Petrogenesis and geodynamic setting of Ediacaran rocks from the Sirwa massif, Central Anti-Atlas of Morocco

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Abstract

The geodynamic evolution of the post-Pan-African Anti-Atlas belt Orogeny (~650 Ma) remains debated, particularly regarding the basement beneath the Central Anti-Atlas, and the geological processes leading to the formation of the Ediacaran Saghro Group (SG), and Ouarzazate Group (OG). New LA-ICP-MS U-Pb ages of 575 ± 3 Ma and 564 ± 2 Ma were obtained from two magmatic rocks of the OG. In addition, detrital zircons from SG yield a 2025 Ma maximum depositional age (MDA) and a prominent 2100 Ma peak, indicating exclusive recycling of Paleoproterozoic basement into the Ediacaran SG basin. Geochemically, two magmatic series are identified: (i) SG mafic rocks displaying a calc-alkaline signature of within-plate character with Nb-Ta and Ti negative anomalies from a back-arc basin setting; and (ii) a felsic-intermediate high-K calc-alkaline to shoshonitic series of the OG of a post-collisional character. Isotope data (εNd_{620}: +3.2 to +4.6, TDM = 1.02–0.91 Ga for SG; εNd_{570}: -0.8 to +1.1, TDM = 1.30–1.15 Ga for OG), indicate that the SG formed from a near-pristine mantle source, with limited crustal input; whereas the younger OG involved significant reworking of older, evolved continental crustal material.

These findings sustain a model where early Ediacaran SG sediments and associated magmatic rocks were deposited in a back-arc basin. During this basin development, its shoulders were locally formed by the 2100 Ma Paleoproterozoic basement, supplying Paleoproterozoic zircons to the Saghro basin without interaction with Ediacaran sediments, and corroborating the extension of the Eburnian basement north of the Anti-Atlas Major Fault (AAMF). Subsequently, the younger OG recorded a late Ediacaran post-collisional crustal collapse event, where lithospheric delamination and potential slab break-off drove widespread crustal reworking and the emplacement of a Silicic Large Igneous Province (SLIP).

Keywords

Anti-Atlas; Ediacaran; LA-ICP-MS U-Pb geochronology; Saghro Group (SG); Ouarzazate Group (OG); 2.1 Ga Paleoproterozoic crust

1 Introduction

The Anti-Atlas belt of Morocco in the northern margin of the West African Craton (WAC) bears witness to a long-lived geological evolution since the break-up of Rodinia (Hefferan et al., 2014; Gasquet et al., 2008; Thomas et al., 2002). Accordingly, the initial rifting at ca. 900–700 Ma was evidenced by the 885 Ma Tonian mafic dikes. The rifting in question generated a WAC passive margin and the eventual development of a Cryogenian ocean lithosphere (Hefferan et al., 2014). This period is characterized by the deposition of the Lkest-Taghdout Group, a thick sequence of quartzites and carbonates (Alvaro et al., 2014b) (Fig. 1B). The subsequent evolution of the Anti-Atlas belt during the Ediacaran is still debated despite the improvements in the understanding of the multiple events that prevailed during Neoproterozoic times (D’Lemos et al. 2006; Samson et al. 2004; Gasquet et al. 2008, 2005, 2004; Thomas et al. 2004, 2002; Ennih and Liégeois, 2008, 2001; Walsh et al. 2002), and led to the final amalgamation of Gondwana (D’Lemos et al., 2006; Gasquet et al., 2008, 2005). Within this time frame, and based on paleogeographic reconstruction and lithostratigraphic correlations (Linnemann et al., 2014; Errami et al., 2021a; Walsh et al., 2012), the Anti-Atlas belt was close to the Cadomian subduction system. While the internal amalgamation of Gondwana was driven by large-scale Pan-African collisions between major cratonic blocks, the northern margin of the WAC experienced a synchronous but distinct tectonic regime (Rojo-Pérez et al., 2024; Stern, 2024; Hefferan et al., 2014). During the Ediacaran, this margin was proximal to the Cadomian accretionary system, a long-lived subduction-related orogen that developed along the Gondwana periphery (Linnemann et al., 2014; Nance et al., 2008).

Moreover, it is still debated whether the Anti-Atlas records the post-collisional phase of the Pan-African belt, or if it is related to the establishment of a back-arc basin induced by the southward-dipping Cadomian subduction beneath the amalgamated WAC-Iriri/Tazigzaout arc Complex at ca. 620 Ma (Errami et al., 2021a; Walsh et al., 2012; El Hadi et al., 2010; Abati et al., 2010). Furthermore, the basement nature north of the AAMF, is also still a matter of debate (Ennih and Liégeois, 2008, 2001). In the Zgounder Mine Region (ZGMR), a well-preserved section of Ediacaran sedimentation and magmatism, provides key insights into the final stages of Pan-African tectono-magmatic evolution along the northern margin of the WAC. We present new whole-rock geochemical, and Sm-Nd isotopic data of these rocks in order to decipher their petrogenesis, explore magma sources, and investigate their geodynamic significance in Ediacaran evolution of the WAC. We also report new LA-ICP-MS U-Pb dating on magmatic and detrital zircons to constrain the lower Ediacaran magmatism and challenge the source of the Saghro Group's sedimentary units, hence, refining existing geodynamic models.

2 Geological background

The Anti-Atlas belt, located on the northern edge of the WAC, and consist of a Proterozoic basement and a late Ediacaran to Paleozoic cover (Leblanc and Lancelot, 1980) (Fig. 1B). These mountains record two major orogenic cycles: the Paleoproterozoic Eburnean and the Neoproterozoic Pan-African, classically separated by the AAMF (Fig. 1B). The Paleoproterozoic Eburnean Orogeny is preserved in the Western Anti-Atlas, where low- to high-grade metamorphic rocks are intruded by a series of granitoids dated at ~2.2 Ga (Hefferan et al., 2014, and references therein; O'Connor et al., 2010; El Hadi et al., 2010; Gasquet et al., 2008, 2005; Thomas et al., 2002; Walsh et al., 2002; Aït Malek et al., 1998). The Central Anti-Atlas features the ophiolitic sequences and island-arc complexes of the Bou Azzer and Sirwa massifs (Admou et al., 2012; D'Lemos et al., 2006; Thomas et al., 2002, 2004). To the east, the Eastern Anti-Atlas comprises the Jbel Saghro and Ougnat massifs, which are composed exclusively of Neoproterozoic Pan-African units (Fig. 1B). These include an early Ediacaran basement of SG, consisting of folded meta-sedimentary rocks metamorphosed under greenschist facies conditions, and unconformably overlain by the late Ediacaran OG successions of volcanic and volcano-sedimentary nature (Ouabid and Garrido, 2023; Errami et al., 2021a; Yajioui et al., 2020; Michard et al., 2017; Blein et al., 2014; Álvaro et al., 2014, 2014b; Walsh et al., 2012; Abati et al., 2010; Errami et al., 2009; Gasquet et al., 2008; Liégeois et al., 2006; Thomas et al., 2002; Fekkak et al., 2001; Bajja, 2001; Ouguir et al., 1996).

This study focuses on the Ediacaran period (630–539 Ma) within the Sirwa massif. The recent geological mapping of 1/50 000 scale sheet maps of Douar Çour, Assarrag, Tachoukacht, Tamallakout, Sirwa, Taghdout, and Açdif (see Fig. 1C for relevant sheets) has subdivided the Sirwa massif into several distinct groups (Thomas et al., 2000a; De Beer et al., 2000; Gresse et al., 2000). The oldest mapped units belong to the Bleida Group, comprising schists and orthogneisses dated at 743 ± 14 Ma (Fig. 1C) (Thomas et al., 2002). This is overlain by the SG (Thomas et al., 2002), a thick succession of deformed sedimentary, volcanoclastic, and volcanic rocks characterized by a calc-alkaline composition, and metamorphosed under greenschist-facies metamorphism. The SG includes six formations: Tittalt, Agchtim, Imghi, Tizoula, Azarwas, and Tafiat (Thomas et al., 2002). The lower sequence features greywacke/turbidites with volcanic rocks, while the upper formations consist of coarse-grained clastic rocks (Thomas et al., 2002). U-Pb dating on detrital zircons indicates a maximum depositional age at ca. 610 Ma (Abati et al., 2010; Liégeois et al., 2006), with more recent detrital ages around 607 ± 6 Ma and 604 ± 5 Ma (Errami et al., 2021a). Crucially, in the Sirwa inlier, the SG is significantly older as it is intruded by the Mzil granite dated at 614 Ma (Thomas et al., 2002, 2004).

The Bou Salda Group, a volcano-sedimentary succession from 610 to 580 Ma (Gasquet et al., 2008), represents basin infills of grabens and pull-apart basins within the AAMF (Errami et al., 2021a; Gasquet et al., 2008; Thomas et al., 2002). The age of Bou Salda Group is derived from the Tadmant and Tamriwine rhyolites, dated respectively at 606 ± 6 Ma and 605 ± 9 Ma (Thomas et al., 2002) (Fig. 1C, and Fig. 2). Pelleter et al. (2016), also dated the Tadmant rhyolite at 610 ± 7 Ma (Fig. 2). Nonetheless, Abati et al. (2010) reported detrital zircon ages of 600 ± 12, and 603 ± 13, establishing a maximum depositional age for the Bou Salda Group.

The OG sequences (580–539 Ma; Blein et al., 2014b; Toummite et al., 2013; Thomas et al., 2002, 2004) of immature, coarse clastic sedimentary rocks (conglomerates, arkoses, reworked volcanic rocks) acid to intermediate volcaniclastic rocks (lapilli tuff, volcanic breccias, ignimbrites, etc.) and lavas (minor basalt, andesite and rhyolite) are associated with post-collisional high-K calc-alkaline to shoshonitic magmatism (Soulaimani et al., 2018). Briefly, throughout the Sirwa inlier, the OG is subdivided into four subgroups (Fig. 1C for relevant subgroups) (Tiouin, Bouljama, Tafrant and Achkoukchi) (Thomas et al., 2000a; Gresse et al., 2000; De Beer et al., 2000). Under an extensional regime, typical foreland basin successions of Tata Group were deposited, following the post-orogenic molasse volcaniclastic rocks of the OG (Thomas et al., 2002) (Fig. 1C).

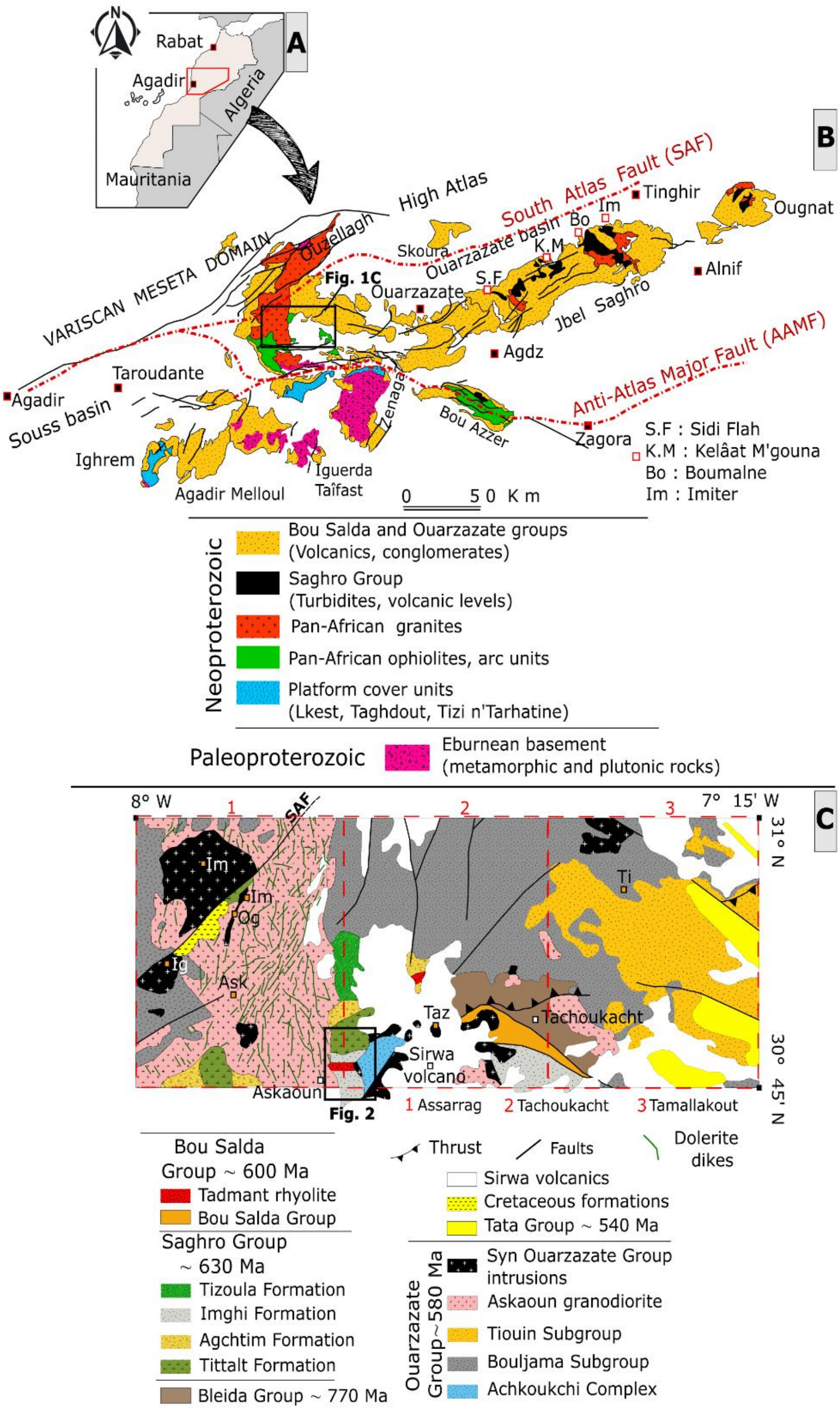

Figure 1. (A) Sketch map locating the Anti-Atlas belt in respect to Morocco (Saadi, 1985); (B): geological map of the Central and Eastern Anti-Atlas Proterozoic inliers (redrawn and modified after Michard et al. (2017); (C): Schematic representation of the

geology of the Sirwa massif (compiled and redrawn from Thomas et al. (2002); location of the ZGMR in Figure. 2. Abbreviations: Taz : Tazoult quartz-porphyry (559 ± 6 Ma); Im: Imourkhssen granite (562 ± 5 Ma); Ti: Tikhfist rhyolite (571 ± 8 Ma); Ask: Askaoun granodiorite (575 ± 8 Ma); Ig: Ighrem granite; Og: Ougougane granite; and SAF: South Atlas Fault. U-Pb ages are from Thomas et al. (2002).

2.1 Field characteristics and sample distribution

The study area (Fig. 2), so-called the ZGMR "Zgounder Mine Region" in this contribution corresponds to the vicinity of the Zgounder Ag-Hg deposit. The Zgounder deposit is situated at approximately 265 km east of Agadir, and 220 km west of Ouarzazate, along the southern flank of the Ouzellagh-Sirwa Salient in the Central Anti-Atlas Mountains (Ben-Tami et al., 2024). Detailed geological mapping was conducted across the ZGMR to establish the primary lithostratigraphic relationships (Fig. 2). The Ediacaran period of the ZGMR (630–539 Ma), is represented by : (i) the SG sedimentary successions and coeval magmatic rocks deposited at around 630 to 600 Ma (Errami et al., 2021a; Abati et al., 2010); (ii) large felsic plutons, subvolcanic formations, along with coeval pyroclastic rocks referred to as the OG (600–539 Ma; Thomas et al., (2002)).

The oldest rocks in the study area belong to the SG, represented by the northern, E-W-striking Tittalt Formation and the southern Imghi Formation (Fig. 2). The lowermost Tittalt Formation consists of basaltic and andesitic volcanic rocks associated with a gabbroic intrusion, bounded to the south by the Imghi Formation. The Imghi Formation features poorly graded, thick-bedded greywacke composed of stacked fine- to very fine-grained sandstone beds and greyish-green, well-bedded, graded turbidites that strike east and dip steeply south at 70° (Fig. 2). Felsic magmatism is represented by the E-W-trending Tadmant rhyolite (Bou Salda Group; Thomas et al., 2002), which forms the core of the area between the western Askaoun granodiorite and the eastern OG sequences (Fig. 2). Other subvolcanic activities include the E-W-trending rhyolitic dikes and plugs of the Assarrag suite (Thomas et al., 2002). Post-SG and post-Bou Salda magmatism includes the Askaoun granodiorite, which intrudes the western Imghi Formation, and the syn- to late-Ouarzazate Bou-Tazart granite (Amassine Suite; Thomas et al., 2002). To the east, the sub-horizontal volcano-sedimentary packages of the OG consist of laminated ignimbrites, ignimbritic rhyolites, andesites, and lapilli tuffs containing volcanic glass lenses. Associated mafic activity is recorded by an intermittent, fault-offset dolerite/diabase sill-like body (~25 m surface width) running parallel to the rhyolite-sediment contact (Fig. 2).

For the purpose of this study, a total of 32 samples were collected from the Saghro and Ouarzazate groups for petrographic and geochemical analysis. For each sample, lithostratigraphic position, sample type, drill core name and depth, short description and analytical methods applied are reported in supplementary table 1. For U-Pb geochronology, three specific samples were selected: (i): a laminated, light-pink to brownish rhyolitic dike crosscutting the Tittalt Formation (Zg-106; 46 m long, 4–5 m thick; Fig. 2); (ii): a fine- to medium-grained, light grey granite (Zg-119) from drill hole ZG-20-21 at 555.30–568.50 m intruding the Imghi Formation; and (iii): a fine- to medium-grained greenish SG sandstone collected near the Zgounder Mine main entrance for detrital zircon analysis (Zg-132; Fig. 2) (Supplementary table 2).

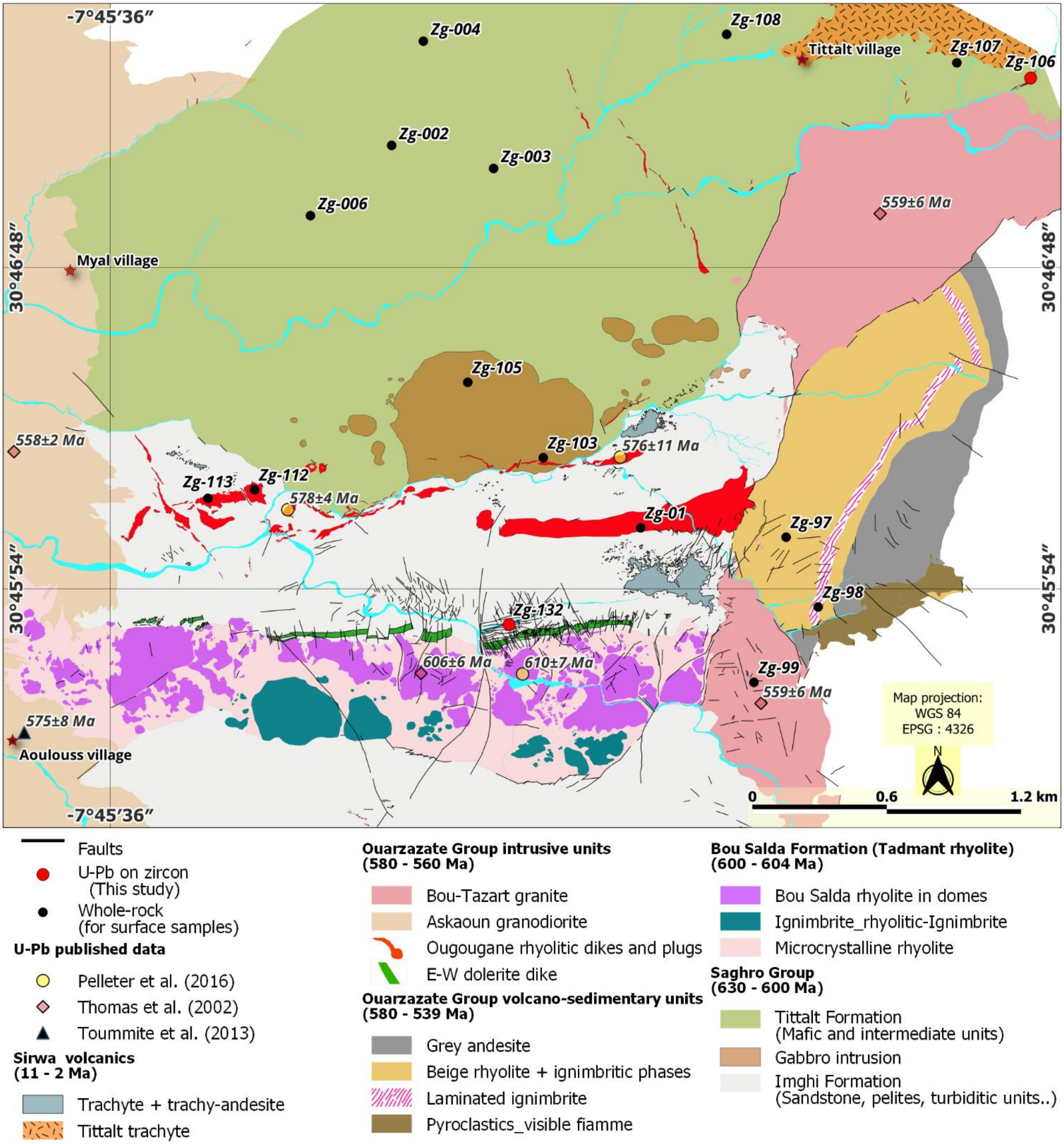

Figure 2. Detailed geological map of the ZGMR (this study). Locations of surface samples are indicated on the map. Underground samples (Mine levels, drill holes) including the dated Zg-119 are not represented on the map.

3 Data and methodology

3.1 U-Pb zircon geochronology

Three samples from the ZGMR (Zg-106; Zg-119; Zg-132) were selected for U-Pb zircon geochronology (Fig. 2 for location: Zg-106, and Zg-132). They were crushed, sieved to 50–250 µm, and weighed (1.4 kg for Zg-106; 1.5 kg for Zg-119; 2.3 kg for Zg-132), at the preparation unit of the Département de Géologie, Faculté des Sciences, Université Ibn Zohr, Maroc. Samples were then shipped to the Geotop Research Center, Université de Québec à Montréal (UQAM), Canada. Analytical parameters are detailed in supplementary data 1, following Horstwood et al. (2016). Ages of intrusive rocks are reported as weighted mean $^{206}Pb/^{238}U$ dates, and detrital zircon data as concordia dates. LA-ICP-MS U-Pb data are in supplementary table 2.

3.2 Whole-rock geochemistry and Sm-Nd isotopes

Fresh rock samples were collected for whole-rock geochemistry and Sm-Nd isotopes from outcrops (surface and underground), as well in various diamond drill holes from the ZGMR. Crushing and powdering of the rock samples were performed at the facilities of the Zgounder Millennium Silver Mining Company (ZMSM). Further details on the analytical procedures are given as supplementary data 1, and the results are shown in supplementary table 3.

4 Results

4.1 Petrography

4.1.1 The SG magmatic rocks

- The SG is mainly represented by fine to medium-grained, dolerite to basaltic-andesite samples. A medium- to coarse-grained equigranular and dark green gabbroic facies is also present, and shows heavily altered pyroxenes and amphiboles (Fig. 3a). The SG mafic volcanics contain fine-grained plagioclase and clinopyroxene phenocrysts dispersed in the groundmass. Dolerite sample (Fig. 3b) has an intergranular texture, with primary Fe-Ti oxides, clinopyroxene aggregates, and lath-shaped plagioclase. Sample Zg-108 is andesitic in composition (Fig. 3c), with an ophitic texture. The texture is microlitic to microlitic-porphyritic for basalt and basaltic-andesite samples (Fig. 3d).

4.1.2 The SG sedimentary sample

- The dated sandstone sample (Zg-132), displays alternating patterns with distinct well-defined, millimeter-scale laminations, controlled by compositional variations. Darker bands are enriched in chlorite, whereas lighter laminae are mainly composed of quartz and muscovite (Fig. 3e).

4.1.3 The OG magmatic rocks

- Rhyolite samples show a microcrystalline locally glassy texture. Primary mineral assemblages are composed of quartz megacrysts and, K-feldspar altered to albite, and embedded in a devitrified matrix. Secondary alteration minerals are sericite, albite, with some local carbonate veinlets (Fig. 3f). Dolerite samples (Zg-13, Zg-15; Fig. 3g) are fine-grained, exhibiting an intergranular texture. It shows equant opaque grains enclosed in the primary minerals (plagioclase, pyroxene), with plagioclase crystals, locally transformed to albite are moderately sericitized and locally altered to epidote. A dolerite sample (Zg-14) collected next to the mineralized zone has an intergranular texture in which laths of black oxidized plagioclase were included in pyroxene crystals (Fig. 3h). Clinopyroxene is mainly replaced by hornblende and actinolite, and partially by pyrite, while the plagioclase crystals are strongly altered and replaced by a mixture of blue chlorite, weak and sparse grains of epidote. Ignimbrite samples show an eutaxitic texture with remarkable fiamme and dense welded volcanic glass, along with cryptocrystalline facies locally fluidal, mainly composed of quartz, opaque minerals, sericitized phenocrysts of plagioclase and K-feldspars (Fig. 3i).
- Granodiorite and quartz-diorite samples are grey to light brown with a moderate pinkish tint related to K-feldspar alteration, and they show a homogenous coarse-grained texture. Opaque minerals are enclosed in hornblende, biotite and plagioclase. Sericite and clay minerals replace lath-shaped plagioclase phenocrysts, and are associated with chlorite and iron oxides (Fig. 3j). Chlorite replaces biotite, which locally substitutes hornblende crystals. Granite is medium- to locally fine-grained; it is distinguished from the granodiorite and quartz-diorite by its white to pink color (Fig. 3k).

More details regarding the mineralogical compositions of the studied samples for both Saghro and the Ouarzazate groups are given as supplementary table 4.

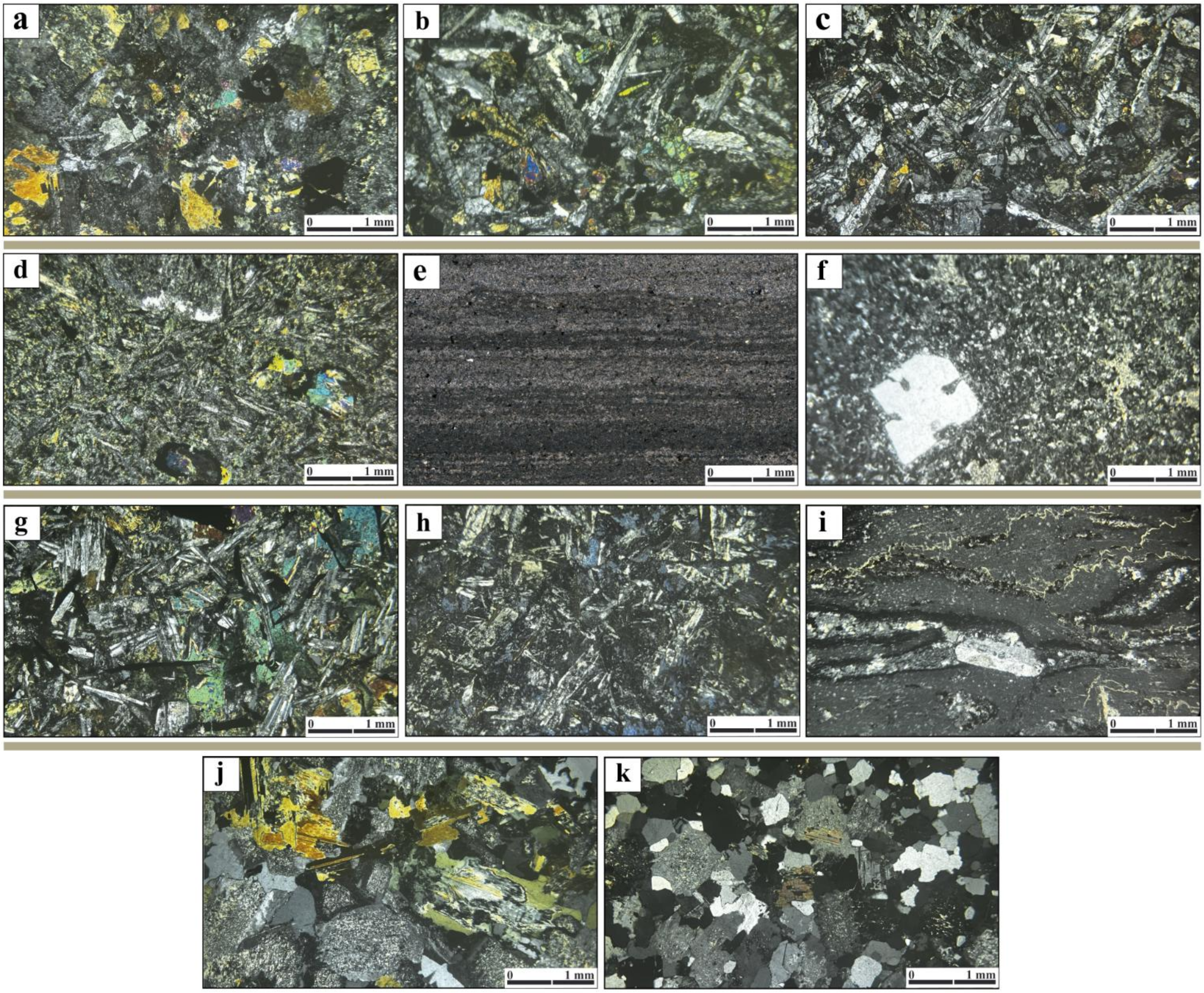

Figure 3. Photomicrographs (all in cross-polarized light) of the studied SG and OG rocks. (a) Gabbro sample showcasing a medium to coarse- grained locally equigranular texture; (b) An intergranular texture for dolerite; (c) Andesite showcasing an ophitic texture; (d) Microlitic-porphyritic texture for basaltic-andesite; (e) Sandstone (Zg-132) exhibiting millimetre-scale laminations showcasing darker bands enriched in chlorite, with quartz-muscovite lighter laminations; (f) Microcrystalline texture for rhyolite with embayed quartz phenocrysts; (g) Dolerite exhibiting an intergranular texture; (h) Diabase characterized by an intergranular texture with patches of blue chlorite; (i) Welded ignimbrite with an eutaxitic texture displaying flow textures with feldspars (sanidine) crystals embedded in a glassy fiamme; (j) Quartz diorite with subhedral to anhedral amphiboles and sericitized plagioclase; (k) Medium to locally fine-grained granite, with an anhedral to subhedral equigranular texture.

4.2 Cathodoluminescence (CL) imaging and LA-ICP-MS U-Pb zircon geochronology

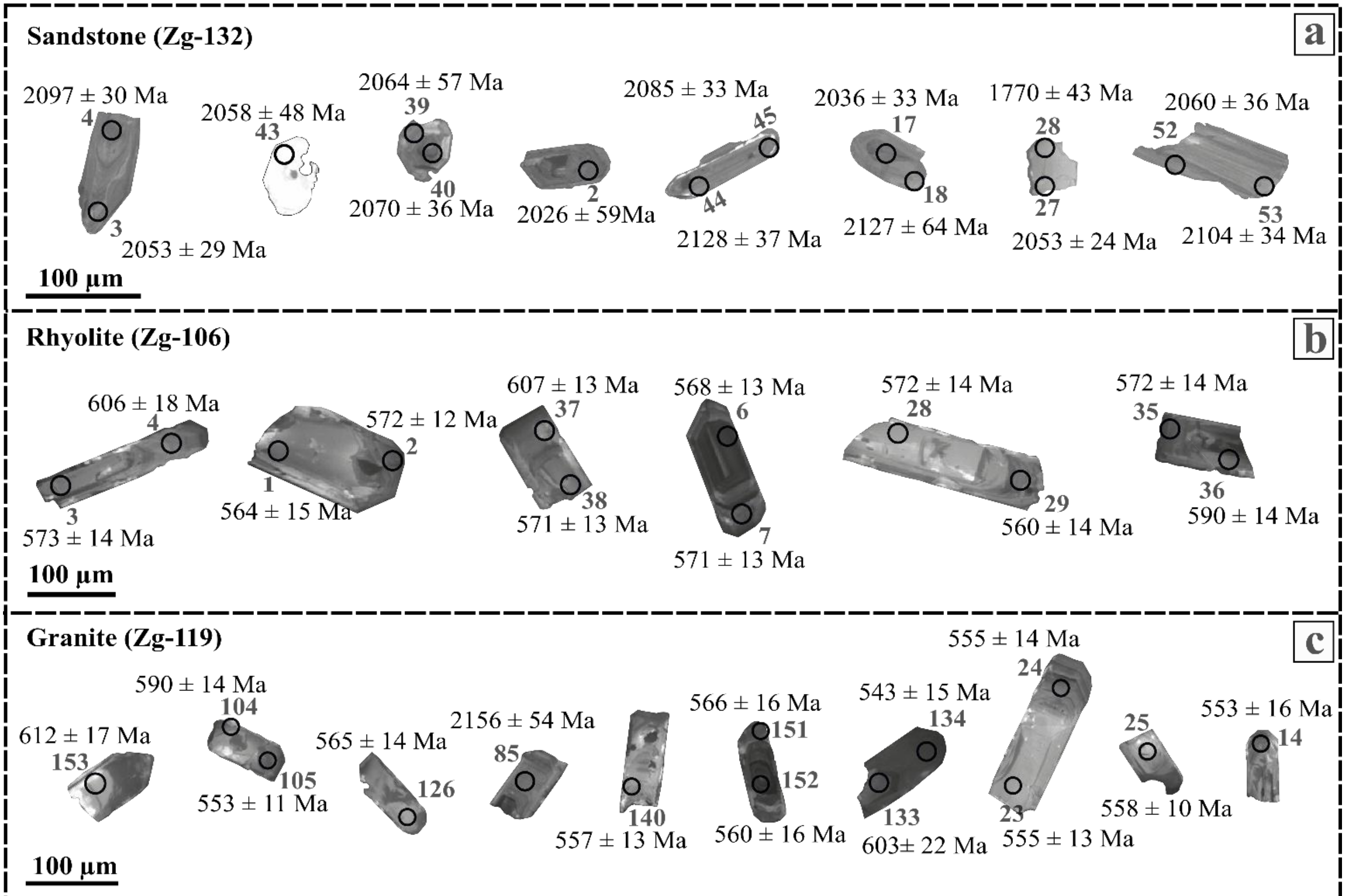

Figure 4. Cathodoluminescence (CL) images of representative zircon grains from the (a): SG sandstone (Zg-132); (b): OG rhyolite (Zg-106); and (c): OG granite (Zg-119). Black circles indicate analytical spots, with corresponding $^{206}Pb/^{238}U$ ages.

4.2.1 Sandstone (Zg-132)

Most zircons from sample Zg-132 (sandstone) are uniformly rounded and fragmented, with some being subhedral and showing rounded borders. They measure ca. 75–200 µm. They are distinguishable by their low CL signal with some being preferentially zoned (Fig. 4a). A total of hundred and thirty-eight analysis were obtained from ninety-three zircons (rims and cores) from this sample, of which 90 are concordant (Fig. 5A; supplementary data 2). The dated zircon grains have Th and U contents of 13–908 ppm and 9–3462 ppm, respectively; Th/U ratios range between 0.03 and 2. For the detrital zircons, we calculated a maximum depositional age (MDA) using the weighted mean of the youngest zircon cluster of three grains with a 98–100% concordance and overlapping in age at 1σ (YC1σ [2+]) (Dickinson and Gehrels, 2009). This yielded a MDA age of 2025 Ma (MSWD = 1.4; n = 3; (Fig. 5A-1)). Moreover, the ages distribution is dominated by one single population, with one uniform peak at 2100 Ma, and one zircon recording an age at 3700 Ma (Fig. 5A-2). The significance of the detrital age will be discussed below (see section 5.4.1).

4.2.2 Rhyolite (Zg-106)

Zircon grains from the Zg-106 (rhyolite) are transparent with subhedral to euhedral habitus. They measure ca. 100–350 μm in length. CL images reveal that zircon grains exhibit typical oscillatory zoning with rare and limited dark rim overgrowths (Fig. 4b). Forty analyses were obtained on twenty-eight zircon grains from this sample (Supplementary data 2). The dated zircon grains have Th and U contents of 20–556 ppm and 40–833 ppm, respectively; Th/U ratios range between 0.3 and 0.7. These data yield a $^{206}Pb/^{238}U$ weighted mean age of 575 ± 3 Ma (MSWD = 1.5; n = 21/40), which is interpreted as the crystallization age of the rhyolite (Fig.5B).

4.2.3 Granite (Zg-119)

Zircon grains from sample Zg-119 (granite) are mostly euhedral to subhedral with some being rounded. They measure ca. 100–300 μm in length. CL images show visible oscillatory zoning with local moderately fractured zircons showing dark overgrowths (Fig. 4c). A hundred and sixty analyses were obtained on a hundred and twenty-two zircon grains from this sample (Supplementary data 2). The dated zircon grains have Th and U contents of 12–619 ppm and 39–934 ppm, respectively; Th/U ratios range between 0.1 and 1.3, supporting their magmatic origin. A total of high-quality concordant zircon analyses yielded a reliable concordia age of 564 ± 2 Ma (MSWD = 1.6; n = 34/37). One zircon with a $^{206}Pb/^{238}U$ age of 2156 ± 54 Ma (103.5 % concordance) was excluded from the age calculation after being identified by IsoplotR as a statistical outlier (Fig. 4c). We also calculated a $^{206}Pb/^{238}U$ weighted mean age using a broader selection of concordant zircons within error, which gave an equivalent age of 564 ± 2 Ma (MSWD = 1.1; n = 76/160) (Fig. 5C). As both ages are statistically identical, we interpret the 564 ± 2 Ma as the crystallization age for the granite.

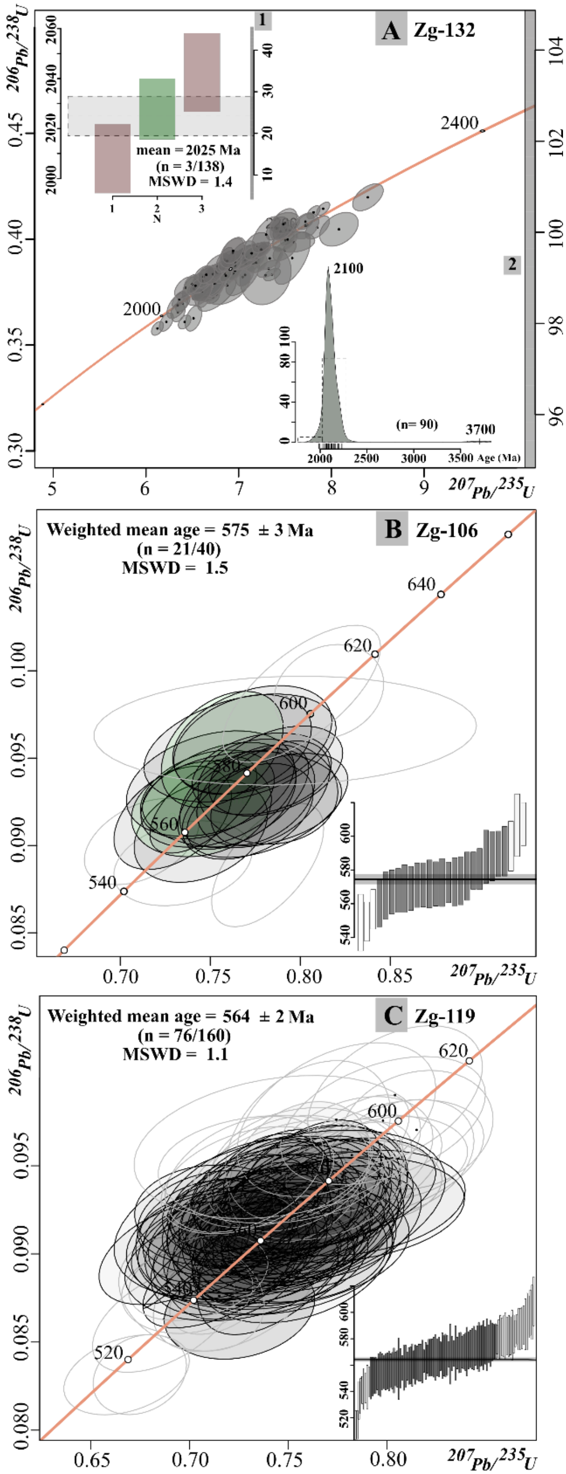
A Zg-132
mean = 2025 Ma
(n = 3/138)
MSWD = 1.4
2100
(n= 90)
3700
Age (Ma)
2000
2400
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
B Zg-106
Weighted mean age = 575 ± 3 Ma
(n = 21/40)
MSWD = 1.5
C Zg-119
Weighted mean age = 564 ± 2 Ma
(n = 76/160)
MSWD = 1.1

Figure 5. Pb^{206}/U^{238} weighted mean age of three concordant grains, U-Pb concordia, and Kernel Density Estimate (KDE) diagram for (A) Zg-132 (sandstone). Along with U-Pb concordia diagrams, and Pb^{206}/U^{238} weighted mean ages for (B) Zg-106 (rhyolite), and (C) Zg-119 (granite). Ages were calculated using Isoplot R 1.0 (Vermeesch, 2018).

4.3 Whole-rock geochemical compositions

4.3.1 Effects of weathering

Given the samples distribution and geological diversity, the selected samples are organized according to their lithostratigraphic positions (Supplementary table 1). The Loss on Ignition (LOI) values at 1100 °C are generally low (< 2 wt.%), except for the mafic terms of the SG, which reach approximately 4 wt.% (Supplementary table 3; n = 32). When plotted on the alteration box plot of Hughes (1972) (Fig. 6a), most samples fall within the igneous spectrum, defining a homogenous hydrothermal trend. However, sample Zg-106 deviates, plotting in the K-altered zone, reflecting localized potassium enrichment. Conversely, two granite samples (Zg-02 and Zg-109) plot in the Na-altered field, suggesting sodium metasomatism.

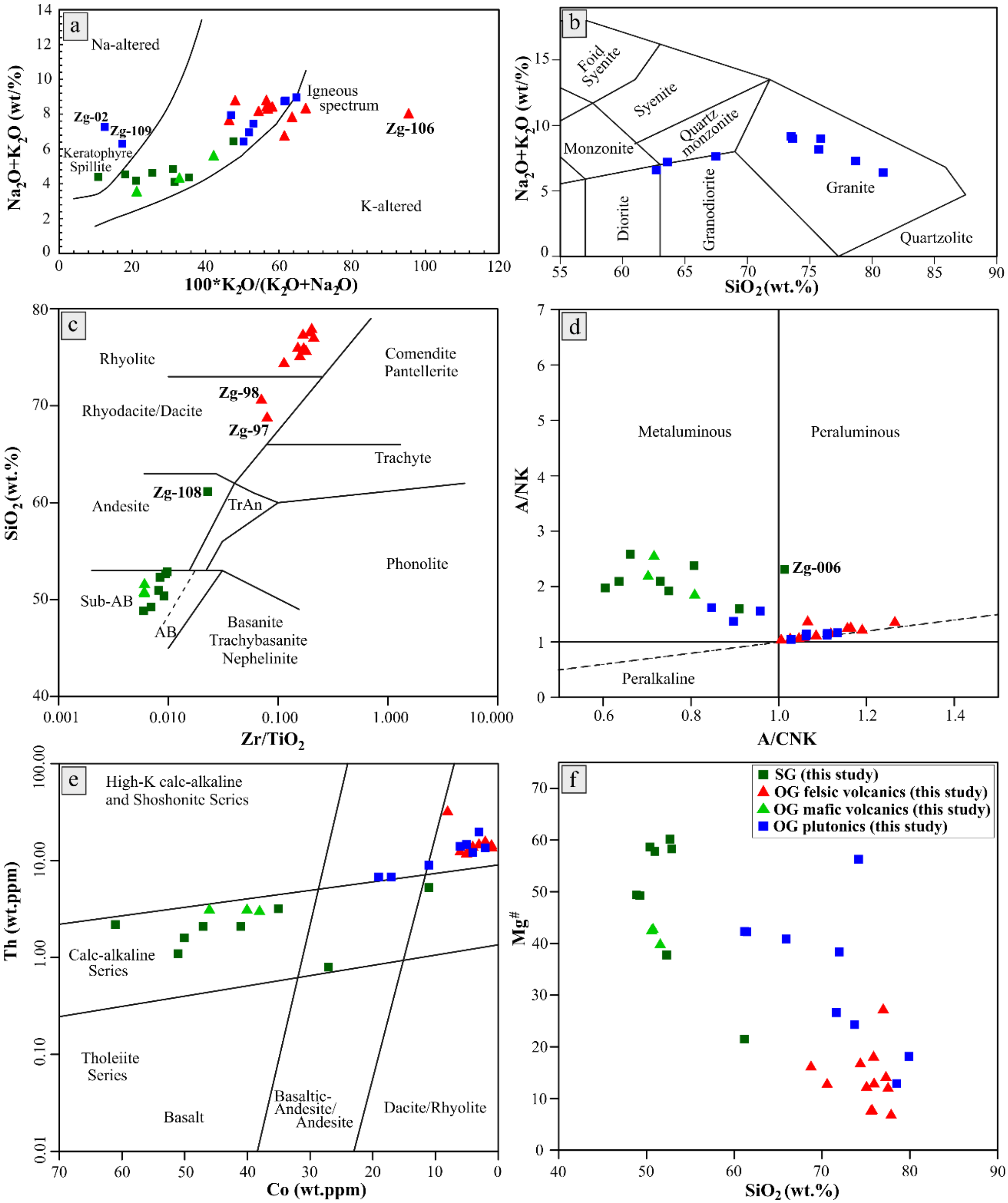

Figure 6. (a) Na_2O+K_2O (wt.%) versus $100*K_2O/(K_2O+Na_2O)$ plot of Hughes (1972); (b) TAS diagram (after Middlemost, 1994); (c) SiO_2 (wt.%) versus Zr/TiO_2 (Winchester and Floyd, 1977); (d) Plot of A/NK versus A/CNK [A/CNK = molar ratio Al_2O_3 / (CaO + Na_2O + K_2O) and A/NK = molar ratio Al_2O_3 / (Na_2O + K_2O)] (Shand, 1943); (e) Plot of Th (ppm) versus Co (ppm) of Hastie et al. (2007); (f) Mg# value versus SiO_2 contents (wt.%).

4.3.2 The SG magmatic rocks

The analyzed SG rocks belong to the Tittalt Formation of the SG in the study area (Fig. 1C; Fig. 2; Thomas et al., 2004, 2002). Geochemically, they define a narrow range of compositions, with SiO_2 contents from 48.85 wt.% to 52.87 wt.%, except for sample (Zg-108) with SiO_2 of 61.15 wt.%. They contain 1.08 – 7.45 wt.% MgO, 13.44 – 15.65 wt.% Al_2O_3, 2.82 – 3.95 wt.% Na_2O, and 0.47 – 3.07 wt.% K_2O. Based on the SiO_2 (wt.%) vs Zr/TiO_2 diagram, all samples plot within a sub-alkaline basalt, except for one sample (Zg-108) with andesitic composition (Fig. 6c). Most rocks are metaluminous except for one sample (Zg-006) which is peraluminous (Fig. 6d). In addition, the SG rocks display a calc-alkaline signature (Fig. 6e). Mg# (Mg# = (MgO+FeO)/MgO×100) values range from 21.50 to 60.20 (Fig. 6f).

The SG samples show a total rare earth elements (∑REE) varying between 60.94 to 231.77 ppm with coherent patterns characterized by a slight enrichments in light rare earth elements (LREEs) and heavy rare earth elements (HREEs) depletion (Fig. 7a), with $(La/Yb)_N$ ratios ranging from 1.83 to 6.42 (N subscript denotes normalization to Chondrite). Almost all samples have slight/negligible negative Eu anomalies (Eu/Eu* = 0.89–0.99) to positive one for gabbro Zg-105 (Eu/Eu* = 1.28; Fig. 7a); (Eu/Eu* = 2EuN / (SmN + GdN, subscript N denotes normalization against chondrite Sm and Gd contents)). For the NMORB-normalized multi-elements diagram (Fig. 7b), the SG rocks exhibit an enrichment of large ion lithophile elements (LILEs, like Cs, Rb, Ba, K) over high field strength elements (HFSEs) with negative anomalies in Nb, Ta, and a prominent positive Pb anomaly.

4.3.3 The OG magmatic rocks

The studied samples of the OG are composed of both volcanic and plutonic rocks. The felsic volcanic and plutonic samples have high contents of SiO_2 (61.16 – 79.89 wt.%), Al_2O_3 (10.83 – 15.18 wt.%), and CaO (0.1 – 4.42 wt.%) and low MgO (0.06 – 2.83 wt.%), Ni (20 – 60 ppm) and Co content (1 – 19 ppm), except for one granite (Zg-119) that has relatively high Co content of 109 ppm (Supplementary table 3). Moreover, they have a Na_2O+K_2O (wt.%) = 6.31 to 8.97 with a K_2O/Na_2O ratio of 0.14 to 20.75. The plutonic rocks occupy the granite field, with three distinctive granodiorites (Fig. 6b). Furthermore, rock types for felsic volcanics are as follows: ignimbrites (e.g., Zg-97, Zg-98) are represented as rhyodacite and dacite, while rhyolites and rhyolitic-ignimbrites plot inside the rhyolite field (Fig. 6c). Furthermore, The whole set consists of peraluminous rocks, except for the granodiorite samples (Zg-07, Zg-08, and Zg-09) that exhibit a metaluminous character (Fig. 6d). They showcase a high-K calc-alkaline to shoshonitic signature (Fig. 6e).

Mafic volcanics (dolerite) have moderate SiO_2 contents of (50.58 – 51.56 wt.%), Al_2O_3 (13.9 – 14.69 wt.%), moderate CaO (5.61 – 7.67 wt.%) and moderate MgO (4.56 – 5.3 wt.%). K_2O/Na_2O ratio values are 0.26 to 0.73, along with Na_2O+K_2O sum = 3.58 to 5.64 (supplementary table 3). They are sub-alkaline basalts (Fig. 6c), with a metaluminous character (Fig. 6d), and a calc-alkaline signature (Fig. 6e). Mg# values range from 37.19 to 40.16 (Fig. 6f).

The OG samples show a total rare earth elements (∑REE) varying between 93.52 to 646.17 ppm. In the REE diagram (Fig. 7c), all felsic volcanic and plutonic samples show homogeneous patterns, with enriched LREEs over HREEs. $(La/Yb)_N$ ratio varies between 2.91 and 17.93, except for one rhyolitic sample Zg-106 with $(La/Yb)_N$ of 0.89. All samples have high Eu negative anomaly (Eu/Eu* = 0.34 – 0.61, except for the same Zg-106 sample, that exhibits a prominent Eu anomaly with Eu/Eu* = 0.04. In the multi-element spider diagram, all samples display enrichments in LILEs (Cs, Rb, Ba, Th, and U) and depletion in HFSEs (Zr, Nb, Hf and Ta), relative to Primitive Mantle (Fig. 7d). Plus, samples show a prominent negative anomaly in Nb, Ta, P and Ti along a positive anomaly in Pb, Ba and Th, except for sample Zg-106 that lacks negative Nb anomaly (Fig. 7d). For the OG dolerites, the REE normalized to chondrite (Fig. 7c) show moderate LREEs enrichments over HREEs with less fractional patterns ($(La/Yb)_N$ = 5.94 to 6.22) and very low/absent Eu anomaly (Eu/Eu* = 0.88 to 0.98). However, they are distinguished by their homogenous pattern with a prominent Pb enrichment, with less significant Sr anomaly (Fig. 7d).

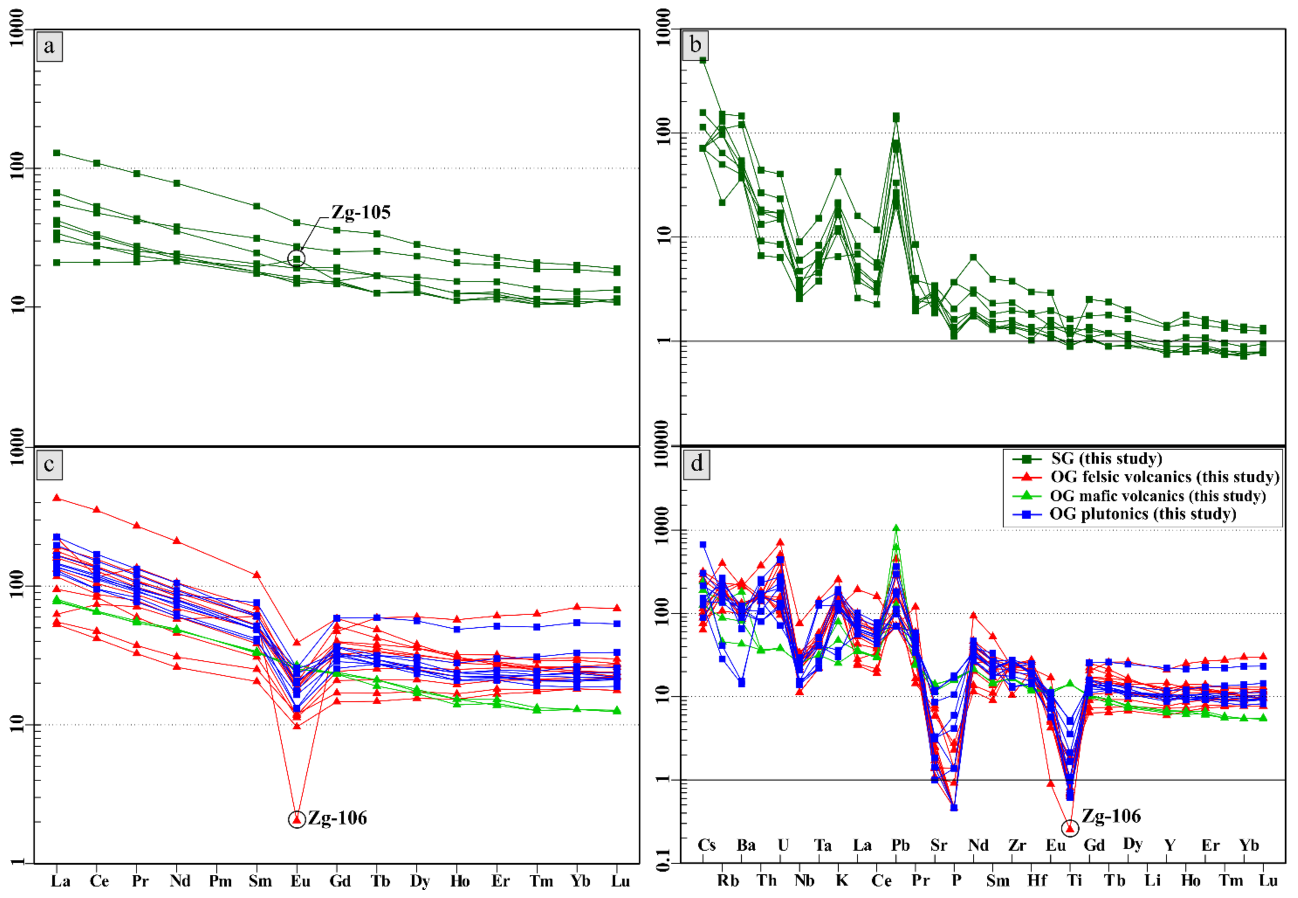

Figure 7. (a) Chondrite-normalized REE diagram of Boynton, (1984) for SG; (b) NMORB normalized diagram of Sun and McDonough (1989) for SG; (c) Chondrite-normalized REE diagram of Boynton, (1984) for OG; (d) Primitive-mantle normalized diagram of Sun and McDonough (1989) for OG.

4.4 Whole-rock Sm-Nd isotope compositions

Sm-Nd isotopic studies of seven representative samples covering the Ediacaran record of the Sirwa massif reveal petrogenesis processes and orogenic evolution between the 630 to 539 Ma evolution of the Anti-Atlas belt post-Bou Azzer-Sirwa ophiolite accretion. Results are listed in table 1.

Table 1: Whole rock Nd isotopic compositions for the analyzed SG and OG rocks. TDM Goldstein is the Depleted Mantle Age in Ga calculated using the linear model of Goldstein et al. (1984); and is not calculated for samples with $^{147}Sm/^{144}Nd$ ratios greater than 0.145 (Zg-106). Abbreviations: ± 2 SE: Standard Errors (Uncertainty in Nd isotopic composition); N/A : Not Available.

Sample	Lithology	Age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ measured	± 2SE	$^{143}Nd/^{144}Nd_{(t)}$	$\varepsilon Nd^{(t)}$	TDM (Goldstein) Ga	TDM (2stage) Ga
SG rocks											
Zg-105	Gabbro	620	3.73	13.27	0.1704	0.512762	0.000011	0.512071	+4.6	1.36	0.91
Zg-108	Andesite	620	9.94	40.03	0.1351	0.512550	0.000007	0.512002	+3.2	1.16	1.02
OG rocks											
Zg-09	Granodiorite	570	10.23	50.70	0.1220	0.512414	0.000005	0.511959	+1.1	1.22	1.15
Zg-119	Granite	570	9.10	42.92	0.1283	0.512381	0.000009	0.511903	+0.0	1.37	1.24
Zg-14	Dolerite	570	6.51	28.99	0.1359	0.512390	0.000010	0.511884	-0.3	1.50	1.26
Zg-106	Rhyolite	570	11.50	32.75	0.2124	0.512693	0.000007	0.511902	+0.0	N/A	1.25
Zg-117	Rhyolite	570	10.69	50.59	0.1278	0.512332	0.000011	0.511856	-0.8	1.45	1.30

$(^{143}Nd/^{144}Nd)_t = (^{143}Nd / ^{144}Nd)_0 + (^{147}Sm / ^{144}Nd)_t \times (e^{\lambda t} - 1)$

$\varepsilon Nd^{(t)} = [(^{143}Nd/^{144}Nd_{sample}{}^{t} / ^{143}Nd/^{144}Nd_{CHUR}{}^{t}) - 1] \times 10000$

$T_{DM2} = 1/\lambda \times Ln\ \{1 + [(^{143}Nd/^{144}Nd)_{DM} - (^{143}Nd / ^{144}Nd)_{sample} + ((^{147}Sm / ^{144}Nd)_{sample} - (^{147}Sm / ^{144}Nd)_{CC)} \times (e^{\lambda t} - 1)] / ((^{147}Sm / ^{144}Nd)_{DM} - (^{147}Sm / ^{144}Nd)_{CC)}\}$

$\lambda\ ^{147}Sm = 0.654 \times 10^{-11}\ a^{-1}$: the decay constant of ^{147}Sm.

$(^{143}Nd/^{144}Nd)_{DM} = 0.51315$: present-day ratio of the Depleted Mantle (DM).

$(^{147}Sm / ^{144}Nd)_{DM} = 0.2137$: present-day parent/daughter ratio of the DM.

$(^{147}Sm / ^{144}Nd)_{CC)} = 0.12$: average parent/daughter ratio assigned to the Continental Crust (CC).

Error of initial ratio is calculated from the measurement of error of the isotope ratio, the estimated concentration error and the age error. The decay constant is considered to be a fixed value.

$$\sigma_{Nd(t)} = \sqrt{\sigma^2_{Nd} + \sigma^2_{Sm}\ (e^{\lambda t} - 1)^2 + \sigma^2_t\ \left(\lambda e^{\lambda t}\left(\frac{^{147}Sm}{^{144}Nd}\right)\right)^2}$$

$\sigma_{Nd(t)}$ is mean-square deviation of $(^{143}Nd/^{144}Nd)_t$

σ_{Sm} is mean-square deviation of $(^{143}Sm/^{144}Nd)_{sample}$

σ_t is mean-square deviation of age

Based on field relationships, an angular unconformity (Errami et al., 2009; Thomas et al., 2002), a significant sedimentary/magmatic gap exist between the 630–600 Ma SG and the overlaying 570–539 Ma OG (Errami et al., 2021a). We have used the 620 Ma as a reference age for εNd analyses of SG samples (Zg-105, and Zg-108). They show narrow (^{143}Nd /^{144}Nd) 620 Ma ratios, ~ 0.512, and positive εNd_{620} values of +3.2 and +4.6. Additionally, the TDM model ages (Fig. 8a), of 1.02 and 0.91 Ga, exceed the individual maximum depositional ages of 630 to 600 Ma, and the crystallization ages of older to contemporaneous igneous intrusions found elsewhere in the Anti-Atlas belt that fall within the bracket of 640 Ma to 580 Ma, (Errami et al., 2021a; O'Connor et al., 2010; Liégeois et al., 2006; Gasquet et al., 2005; Mrini, 1993).

The OG rocks calculated at 570 Ma exhibit a mostly uniform distribution with ($^{143}Nd/^{144}Nd$) values from 0.5118 to 0.5119. These ratios are close to or slightly lower than the Chondritic Uniform Reservoir (CHUR) values. (εNd_{570} = -0.8 to +1.1).

Volcanic rocks show negative εNd_{570} values: -0.8 (Tadmant rhyolite), +0.0 (OG rhyolite), and -0.3 (dolerite). Granitoids have εNd_{570} values of +0.0 and +1.1 for Zg-119 and Zg-09, respectively. In addition, the TDM model ages for all of these samples range from 1.30 to 1.15 Ga (Fig. 8a). Overall, the distinct $\varepsilon Nd_{(t)}$ isotopic signatures for both groups is further supported by the negative correlation of $\varepsilon Nd_{(t)}$ values with SiO_2 (Fig. 8b).

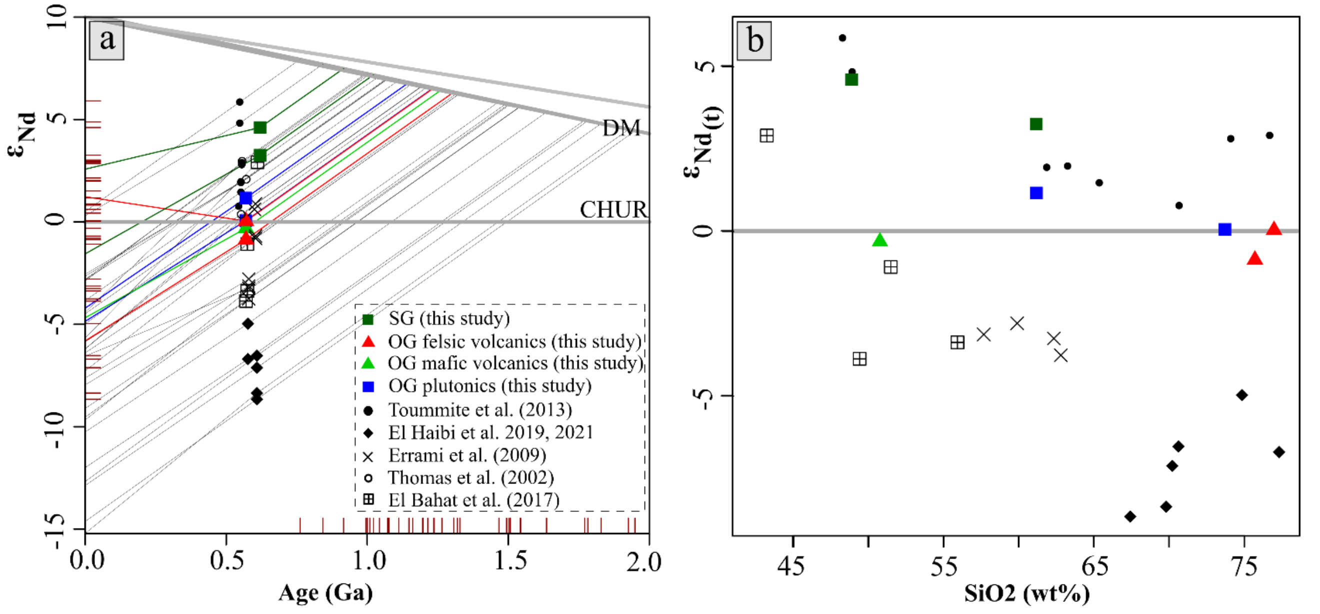

Figure 8. (a) two-stage εNd isotope growth diagram for SG and OG rocks versus Age (Ga). DM, Depleted Mantle evolution lines after Goldstein et al. (1984) and Liew and Hofmann (1988); CHUR, Chondritic Uniform Reservoir. The tick marks on the axes denote two-stage Nd model ages along the x-axis and initial εNd values along the y-axis; (b) Initial εNd versus SiO2 (wt.%) for SG and OG rocks. All samples are compared with selected and available reference rocks from the literature. Calculations and diagrams are produced using GCDkit (Janoušek et al., 2006).

Further, to quantify the mixing proportions for the Saghro and Ouarzazate groups, this study employs a binary mixing model based on the equations of Faure (1986), utilizing the computational approach detailed by Janoušek et al. (2016). In this model, the isotopic ratio of a mixture (I_M) is defined as the mean of the isotopic ratios of two end-members (I_1 and I_2), weighted by their respective mass fractions and elemental concentrations. f_1 represents the mass fraction of end-member 1 (where $f_1 + f_2 = 1$), while C_1, C_2, and C_M represent the elemental concentrations of the end-members and the resulting mixture. The mantle end-member 1 is defined by a metasomatized lithospheric source with values of $I_1 = 0.512265$; $C_1 = 13.27$ ppm, and $\varepsilon Nd_{620} = +8$ from Errami et al. (2009), reflecting an enriched mantle by prior subduction processes. For the crustal end-member 2, we utilized parameters from Ennih and Liégeois, (2008) ($I_2 = 0.511472$; $C_2 = 47$ ppm; $\varepsilon Nd_{620} = -16$), representing the Paleoproterozoic basement of the WAC.

The mixing equations are defined as :

$$I_M = I_1 \left(\frac{C_1}{C_M}\right) f_1 + I_2 \left(\frac{C_2}{C_M}\right) (1 - f_1)$$

Where:

(1)

$$C_{\mathrm{M}} = f_1 C_1 + (1 - f_1) C_2$$

(2)

$$f_1 = \frac{C_2(\mathrm{I_M} - \mathrm{I_2})}{C_1(\mathrm{I_1} - \mathrm{I_M}) + C_2(\mathrm{I_M} - \mathrm{I_2})})$$

Applying this mixing model reveals that SG rocks are characterized by a dominantly mantle origin; the andesite (Zg-108) and gabbro (Zg-105) yield high mantle-derived mass fractions (f_1) of 88 % and 92 %, respectively, with minor crustal inputs ($f_2 \approx$ 8 % to 12 %). Conversely, the OG magmas have mantle mass fractions (f_1) ranging from 75 % to 85 %. Moreover, the calculated crustal contribution (f_2) increases from 15 % in granodiorite (Zg-09) to 25 % in the rhyolite (Zg-117).

5 Discussion

5.1 Petrogenesis

The SG and OG rocks exhibit chemical evolution that can be explained by fractional crystallization. The general trends for major elements (e.g., Al_2O_3, CaO, and TiO_2) show positive correlations versus Mg# (Fig. 9a,b, and c). For instance, Al_2O_3 contents decrease with decreasing Mg# suggesting the crystallization of plagioclase (Fig. 9a). CaO contents exhibit a sharp drop as Mg# decreases (below ~40), indicating clinopyroxene or calcic plagioclase fractionation (Fig. 9b). TiO_2 also decreases with decreasing Mg#, pointing to the early crystallization of Fe-Ti oxides (e.g., ilmenite or titanomagnetite) (Fig. 9c).

On the A/CNK versus Mg# plot (Fig. 9d), the SG rocks are metaluminous (A/CNK < 1.0), while the OG felsic and plutonic rocks are peraluminous (A/CNK > 1.0). This shift to peraluminous composition suggests that the felsic rocks involved the melting of aluminum-rich material or the fractionation of aluminum-poor minerals (e.g., hornblende, pyroxene). In Figure. 9e, the SG rocks retain the highest Sr concentrations (~200–350 ppm), indicating a more aluminum enriched source or less plagioclase removal. Furthermore, this is supported by the absence of a negative Eu anomaly (Eu/Eu* = 0.89–1.28), to positive one for gabbro Zg-105 (Eu/Eu* = 1.28) indicating limited plagioclase fractionation (Fig. 7a). On the contrary, the OG rocks showcase a dramatic drop in Sr from the OG mafic volcanics, passing through the OG plutonics to the OG felsic volcanics. This steep decline proves that plagioclase crystallization was the dominant driver for OG differentiation (Fig. 9e). This is corroborated by the prominent negative Eu anomaly in rhyolite Zg-106, while the absence of an Eu anomaly in dolerites suggests limited plagioclase involvement (Fig. 7c).

On the Th (ppm) versus Mg# (Fig. 9f), both the SG rocks and OG mafic volcanics showcase low Th concentrations (<5 ppm) typical of mantle-derived melts. However, for the SG, the Mg# values of 21.50 to 60.20, reflect early fractionation of ferromagnesian minerals, and suggest that rocks are not derived from a primitive melt. For the OG, Th levels spike to up to 32 ppm for the OG felsic volcanics and plutonics, suggesting possible influence by crustal melting or assimilation during magma ascent (Fig. 9f). The lack of a negative Eu anomaly in the SG rocks (Fig. 7a), despite the evolved nature of the magmas, is likely due to the mixing of evolved basaltic magmas, with more primitive magmas that lacked plagioclase fractionation. The OG felsic volcanics and plutonics show Sr and P depletion that can be explained by plagioclase and apatite fractionation (Fig. 7d).

Eu/Eu* values versus Sr contents (ppm) evince a clear positive correlation (Fig. 9g). The mafic rocks of the Saghro and the Ouarzazate groups have high Sr and Eu/Eu* values near 1.0 suggesting plagioclase accumulation in relation to their more primitive nature. On the contrary, the OG felsic volcanics and plutonics have significantly lower Sr and Eu/Eu* values, providing evidence that fractionation of plagioclase from the melt was significant (Fig. 9g). Whole rock Zr/Sm versus Zr and Rb/Nb versus Rb correlations are as expected for a fractional crystallization process (Fig. 9h-i). The localized spike in Zr/Sm at high Zr contents (~350 ppm) indicates late stage mineralogical control, involving zircon or amphibole fractionation in the more evolved magmas of the OG, distinct to the relatively stable ratios for most samples (Fig. 9h). This implies that the magmatic evolution of the SG and the OG rocks was characterized by both fractional crystallization and progressive crustal contamination or a subduction modified source (Fig. 9i).

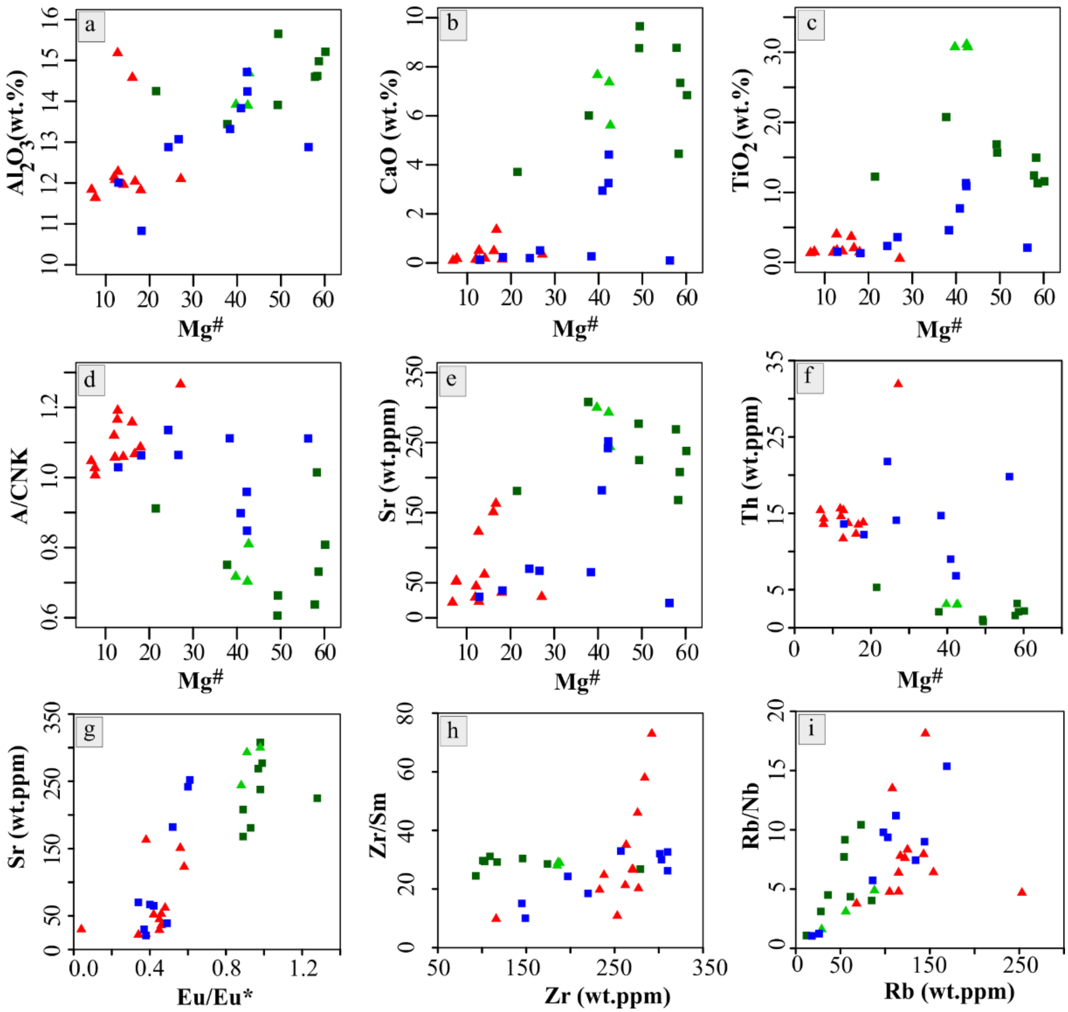

Figure 9. (a) Al_2O_3 (wt.%) versus Mg#; (b) CaO (wt.%) versus Mg#; (c) TiO_2 (wt.%) versus Mg#; (d) A/CNK (A/CNK = molar ratio Al_2O_3 / (CaO + Na_2O + K_2O)) versus Mg#; (e) Sr (ppm) versus Mg#; (f) Th (ppm) versus Mg#; (g) Zr / Sm value versus Zr content (ppm); (h) Rb / Nb value versus Rb content (ppm); (i) Eu / Eu* value versus Sr (ppm). Symbols as those in Figure 6.

The εNd_i versus $^{147}Sm/^{144}Nd$ plot evince a clear distinction between the SG and the OG rocks (Fig. 10a). The SG rocks exhibit strongly positive εNd_i values of +3.2 and +4.6, indicating a juvenile, depleted mantle origin with minimal crustal interaction. In contrast, the OG rocks cluster near or below the CHUR line (εNd_i values of -0.8 to +1.1), signaling a hybrid source involving the significant reworking of older, evolved continental crust. Notably, while sample Zg-106 shares this near-zero isotopic signature, its unusually high $^{147}Sm/^{144}Nd$ ratio of ~0.21 confirms it underwent a distinct petrogenetic process, likely a low degree of partial melting that fractionated REE without significantly altering the initial Nd isotopic composition of its source (Fig. 10a).

The geochemical fingerprints for the SG and OG are distinct. For samples with Nb < 25 ppm (Fig. 10b), a significant vertical spread in Nb/Ta ratios (~3–15) is observed; specifically, the OG plutonics exhibit a sharp decline in Nb/Ta (~3), indicating advanced fractional crystallization of ferromagnesian and accessory minerals. Conversely, the SG mafic rocks maintain higher, stable ratios (~10–15), identifying them as more primitive melts. While Nb and Ta typically behave as geochemical twins, they can fractionate during subduction (Hofmann et al., 1986). The OG rocks cluster below a Nb/Ta ratio of 14, well under the mantle value of 17.5 (Sun and McDonough, 1989), matching the bulk continental crust value of ~11 (Green, 1995) and confirming a dominant crustal signature. This is further corroborated by an enrichment in LILEs (like Rb, Ba, and Th), coupled with prominent negative Nb-Ta and Ti anomalies (Fig. 7d), signature of subduction-related magmatism or the recycling of metasomatized lithosphere (Ikenne et al., 2007). Finally, the OG rhyolite (Zg-106) displays a horizontal shift toward higher Nb contents at a fixed Nb/Ta ratio (~9) (Fig. 10b), suggesting magma enrichment via a low degree of partial melting from a source already characterized by a low Nb/Ta ratio and a pre-existing subduction-modified signature.

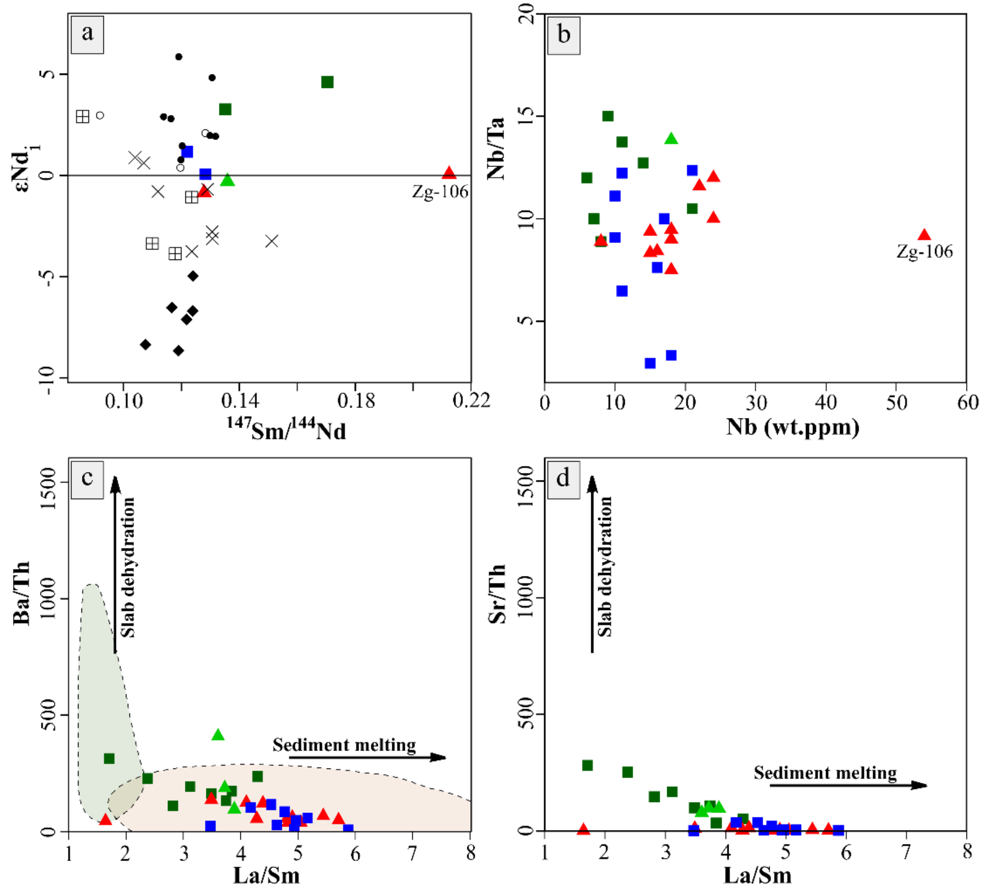

Figure 10. Plots (a) Initial εNd versus $^{147}Sm/^{144}Nd$; (b) Nb/Ta versus Nb contents (ppm); (c) Ba/Th versus La/Sm and (d) Sr/Th versus La/Sm (domains are modified from Labanieh et al. (2012). Legend is the same as in Figure 8.

The SG and OG rocks show enrichment in LILEs and LREEs relative to HFSEs and HREEs. They also exhibit pronounced negative anomalies in Nb, Ta, and Ti (Fig. 7), suggesting a subduction zone fluids influence (Wilson, 1989). Admittedly, for the OG rocks, this inherited geochemical signature is attributed to oceanic arc rocks previously subducted into the mantle (Toummite et al., 2013; Gasquet et al., 2008; Ikenne et al., 2007; Thomas et al., 2002).

Trace elements can clarify subduction input versus crustal contamination. As shown in the Ba/Th versus La/Sm diagram (Fig. 10c), most samples display low Ba/Th, high and variable La/Sm ratios, favoring the dominant role of the sediment melting process. Similarly, the role of the sediment melt is also observed for all samples in the Sr/Th versus La/Sm diagram (Fig. 10d). For the SG rocks, their relatively high Sr/Th ratios are attributed to plagioclase accumulation. Furthermore, high La/Sm ratios indicate a sediment-dominated influence, suggesting that the slab pressure-temperature conditions were sufficient to trigger sediment melting (Labanieh et al., 2012). The melting process acted as the primary mechanism for transferring the slab signature into the analyzed samples.

5.2 Initial Sm-Nd isotopes composition and magma source characteristics

The whole-rock Sm-Nd isotope compositions of the Saghro and Ouarzazate groups suggest a heterogeneous magma source, exhibiting negative correlation of $\varepsilon Nd_{(t)}$ values versus SiO2 (Fig. 8b). For instance, the SG maintains high $\varepsilon Nd_{(620)}$ values (+3.2 and +4.6) even as silica increase, reinforcing their juvenile mantle source with minimal crustal input,. Eventually, the obtained TDM model ages of 1.02 and 0.91 Ga confirm a depleted mantle source. Within the OG, the decreasing trend of εNd_{570} = +1.1 to -0.8 with increasing SiO_2 is a classic signature of Assimilation-Fractional Crystallization (AFC), where the cooling magma is simultaneously evolving toward a felsic composition and incorporating more evolved, negative εNd continental crust. Notably, the calculated TDM model ages clustering around 1.30 to 1.15 Ga indicates that the OG magmas were not purely mantle-derived but involved the significant recycling of much older underlying basement (Mesoproterozoic and/or Paleoproterozoic).

Indeed, quantitative binary mixing model validates these isotopic trends. the SG rocks showcase a near-pristine mantle signature (f_1 = 88–92 %). However, the increase in the crustal contribution (f_2) of the OG rocks from 15 % in granodiorite (Zg-09) to 25 % in the rhyolite (Zg-117) confirm a coupling of increasingly felsic compositions with higher crustal input. The 25 % contribution from an ancient Paleoproterozoic source with εNd_{620} = -16 constitutes a major contamination event, exerting a significant isotopic pull by shifting the εNd values of the samples to near zero. Normally, without the recycling of this ancient basement, a purely mantle-derived magma at 570 Ma would exhibit strongly positive values up to +7 to +8. This hybridization is further supported by the TDM model ages of 1.30 to 1.15 Ga, proving the significant involvement of the underlying Eburnean WAC basement.

5.3 Tectonic implications

Previously, the SG basin was interpreted as consisting of distal deep marine sediments equivalent to the platform series of Tachdamt Group, formed during the initial rifting associated with the Rodinia breakup (Thomas et al., 2002). However, recent zircon data from the SG sediments in the Sirwa and Saghro inliers suggest its deposition occurred post the Bou Azzer–Sirwa ophiolite accretion, during the main Pan-African Orogeny (Abati et al., 2010; Errami et al., 2009; Liégeois et al., 2006). Furthermore, the Ediacaran magmatism of the OG is still debated as being fully post-collisional and linked to asthenospheric rise (upwelling) beneath the WAC during its metacratonic evolution (Gasquet et al., 2008, 2005; Liégeois et al., 2006; Thomas et al., 2002), or related to subduction (Walsh et al., 2012; Benziane, 2007; El Baghdadi et al., 2003), or even representing the Iapetus Ocean opening with ties to the Ediacaran Central Iapetus Magmatic Province (CIMP; Youbi et al., 2020). Based on similarities in ages and chemical characteristics, this magmatism is associated with the Avalonian-Cadomian marginal belt along the Northwestern edge of Gondwana, and constitutes a major magmatic flare-up spanning roughly 590–540 Ma (Letsch et al., 2018; Tahiri et al., 2010; Linnemann et al., 2008).

For our samples, the multi-elemental discrimination plots (Fig. 11a–f) provide a framework for deciphering the petrogenesis and tectonic transition of the Ediacaran magmatic sequences in the Anti-Atlas. For a start, the SG basalts feature high Zr and relatively low Y concentrations, classifying them as within-plate basalts (WPB) (Fig. 11a), indicating an extensional or transtensional geodynamic setting. On the Th/Nb versus Ti/V diagram of Shervais (2022), these samples plot in the Continental Flood Basalts (CFB) field (Fig. 11b). Admittedly, and placed in the regional context of the Anti-Atlas; the geodynamic setting of the SG has been interpreted as an intracontinental rift evolving into either a mature back-arc basin (Errami et al., 2009; Fekkak et al., 2001) or a continental passive margin (Fekkak et al., 2002). This evolution is characterized by a transition from early, sediment-influenced tholeiites to more evolved magmatic suites rather than a massive subaerial flood province. The calc-alkaline character for the SG mafic rocks reflects an enrichmentt in Th, typical of subduction-influenced or crustally contaminated suites (Fig. 6e). This apparent transitional character exhibiting a calc-alkaline affinity (Fig. 6e) but a within-plate (Fig. 11a), continental tholeiites (Fig. 11e) character represents an early Ediacaran extensional phase where advanced lithospheric thinning allowed asthenospheric decompression triggering large-scale melting of the Sub-Continental Lithospheric Mantle (SCLM). In contrast, the younger OG volcanic and plutonic rocks plot at higher Th/Nb ratios (>0.5) along the Upper Continental Crust (UCC) and Andean Arc fields, with extreme Th enrichment pointing to a regional thermal regime shift (Fig. 11b). The OG magmatism marks a massive crustal melting event, which we interpret as a response to post-collisional lithospheric delamination and possible slab break-off. This process generated highly differentiated and evolved magmatic suites with wide variations in Ti/V ratios (Fig. 11b).

Furthermore, there is a clear lithospheric transition between the SG and the OG rocks based on their trace element enrichments. For instance, the SG mafic rocks follow the MORB-OIB array (Fig. 11c), indicating a magma source derived directly from an enriched mantle source akin to the source of enriched mid-ocean ridge basalt (E-MORB). This infers that the primary magmas were derived via partial melting of an enriched lithospheric mantle that carried a fossil subduction signature from earlier Cryogenian cycles. Conversely, the younger OG volcanic and plutonic rocks evince a considerable crustal contamination. This shift toward higher Th/Yb ratios reflects an input of continental crust or the widespread tapping of a SCLM domain deeply metasomatized by subduction-related sediments (Fig. 11c). Moreover, for SG rocks, their lower Th/Nb ratios suggest a more primitive mantle-dominated source modified by an ancient subduction-preconditioned lithospheric root rather than an active deep-mantle plume head, as they cluster within the vertical Subduction Zone-Modified Lithospheric Mantle (SZLM) array, near the LCC (Lower Continental Crust) (Fig. 11d).

In addition, the OG rocks plot within the upper limits of the SZLM array, clustering inside the IAB and CAB fields. This geochemical footprint might signifies slab break-off where the crustal recycling or the melting of the thickened lithospheric root was driven directly by the severe thermal anomaly of the upwelling asthenospheric mantle (Fig. 11d).

Ultimately, a coherent geodynamic transition emerges between both Saghro and Ouarzazate groups. On Figure. 11e, the SG mafic rocks cluster within the Continental Tholeiites (CT) field, adjacent to the Back-Arc Basin (BAB) domain. This position, combined with their calc-alkaline signature (Fig. 6e), and a within-plate character (Fig. 11a) confirms that these rocks were formed in an extensional continental setting. The proximity to the BAB field suggests that while the crust was thinning, the magmatism still retained a slight transitional character, typical of a maturing continental rift or a back-arc basin environment, with a distinct geochemical overprint from a pre-modified lithospheric root. Finally, the OG felsic and plutonic samples plot decisively within the A2-type granite field, supporting their post-collisional nature (Fig. 11f). Eby (1992) suggests that A2-type granites originate from the partial melting of continental or underplated mafic crust, typically within extensional environments. In this context, crustal recycling was driven by the mechanical and thermal effects of lithospheric delamination and potential slab failure (Blein et al., 2023; Ougadire et al., 2023). This triggered the rapid basin development and the accumulation of the thick volcano-sedimentary sequences characteristic the OG across the already rigid and fractured metacratonic margin of the WAC, providing preferential pathways for the rapid upward migration of deep-sourced magmas (Walsh et al., 2012, and references therein; Ennih and Liégeois, 2001, 2008; Gasquet et al., 2008).

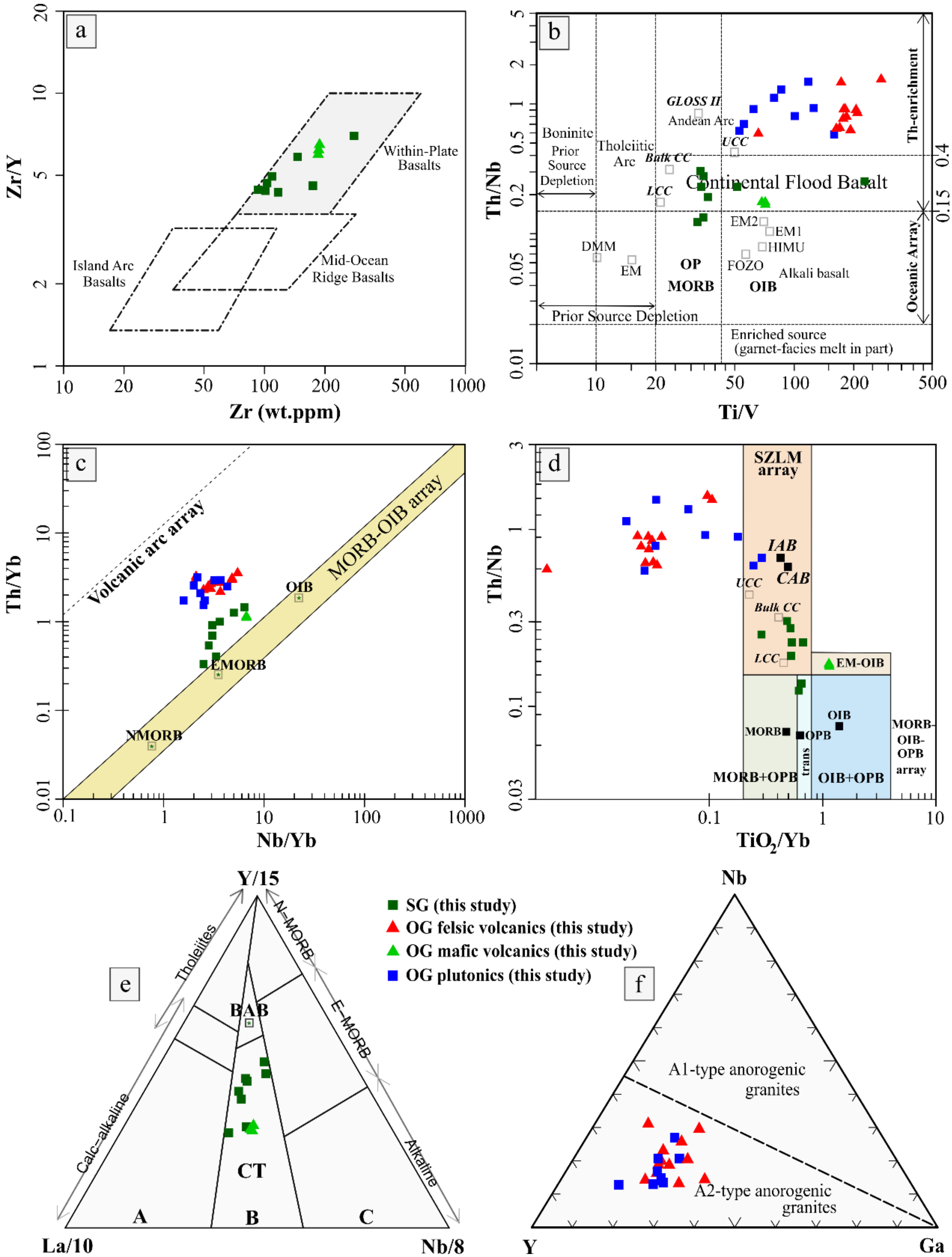

Figure 11. (a) Zr/Y vs Zr (ppm) plot for SG rocks and OG mafic volcanics (Pearce and Norry, 1979); (b) Th/Nb versus Ti/V diagram of Shervais (2022); (c) Th/Yb versus Nb/Yb diagram of Pearce (2008); (d) Th/Nb versus TiO_2/Yb plot of Pearce et al. (2021); (e)

La/10 – Y/15 – Nb/8 ternary diagram for the tectonic discrimination of basaltic rocks (Cabanis and Lecolle, 1989); (f) Nb – Y – Ga ternary diagram for the classification of A1 and A2-type anorogenic granites (Eby, 1992). Abbreviations: Bulk CC: Bulk Continental Crust; GLOSS: Global Subducting Sediment; LCC: Lower Continental Crust; UCC: Upper Continental Crust; EM1 / EM2: Enriched Mantle (Type 1 & 2); DMM: Depleted MORB Mantle; HIMU: High μ (high $^{238}U/^{204}Pb$ ratio) mantle reservoir; OIB: Ocean Island Basalt; SZLM: Subduction Zone-Modified Lithospheric Mantle; CAB: Calc-Alkaline Basalt; IAB: Island Arc Basalt; OPB: Oceanic Plateau Basalt; MORB: Mid-Ocean Ridge Basalt; N-MORB: Normal Mid-Ocean Ridge Basalt; E-MORB: Enriched Mid-Ocean Ridge Basalt; EM: Enriched Mantle; OP MORB: BAB: Back-Arc Basin; CFB: Continental Flood Basalt; CT: Continental Tholeiites; A: Orogenic (compressive) domains (island arc, active margins); B: Late to post-orogenic (compressive to distensive) intra-continent domains; C: Anorogenic (distensive) domains.

5.4 Significance of LA-ICP-MS U-Pb data

5.4.1 The SG detrital age

The existence of a Paleoproterozoic basement in the Sirwa massif and the northern margin of the WAC is debated (Ennih and Liégeois, 2008). While traditionally thought to be confined to the Western Anti-Atlas (Choubert, 1963), recent studies suggest Paleoproterozoic rocks may also be present in the Central and Eastern Anti-Atlas and the Western Meseta (Liégeois et al., 2013; Abati et al., 2010; Gasquet et al., 2008; Pereira et al., 2015, and references therein; Blein et al., 2014). Historically, the WAC's northern boundary was defined by the deformed Tazagzaout migmatites and gneisses in the Bou-Azzer inlier (Leblanc and Lancelot, 1980). However, new U-Pb dating of the Tazagzaout gneisses (752 ± 2 Ma; D'Lemos et al., (2006) and the Oumlil granite (741 ± 9 Ma; El Hadi et al., (2010)) coupled with juvenile Nd signatures (D'Lemos et al., 2006), indicates a juvenile depleted mantle source, not akin to the 2 Ga Eburnean WAC basement.

According to Thomas et al. (2002), the Imghi Formation represents the lower thick beds of greywacke/turbiditic section of SG, and seems to represent a typical flysch succession, which is interpreted as the primary sedimentary fill of a back-arc basin associated with the Khzama ophiolite Complex. For the Zg-132, the alternating patterns (Fig. 3e) suggest fluctuating depositional conditions, specifically changes in hydrodynamic energy and the amount of clay input, consistent with a low-energy, suspension-dominated sedimentation typical of distal turbidites or quiet shallow-marine environment. The calculated MDA at 2025 Ma (n= 3; MSWD = 1.4; Fig. 5A-1) is similar to the ages of syn-to-post-tectonic Eburnean granites in the Central and Western Anti-Atlas (Gasquet et al., 2008, 2005; Aït Malek et al., 1998). Moreover, the detrital zircon age distribution is characterized by a prominent population peaking at ca. 2100 Ma (Fig. 5A-2), reflecting a dominant provenance from the Eburnean-aged basement of the WAC (O'Connor et al., 2010; Gasquet et al., 2008, 2005; Thomas et al., 2002). This primary pulse, coupled with a single Paleo-Archean grain at 3700 Ma, indicates the recycling of ancient cratonic material (Fig. 5A-2). Interestingly, no ages younger than 1600 Ma were found in our sample. In particular 883–640 Ma Pan-African zircons, which are common in outcrops of the Sirwa inlier and have been consistently reported in SG sediments (Letsch et al., 2018; Abati et al., 2010), are absent. Such a narrow gap between the 2100 Ma peak and the 2025 MDA suggests that sedimentation occurred in a basin directly overlaid or adjacent to an uplifted, pristine block of Paleoproterozoic Eburnean basement that acted as the exclusive sediment source without interaction with Ediacaran sediments. Indeed, the returned age may reflect insufficient sampling of detrital zircons. However, the number of analyzed zircons (up to 138; see supplementary table 2) is considered adequate to address paleogeographic questions and sediment source areas (Vermeesch, 2004). Based on these findings, the

WAC crust likely extends beneath the Sirwa massif and continues northward far beyond the Anti-Atlas belt. Notably, Paleoproterozoic rhyolites have been reported in the Meseta Block, north of the Anti-Atlas, with a magmatic age of 2050.6 ± 3 Ma (Pereira et al., 2015). These findings do support the presence of the WAC Paleoproterozoic crust northward beyond the AAMF.

5.4.2 Magmatic record on the OG

New U-Pb zircon dating on two magmatic samples (rhyolite Zg-106, and granite Zg-119; Fig. 4), representing the OG from the Sirwa massif, returned ages of 575 ± 3 Ma and 564 ± 2 Ma, respectively. These ages are consistent with a lower OG affinity, and represent an expression of the Ediacaran magmatism previously described in numerous inliers of the Anti-Atlas belt (Yajioui et al., 2020; Walsh et al., 2012; Gasquet et al., 2005; Thomas et al., 2002).

Indeed, in the ZGMR, similar volcanic activity of this type can be bracketed between 620 Ma to 550 Ma (Pelleter et al., 2016; Thomas et al., 2002; this study). Pelleter et al. (2016) reported mean age of 578 ± 4 Ma from the Zgounder Mine for the rhyolitic dikes and plugs using the ^{207}Pb/^{206}Pb ages. Moreover, in the Sirwa massif, similar U–Pb ages of 579 ± 7 Ma, 571 ± 8 Ma, 577 ± 6 Ma, 579 ± 7, and 575 ± 8 Ma were obtained for the Tourcht diorite, the Tikhfist rhyolite (Tiouin Subgroup, Fig. 1C), the Aguins member (Tafrant Subgroup), the Tilsakht granite, and the Askaoun granodiorite, respectively (Thomas et al., 2002). Given that the 575 ± 3 Ma age of our rhyolite is identical within error to the ages of these rocks, a rapid sequence of intrusive events had to occur within a few million years.

For the granite sample (Zg-119); the obtained age of 564 ± 2 Ma is also identical within error to the ages of the neighbouring Imourkhssen granite dated respectively at 561 ± 3 Ma, 562 ± 5 Ma, and 558 ± 1 Ma by Toummite et al. (2013), Thomas et al. (2002), and Ferraq et al. (2024) (Fig. 1C). The Imourkhssen granite intrudes the lower and older part of the OG in the Sirwa massif (Thomas et al., 2002). Additionally, in the Sirwa massif, numerous syn- to late-OG granites provided ages of c. 560 Ma, making them the Ouarzazate Group's youngest components (Thomas et al., 2002). According to Thomas et al. (2002), these granites belong to the Achkoukchi Complex (Fig. 1C), and are grouped into the Amassine Suite (e.g., Bou-Tazart, Aït Nabdas, and Tikitar granites, and the Tazoult Quartz-porphyry at 559 ± 6 Ma). The inherited age of 2156 ± 54 Ma in sample Zg-119 indicates a Paleoproterozoic crustal component, confirming the reworking of ancient Eburnean basement during the genesis of the OG. This result aligns with significant inherited Paleoproterozoic zircon population reported for the OG rocks across the Anti-Atlas. For instance, Baidada et al. (2019) reported Paleoproterozoic signature for the Saghro massif granitoids, while Blein et al. (2014b) and Thomas et al. (2002) documented similar inheritance in OG ignimbrites from the Agadir Melloul area and syn-extensional granites in the Sirwa massif, respectively.

5.5 Further discussions

At a regional scale, basaltic flows have been described as interbedded within the sediments of the SG in the Saghro massif (Errami et al., 2009; Fekkak et al., 2003, 2001). They exhibit diverse geochemical signatures. For a start, the basalts in Sidi Flah (SF) are of Initial Rift Tholeiites (IRT) and Ocean Island Basalts (OIB) character (Fekkak et al., 2001). In contrast, the

Anou N'Izem basalts in the Boumalne (BO) inlier possess typical Mid-Ocean Ridge Basalt (MORB) signatures (Errami et al., 2009). U-Pb dating of detrital zircons from the SG in various inliers suggests that this unit was deposited between 640–600 Ma across the entire Central-Eastern Anti-Atlas region (Errami et al., 2021a; Abati et al., 2010).

In liaison, this geochemical variation within the SG likely reflects a single, continuous geodynamic event. Specifically, during the evolution of a back-arc basin, the earliest magmas often exhibit magmatic arc characteristics due to the proximity of the back-arc to the arc itself. As the back-arc matures and the magma source becomes further removed from the metasomatized mantle, the magmas transition toward within-plate (OIB) and MORB-like signatures (Vasey et al., 2021; Saunders and Tarney, 1984). This interpretation is further supported by sediment geochemistry which points toward a back-arc basin depositional environment (Ouguir et al., 1996). In the Anti-Atlas, this footprint is widely ascribed to the activation of a sub continental lithospheric mantle source previously metasomatized during earlier Cryogenian Pan-African subduction events, operating in tandem with distal stress fields from the emerging Cadomian orogenic system (Hefferan et al., 2014). As the basin matured and lithospheric extension advanced, the magma source increasingly tapped deeper, uncontaminated asthenospheric reservoirs, driving a compositional transition toward within-plate (OIB) and MORB-like signatures higher up the stratigraphy. Basaltic magmatism in the SG fits this evolutionary framework: the calc-alkaline basalts from the Sirwa inlier (Thomas et al., 2002; this study) represent the initial stages of back-arc formation, and record the activation of this strongly metasomatized mantle source. Whereas the IRT, OIB, and MORB-type basalts found higher in the stratigraphy indicate a more mature, extensional stage tapping deeper, uncontaminated asthenospheric reservoirs.

The thick volcano-sedimentary successions of the OG are dominated by silicic and intermediate high-K calc-alkaline to shoshonitic volcanism (Blein et al., 2014b; Toummite et al., 2013; Walsh et al., 2012; Gasquet et al., 2008, 2005; Benziane, 2007; Thomas et al., 2004; El Baghdadi et al., 2003). Based on the findings of this study, and regional correlations with similar magmatism (see Table 1 in Hefferan et al. (2014) for reported precise ages from selected inliers of the Anti-Atlas Mountains), we attribute the OG rocks to a widespread post-collisional event exemplified across numerous inliers of the Anti-Atlas (Yajioui et al., 2020; Karaoui et al., 2015; Linnemann et al., 2014; Toummite et al., 2013; Walsh et al., 2012; Gasquet et al., 2005, 2004; Thomas et al., 2002). For the studied OG rocks, high Th/Nb ratios suggest that slab break-off induced a thermal pulse supplying heat to melt the Lower Continental Crust (LCC), with variable input from the metasomatized mantle wedge previously primed during proceeding subduction phase. Moreover, the clustering near and above the Upper Continental Crust (UCC) indicates that lithospheric delamination provided the necessary thermal energy to trigger widespread crustal melting, leading to high-K and shoshonitic signatures of the OG rocks (Bonin, 2004). This period of magmatism was coeval with a Silicic Large Igneous Province (SLIP) recognized all over the Anti-Atlas (Ousbih et al., 2024, and references therein; Schulte et al., 2022).

6 Conclusions

In the light of the above, the following conclusions can be drawn:

i. LA-ICP-MS U-Pb zircon ages of 575 ± 3 Ma and 564 ± 2 Ma of the OG evidence an expression of a post-collisional syn-orogenic magmatism in the ZGMR. They define a highly rapid sequence of felsic intrusive and extrusive events spanning roughly 11 million years. Detrital zircons from the SG reveal a single-population at ca. 2100 Ma and a MDA of 2025 Ma. This total absence of younger Neoproterozoic/Pan-African zircons demonstrates exclusive sediment derivation from an adjacent, uplifted pristine block of Eburnean basement, confirming the northern extension of the WAC further north of the AAMF.

ii. Based on geochemical proxies (major and trace elements). The SG magmatic rocks were emplaced at early stages of back-arc basin opening, testified by their calc-alkaline affinity, geochemical characteristics and regional correlations. Further, their εNd_{620} = +3.2 and +4.6, and TDM ages of 1.02 and 0.91 Ga reflects a mixed origin, combining mostly mantle-derived magma with limited contribution from older crustal material. Thus admitting the existence of an old, Paleoproterozoic to Mesoproterozoic, crust beneath.

iii. For the OG magmatic rocks, the evolution in chemical compositions for the suite of high-K calc-alkaline to shoshonitic rocks was controlled in the most part by fractional crystallization and crustal contamination. They were deposited in a post-collisional setting, and their parental magma was sourced from an enriched continental lithospheric mantle, previously underwent metasomatism by fluids from former Neoproterozoic subduction. Further, their εNd_{570} = -0.8 to +1.1, and TDM ages of 1.30 to 1.15 Ga imply significant reworking of older, evolved Paleoproterozoic continental crustal material during Ediacaran times.

iv. Investigation of the OG magmatic rocks within the ZGMR provides insights into how lithospheric delamination and potential slab break-off drove the petrogenesis of post-collisional magmatism, related to the formation of the late Neoproterozoic SLIP along the northwestern edge of the WAC.

Code, data, or code and data availability

Data used in this paper is given in electronic supplements.

Supplement link

Author contributions

Abdelhay Ben-Tami: Field work, Sampling and preparation, Thin-sections preparation, Investigation, Data visualization, Data curation, Formal analysis, Writing of original draft, Finalization. **Said Belkacim:** Supervision, Resources, Writing - review and editing. **Jamal El Kabouri:** Data visualization, Writing of original draft. Review and editing. **Joshua H.F.L. Davies and Morgann G. Perrot:** LA-ICP-MS U-Pb data and methodology, writing of original draft, review and editing.

Mariam Ferraq: Data curation and visualization. **Mohamed Bouabdellah:** review and editing. **Bouchra Baidada, Mohamed Bhilisse** and **Mohamed Assalmi:** Resources, accommodation, field trips, hosting.

Competing interests

The authors declare that they have no conflict of interest. Corresponding author (Abdelhay Ben-Tami), discloses an employment relationship with the Zgounder Millenium Silver Mining Company (ZMSM).

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Review statement

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