

Genetic and province-scale relationships of alkaline leucogranite-fooid syenite in the Haruchas Dual Complex (South Namibia)

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ABSTRACT

The Haruchas Dual Complex in southern Namibia is part of the Richtersveld Suite and formed by two stocks that comprise coexisting silica-oversaturated alkaline granite and silica-undersaturated foid syenite, respectively. This contribution integrates mapping, petrography, whole-rock and mineral geochemistry, and U-Pb geochronology to constrain the magmatic evolution, crustal assimilation, and post-magmatic alteration of the complex. Three magmatic stages are distinguished: (1) emplacement of the main intrusive bodies between 914 and 891 Ma; (2) intrusion of a second magma pulse with similar magma composition at 866 Ma; and (3) the intrusion of a dike suite at ~815 Ma. These intrusion ages confirm the Haruchas Dual Complex as the northernmost and oldest intrusion of the Richtersveld Suite and the coeval emplacement of the two stocks. Geochemical data indicate that the parental magmas were mantle-derived and generated in a within-plate extensional setting, evolving through variable degrees of fractional crystallization and crustal contamination. The southern stock, dominated by leucogranite, records stronger crustal assimilation, whereas the northern stock, composed of varieties of foid syenite, and tawite, exhibits minor contamination, reflecting spatial and temporal heterogeneity in magma evolution. Post-magmatic alteration overprinted the central portion of the northern stock in two stages: an earlier autometasomatic stage related to Na-rich orthomagmatic fluids and characterized by aegirine growth, followed by a later hydrothermal stage associated with trachyte dike emplacement and characterized by replacement of feldspatoids by natrolite and cancrinite. Combined, geochronological and geochemical data indicate a southward migration of the magmatic center within the Richtersveld Suite during early Rodinia-related crustal thinning.

1. Introduction

Significant progress has been made over the past two decades in understanding the source and origin (e.g., Larsen and Sørensen, 1987; Kramm and Kogarko, 1994; Sørensen, 1997; Stevenson et al., 1997; Pilet

et al., 2002; Marks et al., 2011), differentiation processes (e.g., Brooks and Gill, 1982; Duda and Schmincke, 1985; Foland et al., 1993; Marks and Markl, 2001, 2003; Riishuus et al., 2008) and late crystallization stages (e.g., Marks et al., 2003; Mann et al., 2006; Markl et al., 2010) of alkaline igneous systems. These studies have substantially advanced the

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knowledge of how such lithologies evolve, providing geochemical and petrological constraints on compositional evolution, mineralogical transformations, and textural changes associated with magmatic and post-magmatic processes. New detailed data from known and still unexplored localities are, however, essential for refining existing evolution models, particularly regarding the type and degree of crustal assimilation and subsequent autometamorphic and hydrothermal alteration. In particular, large-scale alkaline igneous provinces may reveal information about the evolution of such complexes.

Two provincial-scale districts that are ideally suited as natural laboratories for studying the evolution of alkaline rocks are the Richtersveld Suite (RS; Frimmel et al., 2001; Zech et al., 2025) and the Kuboos-Bremen Line (KBL; Zech et al., 2025), situated north of the lower Orange River Valley in an area covering parts of north-western South Africa and southern Namibia. Although these two igneous provinces have been known since the 1920s (e.g., Haughton and Frommurtze, 1929, 1936; Van Biljon, 1939; Söhnge and De Villiers, 1946, 1948; De Villiers and Söhnge, 1959; Martin, 1963, 1965; Middlemost, 1967, 1969), few studies have focused on their origin and evolution (e.g., Allsopp et al., 1979; Smithies, 1991; Frimmel, 2000; Frimmel et al., 2001; Zech et al., 2025), leaving critical gaps, particularly regarding the petrological evolution of coexisting silica-undersaturated and silica-oversaturated lithologies. Foundational studies mainly focused on the mapping and characterization of the lithologies (e.g. Söhnge and De Villiers, 1946, 1948; De Villiers and Söhnge, 1959; Middlemost, 1967; Reid, 1991). Recent work has focused primarily on geochronological and isotopic aspects of the basement (e.g. Macey et al., 2017, 2022) and broader magmatic provinces (e.g. Frimmel, 2000; Frimmel et al., 2001; Zech et al., 2025), providing regional context but little insight into the petrogenesis, crustal assimilation and post-magmatic to hydrothermal alteration of individual complexes.

The Haruchas Dual Complex in southern Namibia (situated near the junction of the RS and KBL) is particularly well suited to address these broader questions because it preserves a close spatial association between foid syenite and alkaline granite, together with clear intrusive relationships and post-magmatic overprint within a single, well-

constrained complex. This makes it possible to examine magmatic differentiation, evaluate the type and extent of crustal assimilation, and explore their relationship to subsequent autometamorphic and hydrothermal alteration.

This study integrates geological mapping, petrography, mineral chemistry, whole-rock geochemistry, and U-Pb geochronology to examine the evolution of the Haruchas Dual Complex. On this basis, the study aims to characterize (1) the lithological architecture of the complex, (2) constrain the timing of emplacement of its main units and associated dikes, and (3) evaluate the relative roles of fractional crystallization, crustal assimilation, and late-to post-magmatic overprint in its evolution. Rather than serving as a direct regional model, the Haruchas Dual Complex is used here as a case study through which these processes can be examined in an integrated way.

2. Geological setting

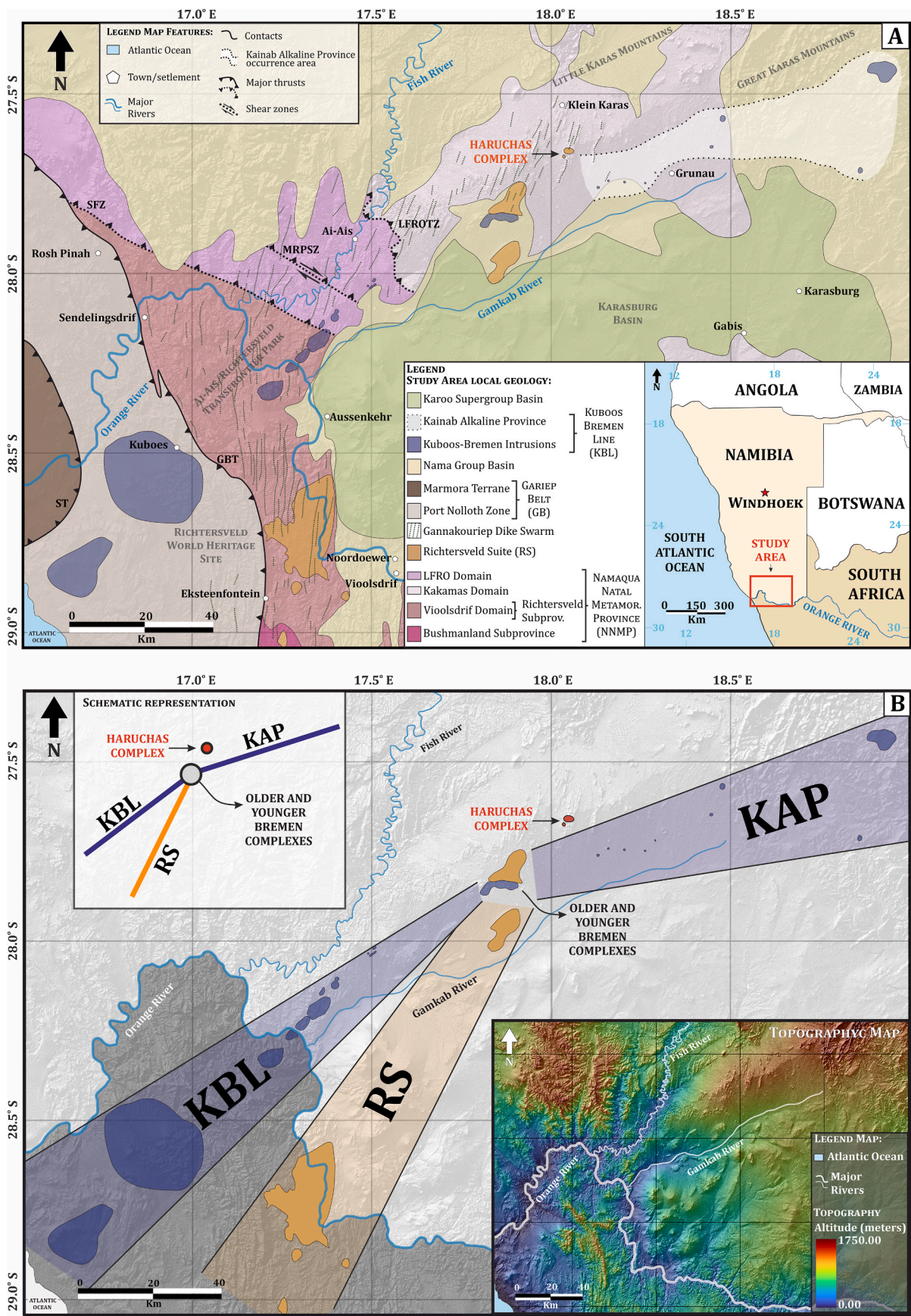
Southern Namibia (Karasburg Plateau and the Lower Orange River Valley; Dauteuil et al., 2015) and north-western South Africa (Alexander Bay and Richtersveld National Park) are dominated by igneous and metamorphic rocks of the Mesoproterozoic Namaqua-Natal Metamorphic Province (NNMP), Neoproterozoic metasedimentary Gariep Belt, and igneous rocks of the Richtersveld Suite to which the Haruchas Complex belongs (Table 1 and Fig. 1A; Allsopp et al., 1979; Hartnady et al., 1985; Reid, 1991; Thomas et al., 1994; Frimmel, 2000; Cornell et al., 2006; Miller, 2008, 2012; Macey et al., 2017, 2018, 2022; Frimmel, 2018 in Siegesmund et al., 2018; Zech et al., 2025). These rocks are cross-cut by the N-S to NE-SW trending Gannakouriep Dike Swarm (Reid, 1979; Onstott et al., 1986; Rioux et al., 2010) and the NE-SW trending Kuboos-Bremen Line (Fig. 1A and B; Söhnge and De Villiers, 1946, 1948; Reid, 1991; Smithies, 1991; Frimmel, 2000; Miller, 2008; Zech et al., 2025).

The southernmost intrusions of the Richtersveld Suite intruded the Paleoproterozoic (1.91–1.86 Ga) Vioolsdrif Domain of the Richtersveld Subprovince, and the northmost parts of the Bushmanland Subprovince, both part of the NNMP (Fig. 1A; Macey et al., 2017, 2018). The

Table 1

Relative ages between the magmatic, metamorphic and sedimentation occurrences of the studied region. Table based on Reid et al. (1991). It contains also ages from: Allsopp et al. (1979); Gresse and Germs (1993); Gresse and Scheepers (1993); Frimmel (2000); Frimmel et al. (2001); Rioux et al. (2010); Linnemann et al. (2018); Nelson et al. (2022); Macey et al. (2022) and Zech et al. (2025).

Ages (Ma)	Magmatic events		Deformation metamorphism	Sedimentation
480	Kuboos-Bremen Line			
500				
520				Nama Group
540				
560			Gariep Orogeny	
580				
600				Gariep Supergroup
620				
640				
660				
680				
700				
720				
740				
760				
780	Gannakouriep Dike Swarm	Richtersveld Suite		
800				
820				
840				
860				
880				
900				
920				
940				
960			Namaqua-Natal Metamorphic Province	
980				
1000				
1020				
1040				



(caption on next page)

Fig. 1. (A) Simplified Geological Map of South Namibia and Northwestern South Africa with main tectonic units and igneous intrusions. Based on Allsopp et al. (1979); Hartnady et al. (1985); Reid (1991); Thomas et al. (1994); Frimmel (2000); Cornell et al. (2006); Miller (2008, 2012); Macey et al. (2017, 2018, 2022) and Frimmel et al. (2001) in Siegesmund et al. (2018). Abbreviations of the major thrusts and shear zones: ST - Schakalsberge Thrust; GBT - Gariep Base Thrust; SFZ - Southern Front Zone; MRPSZ - Marshal Rocks-Pofadder Shear Zone; LFROTZ - Lower Fish River-Onseepkans Thrust Zone; (B) Map and schematic representation showing the location of the Richtersveld Suite (RS) and the Kuboos-Bremen Line (KBL) and the topographic map of the area. Note that the area around both the Older and Younger Bremen Complexes and the Haruchas Complex is the meeting point of both provinces, and also where the KBL kink in the direction of the Kainab Alkaline Province (KAP) occurs (Miller, 2008).

Violsdrif Domain is characterized by belts of metavolcanic and metasedimentary rocks and voluminous, mostly granitoid, intrusions (Reid, 1979, 1982, 1997; Reid et al., 1987; Macey et al., 2017). The meta-volcanic and metasedimentary rocks are folded and developed a NW-SE trending, moderately-steeply NE-dipping axial planar foliation at greenschist-facies conditions during the ~1.89 Ga Orange River Orogeny (Macey et al., 2017, 2022). The northern Bushmanland Sub-province consists of older Paleoproterozoic migmatitic gneiss (Gladkop Suite, 1.81 Ga; Nke et al., 2020) and Mesoproterozoic granite gneiss and granite (~1.21–1.05 Ga; Macey et al., 2018).

The northmost Richtersveld Suite intrusions, including the Haruchas Complex, are hosted in garnet-bearing leucogranite gneiss from the Mesoproterozoic Kakamas Domain of the NNMP (Witwater Gneiss; Kröner and Blignault, 1976; Blignault, 1977; Macey et al., 2022). Its igneous precursors intruded interlayered sheets of granulite-facies metapelites (Narries Group, ~1.22 Ga), garnetiferous augen gneiss (Eendorn Suite, ~1.20 Ga) and leucogranite gneiss (Ham River Suite, ~1.19 Ga) at ~1.14 Ga, and were subsequently intruded by the Komsberg Suite granites (~1.11 Ga; Macey et al., 2022). The ~NW-trending foliation, developed during the main phase of the Namaqua Orogeny (~1.20–1.12 Ga), were refolded into km-scale open domes-and-basins, and are locally reworked by NW-trending late-Namaqua shear zones associated with granite and pegmatite magmatism at ~1.01–0.96 Ga. The western margins of the Violsdrif Domain and Bushmanland Sub-province were reworked along ~N-S shear zones during late Ediacaran deformation related to development of the SE-vergent Gariep fold-and-thrust belt, which contains Neoproterozoic (~750–550 Ma) greenschist-facies metasedimentary rocks.

The Richtersveld Suite consists of three main complexes and smaller intrusions that are aligned along an NNE-SSW trend (De Villiers and Söhne, 1959; Middlemost, 1967; Kröner and Blignault, 1976; Allsopp et al., 1979; Frimmel et al., 2001; Zech et al., 2025). The Older Bremen Complex (also called Wetterkopf Complex) has the oldest U-Pb magmatic crystallization zircon ages between ~920 and 880 Ma (Allsopp et al., 1979; Zech et al., 2025). The predominant lithologies are granite, quartz syenite, and foid syenite (Middlemost, 1967; Allsopp et al., 1979; Miller, 2008; Zech et al., 2025).

The Haruchas Dual Complex, located in the Warmbad District of Namibia, is situated 20 km east of Grünau (Fig. 1A) on farm Haruchas 10 (Genis, 1972; Schreuder, 1975; Kröner and Blignault, 1976; Blignault, 1972, 1977). The Haruchas Dual Complex is the northernmost intrusion of the Richtersveld Suite and is composed of two distinct stocks (Fig. 2A; Table 2) that intruded the Witwater Gneiss. The northern stock contains 897 ± 17 Ma and 895 ± 19 Ma foid syenite, with different varieties from rim to the core (Genis, 1972; Zech et al., 2025). The undated southern stock, located approximately 1 km to the southwest, is composed by alkali granite (Genis, 1972; Schreuder, 1975; Blignault, 1977; Miller, 2008; Zech et al., 2025). Both stocks of the Haruchas Complex are crosscut porphyritic trachyte dikes.

To the southwest, the 833–771 Ma Richtersveld Igneous Complex (RIC; namesake for the entire suite) is the biggest complex of the Richtersveld Suite (Frimmel et al., 2001; Macey et al., 2018). The vertical, N-S to NE-SW trending Gannakouriep Dike Swarm (Fig. 1A; Reid, 1979, 1982; Reid et al., 1991) intrudes an area of ~300 km length and 150 km width. Dikes locally crosscut the Richtersveld Suite intrusions (Onstott et al., 1986; Frimmel et al., 2001; Miller, 2008), although intrusion ages are similar (~795 Ma; Rioux et al., 2010). The dikes are locally metamorphosed at greenschist to amphibolite facies grades in their

northern and western occurrences, due to younger Pan-African metamorphism at ~550 Ma (Reid et al., 1991; Ransome, 1992).

3. Materials and analytical methods

3.1. Sample selection

Samples were collected during a field campaign in November 2022. A representative collection of the country rocks and intrusive units was sent to the Karlsruhe Institute of Technology (KIT, Germany; see Supplementary Material Table S1 and Fig. S1 for sample locations and map). From a total of 47 samples, 15 representative samples were selected for whole rock analyses and 22 for thin section preparation. For comparison, a sample from the Older Bremen Complex was collected and used for geochronological analysis (see Supplementary Material Table S1 and Fig. S1).

3.2. Microscopy

Petrographic observation, description, and photomicrographs were produced using a Zeiss AxioScope A1 polarized light microscope equipped with an Axiocam camera (visual field 10.0–0.49 mm and 10–40× magnification) at the Chair of Mineralogy and Petrology, Institute of Applied Geosciences (AGW), KIT. Mosaic images were produced by stitching multiple photomicrographs using Microsoft Image Composite Editor (ICE) to yield high-resolution images, from which the modal mineralogy was calculated and then plotted in a QAPF diagram (Streckeisen, 1976) to assist in rock classification.

Scanning Electron Microscope (SEM) images and Energy Dispersive Spectroscopy (EDS) were also used, with elemental maps made using a TESCAN VEGA SEM equipped with an INCAx-act EDS at the Chair of Mineralogy and Petrology, AGW, KIT. The SEM was operated under an acceleration voltage of 15 kV and a current beam of 10 nA.

3.3. Micro X-ray fluorescence (μ XRF)

Qualitative elemental μ XRF mapping was carried out on selected representative thin sections using a Bruker Tornado M4 μ XRF instrument equipped with two spectrometers housed at the Technical University of Berlin (Germany), Mineralogical and Geochemical Micro-Analytical Laboratory (MAGMA Lab). The operating conditions included an amplifying time of 40 ms (per spot), acceleration voltage of 50 kV, beam current of 600 μ A, a beam size of 20 μ m, and spot distances of 20 μ m. The generated images and elemental maps data were processed by the M4 Tornado software.

3.4. Electron microprobe analysis (EMPA)

The EMPA analysis for major and trace element composition of clinopyroxene, titanite, and apatite was carried out using a JEOL JXA-8230 electron microprobe at the Department of Petrology and Mineral Resources of the University of Tübingen (Germany). Analyses were made by Wavelength Dispersive Spectroscopy (WDS). The acceleration voltage was 15 kV for all samples. For clinopyroxene and titanite, the beam current was 20 nA, while for apatite it was 10 nA. The probe diameter varied from focused in clinopyroxene, to 5 μ m in titanite and 10 μ m in apatite. Counting times (peak/background) were 16/08 s for major elements and 30/15 s for minor elements.

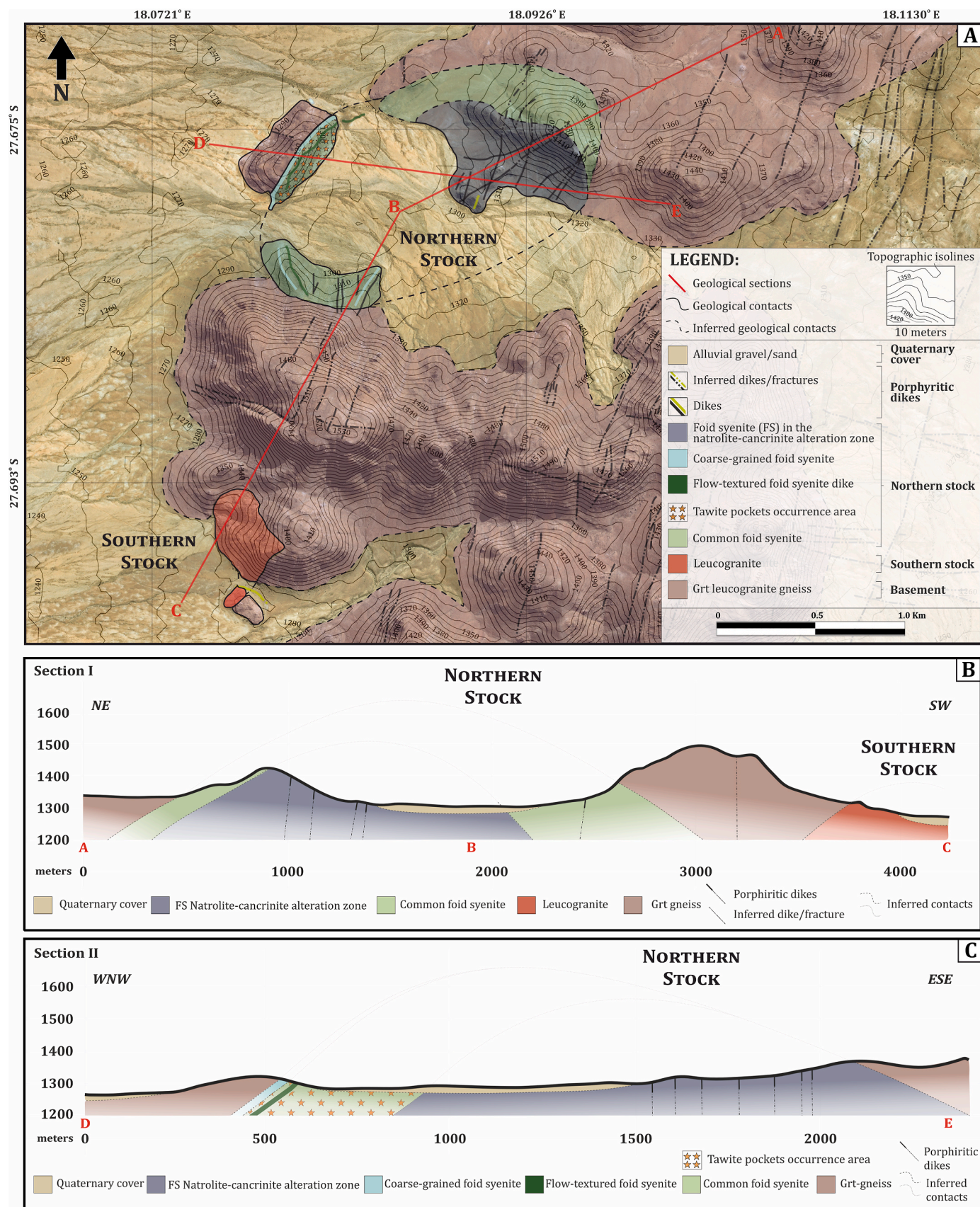


Fig. 2. (A) Geological map of the intrusive units of the Haruchas Complex and alteration zone; (B) and (C) Geological cross-sections NE-SW and WNW-ESE, respectively, of the Haruchas Complex. Note the ring dike structure.

Table 2
Mapped intrusive units/lithologies/varieties of the Haruchas Complex.

Intrusive Units	Lithologies	Studied Varieties	Location	Observation
Southern Stock	Granitoids	Leucogranite	Southern Stock	Red colored; coarser/porphyritic textures and pegmatite veins occur but are less common across the stock.
		Aplite		Fine-grained, hololeucocratic and with a brighter color
Northern Stock	Foidolite	Tawite	Rim Northern Stock	Small occurrence; rounded pockets with a sharp contact with the hosting foid syenite
		Common foid syenite		Dominant lithology and with the biggest number of textures and mineral assemblages' varieties
	Foid syenites (FS)	Flow-textured foid syenite		Platy sodalite and alkali feldspar oriented in a flow texture
		Coarse-grained foid syenite		Elongated outcrop in the western contact margin of the northern stock and also occurring as smaller dikes cutting the Northern Stock
		FS in the natrolite-cancrinite alteration zone	Core Northern Stock	Central area of the Northern Stock. Samples with a replacement texture of the main foid minerals by Ntr and Ccn; aegirine-augite to aegirine and with altered perthitic orthoclase
Porphyritic Dikes	Trachyte	Altered Unaltered	Both Stocks and Basement rocks	Usually with xenoliths and xenocrysts besides the phenocrysts

Calibration conditions, internal overlap corrections and factors, and detection limits are reported with the complete EMPA results and protocols in the [Supplementary Material Tables S2–4](#). The detection limits used are two times the average detection limit of the machine for each element. The raw data were processed using the *JEOL-integrated ZAF* correction (Armstrong, 1991) and quantification (Bence and Albee, 1968). The clinopyroxene formulae were recalculated on the basis of 6 oxygen equivalents ($\text{Fe}^{2+}/\text{Fe}^{3+}$ allocation method; 4 cations per formula unit; Droop, 1987); the apatite formula was calculated on the base of 8 cations (12.5 oxygen equivalents; OH was calculated using $\text{F} + \text{Cl} + \text{OH} = 1$); and the titanite formula was calculated on the basis of 4 atoms of Si; all using the *GCDKit* software (Janoušek et al., 2024). Clinopyroxene geothermobarometry uses the spreadsheets of Neave and Putirka (2017) and Gündüz and Asan (2023). Multiple models implemented in the spreadsheets (Nimis, 1995; Putirka et al., 1996; Nimis and Ulmer, 1998; Putirka, 2008; Wang et al., 2021) enable data comparison. Apatite geothermometry was calculated using the method of Piccoli and

Candela (2002) within the Gündüz and Asan (2023) spreadsheet. Titanite Zr geothermometry was calculated following Hayden et al. (2008). As the studied rocks are quartz-free and feldspathoid-rich, two silica activities (a_{SiO_2} of 0.2 and 0.5) compatible with the stability of both orthoclase and feldspathoids were considered based on Hayden et al. (2008). The calculations used $a_{\text{TiO}_2} = 0.8$ based on Hayden et al. (2008), consistent with the presence of ilmenite and zircon and the absence of rutile.

3.5. Whole rock geochemistry

Samples were crushed, and ground with an agate disc mill for 5 min to an $\sim 100 \mu\text{m}$ grain size. The loss on ignition (LOI) was determined by weighing the samples before and after heating them at 950°C for 3 h and letting them cool for the same amount of time. Wavelength dispersive X-ray fluorescence (WD-XRF) analysis was done on fused beads (lithium tetraborate 66.5% and lithium metaborate 33.5%; flux:sample ratio = 10:1; 1100°C) with a *S4 Explorer*, Bruker AXS spectrometer in the Laboratory for Environmental and Raw Materials Analysis (LERA), AGW, KIT. A Rh X-ray tube (50 keV, 1 kW) served as radiation source. Signal detection was carried out using a proportional flow counter (Ar- CH_4 gas) and a scintillation counter. Analyzer crystals used are XS-55, LIF2000, and PET. Calibration involved various certified rock standards such as SY-2 (CANMET), AGV-1 (USGS; Govindaraju, 1994), and MEG-2 (GeoPT), with the accuracy of approximately $\pm 10\%$ being verified by including these reference materials in the in the measurement protocol.

Trace elements and REE concentrations were measured on acid digests. The sample was heated in a closed *Teflon*® vessel for 16 h at 120°C (*DigiPrep*, SCP Science) using 5 mL of 40% HF (*Suprapur*), 1 mL of 65% HClO_4 (*Normatom*), and 2 mL of 65% HNO_3 (*distilled in-house*). Two blanks and reference standards from Govindaraju (1994) such as SY-2 (CANMET) and MEG-1 (GeoPT) were included into the digestion protocol for quality control. Aliquots were taken and evaporated until dry, then resolubilized in 1% HNO_3 for analysis by ICP-MS (*iCap RQ*, Thermo Fisher Scientific; LERA, AGW, KIT). Measurements were performed in a combination of standard and CCT mode using He as collision gas. The calibration stock solution for trace elements was prepared with *Certi-PUR® ICP Multi Element Standard VI* (Merck). A separate calibration was done for REE measurements using the *Claritas PPT® ICP-MS Multi-Element Solution 1*. Instrumental drift was monitored by internal standard addition (50 μL) to the samples and blanks (1% HNO_3) of a solution containing Sc, Rh, In, and Tm. Quality assurance of the ICP-MS measurement was performed with the certified reference material CRM-TMDW-A (*High Purity Standards*) with an overall accuracy of approximately $\pm 6\%$, for most elements. The accuracy of all results is approximately $\pm 10\%$.

The total carbon (TC) and sulfur (TS) content of the powdered bulk rock material was determined using a Carbon-Sulfur Analyzer (CS, 2000; *Eltra*) at LERA, AGW, KIT. The powdered material was heated to 2000°C in an induction furnace with added Fe chips and W granules. Released CO_2 and SO_2 gases were quantified via IR spectrometry after passing through several traps to ensure dust and H_2O removal. A steel standard (92400-3050; *Eltra*) was used as reference material to monitor analytical precision, that was $<0.5\%$ for TC and $<3\%$ for TS. All results from whole rock (major and trace elements), TC and TS were organized and plotted using the *GCDKit* software (Janoušek et al., 2006), where they assisted rock classification and nomenclature using the TAS diagram (Middlemost, 1994).

3.6. U-Pb geochronology

Uranium-Pb data measured from zircon, apatite and titanite were collected on a Thermo Fisher Scientific Element XR sector field ICP-MS coupled to a 193-nm ArF Excimer laser with a HelEx 2-vol cell (*Analyte Excite+*, Teledyne PhotonMachines) at LERA, AGW, KIT, using a method

as previously described in Beranoaguirre et al. (2022). All of the information regarding the analytical parameters (spot size, repetition rate, acquisition times, gas flows, etc.) is detailed in the supplementary material. The primary reference material used was GJ1 (Jackson et al., 2004), with the exception of session 5 that used NIST612 (Jochum et al., 2011). Secondary zircon reference materials, used for validation, were Blueberry (BB; Santos et al., 2017) and Plesovice (Slama et al., 2008).

The results of the reference materials in each session are shown in the appendix and are within $\pm 2\sigma$ of accepted values. For apatite and titanite, an additional correction was applied to the $^{206}\text{Pb}/^{238}\text{U}$ ratios to account for compositional matrix differences using the Durango (McDowell et al., 2005) as apatite calibration material and Sumé (Lana et al., 2021) as apatite validation reference materials, as well as the Bear Lake and Khan titanite crystals (Mazoz et al., 2022) as calibration and validation materials, respectively. Data processing was performed using Microsoft Excel, as detailed in Gerdes and Zeh (2006), 2009, with each analysis spectrum being manually checked to ensure stability and homogeneity of the integrated time period. Zircon U-Pb analyses were common ^{208}Pb -corrected following the method described in Millonig et al. (2012). Plots and ages were calculated using Isoplot (Ludwig, 2012) and all uncertainties/errors are reported as $\pm 2\sigma$. The weighted averages and errors were calculated using the Taylor (1997) methodology for combining separate measurements.

4. Results

4.1. Geology of the Haruchas Complex

4.1.1. Intrusive units

The southern stock occupies an outcrop area of $\sim 0.1\text{ km}^2$ at the south-western flank of the hills formed by the Witwater Gneiss, where the stock moderately dips NE, below the gneiss (Fig. 2B and C). Most of the lower terrain is covered by Quaternary sand and gravel, which separates a small satellite outcrop of the stock south of the main outcrop area (Fig. 2A and 3A).

The main lithology is a red-colored, medium-grained leucogranite with a characteristic leucocratic to hololeucocratic nature and a holocrystalline inequigranular texture (Fig. 4A and B). It contains orthoclase, quartz and plagioclase, with subordinate biotite and magnetite. Fine-grained aplite veins and a single pegmatite locally cross-cut the leucogranite with sharp contacts (Fig. 4A). Aplites have a similar composition to that of leucogranite (euhedral to subhedral orthoclase, quartz and plagioclase), but are slightly lighter in color due to their lower mafic mineral content. While pegmatite contains no visible mafic minerals, differing only in their grain size.

All rocks are often strongly weathered at surface with feldspars being locally kaolinized. A black patina on top of most of the outcrops (Fig. 4B) is evidenced by the presence of Fe-oxy-hydroxides in biotite and magnetite dominant areas.

The northern stock is located $\sim 1.1\text{ km}$ northeast of the southern stock. It has an elliptical shape in map view ($\sim 2 \times 1\text{ km}$), with the long axis trending NE-SW (Fig. 2A). The intrusion dips outwards beneath the Witwater Gneiss with a sharp contact (Fig. 2B and C). Outcrops are limited to the northern (and north-eastern), western and southern margins of the stock, with the south-eastern and central portions covered by Quaternary sand and gravel (Fig. 2A, B and C).

The predominant rock is a leucocratic, medium-grained foid syenite (Fig. 2A, B and C) composed of subhedral orthoclase, sodalite, nepheline, and aegirine-augite. Natrolite with small amounts of cancrinite are present as fine-grained anhedral grains around sodalite and nepheline. Locally, fine-grained varieties occur. These finer-grained zones additionally comprise small amounts of fine-grained anhedral calcite and fluorite. Due to its simple texture, this lithology is referred to as common foid syenite.

A sodalite-rich foidolite (sodalitite) with aegirine-augite occurs as

small sized (5 cm to 1 m in diameter) rounded pockets/lenses in the common foid syenite with a sharp contact. These pockets are restricted to a 500 m wide zone spatially close to contact in the western marginal zone (Fig. 2A). According to Le Maitre et al. (2005) this aegirine-augite-bearing sodalitite is named as tawite. It comprises predominantly dark grey, coarse-grained, euhedral sodalite (cumulate texture), interstitial orthoclase (intercumulus), and subordinate aegirine-augite. The sodalite has an intense orange fluorescence (Fig. 4C) and some sodalite phenocrysts show penetration twinning. In loose tawite blocks, where sodalite is more exposed to weathering, sodalite has a light blue to white color. Tawite is quite rare in the geological record and is known from only a few localities worldwide. The best-documented occurrence is the Mt. Saint Hilaire Complex, Canada, where it occurs in limited volumes as fine-grained, centimeter-sized xenoliths hosted within foid syenites (O'Neill, 1914; Clark, 1955; Currie et al., 1986; Tice, 2010).

Flow-textured foid syenite (previously named as foyaite ring dike; Genis, 1972) occurs as 1 to 2 m wide and 500 m long, winding dike in a sharp contact with the common foid syenite, that locally can become sinuous. This variety occurs spatially associated with the tawite. The flow-textured foid syenite appears parallel to the western contact with the Witwater Gneiss (30 m away from the W and SW margins) dipping outward, forming a ring dike. The flow-fabric is defined by preferred orientation of coarse-grained, tabular orthoclase and platy sodalite that follow the ring-dike geometry. The matrix is mostly aphanitic, while locally small amounts of fine-to medium-grained, subhedral nepheline and aegirine-augite occurs (Fig. 4D).

Coarse-grained foid syenite intruded along the western margin of the northern stock (noticeable as a 20 m wide ridge for $\sim 500\text{ m}$), into the sharp contact between the Witwater Gneiss and the common foid syenite with an outward dipping orientation (ring dike architecture; Fig. 3E). Along the southern margin of the northern stock a coarse-grained foid syenite dike shows local textural variation. It mineralogically closely resembles the coarse-grained foid syenite of the western margin but shows gradual transitions into porphyritic zones. This one vertical dike strikes parallel to the contact with the Witwater Gneiss, and at the southern margin, where a 10 m wide N-S trending dike occurs. The coarse-grained foid syenite contains tabular orthoclase, with subordinate subhedral nepheline and sodalite. Subhedral aegirine forms coarse-grained clusters. Locally anhedral biotite occurs. Weathering is strong, with the ridge and southern dike showing intense kaolinization and erosion. Biotite shows signs of limonitization.

Both the northern and the southern stocks, as well as the Witwater Gneiss, are intruded by a suite of vertical, NE-SW to N-S trending, dark grey to dark green porphyritic trachyte dikes. These dikes occur more frequently in the center of the northern stock. The dikes display irregular compositional-influence halos extending into the surrounding host rocks. Only one dike crosscuts the southern stock leucogranite (Fig. 2A and 3A). The dikes vary in width from 30 cm to 4 m (Fig. 3D). The rocks contain subhedral to euhedral feldspar phenocrysts that reach 1 cm in length. Abundant rounded xenoliths from the Witwater Gneiss as well as common foid syenite are dispersed irregularly within the dikes and have a size range of 5–20 cm (Fig. 4F and G). The porphyritic trachyte has a diverse compositional range with various amounts of chlorite, epidote and biotite yielding a more greenish color along the dike margins.

4.1.2. Hydrothermal alteration

The central area of the northern stock is characterized by a strong alteration of the common foid syenite. In the following this zone is described as natrolite-cancrinite alteration zone (Fig. 2A). This hydrothermal alteration zone is dark grey in color, and is characterized by anhedral natrolite and cancrinite (together comprising $\sim 20\text{ vol}\%$) replacing subhedral to euhedral sodalite and nepheline, as pseudomorphs (Fig. 4E). The contact between the alteration zone and common foid syenite is transitional in the north and northwestern parts of the northern stock but is covered by sand and gravel deposits between the

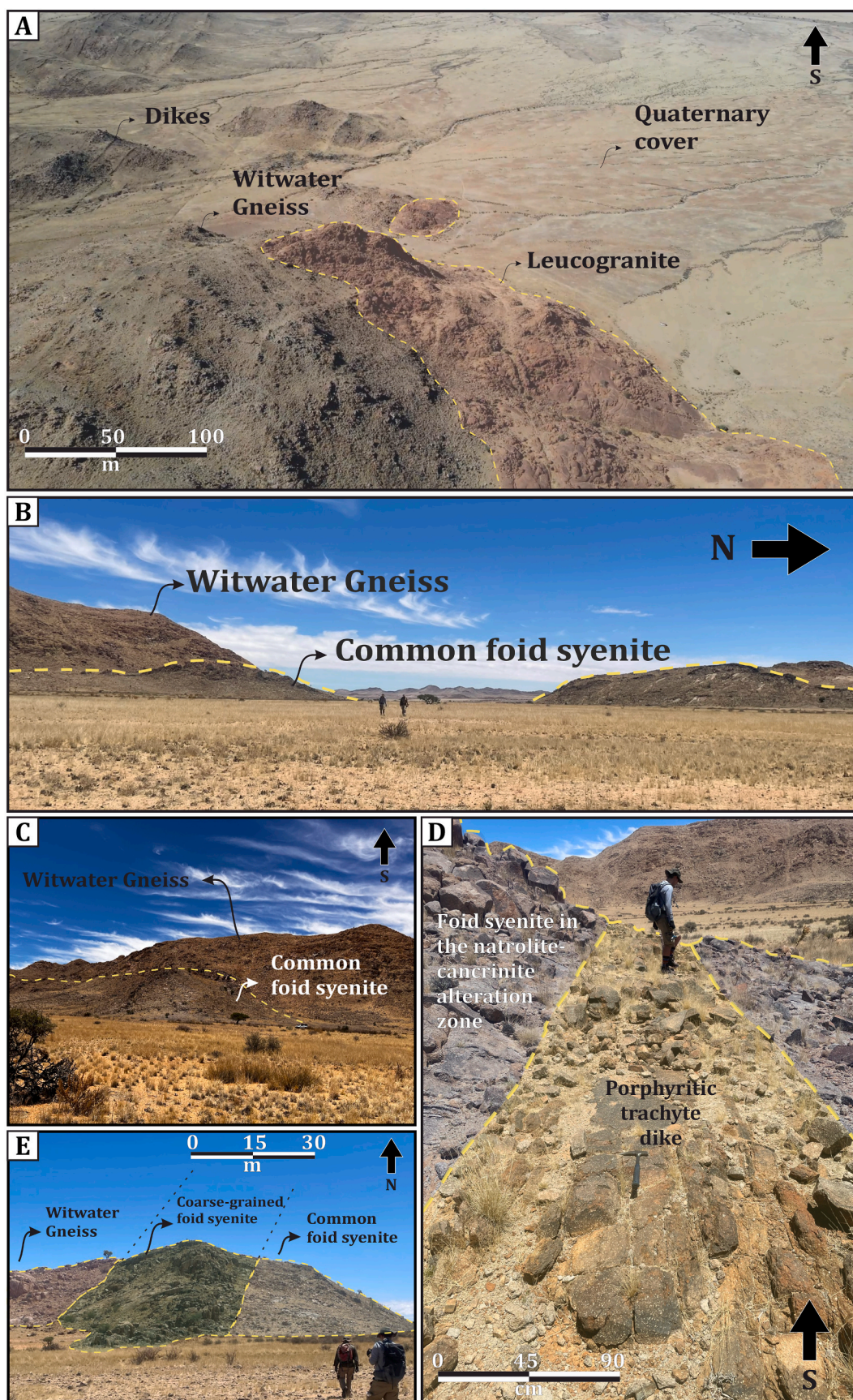


Fig. 3. (A) Aerial view from the southern stock at the edge of the Witwater Gneiss; (B) View from the northern stock, outcrops facing West; (C) Contact between the basement rocks and the common foid syenite from the northern stock, facing South; (D) Porphyritic dike cutting through the central area of the northern stock where the foid syenite in the natrolite-cancrinite alteration zone occurs, facing South; (E) Coarse-grained foid syenite, in the western contact zone, facing North.

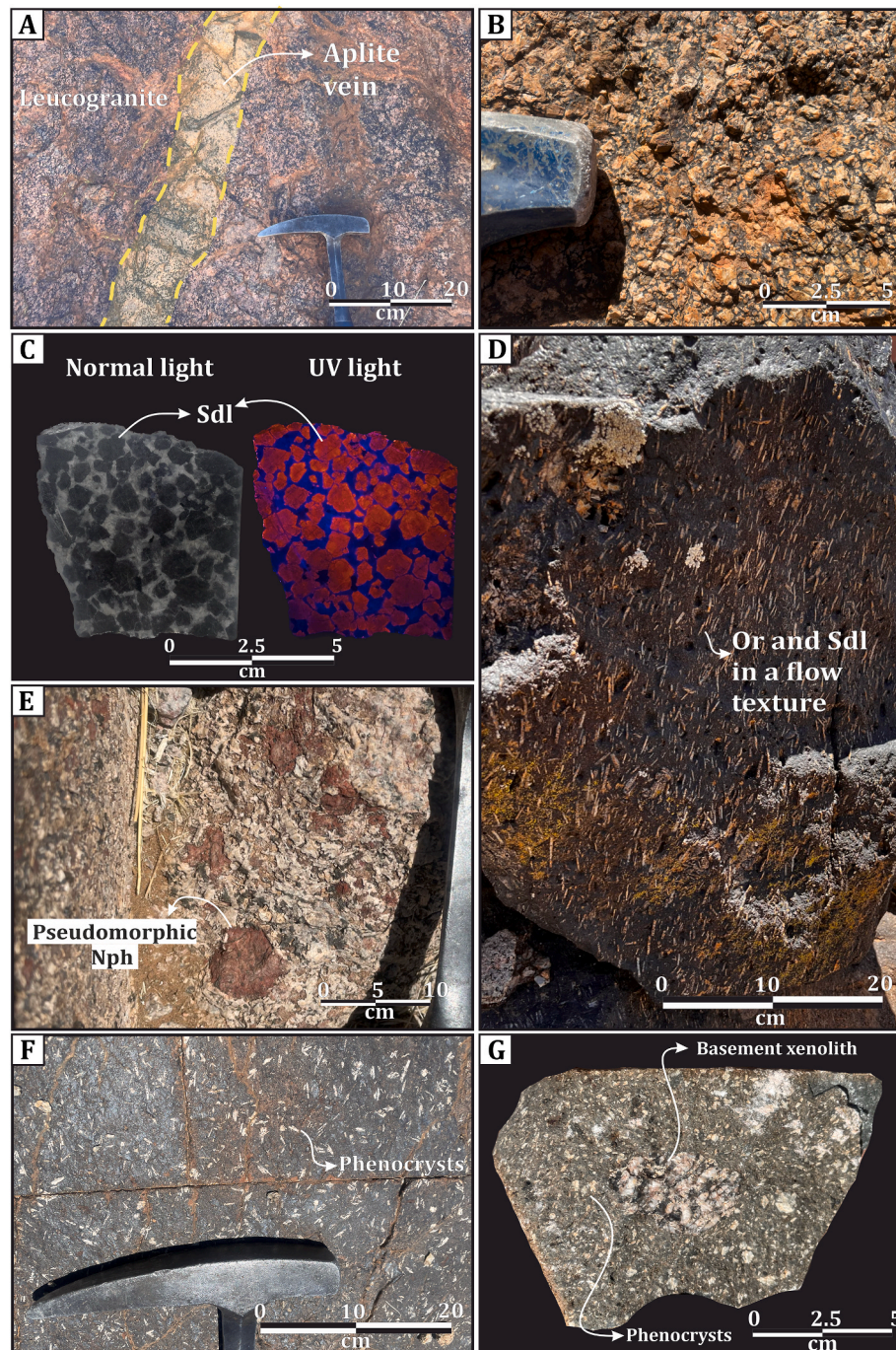


Fig. 4. (A) Aplite vein in medium to coarse-grained leucogranite; (B) Close view of the medium/coarse-grained leucogranite. Note the black patina on top of the red colored leucogranite; (C) Tawite from the northern stock rim under normal and ultraviolet (UV) light; (D) Field outcrop photo of flow-texture foid syenite with oriented orthoclase (Or) and sodalite (Sdl); (E) Pseudomorph of nepheline megacrystal (Nph) with red natrolite in the foid syenite in the natrolite-cancrinite alteration zone, central area of the northern stock; (F) Close view of the phenocryst concentration in one of the porphyritic dykes; (G) Sample of a porphyritic dike containing a xenolith from the gneissic basement. Abbreviations: Nph (nepheline); Or (orthoclase); Sdl (sodalite).

central area and western margin. When coarser-grained, the alteration zone also contains fluorite and biotite. Due to the replacement of the feldspathoids to finer-grained natrolite and cancrinite, the rock in this area is more friable and appears more susceptible to physical and chemical weathering.

In addition, only the coarse-grained foid syenite shows similar replacement textures visible in outcrop scale. These include locally developed anhedral biotite within the aegirine-rich zones and reddish, iron-stained natrolite occurring as pseudomorphic crystals in nepheline-dominated zones.

4.2. Petrography

4.2.1. Intrusive units

In the leucogranite, the first magmatic minerals are accessory zircon, and magnetite, termed magnetite I; these are fine-grained and have orthoclase and quartz inclusions. The major rock forming mineral is orthoclase (50 vol%), which is equant in size, anhedral to subhedral with perthitic exsolution. Quartz (20 vol%) is medium-to coarse-, locally fine-grained, anhedral to subhedral, predominantly occupying the interstitial spaces between orthoclase grains (Fig. 5A). Biotite (5 vol%) forms

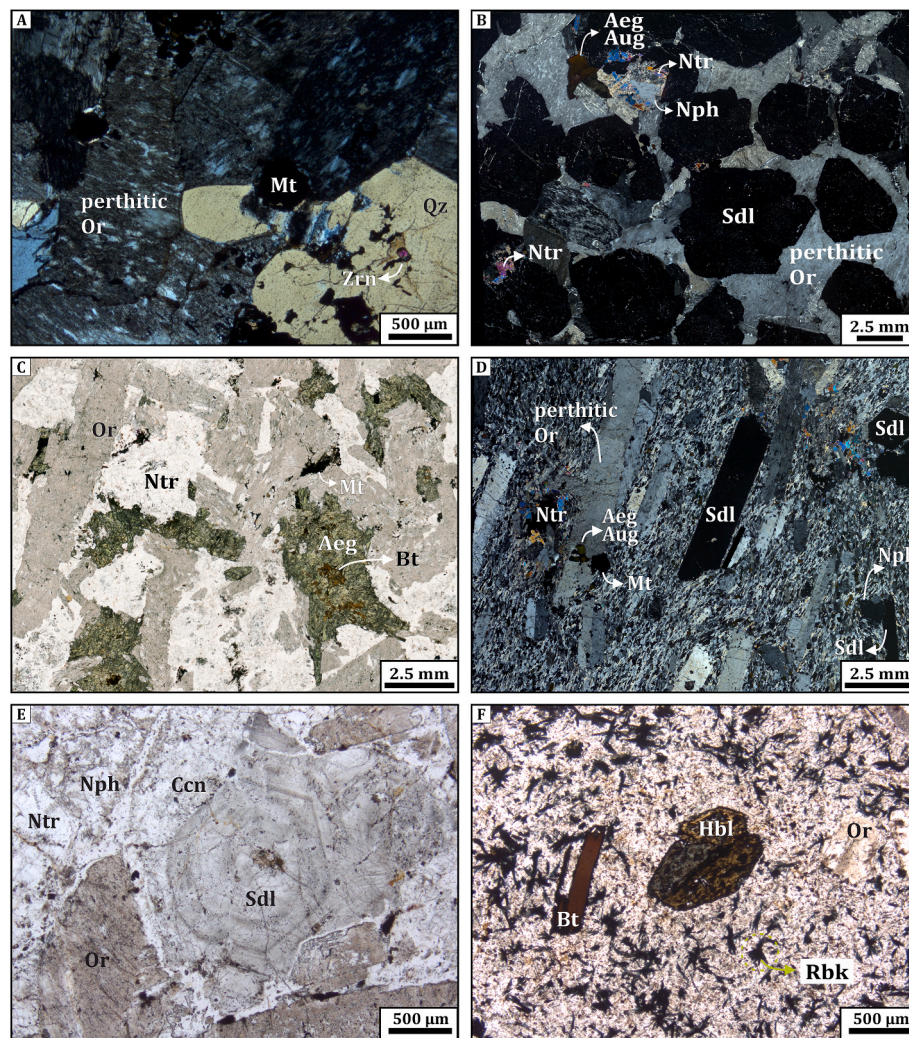


Fig. 5. (A) Average coarse-grained inequigranular texture of the leucogranite from the southern stock (crossed nicols); (B) Euhedral to subhedral megacrysts of sodalite in the tawite from the northern stock western rim (crossed nicols). Note the orthocumulate texture with the sodalite surrounded by late perthitic orthoclase; (C) Coarse-grained foid syenite from the western rim of the northern stock (parallel nicols). Note the natrolite replacement of nepheline, the presence of interstitial aegirine to the orthoclase and the post-magmatic biotite replacement of aegirine; (D) Oriented tabular orthoclase and platy sodalite megacrysts in the flow-texture foid syenite from the northern stock rim (crossed nicols); (E) Zoned sodalite megacrystal from the foid syenite within the natrolite-cancrinite alteration zone in the central portion of the northern stock with altered nepheline crystals in the matrix (parallel nicols); (F) Porphyritic texture with presence of megacrysts of biotite, riebeckite and orthoclase in albite matrix (parallel nicols) from the trachyte dike in the northern stock core. Abbreviations: Ab (albite); Aeg (aegirine); Aeg-Aug (aegirine-augite); Bt (biotite); Ccn (cancrinite); Hbl (hornblende); Mt (magnetite); Nph (nepheline); Ntr (natrolite); Or (orthoclase); Qz (quartz); Rbk (riebeckite); Sdl (sodalite); Zrn (zircon).

isolated medium-grained, anhedral to subhedral grains between the orthoclase. Plagioclase (20 vol%) occurs interstitially to orthoclase and quartz. Very fine-to fine-grained apatite and magnetite II form subhedral to euhedral grains in plagioclase interstices.

The aplite has a similar paragenetic sequence as the leucogranite (Table 3 and Fig. 8A and B). Magnetite I is the only mafic mineral occurring in very low volumes (~5 vol%) as subhedral grains. It is richer in quartz (40 vol%), which is coarse-to fine-grained, anhedral to subhedral. Interstitial spaces contain a characteristic micrographic intergrowth of orthoclase and quartz. These intergrowths frequently occur close to the contact between the aplite dikes and leucogranite. Biotite is absent. The pegmatite has a similar composition to the aplites, but with a coarse-grained texture.

In the common foid syenite, sodalite and nepheline coexist in variable proportions, with a majority of samples having more sodalite (3/2 – sodalite/nepheline; 30 and 20 vol%, respectively; Table 3; Fig. 8A and B). Both minerals are subhedral to anhedral, concentrically zoned, with coarser grain size in nepheline-dominant zones. Commonly, micro-

inclusions of orthoclase appear in zones around the nepheline and sodalite cores (Supplementary Material Fig. S3A). Orthoclase (30–40 vol %) is subhedral to tabular with perthitic to mesoperthitic exsolution textures. Fine-grained, dark green aegirine-augite (~10 vol%) occurs interstitially between the foid minerals and orthoclase. Anhedral, fine-grained zircon is found in the interstices of orthoclase. Small, subhedral biotite is commonly formed along aegirine-augite rims. Locally, the common foid syenite shows a gradual transition into a fine-grained and porphyritic variation (with 3–4 mm sized orthoclase, sodalite and nepheline phenocrysts) having the same mineral assemblage as the main common foid syenite itself.

Sodalite in tawite is coarse-grained, euhedral to subhedral and comprises between 60 and 70 vol% of the rock, while its grain size varies between 0.4 and 1.0 cm in diameter (Fig. 4C; 8A and B; Table 3). Sodalite phenocryst cores are inclusion-free, whereas the intermediate and marginal zones contain 30–100 µm sized orthoclase inclusions. Moreover, sodalite rims have ~10 µm sized anhedral pyrite and ilmenite inclusions. Sodalite grains are arranged in a self-supported framework of

Table 3
Average mineral modes of the studied varieties of the Haruchas Complex.

Studied Varieties	Average modal composition (%)															
	Qtz	Nph	Sdl	Als	Pl	Cpx	Bt	Amp	Chl	Ep	Ser	Ttn	Ap	Fl	Zrn	Pcl
Leucogranite	22	//	//	48	15	//	5	//	//	//	2	//	1	//	1	//
Aplite	40	//	//	40	14	//	//	//	//	//	//	//	//	//	1	//
Tawite	//	3	63	18	//	5	//	//	//	//	//	//	//	//	1	//
Common foid syenite	//	15	25	40	//	8	2	//	//	//	//	//	//	//	1	//
Flow-textured foid syenite	//	18	27	35	//	10	//	//	//	//	//	3	//	//	1	//
Coarse-grained foid syenite	//	10	5	52	//	10	//	//	//	//	//	//	//	2	1	//
FS Ntr-Ccn alteration zone	//	4	10	35	//	10	5	5	//	8	15	//	4	5	1	//
Altered trachyte	//	//	//	40	18	//	8	//	15	8	2	//	2	1	1	//
Trachyte	//	//	//	41	20	//	10	20	//	//	2	//	2	//	1	//
Grt-leucogranite gneiss	25	//	//	35	20	//	3	//	//	//	2	//	//	//	//	5
																15

early euhedral crystals, configuring an orthocumulate texture that is surrounded by poikilitic perthitic orthoclase intercumulus (~20 vol%; Fig. 5B). Anhedral to subhedral ilmenite and pyrite, and anhedral nepheline are found as traces in the intercumulus material. Fine-to medium-grained, subhedral primary aegirine-augite at ~5 vol% occurs in the interstices of perthitic orthoclase and sodalite (Fig. 6A–7A). Within larger aegirine-augite grains, aegirine needles (10 µm wide and 70 µm long) and anhedral zircon (50 µm wide) are found along cleavage planes (Supplementary Material Figs. S4G and S6). Furthermore, subhedral zircon occurs together with perthitic orthoclase in the intercumulus. Rare subhedral to euhedral, fine-grained apatite occurs in the intercumulus alongside perthitic orthoclase, displaying no apparent zoning.

The flow-textured foid syenite (Fig. 5D, 6C and 7C, D and E) includes coarse-grained, tabular up to 1 cm sized perthitic orthoclase phenocrysts, making up ~30 vol% of the rock. Platy sodalite phenocrysts occur as 0.5–1.0 cm long grains and comprise 30 vol%, while aegirine-augite phenocrysts about 1 mm long comprises ~10 vol% of the rock. These three minerals define the flow-fabric by grain-shape preferred orientation. Subhedral nepheline (20 vol%) phenocrysts (~3 mm) are rotated and surrounded by the flow-fabric, that is bent around them. Locally, subhedral magnetite occurs at 5 vol%. Magnetite can also form inclusions in aegirine-augite. Up to 3 vol% titanite is divided into three different types based on textures (titanite I, II, and III): Titanite I forms subhedral and fine-grained inclusion of glomeroporphyritic clusters in nepheline and sodalite megacrysts. Titanite II occurs together with perthitic orthoclase, sodalite, nepheline and aegirine-augite as subhedral to euhedral grains. It forms clusters, with the long axis of the euhedral crystals oriented parallel to the flow texture (Fig. 7D), and shows sectorial zoning that in some grains varies to an irregular patchy zoning, usually having a core with a sinuous transition between zones (supplementary material). Titanite III is found surrounding magnetite as a thin (<20 µm) corona. Other accessory minerals are fine-grained subhedral zircon and pyrochlore located in the interstices of orthoclase, nepheline and sodalite phenocrysts.

The coarse-grained foid syenite is hololeucocratic to leucocratic. Fine-grained, subhedral magnetite appears as inclusions in subhedral to euhedral, unoriented tabular grains (0.5–1.5 cm in length) of orthoclase. Orthoclase is the dominant phase with more than 50 vol%. Larger orthoclase grains show more exsolved perthitic textures, some even forming albite-rich zones. Foids occur interstitially to orthoclase, with some smaller, anhedral grains being included in the rims of the coarse-grained, tabular orthoclase. In most samples, nepheline is the major foid with an average of ~10 vol%. Sodalite only occurs rarely with an average of <5 vol%. The major mafic mineral is aegirine, forming isolated, medium-to coarse-grained, glomeroporphyritic clusters interstitially to orthoclase (10 vol%; Fig. 5C–6B). Uncommon subhedral to euhedral megacrysts of aegirine are found in the orthoclase interstices. Locally, coarse-grained glomeroporphyritic, green to dark green clusters of aegirine have formed. In a few samples, zircon is present as an interstitial phase to orthoclase and aegirine, with a medium-grained, anhedral shape.

A local variety of the coarse-grained foid syenite occurs as a dike along the southern margin of the northern stock and closely resembles the western marginal variety, but locally has a porphyritic texture. It contains subhedral to euhedral perthitic orthoclase phenocrysts set in a fine-grained groundmass, together with intermediate medium-grained domains resembling the common foid syenite. No systematic textural transition between the coarse-grained, porphyritic, and intermediate domains was observed. All foid syenites show similar QAPF compositions (Fig. 11A) with comparable orthoclase proportions but variable nepheline and sodalite contents, with the lowest in the coarse-grained foid syenite and highest in the flow-texture foid syenite.

In the trachyte dikes, the most common accessory phases are anhedral zircon and apatite microphenocrysts included in hornblende and biotite. Euhedral zircon grains of 1 to 5 mm length are included in both

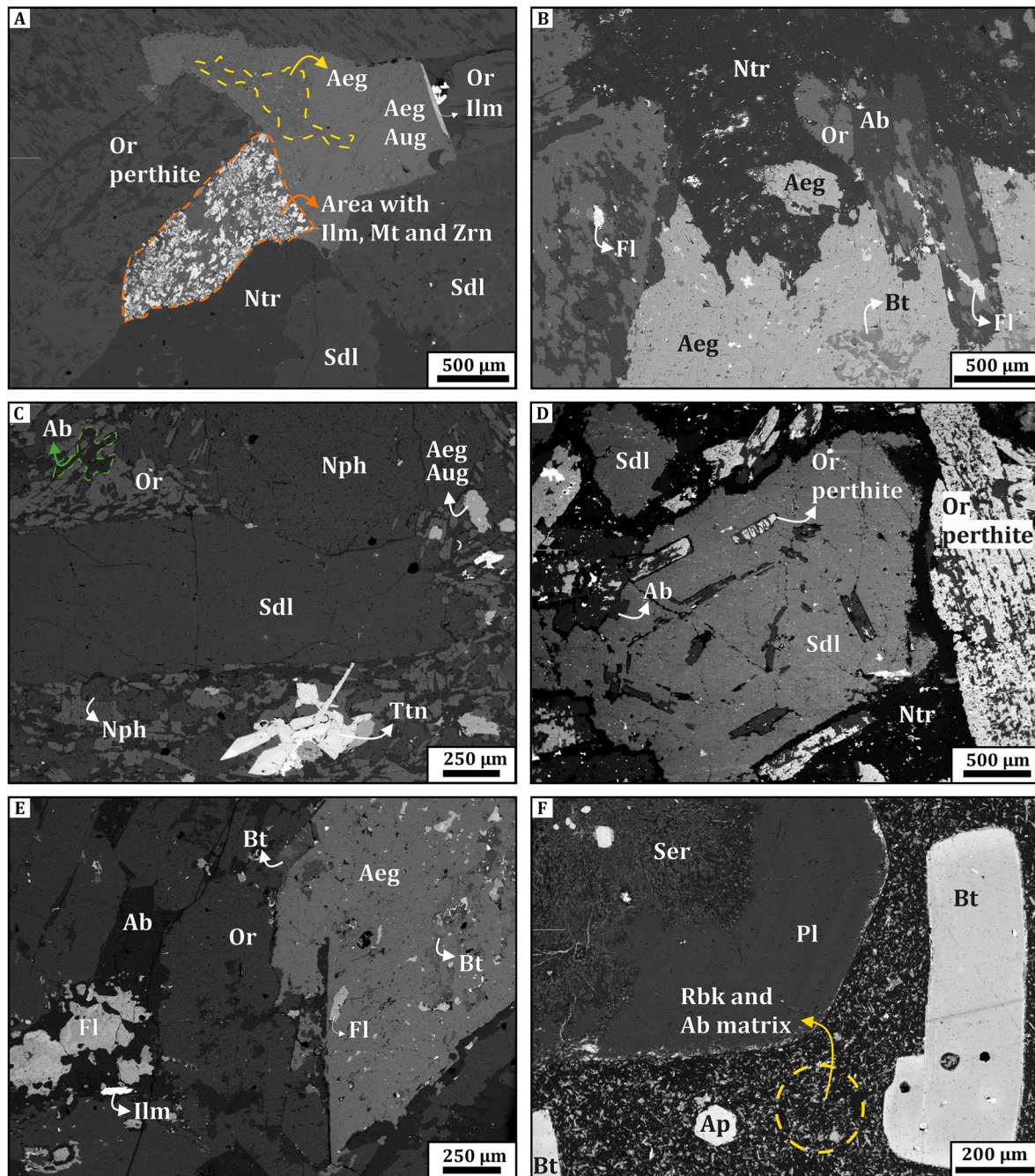


Fig. 6. BSE-SEM images (A) Subhedral aegirine-augite crystal interstitial to sodalite and orthoclase from the tawite. Note the replacement to aegirine and the ilmenite, magnetite and zircon rich area; (B) Subhedral aegirine crystal with biotite replacement from the coarse-grained foid syenite. Note the presence of anhedral fluorite and natrolite; (C) Megacrystal of tabular sodalite in equilibrium with euhedral nepheline in the flow-textured foid syenite. Note the finer texture formed by subhedral orthoclase, nepheline and sodalite and the euhedral titanite cluster; (D) Subhedral sodalite megacrystal with orthoclase and albite replacement inclusions concentric to the crystal form in the foid syenite within the natrolite-cancrinite alteration zone; (E) Interstitial subhedral aegirine megacrystal with anhedral biotite replacement from the foid syenite within the natrolite-cancrinite alteration zone. Note the anhedral fluorite together with albite interstitial to orthoclase; (F) Subhedral to euhedral plagioclase, biotite and apatite phenocrysts from the trachyte dike. Note the sericitisation of the plagioclase and the fine-grained matrix formed by albite and riebeckite. Abbreviations: Ab (albite); Aeg (aegirine); Aeg-Aug (aegirine-augite); Ap (apatite); Bt (biotite); Fl (fluorite); Ilm (ilmenite); Mt (magnetite); Nph (nepheline); Ntr (natrolite); Pl (plagioclase); Or (orthoclase); Sdl (sodalite); Ser (sericite); Ttn (titanite); Zrn (zircon).

orthoclase (40 vol%) and plagioclase (oligoclase, 20 vol%). Both feldspars form larger radial, glomeroporphyritic clusters up to 1 cm in size. Fine-to medium-grained plagioclase phenocrysts occur with quenched textures such as swallow tails and hollow grains. Euhedral hornblende phenocrysts reach a maximum of 3 mm in length (Fig. 5F) and form between 5 and 10 vol%. Biotite (10 vol%) forms euhedral to subhedral phenocrysts of 0.5 mm in length (Fig. 6F). Apatite grains of 100 µm in

diameter are dispersed in the matrix and locally occur on feldspar and biotite grain boundaries. Moreover, they form elongated, euhedral microphenocrysts that locally show quenching like those detected in plagioclase (Fig. 7F). Magnetite occurs as subhedral microphenocrysts (up to 100 µm) dispersed in the matrix. The major mafic mineral is very fine-grained, subhedral to euhedral blue riebeckite (10–20 vol%) occurring in an anhedral groundmass of albite (Fig. 7F). The riebeckite

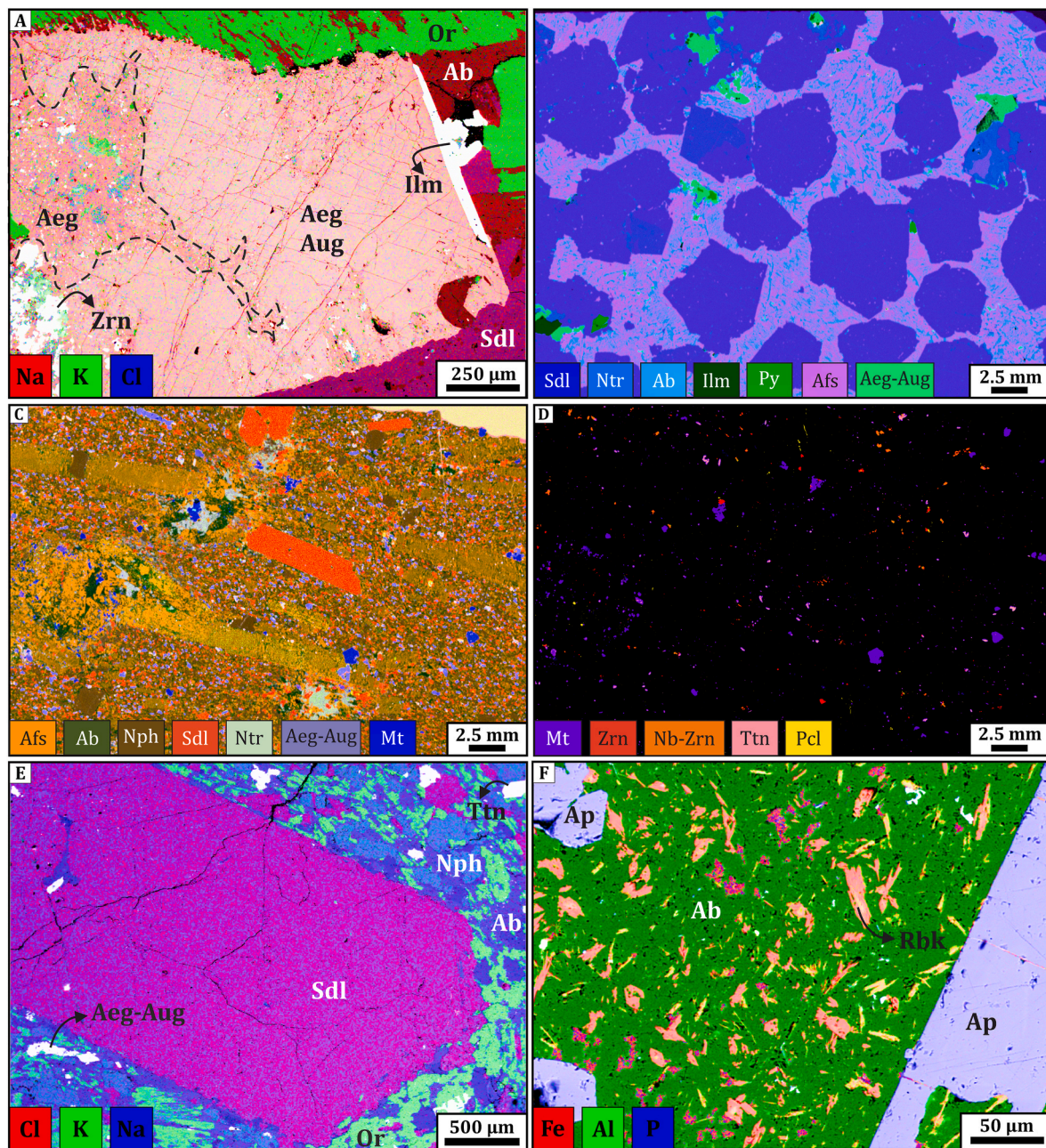


Fig. 7. (A) SEM-EDS Na-K-Cl mapping of the tawite evidencing the aegirine-augite megacrystal; (B) μ XRF mapping of the tawite; (C) and (D) μ XRF mapping of the flow-textured foid-syenite; (E) SEM-EDS Cl-K-Na mapping of the tabular/platy sodalite from the flow-textured foid syenite; (F) SEM-EDS Fe-Al-P mapping of the matrix around the apatite phenocrysts in the trachyte dike. Note *swallow-tail* fast crystallization texture on the larger apatite. Abbreviations: Ab (albite); Aeg (aegirine); Aeg-Aug (aegirine-augite); Afs (alkali-feldspar); Ap (apatite); Bt (biotite); Fl (fluorite); Ilm (ilmenite); Mt (magnetite); Ntr (natrolite); Nph (nepheline); Pcl (pyrochlore); Pl (plagioclase); Py (pyrite); Or (orthoclase); Rbk (riebeckite); Sdl (sodalite); Ttn (titanite); Nb-Zrn (niobium-rich zircon) and Zrn (zircon).

forms needle-like grains (with an average length of 20 μ m) and locally small radial clusters (Fig. 5F–7F). In samples with increased grain size (central portion of the dikes) riebeckite is subhedral to euhedral with grains reaching up to 250 μ m in length (Supplementary Material Fig. S2F). A weak sericitisation of plagioclase is present in most of the samples. Sericitisation is advanced in both phenocrysts and matrix grains, which are located close to the host rock, or to the rock xenolith contacts (from the contact up to 1 cm away). Similarly, where the matrix becomes finer grained adjacent to the contacts with the host rocks, both amphiboles have an increased content of fine-grained biotite and mica inclusions along the grain margins.

Some trachyte dikes display an intense green color, have a slightly coarser matrix, and slightly differ mineralogically from the grey trachyte

dikes. These dikes exhibit advanced saussuritization and sericitisation of feldspars, along with chloritization of hornblende, riebeckite and biotite (biotite I) imparting a characteristic green coloration. Chlorite (15 vol%) occurs as medium-grained pseudomorphs after hornblende, riebeckite, and biotite I, or as fine-grained anhedral crystals dispersed within the matrix. Primary biotite I can be found as subhedral isolated grains, whereas fine-grained anhedral and dispersed biotite II, observed in the margins and within hornblende grains, is more abundant (biotite I + biotite II form 10 vol%). Epidote (~10 vol%) is associated with medium- to coarse-grained chlorite pseudomorphs after hornblende and biotite I and forms anhedral fine-grained, aggregates in the matrix. In contrast to the other trachyte dikes, fine-grained magnetite is also associated with the pseudomorphic assemblage and comprises around 10 vol%.

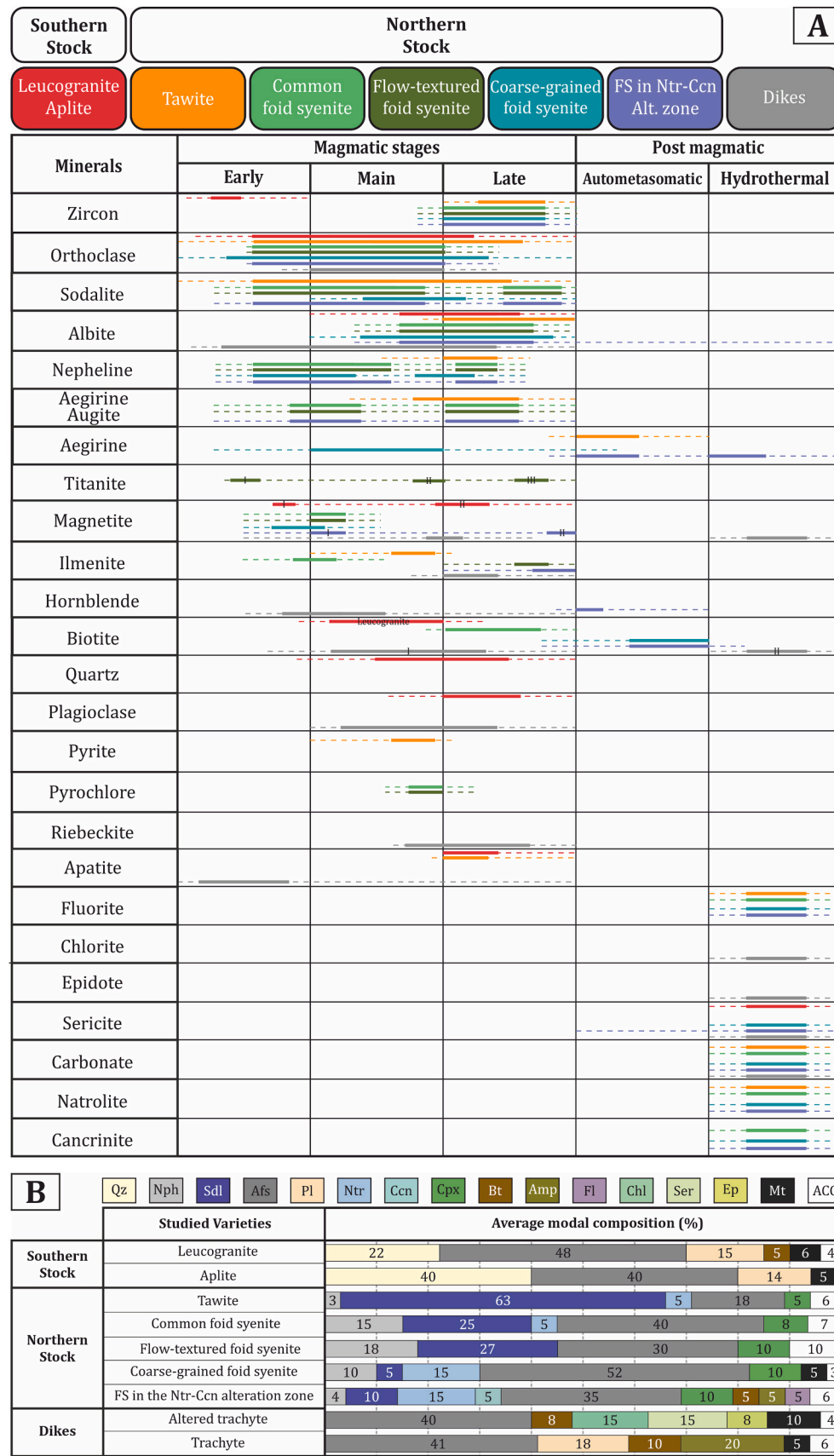


Fig. 8. (A) Paragenetic sequence and (B) average mineral modal composition (%) of the studied lithologies of the Haruchas Complex. Abbreviations: FS (foid syenite); Qz (quartz); Nph (nepheline); Sdl (sodalite); Afs (alkali-feldspar); Pl (plagioclase); Ntr (natrolite); Ccn (cancrinite); Cpx (clinopyroxene); Bt (biotite); Amp (amphibole); Fl (fluorite); Chl (chlorite); Ser (sericite); Ep (epidote); Mt (magnetite); ACC (accessory minerals).

4.2.2. Hydrothermal alteration

Within the natrolite-cancrinite alteration zone, most of the original foid syenite texture is preserved with accessory phases such as magnetite and zircon being unaffected by the overprint. The main differences are related to the pseudomorphic replacement of original minerals. The major foid mineral preserved is euhedral to subhedral sodalite with visible oscillatory zoning (~1 mm; 10 vol%; Fig. 5E), marked in some grains by concentric orthoclase inclusions, like those from the protolith common foid syenite (Fig. 6D and Supplementary Material Fig. S3B). Nepheline and sodalite are replaced by natrolite and cancrinite (~15 and 5 vol%, respectively), with this replacement minerals forming anhedral micro poikilitic zones around nepheline, sodalite and orthoclase grains. Natrolite is fibrous in zones where the pseudomorphic texture with nepheline megacrysts are more frequent. These natrolite pseudomorphs after nepheline are recognized by a line of fine-grained natrolite and iron oxy-hydroxides marking the older grain boundary (see Supplementary Material Fig. S3C and S3D). Blue and purple, fine-grained, anhedral fluorite (100–200 µm; 5 vol%; Fig. 6E) is present in the natrolite dominant zones, occurring interstitially to natrolite grains. Fluorite is also found in the same microfractures along the rim of aegirine-augites, together with biotite. The altered rocks show an increased amount of fine-grained subhedral to anhedral biotite (5 vol%) that commonly occurs within the aegirine-augite, along grain boundaries, microfractures and rims (Fig. 6E). In the coarse-grained glomeroporphyritic clusters of aegirine-augite the rims have a higher content of fine-grained anhedral aegirine. Anhedral to subhedral aegirine occurs along the margins of the aegirine-augite and are also interstitial to alkali feldspar and foids. Very rarely, anhedral to subhedral, fine-grained hornblende occurs together with biotite along the rims of aegirine-augite.

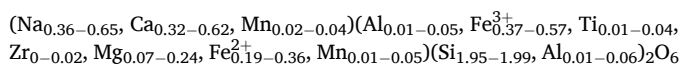
The common foid syenite, coarse-grained foid syenite and tawite, show broadly similar alteration textures, but to a much lesser degree than the foid syenite within the main hydrothermal alteration zone. They display an analogous feldspathoid alteration, with nepheline and sodalite locally surrounded or pseudomorphically replaced by fine-grained anhedral natrolite (generally ≤5 vol%) and minor cancrinite (generally ≤1 vol%), with local anhedral calcite and fluorite. The coarse-grained foid syenite contains local anhedral biotite rims and seams associated with anhedral aegirine, as well as reddish natrolite and Fe-oxy-hydroxides around nepheline, and in the tawite, aegirine-augite show rare replacement to anhedral aegirine along its seams (Fig. 6A).

4.3. Mineral chemistry

4.3.1. Clinopyroxene

Clinopyroxene composition in the foid syenite varieties and tawite varies along the general aegirine-augite to aegirine trend, forming three distinct populations (Fig. 9A and B): (1) a low-Na aegirine-augite population (Ca: 0.32–0.62 apfu; Na: 0.36–0.65 apfu); (2) a higher-Na aegirine-augite population (Ca: 0.09–0.29 apfu; Na: 0.68–0.89 apfu); and (3) an aegirine population (Ca: below detection limit – bdl–0.06 apfu; Na: 0.71–0.98 apfu).

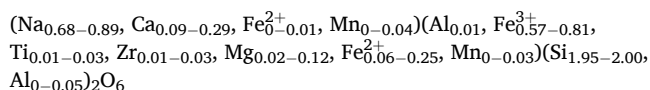
Population 1 (low-Na aegirine-augite) has a compositional range of:



The low-Na population represents all aegirine-augite generations in the flow-textured foid syenite and one grain in the tawite. It shows the highest CaO (7.74–14.89 wt%), FeO (5.99–11.03 wt%), MgO (1.20–4.10 wt%) and MnO (1.25–2.11 wt%) contents of all aegirine-augites. It has an Al₂O₃ content between 0.97 and 2.06 wt%, and the lowest Na₂O (4.73–8.60 wt%) contents of all grains, without strong correlation between Al, Zr and Ti (Fig. 9C and D). The studied grain from the tawite with the highest CaO content of 7.74 wt%, is also enriched in TiO₂ 1.29 wt% and represents an overlap with the following population

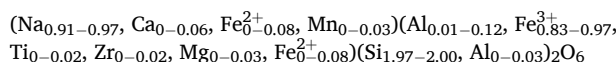
2.

Population 2 (higher-Na aegirine-augite) has a compositional range of:



The higher-Na population comprises the majority of the primary aegirine-augite grains of the tawite, the foid syenite in the natrolite-cancrinite zone and common foid syenite with the lowest Ca aegirine-augite grain from the flow-textured foid syenite representing an overlap with population 1. It is characterized by higher Na₂O contents (9.16–11.63 wt%), lower CaO (2.17–7.12 wt%), MgO (0.35–2.05 wt%) contents, and slightly lower to comparable MnO contents (0.62–1.66 wt%) relative to the low-Na population (Fig. 9E and F; supplementary material). Contents of FeO (1.85–7.77 wt%) and Al₂O₃ (0.81–1.77 wt%) are generally lower or comparable to those in the low-Na population, with the lowest values observed in aegirine-augite from the common foid syenite and highest in those from the tawite. Within this population, aegirine-augite from the tawite is notably enriched in ZrO₂, with maximum values reaching 1.29 wt%, and a variable range of TiO₂ between 0.39 and 0.90 wt%, (Fig. 9C and D).

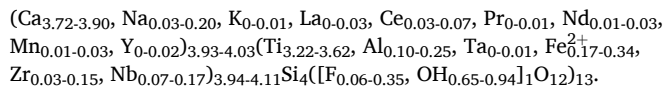
Population 3 (aegirine) has a compositional range of:



This population includes all aegirine grains from the coarse-grained foid syenite variety, along with aegirines located at the rims and within cleavages of aegirine-augite in tawite and the natrolite-cancrinite alteration zone. It forms a compositional cluster within the aegirine field and is distinguished by the highest Na₂O contents among all studied clinopyroxenes (11.69–13.24 wt%) and the lowest CaO contents (0.05–1.34 wt%). MgO (0.06–0.43 wt%) and MnO (0.12–0.76 wt%) concentrations are in average lower than in the other two populations, but their maximum values slightly overlap with the lower contents of population 2. The FeO contents are considerably lower (0.74–2.85 wt%), except for one outlier from the coarse-grained foid syenite variety that has 4.51 wt% FeO (Fig. 9E and F). The Al₂O₃ contents are relatively consistent between 0.82 and 2.71 wt%.

4.3.2. Titanite

Titanite only occurs in the flow-textured foid syenite. Titanite generations I and III were too small to yield reliable geochemical data. Titanite II has bright cores grading into darker rims with sectorial zoning in the BSE images (Supplementary Material Fig. S10). The compositional range for titanites II is:



Titanite II contains low contents of Al₂O₃ and FeO, varying from 0.62 to 1.59 wt% and 1.48–3.37 wt%, respectively. The Na₂O is also low, varying from 0.10 to 0.76 wt%. Fluorine is present in low concentrations, from 0.13 to 0.83 wt%, with the lowest concentrations usually associated with brighter cores in the backscatter SEM image (Supplementary Material Fig. S10). Some of these bright cores are enriched in Ti (max 35.47 wt% TiO₂) and in total REEs, with a maximum of 2.77 wt% (Supplementary Material Fig. S19C). All titanites show variable ZrO₂ (0.49–2.20 wt%), and Nb₂O₅ (1.06–2.79 wt%), with the brighter cores being slightly enriched in these elements when compared to the most of the zones. However, the highest concentrations show no consistent correlation with zones within the crystals. Total REE (ΣREE) shows no clear correlation with Ca, Fe²⁺, Al, or Zr (supplementary material, Fig. S19A and B), but show a weak negative correlation with Ti (supplementary material, Fig. S19C).

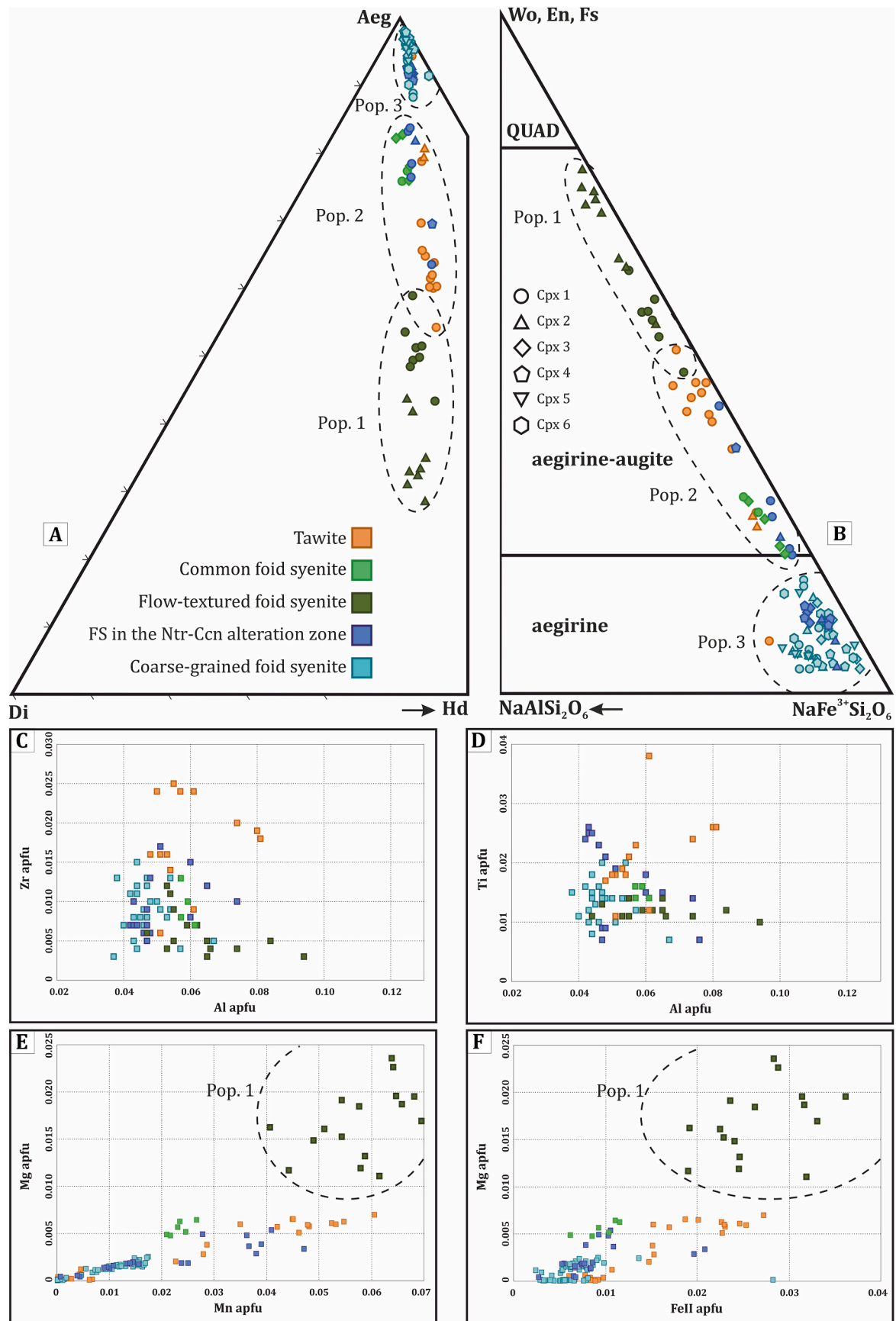


Fig. 9. Clinopyroxene chemistry: (A) Na, Mg and $\text{Fe}^{2+} + \text{Mn}$ in atoms per formula unit (apfu) triangular plot; (B) QUAD, aegirine and jadeite triangular plot; (C) Al vs. Zr in apfu; (D) Al vs. Ti in apfu; (E) Mn vs. Mg apfu; (F) FeII vs. Mg apfu. Abbreviations: FS (foid syenite); Ntr (natrolite); Ccn (cancrinite).

4.3.3. Apatite

Apatite is exclusively present in leucogranite, tawite and trachyte dikes as an accessory mineral (Fig. 10A). The ones present in the leucogranite could not be analyzed due to their small size ($<5\ \mu\text{m}$). The apatite compositional range in the tawite is:

(Ca_{4.90–4.98}, Na_{0.08–0.10}, K_{0–0.01}, La_{0–0.05}, Ce_{0–0.08}, Nd_{0–0.02})_{5.11–5.14}(P_{2.89–2.96}, Si_{0–0.05})_{2.94–2.96}O_{12.5}(F_{1.00–1.07}, OH_{0–0.01})_{1–1.07}

Besides Ca (4.90–4.98 apfu), the apatite M site hosts minor total REE (La + Ce + Nd; with a total range between 0.051 and 0.148 apfu; Fig. 10B and C). Besides P (2.89–2.96 apfu), the T site contains up to 0.05 apfu Si. The X site is almost completely filled with F (0.99 up to 1.06 apfu), a maximum OH of 0.01 apfu and no detectable Cl. Na content varies from 0.08 to 0.10 apfu.

Apatites from trachyte dikes have a compositional range as follows:

(Ca_{4.89–4.97}, Sr_{0–0.01}, Mn_{0–0.01}, Fe_{0.03–0.06}, Mg_{0.02}, K_{0–0.01}, Ce_{0–0.02}, Nd_{0–0.01})_{5.01–5.03}(P_{2.96–2.92}, Si_{0–0.04}, Mn_{0–0.01})_{2.99–3.00}O_{12.5}(F_{0.63–0.97}, Cl_{0.02–0.04}, OH_{0.01–0.34})

Apatite grains in this rock are not zoned. Compared to apatite in tawite, apatites in the trachyte dikes lower total REE content (Table 4; Fig. 10B and C). The Fe²⁺ content (0.03–0.06 apfu) is lower than those on the apatites from tawite and Na content is usually bdl (Table 4). The T site exhibits higher P contents (2.96–2.99 apfu) but, on average, has similar Si ranges (bdl to 0.04 apfu) to those from the tawite. In contrast, the X site shows lower F (0.63–0.97 apfu), and higher OH (0.01–0.34 apfu) than the tawite, and exclusively contains, low concentrations of Cl (0.02–0.04 apfu).

In the tawite and trachyte dikes, apatite occurs as euhedral to subhedral crystals distributed across different stages in the paragenetic sequence, with trachyte-hosted apatites spanning a temporally broader paragenetic crystallization (Figs. 7A–8A). In the late-magmatic stage the apatites are represented by smaller euhedral crystals. In the britholite substitution diagram (Fig. 10C), Ca + P contents range from 7.86 to 7.94 apfu, whereas Si + ΣREE contents range from 0.02 to 0.06 apfu with the trendline following the britholite substitution trend.

4.4. Whole rock geochemistry

4.4.1. Intrusive units

Similar to the Witwater Gneiss Basement ($A/\text{CNK} = 1.09$, $A/\text{NK} = 1.20$), the leucogranite ($A/\text{CNK} = 1.01$, $A/\text{NK} = 1.09$) and aplite ($A/\text{CNK} = 1.06$, $A/\text{NK} = 1.06$) of the southern stock are peraluminous (Fig. 11C). While, the leucogranite show an alkaline character with SiO₂-content of 65.4 wt% and Na₂O + K₂O of 9.8 wt% (comparable with the gneiss basement), aplite follows a subalkaline trend with slightly higher SiO₂ of 73.9 wt% and lower Na₂O + K₂O of 8.2 wt% (Fig. 11A; Table 4). Leucogranite has a ΣREE content of 1018 ppm. Tawite have a significant lower ΣREE content of only 135 ppm. The LREE chondrite normalized pattern for both lithologies are similar with a distinct Eu anomaly, which is also detectable in the gneiss basement rocks (Fig. 12B). The aplite has a lower LREE/HREE ratio (Fig. 12B), but exhibits the highest Ta (96 ppm), Nb (374 ppm) and Hf (33 ppm) concentrations in the Haruchas Complex (Fig. 12A). The Ti concentration (336 ppm), in contrast, are the lowest of all Haruchas lithologies.

Tawite has the lowest SiO₂ content (44.72 wt%) and the highest Na₂O (13.37 wt%) and Al₂O₃ (25.54 wt%) contents (Fig. 11D), but is low in K₂O (3.4 wt%). It plots almost on the boundary between the

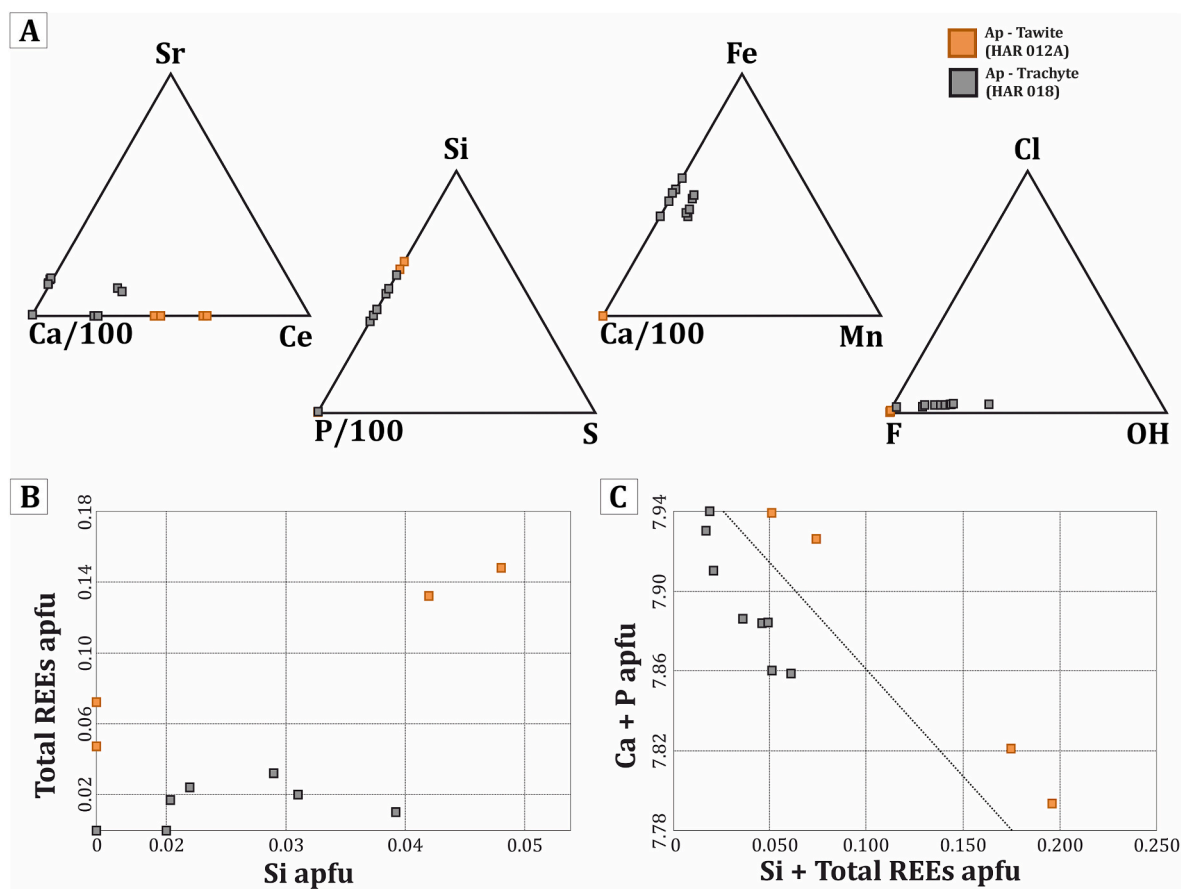


Fig. 10. Apatite chemistry: (A) Apatite element content classification plots based on Teiber et al. (2015); (B) Si vs. Total REEs (La + Ce + Nd) in atoms per formula unit (apfu); (C) Ca + P vs. Si + Total REEs in apfu representing the britholite coupled substitution. Note trendline in C.

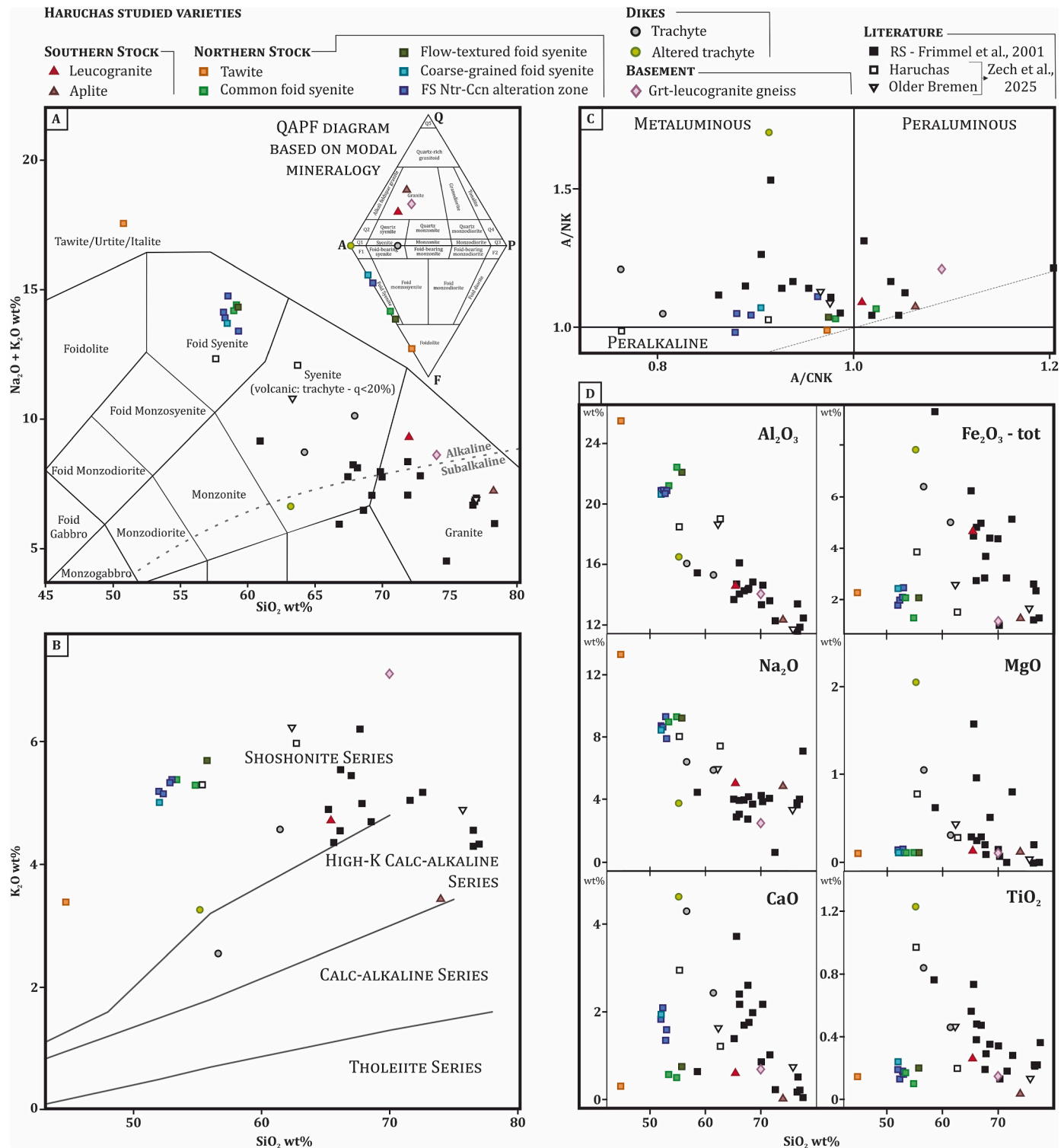


Fig. 11. Major element classification and comparison of the Haruchas Complex studied varieties and basement with the Richtersveld Suite (RS) and Haruchas Samples from previous studies (Frimmel et al., 2001; Zech et al., 2025) in weight percentage – wt.%. (A) TAS diagram (total alkali vs. SiO₂ classification; Middlemost, 1994) and QAPF classification diagram based on modal mineralogy (Streckeisen, 1976); (B) The K₂O vs. SiO₂ classification diagram (Peccerillo and Taylor, 1976); (C) A/CNK ([Al₂O₃]/[CaO + Na₂O + K₂O]) vs. A/NK ([Al₂O₃]/[Na₂O + K₂O]) classification diagram (Shand, 1943); (D) bivariate major element plots (wt.%). Abbreviations: FS (foid syenite); Ntr (natrolite); Ccn (cancrinite).

metaluminous and the peralkaline fields ($A/CNK = 0.97$ and $A/NK = 0.99$), with a slight tendency toward the peralkaline field (Fig. 11C). Tawite has the lowest ΣREE content of the studied lithologies (45 ppm; Fig. 12B).

All foid syenites form a cluster in the TAS and QAPF diagrams

(Fig. 11A) with very similar major element composition and modal mineralogy, respectively (Table 4). They plot as a horizontal trend in the Shand diagram (Fig. 11C) within the metaluminous field, close to the fields of peralkaline and peraluminous compositions. The common foid syenite has the highest A/CNK ratio of the northern stock lithologies,

Table 4
Major and trace element composition for selected samples of the Haruchas Complex and Basement divided by main lithologies.

Lithologies	Granitoids		Foidolite	Foid syenites (FS)				FS in the natrolite-cancrinite alteration zone				Porphyritic dikes			Witwater Gneiss
Studied Varieties	Leuco-granite	Aplite	Tawite	Common foid syenite		Flow-textured foid syenite	Coarse-grained foid syenite	FS in the natrolite-cancrinite alteration zone				Altered trachyte	Trachyte		Grt leucogranite gneiss
Samples	HAR 003A	HAR 003B	HAR 012A	HAR 011B	HAR 012B	HAR 011A	HAR 027	HAR 014A	HAR 014C	HAR 023A	HAR 023C	HAR 004A	HAR 016D	HAR 018	HAR 016S
(w%)															
SiO ₂	65.41	73.98	44.72	53.37	54.82	55.74	52.02	51.98	52.32	53.00	52.84	55.18	61.43	56.61	69.98
TiO ₂	0.26	0.03	0.15	0.17	0.10	0.20	0.24	0.19	0.13	0.16	0.18	1.23	0.46	0.84	0.15
Al ₂ O ₃	14.57	12.29	25.54	21.21	22.43	22.10	20.67	20.89	20.77	20.89	20.69	16.50	15.30	16.06	14.07
Fe ₂ O ₃ -tot	4.66	1.25	2.29	2.07	1.29	2.07	2.43	1.78	1.98	2.46	2.09	7.84	5.01	6.40	1.13
MnO	0.21	0.05	0.11	0.16	0.10	0.13	0.32	0.29	0.34	0.29	0.33	0.19	0.12	0.14	0.02
MgO	0.13	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.14	0.11	0.15	2.05	0.31	1.05	0.11
CaO	0.60	0.00	0.32	0.57	0.50	0.75	1.94	1.83	2.09	1.59	1.35	4.62	2.43	4.29	0.68
Na ₂ O	5.01	4.78	13.37	8.97	9.30	9.22	8.44	8.75	8.64	7.89	9.31	3.73	5.86	6.39	2.42
K ₂ O	4.73	3.42	3.40	5.38	5.29	5.69	5.01	5.19	5.15	5.38	5.33	3.26	4.57	2.55	7.11
P ₂ O ₅	0.06	0.05	0.02	0.10	0.05	0.03	0.12	0.13	0.09	0.09	0.10	0.67	0.14	0.36	0.18
LOI	1.36	0.58	1.42	2.55	1.99	0.52	5.27	4.80	5.21	4.87	3.64	2.23	1.82	2.02	0.81
SUM	96.99	96.55	91.45	94.65	95.99	96.55	96.57	95.95	96.87	96.73	96.01	97.49	97.44	96.72	96.67
(ppm)															
C	466.5	194.1	1218.6	2943.2	2005.0	351.8	3027.5	2728.3	2022.8	2657.6	3764.4	1590.9	3476.8	3765.7	295.5
S	161.6	99.8	1327.5	380.2	178.2	101.9	224.5	94.2	208.8	268.8	210.9	1242.6	139.5	233.2	211.4
Li	6.7	4.3	4.3	21.5	21.9	8.2	83.2	69.8	110.5	92.9	58.7	62.1	66.5	24.6	47.9
Be	10.4	13.1	3.2	5.6	4.1	2.5	22.2	19.3	23.7	20.1	19.3	3.4	6.9	5.9	6.1
Sc	6.4	1.8	0.7	3.7	1.4	1.4	2.2	2.6	3.2	2.3	3.3	10.9	6.7	9.9	2.2
Ti	1635.3	336.8	888.5	1154.0	674.9	1234.9	1668.8	1329.5	937.6	1097.0	1164.4	7034.0	2667.0	4895.0	942.5
V	0.6	0.4	19.7	13.4	7.0	16.9	16.1	10.8	11.1	14.3	12.4	70.2	1.7	12.7	6.0
Cr	4.3	2.4	2.0	2.3	2.7	2.0	1.7	1.3	3.0	2.2	1.3	7.4	4.7	3.5	3.9
Mn	1529.7	359.4	688.3	1044.9	694.9	824.8	2342.5	2074.2	2364.1	2019.0	2371.8	1488.7	870.3	1003.0	135.3
Co	2.4	1.6	4.3	2.8	3.0	2.0	0.9	1.8	1.0	1.0	1.7	6.4	8.2	6.8	7.1
Ni	1.8	0.8	0.7	0.6	0.5	0.6	0.4	0.4	0.5	0.5	0.4	3.9	1.6	0.9	1.4
Cu	3.3	3.6	6.3	1.7	1.2	0.4	0.7	0.5	0.7	0.6	0.5	2.7	6.0	1.3	11.8
Zn	189.7	55.9	76.5	128.2	68.9	60.0	184.9	123.6	81.4	252.9	125.9	128.8	270.7	119.2	48.8
Rb	214.6	187.2	136.4	229.3	206.9	191.3	241.6	239.5	237.9	219.6	231.1	160.3	118.0	70.0	333.4
Sr	20.1	24.4	26.2	25.5	26.2	20.1	56.0	60.3	59.9	75.6	53.2	681.5	214.8	481.3	96.1
Y	75.3	40.4	4.7	9.2	7.1	3.6	39.1	63.3	48.6	32.5	38.1	47.4	52.2	56.8	15.9
Zr	751.4	271.7	155.7	884.3	327.3	323.1	521.3	621.1	773.5	560.7	782.1	312.1	312.4	667.1	71.5
Nb	237.6	374.6	40.8	136.8	81.4	63.6	178.0	149.8	135.9	122.2	144.8	62.7	83.5	54.3	15.6
Mo	7.5	1.1	6.9	5.0	2.4	0.6	10.5	7.1	7.6	3.8	2.9	7.0	6.3	4.8	1.0
Ag	0.1	0.1	0.3	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Sn	8.4	3.5	0.9	1.2	1.8	1.9	3.4	2.2	2.3	2.7	2.8	2.4	4.3	1.3	4.8
Cd	0.6	0.0	0.4	0.8	0.1	0.2	0.5	0.2	0.1	0.4	0.2	0.1	0.8	0.1	0.0
Sb	0.3	0.2	0.2	0.6	0.2	0.0	0.2	0.8	0.7	0.4	0.3	0.5	0.6	0.2	0.2
Cs	0.4	0.5	1.0	2.4	1.2	0.6	5.7	3.2	2.9	4.4	4.8	1.4	0.3	1.2	1.4
Ba	76.0	28.7	16.3	20.0	25.5	30.7	46.7	46.8	39.6	42.4	40.1	913.5	951.4	825.3	505.5
La	191.5	19.7	14.2	28.4	20.9	12.2	207.6	206.5	300.2	179.2	188.6	87.1	73.6	88.9	31.3
Ce	541.6	55.9	20.5	64.7	44.5	31.1	384.9	457.0	580.6	397.5	347.5	197.8	234.4	213.4	56.9
Pr	44.7	5.5	1.7	3.0	2.3	2.2	20.7	31.7	34.6	23.2	23.1	23.7	19.1	24.8	6.5
Nd	152.8	19.7	4.4	7.5	5.7	5.9	46.2	83.1	82.4	56.0	57.0	91.3	70.3	93.2	22.3
Sm	27.4	4.6	0.7	0.9	0.8	0.8	5.3	11.2	9.1	6.5	7.0	17.0	14.2	18.0	4.7
Eu	0.7	0.2	0.2	0.2	0.2	0.2	1.0	2.2	1.7	1.2	1.3	4.4	2.7	3.9	0.6
Gd	20.3	4.7	0.7	0.9	0.7	0.6	4.7	8.9	6.9	5.3	5.7	13.4	11.6	14.3	3.6

(continued on next page)

Table 4 (continued)

Lithologies		Granitoids		Foidolite		Foid syenites (FS)				FS in the natrolite-cancrinite alteration zone				Porphyritic dikes		Witwater Gneiss														
Studied Varieties	Samples	Leuco- granite		Aplite		Tawite		Common foid syenite		Flow-textured foid syenite		Coarse-grained foid syenite		Trachyte				Grt leucogranite gneiss												
		HAR	003A	HAR	003B	HAR	012A	HAR	011B	HAR	012B	HAR	011A	HAR	027	HAR	014A		HAR	014C	HAR	023A	HAR	023C	HAR	004A	HAR	016D	HAR	018
		2.9		1.1		0.1		0.2		0.1		0.1		0.8		1.4		1.1		0.8		0.9		1.9		1.7		2.1		0.6
	Tb	16.0		7.4		0.8		1.1		0.8		0.6		5.1		8.4		6.0		4.5		5.1		9.8		9.7		11.2		2.9
	Dy	2.9		1.5		0.2		0.3		0.2		0.1		1.1		1.7		1.2		0.9		1.0		1.8		1.8		2.1		0.5
	Ho	8.0		4.9		0.5		1.1		0.7		0.4		3.4		4.9		3.8		2.5		3.0		4.8		5.1		5.6		1.3
	Er	1.1		0.9		0.1		0.2		0.1		0.1		0.5		0.6		0.6		0.3		0.4		0.7		0.7		0.8		0.2
	Tm	6.9		7.2		0.5		1.4		0.9		0.5		2.6		3.3		3.5		2.0		2.8		4.0		4.5		4.8		1.1
	Yb	1.0		1.2		0.1		0.2		0.1		0.1		0.3		0.4		0.5		0.3		0.4		0.6		0.6		0.7		0.2
	Lu	23.9		33.1		3.3		18.3		6.6		8.0		11.7		13.3		17.1		13.5		17.4		9.0		10.3		17.3		2.6
	Hf	13.7		96.2		0.8		4.1		2.2		2.6		4.5		4.0		3.0		3.9		4.3		3.7		5.4		2.2		1.2
	Ta	32.0		25.9		20.7		27.7		29.2		20.6		6.0		17.3		8.0		7.5		14.6		19.0		57.6		13.3		35.3
	W	57.0		48.0		6.4		15.2		8.2		1.7		46.2		83.3		56.8		67.6		69.0		18.2		22.3		22.1		23.3
	Th	1.0		0.6		0.3		1.0		0.7		0.7		0.8		0.9		0.9		0.9		1.1		1.2		0.7		0.4		1.5
	Tl	20.4		26.1		9.0		15.0		10.8		3.9		105.2		23.1		23.0		43.9		26.8		19.4		44.3		19.6		32.6
	Pb	0.4		1.0		0.1		0.2		0.1		0.0		1.2		0.2		0.1		0.6		0.2		0.8		0.8		0.0		0.0
	Bi	13.8		13.0		1.3		4.6		4.2		0.5		8.9		13.0		8.6		7.9		6.5		2.7		3.1		2.3		12.8

with one exceptional sample of slightly peraluminous composition ($A/CNK = 1.02$ and $A/NK = 1.06$; Fig. 11C). The coarse-grained foid syenite has a high CaO content (Fig. 11A and B; Table 4). It also has the highest Pb concentration (105 ppm) and a comparatively high Li concentration (80 ppm) with the other foid syenites ranging between 8 and 70 ppm (Fig. 12A and B; Table 4). The coarse-grained foid syenite contains 680 ppm ΣREE , almost one order of magnitude higher than the common foid syenite and the flow-textured foid syenite (Fig. 11A and B; Table 4).

The dikes have a trachytic composition located between the alkaline lithologies of the northern stock and slightly alkaline to subalkaline rocks of the southern stock (Fig. 11; Table 4). The dikes have the highest Ti concentrations among the Haruchas Complex lithologies (2667–7034 ppm) and show ΣREE content of 450–484 ppm (Fig. 12A and B).

4.4.2. Hydrothermal alteration

Foid syenites in the natrolite-cancrinite zone show the second lowest A/CNK ratio of the Haruchas Complex lithologies (only the trachyte dikes exhibit lower ratios), with a generally metaluminous composition ($A/CNK = 0.88$ and $A/NK = 0.98$; Fig. 11C). These rocks also exhibit the highest Li concentration (up to 110 ppm; Fig. 12A). REE patterns have lower LREE/HREE ratios, with ΣREE significant higher (between 644 and 1032 ppm; Fig. 12B; Table 4) than in common and flow-texture foid syenites and tawite.

4.5. Geothermobarometry

Among the studied clinopyroxene grains, only clinopyroxenes of the flow-textured foid syenite met the equilibrium criteria required for geothermobarometric calculations (equilibrium tests and Rhodes diagrams; see supplementary material). Estimates based on the anhydrous model by Putirka et al. (1996) yield clinopyroxene-formation temperatures of 939–994°C and formation pressures of 6–11 kbar. Titanite (exclusively present in flow-textured foid syenite; only titanite II met analytical requirements) geothermometry (Hayden et al., 2008) yields formation temperatures of 1103–1205°C at $aSiO_2 = 0.2$ and 1163–1277°C at $aSiO_2 = 0.5$ (see method sub-chapter 3.4. for more details on the estimated $aSiO_2$) at a fixed pressure of 8.9 kbar based on the average pressure calculated by the clinopyroxene geobarometer. Apatite geothermometry (exclusively applicable for tawite and trachyte dikes; Piccoli and Candela, 2002) yields temperatures of 421°C in the tawite, and 896°C in the trachyte dike. All geothermobarometric results can be found in Table 6.

4.6. U-Pb geochronology

Uranium-Pb geochronology of zircons included in quartz of the leucogranite from the southern stock yield dates of 914.1 ± 13.2 Ma (MSWD = 0.31) and 909.7 ± 10.1 Ma (MSWD = 0.18), with a weighted average of 913.3 ± 8.0 Ma (Fig. 13; Table 5). The zircons in aplite were too small ($< 5 \mu m$) for analysis.

Subhedral zircon of the tawite intercumulus yields U-Pb dates of 893.7 ± 9.8 Ma (MSWD = 1.6). Anhedral zircon of the common foid syenite yields similar U-Pb dates to the tawite including 900.9 ± 10.7 Ma (MSWD = 1.5), 903.4 ± 11.3 Ma (MSWD = 0.92), 897.3 ± 9.6 Ma (MSWD = 0.097), and 896.0 ± 10.5 Ma (MSWD = 0.037) (weighted average of 899.4 ± 5.2 Ma) (Fig. 13; Table 5).

Titanite II from the flow-textured foid syenite yields two dates: 913.9 ± 14 Ma (MSWD = 1.39); and 900.5 ± 13.7 Ma (MSWD = 1.59), with a weighted average of 907.1 ± 9.8 Ma. Titanite I could not be analyzed due to its fine grain size ($< 10 \mu m$). The zircons located at the phenocryst interstices yield 892.2 ± 10.8 (MSWD = 0.09) and 890.2 ± 9.7 Ma (MSWD = 0.97), with a weighted average of 891.1 ± 7.2 Ma (Fig. 13; Table 5).

Zircon in the interstices of orthoclase in the foid syenite within the natrolite-cancrinite alteration zone yield U-Pb dates of 907.8 ± 12.8 Ma

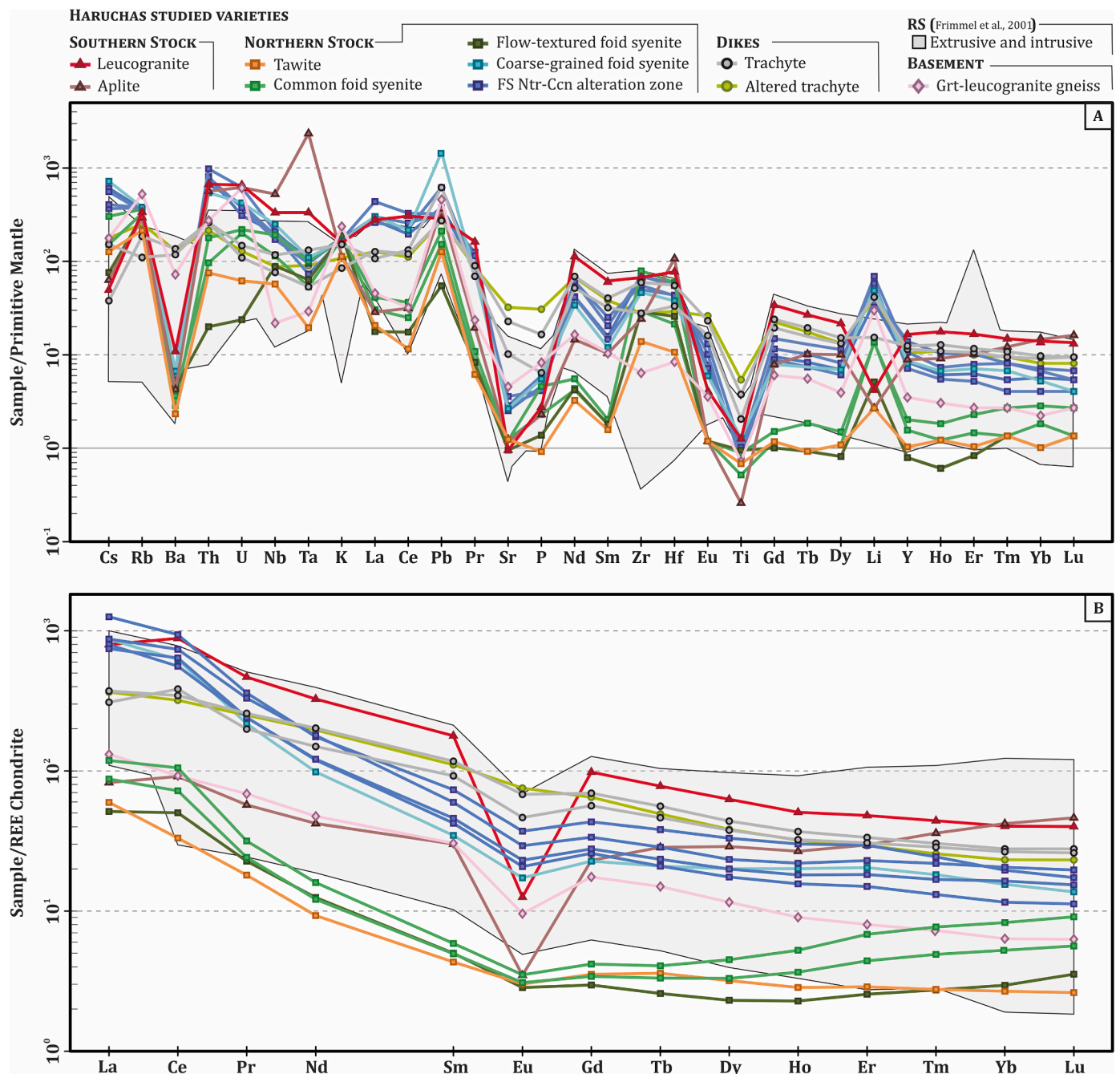


Fig. 12. (A) Primitive Mantle-normalized trace-element (long) plots for Haruchas Complex studied varieties and Basement (normalized after Sun and McDonough, 1989) compared with data from the Richtersveld Suite (RS; Frimmel et al., 2001) intrusive and extrusive units; (B) Chondrite-normalized REE plots for Haruchas Complex studied varieties and Basement (normalized after Sun and McDonough, 1989) compared with data from the RS (Frimmel et al., 2001) intrusive and extrusive units. Abbreviations: FS (foid syenite); Ntr (natrolite); Ccn (cancrinite).

(MSWD = 0.78), 902.4 ± 11.5 Ma (MSWD = 0.12), 899.9 ± 10.1 Ma (MSWD = 1.51), and 899.7 ± 11.0 Ma (MSWD = 2.6), with a weighted average of 901.9 ± 5.6 Ma. In the coarse-grained foid syenite, the zircons present in aegirine and orthoclase interstices yield younger dates of 866.9 ± 9.6 Ma (MSWD = 0.27) and 866.6 ± 9.1 Ma (MSWD = 0.55), with a weighted average of 866.7 ± 6.6 Ma.

Apatite microphenocrysts dispersed in the matrix of trachyte dikes yield 835.3 ± 17.1 Ma (MSWD = 0.27), 805.8 ± 19.9 Ma (MSWD = 1.2) and 799.1 ± 16.9 Ma (MSWD = 1.1), with a weighted average of 814.0 ± 10.3 Ma. Similar dates are obtained for the more greenish trachyte dike, where apatite yield 823.4 ± 23.2 Ma (MSWD = 1.07) and 806.6 ± 25.3 Ma (MSWD = 0.97), with a weighted average of

815.7 ± 17.1 Ma. A fine-grained, rounded, anhedral zircon included in biotite yields a date of 888.3 ± 10.3 Ma (MSWD = 0.22).

A porphyritic syenite from the Older Bremen Complex was dated on fine-grained subhedral zircons yielding 867.6 ± 17.0 Ma (MSWD = 0.32); and 862.0 ± 9.7 Ma (MSWD = 0.52), with a weighted average of 863.4 ± 8.4 Ma.

5. Discussion

5.1. Evolution of the Haruchas Complex

The modal QAPF and whole-rock TAS classifications are mutually

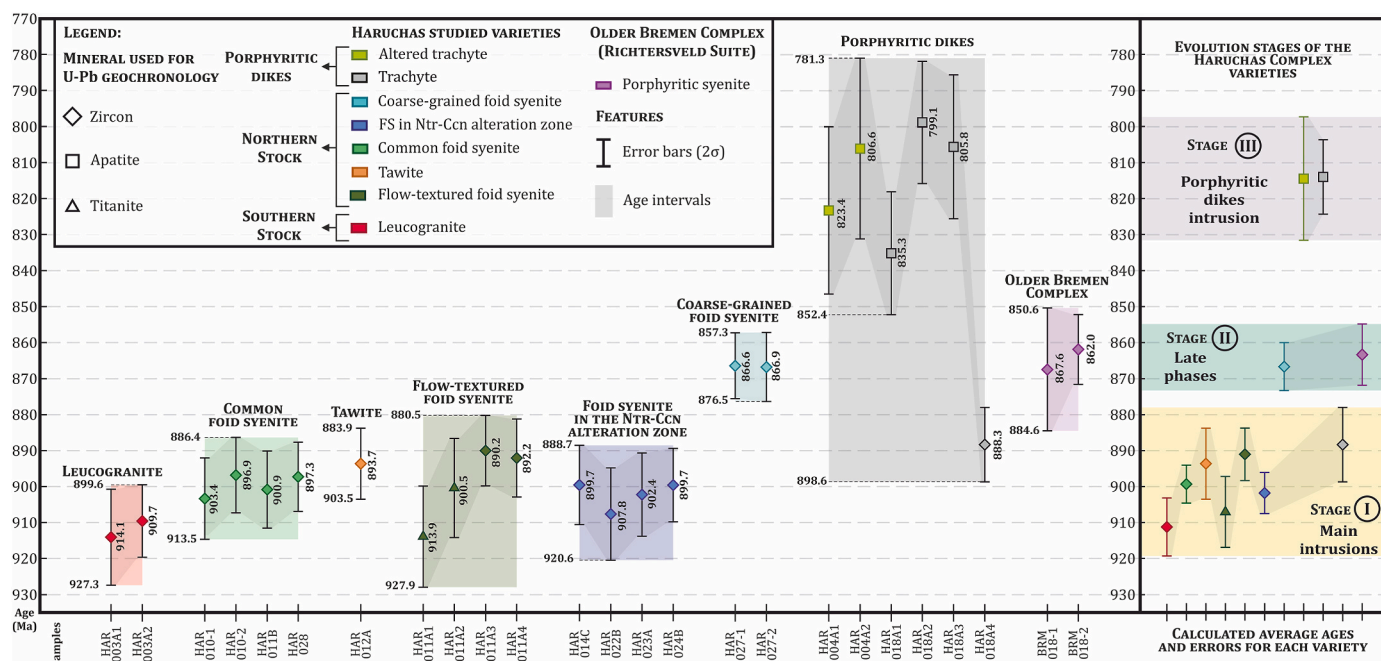


Fig. 13. U-Pb geochronology results for the different samples from the Haruchas Complex and the Older Bremen Complex. Note the different symbols for each mineral used and the division into the different lithologies within the Complex and the three stages of magmatic evolution. Abbreviations: FS (foid syenite); Ntr (natrolite); Ccn (cancrinite).

consistent for the representative Haruchas Dual Complex samples plotted in Fig. 11A. Based on the relationships determined by field observations, geochronology, and geochemistry, three magmatic and two hydrothermal alteration stages are distinguished (Fig. 14). All the geochronological dates are interpreted as crystallization ages as zircon, apatite and titanite are part of the magmatic paragenetic sequence (Fig. 8A). Stage I comprises the intrusion of the leucogranite of the southern stock and the common foid syenite, tawite and flow-textured foid syenites of the northern stock with ages relatively similar situated in a time frame between 913 and 891 Ma (Table 5; Figs. 13 and 14). This study therefore represents the first direct temporal confirmation that both stocks are coeval. The flow-textured foid syenite intruded the common foid syenite indicating that it represents a slightly younger magma pulse within stage I, emplaced shortly after the common foid syenite and while the host was still at least partly plastic and incompletely crystallized. This interpretation is supported by the winding geometry seen in the field and by the locally sinuous contact with the common foid syenite.

Within stage I flow-textured foid syenite, titanite geothermometry yields temperatures of 1103–1277°C during magma cooling. As the Zr-titanite calibration of Hayden et al. (2008) depends explicitly on $a\text{SiO}_2$ and $a\text{TiO}_2$, and because the studied flow-textured foid syenite is quartz-absent and feldspathoid-rich, silica activity could not be assumed to be unity. Two $a\text{SiO}_2$ values, 0.2 and 0.5, were therefore tested to bracket plausible conditions for this silica-undersaturated assemblage, with lower $a\text{SiO}_2$ yielding lower calculated temperatures. Additional caution is required because the analyzed titanites are sector-zoned, and Zr-enriched sectors may overestimate temperatures by approximately 48–70°C (Hayden et al., 2008). No zircon inclusions were observed in the analyzed titanites. Accordingly, these temperatures are best treated as apparent, activity-dependent estimates. Clinopyroxene geothermobarometry in the same flow-texture foid syenite yields 939–994°C and 6–11 kbar. These values are ~100–240°C lower than those obtained from the titanite geothermometry. Thus, likely two different crystallization stages during cooling of the flow-textured foid syenite are recorded, with clinopyroxene recording equilibration during cooling (Putirka et al., 1996; Cherniak, 2006; Kohn, 2017) at

temperatures of ca. 1000–940°C. Apatite geothermometry using the calibration of Piccoli and Candela (2002) yields temperatures of around 420°C for the tawite. This likely reflects cooling during stage I as the apatites are part of the late magmatic paragenetic stage (Fig. 8).

Stage II is represented by the undated apatite and pegmatite dikes, which cut the leucogranite in the southern stock. In the northern stock, stage II is represented by the 866.6 ± 9.1 Ma coarse-grained foid syenite (Table 5; Figs. 13 and 14), which is consistent with the intrusive relationships observed in the field. The temporal overlap between stage II and the 863.4 ± 8.4 Ma Older Bremen Complex, could suggest a larger-scale magmatic event at that time between these two areas separated by ~25 km.

Although not directly dated, an early fluid-related overprint is indicated by aegirine growth and by the partial replacement of primary aegirine-augite by aegirine in the tawite, common foid syenite, and coarse-grained foid syenite. Petrographically, this overprint is expressed by anhedral to subhedral aegirine along aegirine-augite margins and seams, together with fine-grained biotite ± hornblende developed along rims, grain boundaries, and microfractures. These textures, supported by the clinopyroxene evolution toward more aegirine-rich compositions (Fig. 9) and by the paragenetic relationships shown in Fig. 8A, are consistent with an early autometasomatic stage affecting several foid syenite varieties. Although its precise timing relative to the intrusive stage I and II cannot be constrained directly, this overprint is interpreted to predate the main hydrothermal alteration discussed below.

Stage III is indicated by the intrusion of the porphyritic dikes between 823.4 ± 23.2 Ma and 816.3 ± 36.1 Ma (Table 5; Figs. 13 and 14). Given the common occurrence of xenoliths derived from both the Wit-water Gneiss and the foid syenites, the rounded zircon dated at 888.3 ± 10.3 Ma in one of the dikes (sample HAR018) is interpreted as a xenocryst from the foid syenite. Apatite saturation thermometry (Piccoli and Candela, 2002) yields a temperature of 896°C, consistent with an early crystallization stage in this lithology, in agreement with the paragenetic relationships shown in Fig. 8A.

Stage III is also interpreted to be temporally related to the main hydrothermal overprint developed in the core of the northern stock, expressed by the development of the natrolite-cancrinite alteration zone

Table 5

Obtained U-Pb ages (Ma) for the studied samples of the Haruchas Complex and Wetterkop Complex (Older Bremen Complex).

Complex Suite	Intrusive Units	Lithologies	Studied Varieties	Mineral	Sample	Type	Age (Ma)		Error (Ma)	MSWD	Average age (Ma)		Average error (Ma)
Haruchas	Southern Stock	Granitoids	Leucogranite	Zircon	HAR 003A1	Upper Age	914.1	+/-	13.2	0.31	913.3	+/-	8.0
				Zircon	HAR 003A2	Concordia Age	909.7	+/-	10.1	0.18			
	Northern Stock	Foidolite	Tawite	Zircon	HAR 012A	Concordia Age	893.7	+/-	9.8	1.6	893.7	+/-	9.8
				Zircon	HAR 010-1	Lower Age	903.4	+/-	11.3	0.92	899.4	+/-	5.2
		Foid syenites (FS)	Common foid syenite	Zircon	HAR 010-2	Concordia Age	896.0	+/-	10.5	0.037			
				Zircon	HAR 011B	Concordia Age	900.9	+/-	10.7	1.5			
				Zircon	HAR 028	Concordia Age	897.3	+/-	9.6	0.097			
				Zircon	HAR 011A1	Lower Age	913.9	+/-	14	1.39	907.1	+/-	9.8
				Titanite	HAR 011A2	Lower Age	900.5	+/-	13.7	1.59			
				Zircon	HAR 011A3	Lower Age	890.2	+/-	9.7	0.97	891.1	+/-	7.2
				Zircon	HAR 011A4	Concordia Age	892.2	+/-	10.8	0.09			
			Coarse-grained foid syenite	Zircon	HAR 027-1	Lower Age	866.6	+/-	9.1	0.55	866.7	+/-	6.6
				Zircon	HAR 027-2	Concordia Age	866.9	+/-	9.6	0.27			
			FS in the Ntr-Ccn alteration zone	Zircon	HAR 014C	Concordia Age	899.7	+/-	11.0	2.6	901.9	+/-	5.6
				Zircon	HAR 022B	Lower Age	907.8	+/-	12.8	0.78			
				Zircon	HAR 023A	Concordia Age	902.4	+/-	11.5	0.12			
				Zircon	HAR 024B	Lower Age	899.9	+/-	10.1	1.51			
				Apatite	HAR 004A	Lower Age	823.4	+/-	23.2	1.07	815.7	+/-	17.1
				Apatite	HAR 004A	Lower Age	806.6	+/-	25.3	0.97			
			Unaltered	Apatite	HAR 018A1	Lower Age	835.3	+/-	17.1	1.35	814.0	+/-	10.3
				Apatite	HAR 018A2	Lower Age	799.1	+/-	16.9	1.1			
				Apatite	HAR 018A3	Lower Age	805.8	+/-	19.9	1.2			
				Zircon	HAR 018A4	Concordia Age	888.3	+/-	10.3	0.22	888.3	+/-	10.3
Dyke Swarm	Porphyritic Dikes	Trachyte	Altered	Zircon	BRM 018-1	Upper Age	867.6	+/-	17.0	0.32	863.4	+/-	8.4
				Zircon	BRM 018-2	Concordia Age	862.0	+/-	9.7	0.52			
Older Bremen	Wetterkopf	Syenite	Porphyritic syenite	Zircon	BRM 018-1	Upper Age	867.6	+/-	17.0	0.32	863.4	+/-	8.4
				Zircon	BRM 018-2	Concordia Age	862.0	+/-	9.7	0.52			

and related feldspathoid replacement. This interpretation is supported by the close spatial association between the highest dike abundance and the alteration zone, as well as the observed alteration halos starting at the dikes in the field. The natrolite-cancrinite assemblage is therefore considered to record the principal hydrothermal stage recognized in the Haruchas Dual Complex. The greater extent of aegirine-augite to aegirine replacement in the foid syenites affected by the natrolite-cancrinite alteration zone suggests that the later hydrothermal overprint may have intensified a replacement process already initiated during the earlier autometamorphic stage.

The saussuritization, sericitization and biotitization of the trachyte dikes of stage III most likely are the result of the Pan-African metamorphism at ~550 Ma (Reid et al., 1991; Ransome, 1992). The supergene alteration is responsible for the limonitization seen in all lithologies, while weathering and erosion of both stocks is strongest near the contacts and in the central area of the northern stock.

5.2. Tectonic setting and magma source

Most samples plot between the within-plate and syn-collisional granite fields, with only the tawite trending towards the volcanic arc granite field (Fig. 15A and B). These diagrams emphasize Y, Yb, Nb and Ta as they are comparatively less affected by secondary mobility than major elements, while Rb contributes to additional discrimination among felsic suites, although it may be susceptible to disturbance during alteration or metamorphism (Pearce et al., 1984).

In the incompatible trace-element diagrams (Fig. 15C and D), most of the Haruchas Complex samples cluster at low U/Nb and Cs/Nb ratios, near mantle-derived mid-oceanic ridge and ocean island basalt compositions and lie close to the primitive mantle and lower crust fields. This main array is defined by the foid syenites, tawite, and trachytes. In contrast, the leucogranite and the foid syenite affected by the hydrothermal alteration plot at higher U/Nb values, and the leucogranite also shows higher Ce/Pb, indicating that these lithologies depart from the dominant pattern. This variation will be explained in more detail in the following chapter.

Table 6

Obtained thermobarometric values for the Haruchas Complex. Apatite saturation temperature (°C) [Piccoli and Candela \(2002\)](#); clinopyroxene thermobarometer from [Putirka et al. \(1996\)](#); titanite thermometer from [Hayden et al. \(2008\)](#). Abbreviations: Cpx (clinopyroxene); Ap (apatite); Ttn (titanite).

Complex	Intrusive Units	Lithologies	Studied Varieties	Sample	Mineral used	Crystal grain	Apatite saturation temperature (°C) Piccoli and Candela (2002)			
Haruchas	Porphyritic dikes	Trachyte	Unaltered	HAR 018	Ap	Ap1	896.1			
						Ap2	896.1			
	Northern Stock	Foidolite	Tawite	HAR 012A	Ap	Ap1	421			
						Ap2	421			
	Foid syenites	Flow-textured foid syenite		HAR 011A	Cpx	Cpx Thermobarometer Putirka et al., 1996				
						Temperature interval (°C)		Pressure interval (kbar)		Mg#
										Crystal
						Px1	969.1 - 994.2	8.7 - 10.5		Liquid
						Px2	939.1 - 969.6	5.7 - 8.8		
						Calculated temperature intervals (°C); Hayden et al. (2008) (aTiO ₂ = 0.8; zircon and ilmenite present, rutile absent); Pressure estimate from Cpx data = avrg 8.9 kbar Putirka et al. (1996) aSiO ₂ - quartz absent (feldspathoid rich lithology)				
						aSiO ₂ = 0.2		aSiO ₂ = 0.5		
						Ttn1	1109.1-1205.3	1169.3-1276.8		
						Ttn2	1103.6-1182.3	1163.3-1251.0		

5.3. Melt fractionation and contamination processes

Because Cs/Nb and U/Nb are commonly treated as comparatively robust source-related indicators, whereas Ce/Pb is more sensitive to crustal contamination and alteration ([Frimmel et al., 2001](#)), the low Cs/Nb ratios of most lithologies do not strongly support pervasive crustal contamination across the complex. Instead, they may indicate that a mantle-derived source signature is still preserved in much of the foid syenites, tawite and trachytes. In contrast, higher Ce/Pb and U/Nb ratios ([Fig. 15C and D](#)), particularly in the leucogranite, may reflect stronger localized crustal contamination, fractionation of plagioclase and/or hydrothermal modification.

While the whole-rock geochemistry is partly consistent with the trace-element ratio signatures, it also provides additional information on processes that are less clearly resolved by those ratios alone. In the older leucogranite from stage I, high Pb contents ([Table 4](#)), comparatively high SiO₂, and low MgO, Ni, and Cr concentrations ([Table 4](#); [Fig. 12](#)) may be consistent with interaction with felsic crustal material during magma evolution ([Rudnick and Fountain, 1995](#); [Patino Douce, 1997](#); [Frimmel et al., 2001](#); [Rudnick and Gao, 2014](#); [Du et al., 2018](#)), and broadly corroborate the crustal-deviation signal indicated by the discrimination diagrams ([Fig. 15C and D](#)). These same proxies, however, may also indicate additional complexity not evident in the discrimination diagrams for other rocks formed during stage I and II. In particular, the comparatively low Ni and Cr concentrations of the foid syenite varieties (including the one affected by the hydrothermal alteration), tawite, and aplite may suggest a minor crustal component in these lithologies. Within this group, the tawite, with lower SiO₂ and Pb contents, may represent a comparatively less contaminated melt, whereas the coarse-grained foid syenite, which shows the highest Pb contents among the foid syenites, may record a comparatively stronger crustal contribution ([Table 4](#)).

Direct field evidence for contrasting degrees of crustal contamination, such as xenolith entrainment, is lacking. However, the direct contact between the coarse-grained foid syenite and the Witwater Gneiss, together with the geometry of the tawite occurrence within the common foid syenite, may point to different modes or extents of crustal interaction. Taken together, the combined trace-element ratios and whole-rock geochemistry may suggest that the oldest phase, represented by the leucogranite of the southern stock, records a stronger crustal influence than the younger silica-undersaturated foid syenites of the

northern stock. This interpretation does not conflict with the zircon Lu-Hf isotopic data reported by [Zech et al. \(2025\)](#), while also indicating that source-related signatures may have been modified to different degrees of crustal contamination within the complex.

To assess the possible role of crystal fractionation, the pronounced negative Eu anomalies in the leucogranite and aplite may be consistent with plagioclase fractionation during differentiation of these hybrid melts ([Fig. 12B](#); [Barker et al., 1975](#); [Dorais, 1990](#); [Kerr and Fryer, 1993](#); [Sheppard, 1995](#); [Wickham et al., 1996](#); [Riishuus et al., 2005](#)), which is also compatible with the observed discrimination diagrams shift ([Fig. 15C and D](#)). At the same time, the crustal signal indicated by the whole-rock geochemistry suggests that these negative Eu anomaly may not reflect fractionation alone, but could also be attributed to the mixing of the mantle-derived magmas with crustal-derived melts, as also indicated by the similar negative Eu anomaly in the host rock, the Witwater Gneiss ([Fig. 12B](#); [Barker et al., 1975](#); [Dorais, 1990](#); [Kerr and Fryer, 1993](#); [Sheppard, 1995](#); [Wickham et al., 1996](#); [Riishuus et al., 2005](#); [Yang et al., 2005, 2006, 2008, 2012](#)). In contrast, the foid syenites lack the negative Eu anomaly shown by the leucogranites and are therefore interpreted to record a different evolutionary path. Their compositions are most consistent with differentiation from mantle-derived magmas that underwent more limited crustal contamination (e.g. [Brown and Becker, 1986](#); [Turner et al., 1992](#); [Frost and Ronald Frost, 1997](#); [Litvinovsky et al., 2002](#)), as indicated by their comparatively low trace-element ratios in the discrimination diagrams ([Fig. 15C and D](#)) and the absence of clear field or petrographic evidence for strong crustal interaction. Even so, minor crustal contamination and mineral fractionation cannot be ruled out, and this interpretation should be regarded as a preferred model rather than a unique explanation.

The variable Eu anomalies in the Haruchas Complex rocks may also result from mixing between residual melts that have strong negative Eu anomalies and plagioclase cumulates with positive Eu anomalies ([Markl, 2001a](#)) and supported by the observed trace element ratio variations which can indicate fractional crystallization trends of plagioclase, amphibole, clinopyroxene and alkali feldspar ([Fig. 15C and D](#)). This interpretation is consistent with the dual nature of the Haruchas Complex, defined by the coexistence of silica-under- and oversaturated lithologies. Given the mantle-derived source Haruchas Complex magmatism and its emplacement into the Witwater Gneiss, the older silica-oversaturated stage I leucogranite from the southern stock is consistent with formation through mixing between basaltic

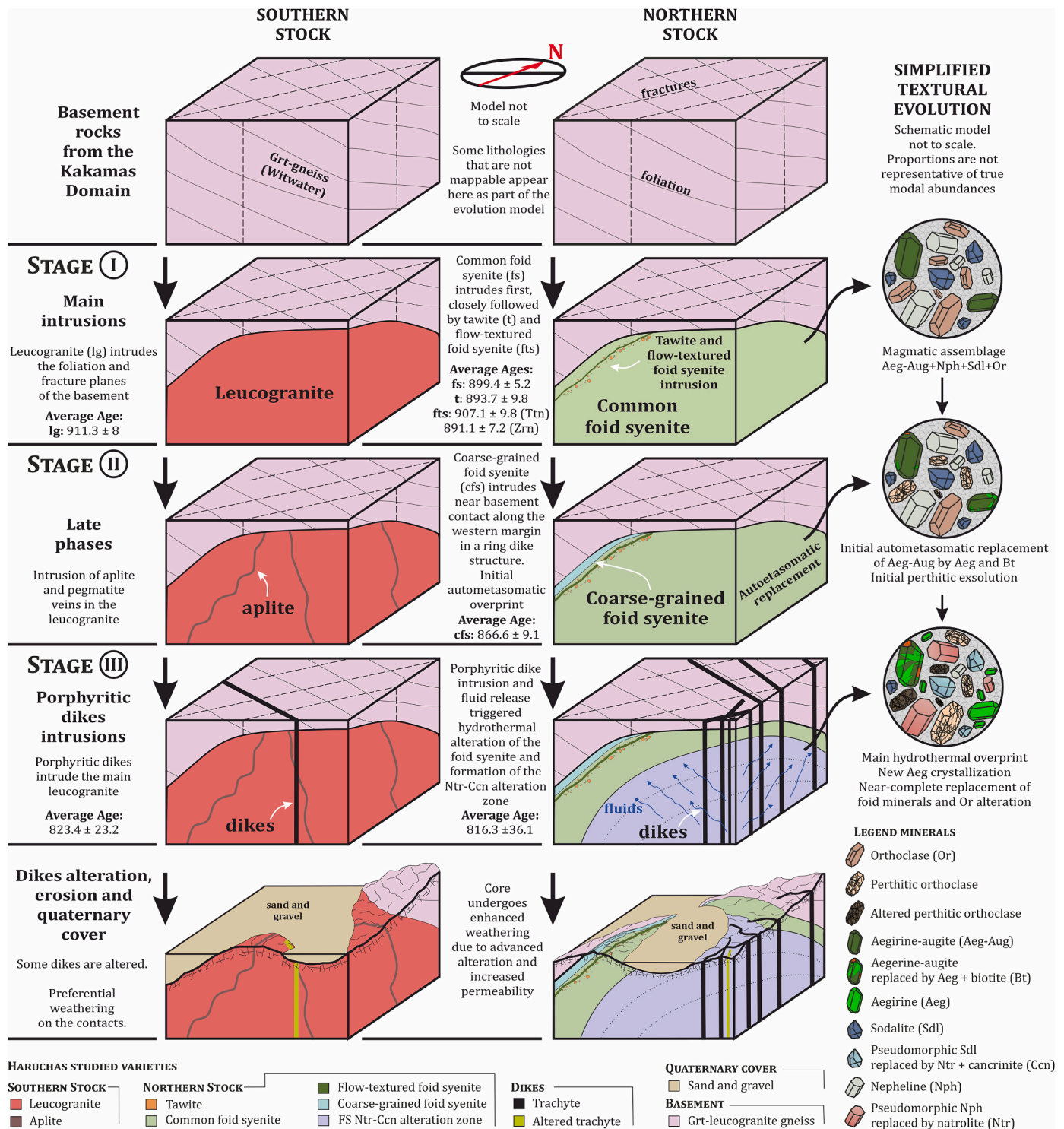


Fig. 14. Schematic evolution model of the different magmatic and post-magmatic stages of the Haruchas Complex southern and northern stocks. In addition, a simplified textural evolution scheme for the foid syenites is present. Abbreviations: FS (foid syenite).

mantle-derived melts and gneissic crustal material (Yang et al., 2005, 2006, 2008, 2012; Markl, 2001a, 2001b). In this context, the younger, silica-undersaturated foid syenites from the northern stock may represent melts that ascended along similar crustal pathways, due to the spatial proximity of both stocks, but experienced less crustal contamination than the stage I leucogranite. This interpretation is consistent with the geochemical data, although the possibility that earlier leucogranite intrusion modified these pathways prior to the foid syenites intrusion remains speculative.

Evidence of crustal contamination and mineral fractionation in the mineral chemistry data is limited. Apatite in tawite defines two discrete compositional populations separated by a gap (Fig. 10C). The apatite rims, although not having a visible zonation, are enriched in Si and REE and show a corresponding decrease in Ca and P concentrations. This is related to the britholite substitution, which is generally interpreted to reflect crustal contamination (Giebel et al., 2019; Anenburg et al., 2025; Raza et al., 2025). However, there is no field evidence by e.g. xenoliths in tawite, and the data is limited by only two apatite grains.

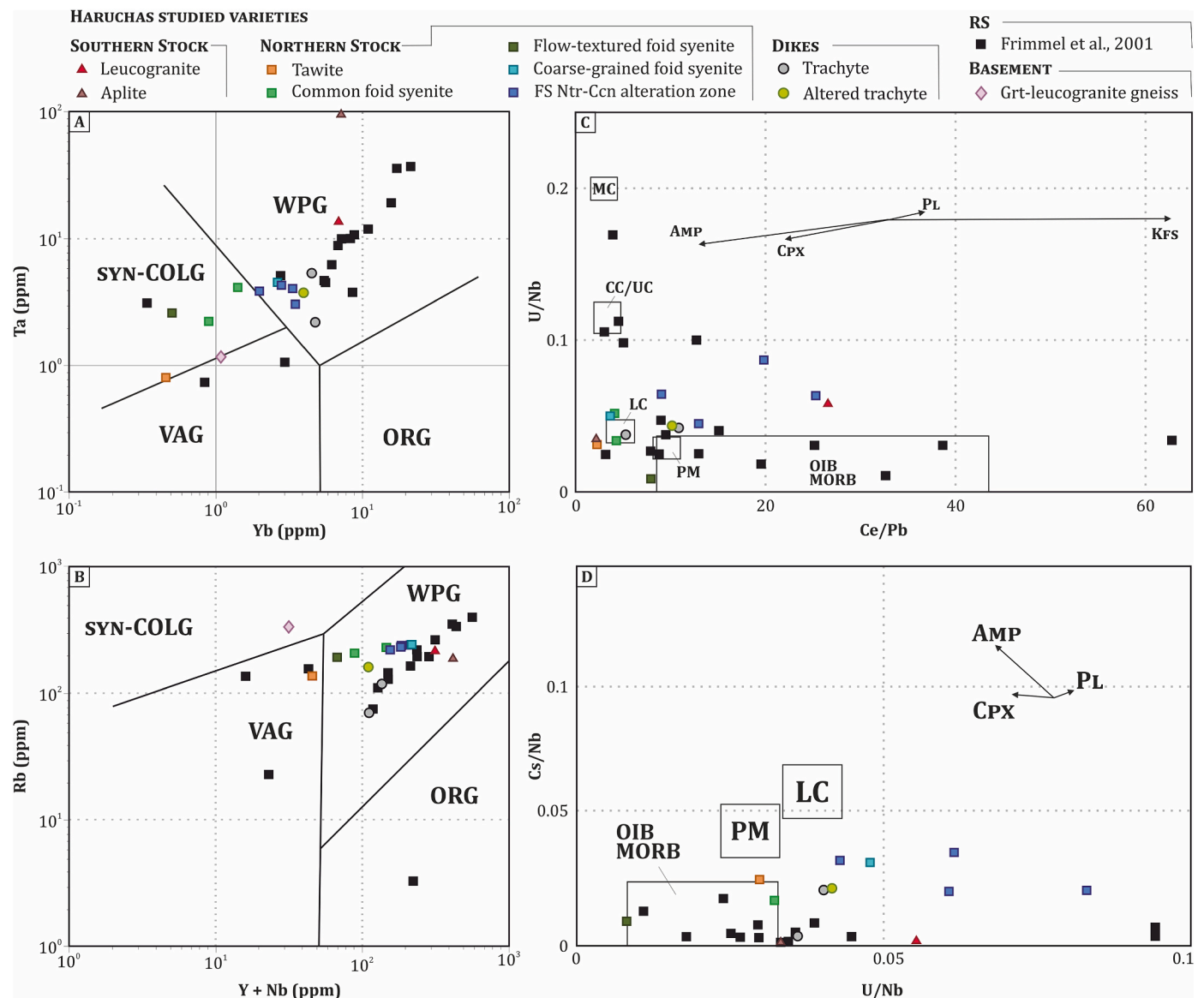


Fig. 15. Discrimination diagrams for rocks from the Haruchas Complex compared to the Richtersveld Suite (RS; Frimmel et al., 2001): (A) Diagram Ta vs. Yb in ppm; (B) Diagram Rb vs. Y + Nb; (C) Diagram of U/Nb versus Ce/Pb; (D) Diagram of Cs/Nb versus U/Nb (ppm/ppm). Fields in (A) and (B): syncollision granites (syn-COLG); volcanic arc granites (VAG); within-plate granites (WPG); ocean-ridge granites (ORG); after Pearce et al. (1984). Fields in (C) and (D): mid-ocean ridge basalts (MORB); ocean island basalts (OIB); primitive mantle (PM); lower crust (LC); middle crust (MC); upper crust (UC); bulk continental crust (CC); sources from Sun and McDonough (1989); Rudnick and Fountain (1995). The fractional crystallization trends with each arrow representing 50% fractional crystallization in (C) and (D) from amphibole (Amp), clinopyroxene (Cpx), plagioclase (Pl), and alkali feldspar (Kfs). The partition coefficients from are from Schmetzler and Philpotts (1970); Henderson (1982); Bacon and Druitt (1988); Villemant (1988); Stix and Gorton (1990); and Ewart and Griffin (1994). The figure is based on Frimmel et al. (2001). Abbreviations: FS (foid syenite); Ntr (natrolite); Ccn (cancrinite).

Apatite in the trachyte dikes show a trend, with slightly higher silica and lower Ca + P contents close to their rims, compared to their cores (Fig. 10B and C). This could suggest that the system was progressively enriching in Si during the latest stage of apatite crystallization where the rim forms (Fig. 8A). This Si enrichment could either result from the magmatic evolution or, more likely, increased Si input due to contamination by assimilation of country rocks, which is corroborated by the observed presence of xenoliths and xenocrysts from the gneissic basement during fieldwork and petrographic studies (see Fig. 4G).

The less-altered foid syenites, which contain only aegirine-augite as the dominant magmatic clinopyroxene, with aegirine only present in the secondary assemblage (Fig. 8A), would represent the direct crystallization of the primary magmas (Markl et al., 2001; Marks et al., 2003, 2004). In contrast, the observed magmatic aegirine in the coarse-grained foid syenite indicates crystallization from a Na-enriched melt that

formed through prolonged fractional crystallization (Markl et al., 2001; Marks et al., 2003, 2004).

The titanite-Ca-rich aegirine-augite assemblage in the flow-textured foid syenite indicates crystallization from a Ca-rich, silica-undersaturated melt. In addition, when comparing with the other foid syenite varieties, this variety shows no petrographic evidence of hydrothermal overprint and lacks field evidence for xenolith assimilation. Its whole-rock geochemistry signature and trace element discrimination patterns (Table 4; Fig. 15C and D) are therefore consistent, showing a more limited crustal interaction. Combined with the interpretation that this variety represents a second intrusive pulse within stage I and occurs as a dike within the common foid syenite, these features may indicate a comparatively less evolved melt, potentially closer to the observed mantle-derived parental composition. Its intrusion within the already emplaced common foid syenite probably shielded it from interacting

with the surrounding country-rock, therefore retaining a non-contaminated character, however, the available data do not allow its subsurface geometry or the extent of magma-wall rock interaction to be constrained directly.

5.4. Hydrothermal alterations

An earlier, small-scale fluid-related overprint within stages I and II of the northern stock is recorded by localized replacement textures in the common and coarse-grained foid syenites. These include partial replacement of aegirine-augite to aegirine and biotite, as well as local replacement of aegirine by biotite, being mostly pronounced along grain boundaries. This is also seen by the transition of unzoned aegirine-augites to patchy, irregular zoning and acicular aegirine that occurs as inclusions or adjacent to altered primary aegirine-augites (Figs. 5–7). These textures are accompanied by mineral-chemical variations in aegirine-augite, including shift in Na/Ca ratios as well as relative Fe³⁺ enrichment (Fig. 9; supplementary material).

By comparing with similar alkaline systems, these textural and mineral-chemical relationships are consistent with an autometasomatic process, where exsolved orthomagmatic fluids interpreted in the literature with high Na/Ca ratios, oxidized, and mildly acidic, with grain boundaries acting as the main fluid pathways (Salvi and Williams-Jones, 1990, 1996, 2006; Boily and Williams-Jones, 1994; Markl et al., 2001; Chakhmouradian and Mitchell, 2002; Coulson, 2003; Marks et al., 2003; Mitchell and Liferovich, 2006; Marks and Markl, 2015; Borst et al., 2016; Lewerentz et al., 2019; Beard et al., 2023). In the Haruchas Complex northern stock, this interpretation is further supported by the localized character of the replacement, its restriction to mainly clinopyroxene-dominated reaction textures, and the absence of a comparably pervasive whole-rock geochemical disturbance in the common and coarse-grained foid syenites (Fig. 15C and D). The timing of this autometasomatic event cannot be constrained directly. It may have originated during the late-magmatic stages of stage I and later been intensified during emplacement of the younger coarse-grained foid syenite of stage II. This interpretation is consistent with the relatively Na-rich and more evolved primary aegirine compositions in the coarse-grained foid syenite (Fig. 9), but remains inferential.

The second and more pervasive fluid-related overprint in the northern stock is expressed by the natrolite-cancrinite alteration zone developed in the central part of the foid syenite occurrence. In contrast with the earlier, localized autometasomatic overprint recorded mainly by clinopyroxene replacement, this event is characterized by extensive pseudomorphic replacement of nepheline and sodalite by natrolite and cancrinite, together with aegirine crystallization, associated fluorite and local biotite. Despite the intense replacement, the foid syenite within the natrolite-cancrinite alteration zone still preserves part of the magmatic protolith fabric, and remains texturally comparable to the common foid syenite, retaining apparently unaffected accessory phases such as magnetite and zircon and with its bulk-rock composition plotting in the foid syenite field (Fig. 9 and Table 3). However, when using the discrimination diagrams, the higher Ce/Pb and U/Nb ratios in the foid syenite within the natrolite-cancrinite alteration zone when compared to the common foid syenite (Fig. 15C and D) may reflect the stronger hydrothermal modification.

This alteration is the main hydrothermal overprint recognized in the Haruchas Complex. This interpretation is further supported by the close spatial association of the alteration zone and the higher abundance of trachyte dikes in the central part of the northern stock, where alteration halos can be seen along contacts between the dike and the foid syenite. By comparison with similar systems, these textural, mineralogical and geochemical features are consistent with pervasive zeolitization and selective foid decomposition during post-magmatic subsolidus hydrothermal alteration, particularly where fluid access is efficient and sustained, commonly at temperatures <150°C (de'Gennaro et al., 2000; Salvi et al., 2000; Bernhard and Barth-Wirsching, 2002; Schilling et al.,

2009, 2011; Weisenberger et al., 2014; Spürghin et al., 2019; Gudmundsson, 2022).

The trachyte dikes may therefore have acted as local heat sources and promoted fracture-controlled fluid circulation, particularly along their margins and associated fractures, thereby enhancing alteration in the surrounding foid syenite (Gudmundsson, 2022). Their intrusion could also have caused an increasing intensity of the earlier autometasomatic process through fluid mixing with the orthomagmatic fluids in the foid syenite protolith (Williams-Jones and Artas, 2014; Gudmundsson, 2022). This interpretation is consistent with the more extensive aegirine development and replacement observed in the rocks affected by the natrolite-cancrinite alteration zone. However, although the spatial relationship suggests a close association between dike emplacement and this hydrothermal stage, the present data do not allow a direct causal link, continued fluid circulation from the earlier autometasomatic stage, or fluid mixing to be demonstrated unequivocally.

The foid syenite within the natrolite-cancrinite alteration zone also shows higher ΣREE contents than the common foid syenite and more similar ΣREE contents with the trachyte dikes (Fig. 12 and Table 4). This relationship may record hydrothermal redistribution of REE during alteration rather than simple primary magmatic inheritance. A plausible scenario is that dike emplacement enhanced permeability and promoted circulation and mixing of late fluids, allowing local remobilization and reprecipitation of REE within the alteration zone (Williams-Jones and Artas, 2014; Gudmundsson, 2022). In the Haruchas Complex, this interpretation is supported by the development of the natrolite-cancrinite alteration zone, where pervasive replacement by finer-grained secondary assemblages made the rock more friable and likely increased permeability, facilitating continued fluid-rock interaction. A contribution from interaction between this later hydrothermal system and earlier autometasomatic fluids is also possible, but cannot be demonstrated directly. This interpretation therefore remains tentative, but it is compatible with studies showing that hydrothermal fluids in alkaline systems can remobilize REE from pre-existing minerals, and that REE transport is favored mainly by chloride and sulfate complexes under acidic to mildly acidic conditions, whereas decreasing temperature and increasing pH promote deposition (Williams-Jones and Artas, 2014; Williams-Jones, 2015; Di and Ding, 2024).

5.5. Implications for the evolution of the Richtersveld Suite

Compared to the other intrusions of the Richtersveld Suite (Frimmel et al., 2001), the Haruchas Complex displays distinct of Ni, Cr, Si, Mg and Pb concentration ranges (Table 4), which may be consistent with a comparatively stronger degree of crustal contamination (this study; Frimmel et al., 2001). The felsic Witwater Gneiss of the Kakamas Domain, into which the Haruchas Complex intruded, is characterized by higher SiO₂ (~75 wt%), very low MgO (~0.2 wt%), high K₂O (~6 wt%) and εNd = -2.39 (Macey et al., 2018, 2022). In contrast, the alkaline arc-related protoliths of the Vioolsdrif Domain, southwest of Haruchas Complex and hosting the main Richtersveld Suite intrusions, have lower Si₂O (~60 wt%), higher MgO (~2 wt%), moderate K₂O (~3 wt%) and εNd ranging from 0.0 to -1.0 (Macey et al., 2017, 2018). These variations in assimilated material (SiO₂, MgO and K₂O content, and εNd) due to the spatial distribution (Haruchas occur ~120 km NE of the RIC), combined with the 30 m.y. earlier timing of the Haruchas Complex emplacement, may be the cause of the differences in both the degree and the nature of crustal contamination across the suite and one of the causes of the divergent magma evolution between the two areas during the early stages of Rodinia-related crustal thinning, as discussed by Reid et al. (1991) and Frimmel et al. (2001).

The crystallization ages of 914–866 Ma for stages I and II of the Haruchas Complex fall within the range of previously reported crystallization ages of the common foid syenite (897 ± 17 Ma and 895 ± 19 Ma; Zech et al., 2025) and overlap with 920–863 Ma ages from the Older Bremen Complex (this study; Allsopp et al., 1979; Gose et al., 2007, in

Bartholomew, 2008; Zech et al., 2025), and may indicate a genetic connection between this stage of the Haruchas Complex and nearby intrusions of the Richtersveld Suite. The 835–799 Ma porphyritic trachyte dikes of stage III overlap with the 833–771 Ma Richtersveld Igneous Complex (RIC), with 801 ± 8 Ma alkali-feldspar syenite and mafic dikes further south, and with the 783 ± 17 Ma Nuwefontein granite (Fig. 13; this study; Frimmel et al., 2001; Macey et al., 2018). However, the shared vertical geometry, N-S to NE-SW trend, similar mafic character, and overlapping emplacement age with the Gannakouriep Dike Swarm (795 Ma age; Rioux et al., 2010) may suggest that the trachyte dikes that cut the Haruchas Complex are most likely part of the northern occurrences of the swarm.

Combined geochronological and whole-rock geochemical data suggest that the Richtersveld Suite magmatism was initiated with the emplacement of the northern Haruchas and Older Bremen complexes and then gradually migrated southward towards the larger intrusions of the suite (this study; Frimmel et al., 2001; Zech et al., 2025). The Haruchas Complex therefore represents the northernmost and oldest known intrusion of the suite, and may record slightly stronger crustal contamination in stage I than later magma pulses within the suite. These results extend the known linear array of the Richtersveld Suite by ~ 25 km and increase its currently recognized age range by ~ 30 m.y.

6. Conclusions

The Haruchas Dual Complex comprises two compositionally contrasting but spatially associated intrusive stocks that record a multi-stage magmatic history. The southern stock is dominated by silica-oversaturated leucogranite with subordinate aplite and pegmatite dikes, whereas the northern stock consists of silica-undersaturated foid syenites and tawite. The U-Pb geochronology places emplacement of the two stocks between ca. 914 and 866 Ma, demonstrating that they are coeval components of the same intrusive complex despite their contrasting compositions. A younger magmatic episode at ca. 815 Ma is represented by steep trachyte dikes that crosscut both stocks.

The two stocks record contrasting degrees of magmatic differentiation and crustal interaction. Whole-rock geochemistry, petrography, and mineral chemistry indicate stronger crustal assimilation in the southern stock, contributing to the development of silica-oversaturated leucogranitic compositions, whereas the northern stock remained predominantly silica-undersaturated and preserves a less contaminated character. The northern stock was subsequently modified by two successive post-magmatic events. An earlier autometamorphic stage is recorded mainly by the replacement of aegirine-augite by aegirine + biotite and associated clinopyroxene chemical evolution. This was followed by a more pervasive hydrothermal stage characterized by feldspathoid replacement by natrolite and cancrinite, together with fluorite and local biotite, particularly within the central alteration zone. These processes substantially modified the primary mineralogy and locally remobilized elements, including REE.

Within the presently recognized Richtersveld Suite, the Haruchas Dual Complex is the northernmost, oldest, and only known foid-bearing complex, and its age and compositional characteristics may indicate greater along-strike heterogeneity in magma evolution and crustal interaction than previously recognized.

CRediT authorship contribution statement

Jorge C.L. Arthuzzi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **R. Johannes Giebel:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Michael W. Marks:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Aratz Beranoaguirre:** Visualization, Methodology, Formal analysis. **Sara R. Kimmig:** Writing – review & editing. **Antonin**

Bilau: Writing – review & editing. **Paul H. Macey:** Writing – review & editing. **David L. Reid:** Writing – review & editing. **Mohsin Raza:** Writing – review & editing. **Lorenz Kemmler:** Writing – review & editing. **Jochen Kolb:** Writing – review & editing, Supervision, Project administration. **Gregor Markl:** Writing – review & editing. **Pete R. Siegfried:** Writing – review & editing. **Benjamin F. Walter:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafrearsci.2026.106352>.

Data availability

Data will be made available on request.

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