the Paleoproterozoic Baoulé-Mossi domain of the Southern West African craton: Precambrian Research, v. 300, p. 1–27.

Parra-Avila, L.A., Baratoux, L., Eglinger, A., Fiorentini, M.L., and Block, S., 2019, The Eburnean magmatic evolution across the Baoulé-Mossi domain: Geodynamic implications for the West African craton: Precambrian Research, v. 332, article 105392.

Pedrosa-Soares, A.C., De Campos, C.P., Noce, C., et al., 2011, Late Neoproterozoic-Cambrian granitic magmatism in the Araçuaí orogen (Brazil), the Eastern Brazilian pegmatite province and related mineral resources: Geological Society, London, Special Publications, v. 350, p. 25–51.

Pell, R., Tijsseling, L., Goodenough, K., Wall, F., Dehaine, Q., Grant, A., Deak, D., Yan, X., and Whattoff, P., 2021, Towards sustainable extraction of technology materials through integrated approaches: Nature Reviews Earth and Environment, v. 2, p. 665–679.

Pezzotta, F., 2001, Madagascar: A mineral and gemstone paradise: Lapis International LLC, 97 p.

——2005, First attempt to the petrogenesis and the classification of granitic pegmatites of the Itremo region (central Madagascar): International Meeting on Crystallization Processes in Granitic Pegmatites, Elba, 2005, Proceedings.

Plunder, A., Le Pourhiet, L., Räss, L., Gloaguen, E., Pichavant, M., and Gumiaux, C., 2022, Pegmatites as geological expressions of spontaneous crustal flow localisation: Lithos, v. 416–417, article 106652.

Pohl, W., 1994, Metallogeny of the northeastern Kibara belt, Central Africa—recent perspectives: Ore Geology Reviews, v. 9, p. 105–130.

Prado Araujo, F., Hulsbosch, N., and Muchez, P., 2023a, Paragenesis and precipitation stages of Nb-Ta-oxide minerals in phosphorus-rich rare-element pegmatites (Buranga dike, Rwanda): American Mineralogist, v. 108, p. 277–296.

Prado Araujo, F., Muchez, P., and Hulsbosch, N., 2023b, The magmatic-hydrothermal transition in P-rich pegmatitic melts: Crystal-melt-fluid interactions recorded by phosphate minerals: Geochimica et Cosmochimica Acta, v. 356, p. 129–148.

Rajesh, H.M., Knoper, M.W., Belyanin, G.A., Safonov, O.G., and Schmidt, C., 2020, Petalite postdating spodumene in pegmatite as a consequence of the ~2.02 Ga meteorite impact in the Vredefort structure, southern Africa: Lithos, v. 376–377, article 105760.

Richards, T., 1986, Geological characteristics of rare-metal pegmatites of the Uis type in the Damara orogen, South West Africa/Namibia, *in* Anhaeusser, C.R., and Maske, S., eds., Mineral deposits of Southern Africa: Johannesburg, Geological Society of South Africa, p. 1845–1862.

Rijks, H.R.P., and van der Veen, A.H., 1972, The geology of the tin-bearing pegmatites in the eastern part of the Kamativi district, Rhodesia: Mineralium Deposita, v. 7, p. 383–395.

Rioyo, J., Tuset, S., and Grau, R., 2022, Lithium extraction from spodumene by the traditional sulfuric acid process: A review: Mineral Processing and Extractive Metallurgy Review, v. 43, p. 97–106.

Roda-Robles, E., Villaseca, C., Pesquera, A., Gil-Crespo, P.P., Vieira, R., Lima, A., and Garate-Olave, I., 2018, Petrogenetic relationships between Variscan granitoids and Li-(F-P)-rich aplite-pegmatites in the Central

Iberian zone: Geological and geochemical constraints and implications for other regions from the European Variscides: Ore Geology Reviews, v. 95, p. 408–430.
——1966, Aspects of the genesis and crystallization sequence of the Karibib pegmatites, South West Africa: Economic Geology, v. 61, p. 1064–1089.
Romer, R.L., and Kroner, U., 2016, Phanerozoic tin and tungsten mineralization—tectonic controls on the distribution of enriched protoliths and heat sources for crustal melting: Gondwana Research, v. 31, p. 60–95.
Safiannikoff, A., and van Wambeke, L., 1967, La pegmatite radioactive à béryl de Kobokobo et les autres venues pegmatitiques et filoniennes de la région de Kamituga-Kivu-Rép. du Congo: Mineralium Deposita, v. 2, p. 119–130.
Sanogo, S., Durand, C., Dubois, M., and Wane, O., 2021, Structural constraints of the Birimian lithium pegmatites of Bougouni (southern Mali, Leo-Man Shield): European Geophysical Union (EGU) General Assembly, Online, 2021, Conference Abstracts, p. EGU21-6752.
Schofield, D.I., Horstwood, M.S.A., Pitfield, P.E.J., Crowley, Q.G., Wilkinson, A.F., and Sidaty, H.C.O., 2006, Timing and kinematics of Eburnean tectonics in the central Reguibat Shield, Mauritania: Journal of the Geological Society, v. 163, p. 549–560.
Schofield, D.I., Thomas, R.J., Goodenough, K.M., et al., 2010, Geological evolution of the Antongil craton, NE Madagascar: Precambrian Research, v. 182, p. 187–203.
Schutte, I.C., 1972, The main pegmatites of the area between Steinkopf, Vioolsdrif and Goodhouse: Geological Survey of South Africa, Memoir 60, p. 19.
Scoates, J.S., and Friedman, R.M., 2008, Precise age of the platiniferous Merensky reef, Bushveld Complex, South Africa, by the U-Pb zircon chemical abrasion ID-TIMS technique: Economic Geology, v. 103, p. 465–471.
Shaw, R.A., Goodenough, K.M., Deady, E., Nex, P., Ruzvidzo, B., Rushton, J.C., and Mounteney, I., 2022, The magmatic-hydrothermal transition in lithium pegmatites: Petrographic and geochemical characteristics of pegmatites from the Kamativi area, Zimbabwe: The Canadian Mineralogist, https://doi.org/10.3749/canmin.2100032.
Silva, D., Groat, L., Martins, T., and Linnen, R., 2023, Structural Controls on the origin and emplacement of lithium-bearing pegmatites: The Canadian Journal of Mineralogy and Petrology, v. 61, p. 1053–1062.
Simmons, W.B., and Webber, K.L., 2008, Pegmatite genesis: State of the art: European Journal of Mineralogy, v. 20, p. 421–438.
Sovacool, B.K., Ali, S.H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., and Mulvaney, D., 2020, Sustainable minerals and metals for a low-carbon future: Science, v. 367, p. 30–33.
Svensen, H., Corfu, F., Polteau, S., Hammer, Ø., and Planke, S., 2012, Rapid magma emplacement in the Karoo large igneous province: Earth and Planetary Science Letters, v. 325–326, p. 1–9.
Tack, L., Wingate, M.T.D., De Waele, B., Meert, J., Belousova, E., Griffin, B., Tahon, A., and Fernandez-Alonso, M., 2010, The 1375 Ma "Kibaran event" in Central Africa: Prominent emplacement of bimodal magmatism under extensional regime: Precambrian Research, v. 180, p. 63–84.
Tchakounté, J., Eglinger, A., Toteu, S.F., Zeh, A., Nkoumbou, C., Mvondo-Ondoa, J., Penaye, J., de Wit, M., and Barbey, P., 2017, The Adamawa-Yadé domain, a piece of Archaean crust in the Neoproterozoic Central African orogenic belt (Bafia area, Cameroon): Precambrian Research, v. 299, p. 210–229.
Thomas, R.J., Agenbacht, A.L.D., Cornell, D.H., and Moore, J.M., 1994a, The Kibaran of southern Africa: Tectonic evolution and metallogeny: Ore Geology Reviews, v. 9, p. 131–160.
Thomas, R.J., Bühmann, D., Bullen, W.D., Scogings, A.J., and De Bruin, D., 1994b, Unusual spodumene pegmatites from the Late Kibaran of southern Natal, South Africa: Ore Geology Reviews, v. 9, p. 161–182.
Thomas, R.J., Chevallier, L.P., Gresse, P.G., et al., 2002, Precambrian evolution of the Sirwa window, Anti-Atlas orogen, Morocco: Precambrian Research, v. 118, p. 1–57, https://doi.org/10.1016/S0301-9268(02)00075-X.
Tomkinson, M.J., Harris, P.O., and Robb, L.J., 1995, The nature and structural setting of rare-element pegmatites along the northern flank of the Barberton greenstone belt, South Africa: South African Journal of Geology, v. 98, p. 82–94.
Touret, J., Smirnov, S., Peretyazhko, I., Zagorsky, V.Y., and Thomas, V., 2007, Magmatic-hydrothermal transition in tourmaline-bearing miarolitic pegmatites: Hydrosaline fluids or silica gels?: International Symposium, Granitic Pegmatites: The State of the Art, Porto, Portugal, 2007, Proceedings, p. 92–93.
Trumbull, R.B., 1993, A petrological and Rb-Sr isotopic study of an early Archean fertile granite-pegmatite system: The Sinceni pluton in Swaziland: Precambrian Research, v. 61, p. 89–116.
——1995, Tin mineralization in the Archean Sinceni rare element pegmatite field, Kaapvaal craton, Swaziland: Economic Geology, v. 90, p. 648–657.
Tucker, R.D., Roig, J.Y., Moine, B., Delor, C., and Peters, S.G., 2014, A geological synthesis of the Precambrian shield in Madagascar: Journal of African Earth Sciences, v. 94, p. 9–30.
Tyndale-Biscoe, R., 1951, The geology of the Bitkita tin-field, southern Rhodesia: South African Journal of Geology, v. 54, p. 11–23.
U.S. Geological Survey, 2024, Lithium: Mineral Commodity Summaries 2024.
Varlamoff, N., 1961, Matériaux pour l'étude des pegmatites du Congo et du Ruanda. IV. Pegmatites à amblygonite et à spodumène et pegmatites fortement albitisées à spodumène et à cassitérite de la région de Katumba (Ruanda): Annales de la Société Géologique de Belgique, v. 84, p. 257–258.
——1972, Central and West African rare-metal granitic pegmatites, related aplites, quartz veins and mineral deposits: Mineralium Deposita, v. 7, p. 202–216.
Veksler, I.V., 2004, Liquid immiscibility and its role at the magmatic-hydrothermal transition: A summary of experimental studies: Chemical Geology, v. 210, p. 7–31.
Villeneuve, M., Gärtner, A., Kalikone, C., and Wazi, N., 2023, Amalgamation in the Central African Shield (CAS) by the Kibaran orogen: New hypothesis and implications for the Rodinia assembly: Journal of African Earth Sciences, v. 202, article 104936.
Vogel, C.N., 2022, Conflict Minerals, Inc.: War, profit and white saviourism in eastern Congo: Oxford University Press, 224 p.
von der Heyden, B.P., Todd, C., Mayne, M.J., and Doggart, S., 2023, Zipf rank analysis highlights the exploration potential for lithium-caesium-tantalum-type pegmatites in the Northern Cape, South Africa: Journal of African Earth Sciences, v. 197, article 104769.
Von Knorring, O., and Condliffe, E., 1987, Mineralized pegmatites in Africa: Geological Journal, v. 22, p. 253–270.
Wilde, A., Otto, A., and McCracken, S., 2021, Geology of the Goulamina spodumene pegmatite field, Mali: Ore Geology Reviews, v. 134, article 104162.
Wise, M., 1999, Characterization and classification of NYF-type pegmatites: The Canadian Mineralogist, v. 37, p. 802–803.
Wise, M., Simmons, W., Webber, K., Falster, A., Roda-Robles, E., Hanson, S., Márquez-Zavalía, M., and Galliski, M., 2013, The discrimination of LCT and NYF granitic pegmatites using mineral chemistry: A pilot study, *in* Simmons, W.B., Webber, K.L., Falster, A.U., Roda-Robles, E., Hanson, S.L., Márquez-Zavalıa, M.L., and Galliski, M.A., eds., 6th International Symposium on Granitic Pegmatites: New Orleans, Rubellite Press, p. 156–157.
Wise, M.A., Müller, A., and Simmons, W.B., 2022, A proposed new mineralogical classification system for granitic pegmatites: The Canadian Mineralogist, v. 60, p. 229–248.
Xu, Z., Zheng, B., Zhu, W., et al., 2023, Geologic scenario from granitic sheet to Li-rich pegmatite uncovered by scientific drilling at the Jiajika lithium deposit in eastern Tibetan Plateau: Ore Geology Reviews, v. 161, article 105636.
Zagorsky, V.Y., Makagon, V., and Shmakin, B., 1999, The systematics of granitic pegmatites: The Canadian Mineralogist, v. 37, p. 800–802.
Zeh, A., Gerdes, A., Klemd, R., and Barton, J.M., Jr., 2007, Archaean to Proterozoic crustal evolution in the Central zone of the Limpopo belt (South Africa-Botswana): Constraints from Combined U-Pb and Lu-Hf Isotope analyses of zircon: Journal of Petrology, v. 48, p. 1605–1639.

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