Dear Editor,

Manuscript "Petrogenesis and geodynamic implications of Ediacaran rocks from the Sirwa massif (Central Anti-Atlas); insights from U-Pb geochronology, whole-rock geochemistry, and Sm-Nd isotopes" by Abdelhay Ben-Tami and co-workers represents a potentially interesting contribution to the ongoing discussion concerned with the nature and petrogenesis of Neoproterozoic (Pan-African) magmatic and sedimentary rocks in the Anti-Atlas Belt (Morocco), and their geodynamic significance. The text brings new, precise whole-rock geochemical dataset, including some Nd isotopic compositions, in situ LA ICP MS U–Pb ages of zircon. However, the presentation, interpretation and discussion of these data could be improved significantly.

The text is in places confusing, wordy, and/or difficult to follow. Also, the petrogenetic models should be better introduced and justified. The same is valid also for the geodynamic setting. In fact, after reading the manuscript carefully, I am still not sure what the preferred scenario is.

Hereafter I give some, usually more general comments; for the more concrete remarks/edits, please refer to the attached annotated PDF document.

To sum up, I cannot recommend the publication of the reviewed manuscript in the present form, nad requires revision. I trust that the authors will be able to revise the manuscript fundamentally, incorporating most of the changes and addressing my criticism, so that it could be published and find its interested readers.

Prof. Vojtěch Janoušek
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General comments to the style, language and grammar of the manuscript

- The Results and Discussion parts should be strictly separated.
- The manuscript is written in English with numerous mistakes. The language requires revision by native speaker. The text tends to wordy and repetitive, and in places does not flow linearly. It can be certainly condensed substantially without a loss of its informative value. Currently it is extensively long. I urge the senior co-authors (and native speakers among them) to take care of these issues.
- Reduce, if possible, the plethora of local names. All of these remaining need to be shown on some map.
- Consider capitalization of the whole formal names, including words such as Orogeny, Group, Pluton or Complex.
- All abbreviations are to be explained just once, at the first occurrence. Except in figure captions, where I would always explain all of those present.
- Past tense should be used always when referring to events in geological past or previous publications.
- Hypotheses should be expressed by some element of uncertainty, e.g. by conditionals.
- In English text (e.g., Table 2), one should use exclusively decimal points, and not commas.
- All the measured/calculated values should be rounded up to their precision.
- All Figures (and their parts), Tables and electronic supplementary materials (ESM) should be quoted in the text, and exactly in the correct sequence.
- Define how you calculate some geochemical parameters. For Eu anomalies, use the standard Eu/Eu* notation. Add all these extra parameters to the data table.

Graphics

- The quality and readability of all graphs should be improved. The isotopic plots are terrible.
- Plotting symbols/colours should be chosen carefully and kept the same for all plots.
- In geochemical plots, label the samples specifically mentioned in the text.
- Add references as appropriate, including those referring to the plotted geochemical reservoirs and trends. Format those on plots according to the Journal in house rules.
- Avoid using underscore, _ as a replacement for space.
- In some figures (most notably Fig. 1), text seems to be interlaced, and is very difficult to read. But maybe it is just some compatibility issue.

Typography

- More attention should be paid to correct, and consistent, typography, placing spaces where necessary, correctly using hyphens and en dashes, etc. For example, the ranges should be indicated by en-dashes, without spaces around. Minus is en-dash, with no space following.
- Special care should be paid to correctly marking super- and subscripts, e.g. in names of major-element oxides.

- There should be always a space between a number and unit, or a percent symbol. There is no space before punctuation marks such as .:;.
- There should be no space between a sign and the number, e.g. +5.5 or –2.7.

References

- The authors should adhere strictly to the journal's style as given in the Instructions to authors.
- What is the logic behind ordering of multiple references in the text? I would say that they are currently completely erratic. Order them consistently; chronologically, or alphabetically, depending on your preference.
- The same applies for Bibliography. See https://www.solid-earth.net/submission.html#references. Check that if there is more than one paper in the same year for a first author (independent of the rest of the team), a letter (a, b, c) is added to the year both in the in-text citation as well as in the reference list.
- The bibliography is rather accurate; there is only a handful of references missing in the list, see the annotated PDF.

Abstract

[23] Instead of sample names, specify the lithologies dated.

[28] Formed from a dominantly juvenile, mantle-derived source – confusing. Do you mean direct contribution of mantle-derived basaltic melts or remelting of metabasic crust?

Introduction

[39–43] Complex sentence, revise.

[47–48] Repetitive. It was said above, combine.

[58] Sirwa or Siroua as on the map?

[60] Mafic and intermediate units? Please be more specific.

Geological setting

[73] Distinguish between orogeny (the orogenic process) and orogen (its product).

[114–148] Are all these details and local names indeed necessary?

[128] Provide errors of age determinations, and dated material/method, whenever possible.

[128] Slightly younger? Probably identical within the error.

[Table 1] Should be moved to electronic supplement. What is the logic behind ordering the individual samples?

U–Pb zircon geochronology – methodology

[154] Show sample Zg-119 on the map.

[159] ± 2 sigma error?

Petrography

[175] I would rather call this texture ophitic(?)

[189] pyroxene? Could you please be more concrete, or at least to write “clinopyroxene”?

[189] List the minerals in the order of decreasing modal abundance.

U–Pb zircon geochronology

[220] Moderate in size? Please be more concrete.
The CL images are too tiny to see any detail.

[235–236] Both? What do you refer to?

[238] Poor style. The age of the sandstone Zg 132 has not been introduced yet.

[243–252] Perhaps it would be interesting to discuss the youngest zircons constraining the maximum age of sedimentation.

Whole-rock geochemistry

[265] But, if I understand it right, a lot of them are altered.

[274] In general, label the samples specifically mentioned in the text on the geochemical plots.

[280 and elsewhere] The Eu anomalies should be expressed in consistent way. δEu, Eu/Eu*)N Eu/Eu* are all used. Eu/Eu* is the standard.

[284] Be specific: what is the “early gabbro sample from Sirwa”?

[296] What is the unit of Na_2O + K_2O? Is their ratio calculated by weight?

[297–298] These rock groups are not distinguished in the plot.

[299] Some nomenclature diagram is to be shown to name the rocks discussed in this text.

[309] This is a hypothesis that should not appear in the Results, but in Discussion. K-feldspar fractionation would have the same effect.

[316–320] Very confusing. First of all, such a discussion is out of scope of the Results section. There is a lot of local information we are not familiar with and these analyses are not plotted here.

ESM 4

- In text and in the relevant ESM table: round off all the data to match the precision of each of the oxides/elements (some are precise to three decimal places, others to none, I suspect). Even add trailing zeroes whenever needed to indicate the real precision.
- Mg numbers are calculated wrongly! The calculation should be based on molar and not weight percentages.

Sm–Nd isotopes

- The Analytical techniques (ESM 2) lack the necessary details of Nd isotopic data recalculation, including the relevant references for decay constant, CHUR composition and model ages computations.

Table 2

- Sample names should come into the first column.
- Add a column with age (Ma) used for correction each of the analyses.
- Format all super- and subscripts as appropriate.
- Show initial Nd ratios, but not the present-day epsilon values.

- The column with initial ratios should be labelled ε_i^{Nd} or similar. Some analyses were not recalculated to 570 Ma.
- Model ages should be given in Ga and rounded to two decimal places.
- What is the difference between *TDM (Goldstein) Ma* and *TDM Ga*? Are these single- or two-stage models?
  Give all these details of model age calculations in the Analytical techniques. As you know, single-stage ones are more appropriate for mantle-derived, mafic rocks, two-stage model ages (Liew and Hofmann 1988) for crustally-derived, felsic rocks.
- The initial ratios of Nd isotopes and epsilon values should have a consistent – and simple – symbology. Ideally, they should be labelled by subscripts '570' or '620', directly indicating the age used for their correction. E.g. ε_{570}^{Nd}.

[338] There are just two values for Saghro rocks, it is thus misleading to describe them as an interval.

[341–343] This is misconception! Intermediate positive epsilon values *per se* may be equally well explained by derivation from less depleted mantle domains, or remelting of fairly juvenile metabasic crust. Additional evidence is needed.

[345–346] This, and some other parts of this section, should move to Discussion.

[351–352] This again should be moved to the Discussion, and additional petrological and geochemical evidence should be considered, also from literature.
What do you mean, a mantle source contaminated by older crustal component? On which evidence? Why not, for instance, AFC or assimilation of crustal material during ascent of doleritic magmas? What compositions of mantle and crust do you envisage? Was the mantle close to canonical depleted mantle, or CHUR-like? Do you really assume that the felsic magmas were generated from mantle-sourced magmas? Or did they come from remelting of a pre-existing crust?

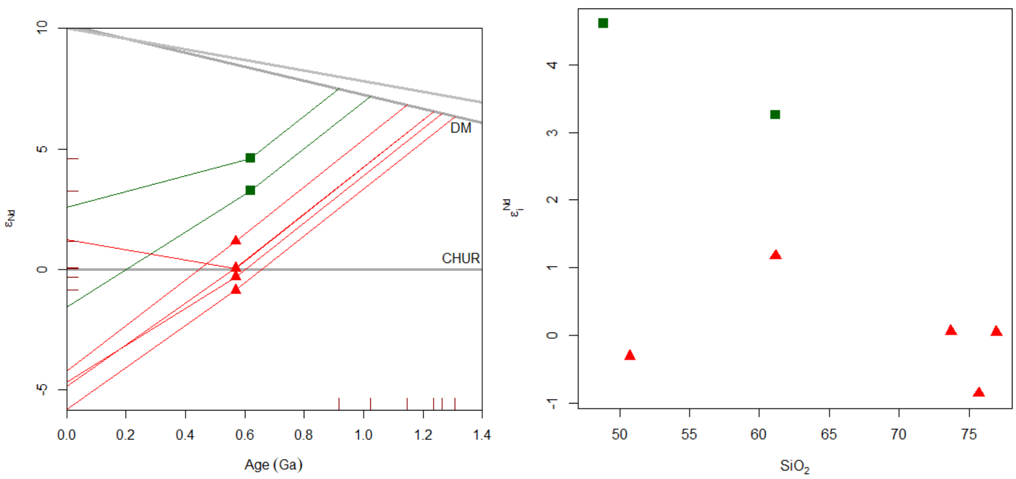
[352–353] If the dolerite came from CHUR-like mantle, the DM model age is just meaningless.

[352–359] Again, this belongs to Discussion.

[358–359] Last sentence seems an overinterpretation of your data.

Figure 8:

- Plotting symbols/colours should be the same like in other plots. Here are even used the same symbols in panels a–b vs. c–d for different things!
- It is graphically very poor, having been apparently exported directly from Excel. It lacks any formatting – superscripts, epsilon letters etc. Needs to be redrawn.
- I suggest a better representation – in the form of two plots: (1) a Nd growth diagram (age vs. epsilon Nd, it can also incorporate the model ages and (2) some independent geochemical parameter (e.g., SiO_2), vs. initial epsilon Nd values. See below, BTW graphs were generated by our software GCDkit (Janoušek et al. 2006) and obviously would need to be supplemented by literature data.



Discussion – Petrogenesis

This chapter is very confusing and scientific argumentation is not sufficient or misleading. It needs to be rewritten completely.

[374–380] There are no such plots shown, neither in the text, nor in the ESM 4. So, the hypothesis cannot be tested. Add these plots, justify your model and do not forget to consider alternatives, such as partial melting. Perhaps better would be diagrams against Mg#, rather than Zr.

[380–385] Mg# are calculated wrongly, so this paragraph needs to be rewritten. What is the evidence for this mixing?

[386] I do not know this "contamination-sensitive" diagram. Contamination by what material? How is it supposed to work? Give a reference. Note that in most magmatic rocks, La and Ce will be strongly corelated and behaving very similarly during fractional crystallization or partial melting. I guess this projection is of very little value in distinguishing closed-system differentiation from continental crustal contamination and I would drop it.

Using Nd isotopes for this purpose is definitely a much more powerful approach.

[389–392] But not like this! The "mixing model" in ESM 4 is calculated without taking the contrasting Nd concentrations (ppm) in the both end-members. The correct approach is (Janoušek et al. 2016):

The mixing equation for two end-members, *1* and *2*, can be seen as a mean of isotopic ratios (I_1 and I_2), weighted by their respective mass-fractions in the mixture. Marking the mass fraction of the end-member *1* as f_1, (with $f_1 + f_2 = 1$) and respective concentrations C_1, C_2 and C_M (Faure 1986):

$$I_M = I_1\left(\frac{C_1}{C_M}\right)f_1 + I_2\left(\frac{C_2}{C_M}\right)(1-f_1) \qquad (0.1)$$

Where:

$$C_M = f_1 C_1 + (1-f_1)C_2 \qquad (0.2)$$

[398–340] I cannot see this, rephrase. Perhaps this is not the best projection, either.

[402–403] This diagram is designed solely to judge the nature of crustal protoliths melted. It does not make sense for mantle-derived rocks and also does not show any effects of fractional crystallization and contamination of primary magmas. Revise.

[404] Enriched in what sense? Enriched mantle? The whole sentence is a bit daring and premature. Neodymium isotopes need to be assessed first.

Fig. 9

- I would omit literature data, as only several points are plotted on a single panel.
- Instead of panels a, b I would rather plot Nb/Yb vs. Th/Yb and Nb/Yb vs. TiO_2/Yb (Pearce 2008) – the first you have as a current Fig. 12b.
- Panel b: normalized by what (reference).
- Panel c: IAT is not shown.
- All abbreviations need to be explained. Give references for compositions of each of the reservoirs plotted.

[411] Why there are not discussed effects of alteration like in the case of SG above?

[414] Again, these diagrams are not plotted.

[421] Calcic phase? Feldspars.

[423–425] High LREE contents can be also due to direct derivation from crustal sources and would be further modified by fractional crystallization.

[424–425] Speculations.

[427] The “trend” is too scattered to reveal anything. The plutonic rocks are not distinguished on the plot.

[431–432] Hydrous metasomatism? What do you mean? Why should be P anomalies linked to Nb and Ti depletions?

[442] Or Nb and Ti anomalies can reflect subduction setting.

[443–444] I cannot understand the bit starting from “as supported by epsilon Nd values…”

Fig. 10

- Not only OG, but also SG rocks. Add legend.
- Technically speaking, Harker plots are binary diagrams of SiO_2 vs. major elements, not traces.
- Nickel will not show anything else than Cr, and determinations of the former are rounded to tens ppm, so rather imprecise. Omit. Are the rocks fresh enough so that Rb and Ba can be used?
- How were the BA, AFC and FC trends obtained? Reference? Assimilation of what? How much? Fractional crystallization of what minerals and in which proportions? What was the degree of crystallization? What Kd values were used (references)?
- Panel b – for intermediate and felsic rocks, the La concentration will be controlled, to a large extent, by accessories, such as allanite or monazite.
- Panel c – why Y/Nb of 1.2? Would not be Nd isotopes much better for this purpose?

[445] What is “enriched continental crust”?

[448] Moderate epsilon Nd values? Not clear, be more specific. Everything depends on local mantle composition, it could have been CHUR-like easily.

[450] What is "sediment zone enrichment"?

[448–452] I am completely lost. What is your preferred scenario? Genesis from earlier (oceanic) subduction-modified mantle or contamination (AFC) of E-MORB-like melts by continental crust?

Fig. 11

- Explain all abbreviations and give the references for compositions of various average mantle and crustal reservoirs.
- Panel c: missing is explanation of the trends for various processes. How were they constructed (see also my previous comment)? BABB symbols look just terrible.

Fig. 12

- Explain all abbreviations and give the references for compositions of various average mantle and crustal reservoirs.
- What is the difference between the Ta/Yb vs. Th/Yb and Nb/Yb vs. Th/Yb projections? Should be giving moreless the same information….
- Panel a: missing is reference, explanation of the trends. How were they constructed?

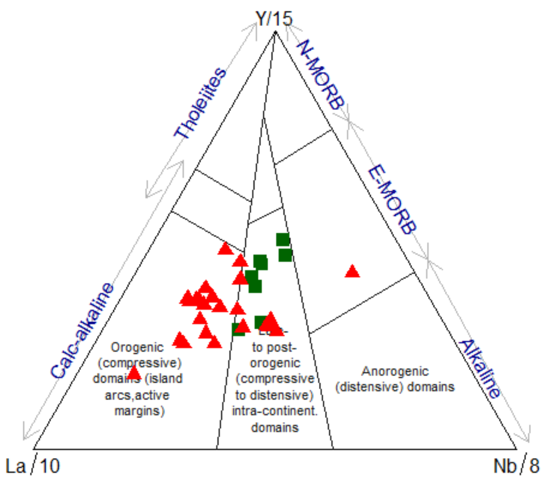
Discussion – Geodynamic implications

Again, this section requires a thorough revision.

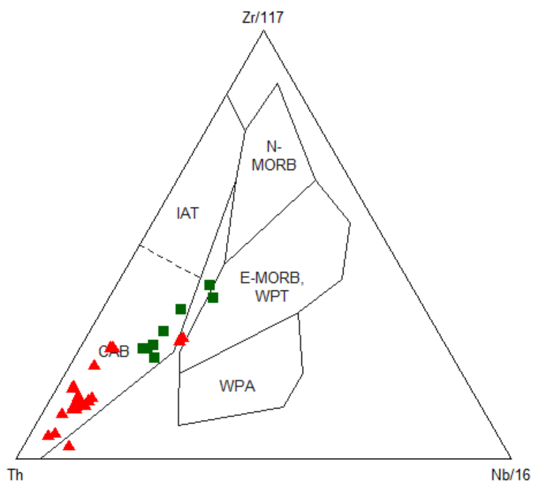
[466] Show it! This is not acceptable.

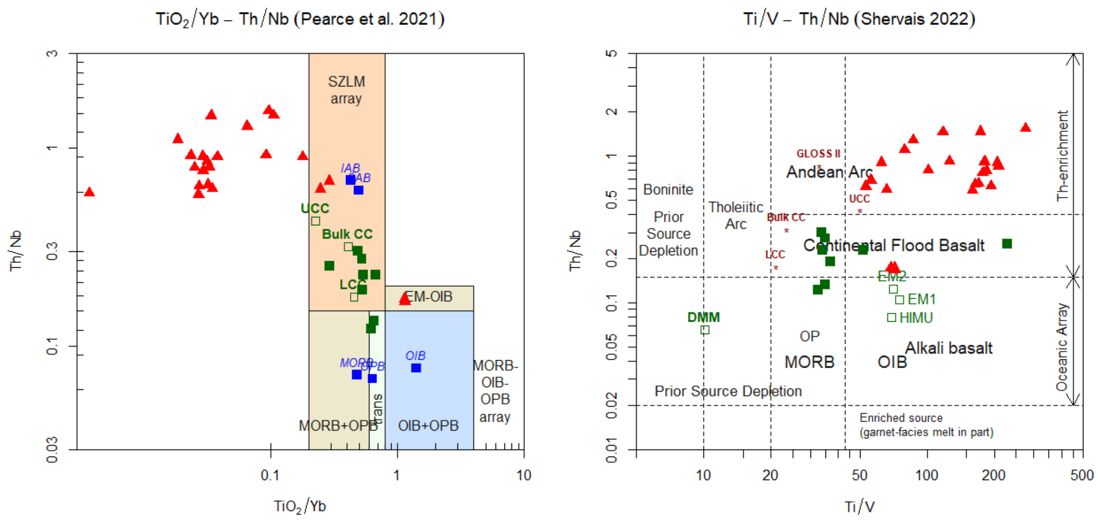
[469] Or simply rifting. I would suggest some other diagrams that could help you resolving the geodynamic setting, namely those of Wood (1980), Cabanis and Lecolle (1989), Pearce et al. (2021) or Shervais (2022). Surprisingly, the basic rocks of the SG and OG look like continental flood basalts in the Ti/V vs. Th/Nb plot of Shervais (2022). I do not know much about local geology, but is any role of plume ruled out?

La/10 – Y/15 – Nb/8 (Cabanis + Lecolle 1989)



Triangular diagrams of the Th-Hf-Ta-Zr-Nb system, Wood 1980





[472] Why is low U/Th ratio indicative of active margin signature?

[473–474] Normalized to what? To my eyes, the SG nicely follow the NMORB–OIB array. CAB should have higher ThN.

[476–479] References missing.

[501] A fragment, a sentence should have a verb. Rephrase. Fig. 11a shows Y vs. Zr, not K, Rb, Ba etc. Plus, these are extremely mobile elements, could not they be compromised by alteration?

[508] Be specific, how?

[510] And what was the cause of such post-collisional event?

[515] evolution?

Discussion – U–Pb ages

[518] Please specify the sample lithologies, this is more important than the sample numbers.

[520] Extension of the magmatism? Rephrase.

[532] How about the dating by Ferraq et al. (2024)?

[535] What is sub-alkaline-calcic?

[538] Did you observe any inheritance?

[549] What is “a prolonged tectono-magmatic event emplaced over multiple pulses over the whole Anti-Atlas belt”?

[551] “SLIP deposited in a strictly continental environment”? I cannot follow this.

[551–556] Tedious and repetitive. Condense.

[558–560] Rephrase and expand the part dealing with regional correlation of the Cadomian arc magmatism and how does it relate to the inferred geodynamic setting of the studied rock units.

[590–593] I cannot follow this argument. Clarify.

[595] “The mono-peak…” does not make any sense to me.

[601] Cryogenian should be older than 635 Ma. These sediments are Ediacaran, or younger.

[610] Reference missing here.

Fig. 12

Explain all the abbreviations.

Conclusions

[627–628] What is the evidence for contamination of the mantle source by continental crust? How does it go with the presumed oceanic subduction context?

[636] How about your sediments?

[637–638] "post-collisional syn-orogenic magmatism (WACadomian arc)"? I am again lost. Regardless, how can you infer this from U–Pb ages only?

References used

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Petrogenesis and geodynamic ~~implications~~ of Ediacaran rocks from the Sirwa massif (Central Anti-Atlas); insights from U-Pb geochronology, whole-rock geochemistry, and Sm-Nd isotopes

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Abstract.

The geodynamic evolution of the Anti-Atlas belt ~~post-Pan-African~~ 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 ~~respectively from samples Zg-106, and Zg-119~~ from the OG. In addition, detrital zircons from SG sediments yield a prominent 2.1 Ga age peak, indicating ~~local~~ recycling of Paleoproterozoic basement ~~material~~. Geochemically, two magmatic series are identified~~-~~: (i) a SG mafic-intermediate calc-alkaline series with Nb-Ta and Ti negative anomalies from early back-arc basin setting; and (ii) a felsic-intermediate high-K calc-alkaline to shoshonitic series of the OG, exhibiting continental magmatic arc signatures. Isotope data (εNd (t): +3.2 to +4.5, TDM = 1431 - 1197 Ma for SG; εNd (t): -0.9 to +1.1, TDM = 1526– 1252 Ma for OG), indicate~~s~~ that the SG formed from a dominantly juvenile, mantle-derived source, with limited crustal contribution; while the slightly younger OG involved significant reworking of older, evolved continental crustal material.

These findings sustain a model where Early Ediacaran SG sediments and associated mafic-intermediate volcanics were formed in a back-arc basin. During this basin development, its shoulders were locally formed by the 2.1 Ga Paleoproterozoic basement, supplying Paleoproterozoic zircons to the Saghro ~~host~~ basin. This~~,~~ further supports the occurrence of the Eburnian basement north of the Anti-Atlas Major Fault (AAMF). Additionally, the younger OG reflects a Late Ediacaran continental crust collapse event involving widespread crustal reworking and the emplacement of a Silicic Large Igneous Province ~~(SLIP)~~.

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Keywords

Saghro Group; Ouarzazate Group; Sirwa massif; LA-ICP-MS U-Pb on zircon; 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 started since the break-up of Rodinia. The Tonian – Cryogenian evolution of this belt record the establishment of a passive margin, and island arc which were accreted to the WAC margin at ca. 650 Ma, with the emplacement of syn-tectonic granitoids (Linnemann et al., 2019, 2014; Pereira et al., 2012a; Abati et al., 2010; Liégeois et al., 2006; Gasquet et al., 2005). 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; the Anti-Atlas belt was close to the Cadomian subduction system. In liaison, this subduction is responsible for the accretion of peri-Gondwana terranes and the final amalgamation of the Gondwana (El Kabouri et al., 2025; Rojo-Pérez et al., 2024; Stern, 2024; Garfunkel, 2015; Hefferan et al., 2014). However, 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 nature of the basement north of the Anti-Atlas Pan-African suture zone, known as the Anti-Atlas Major Fault is also still a matter of debate. However, in the Zgounder Mine Region, 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.

The study area, so-called the "Zgounder Mine Region" in this contribution corresponds to the vicinity of the Zgounder Ag-Hg deposit (Ben-Tami et al., 2024). 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 of the WAC. The Ediacaran period of the Zgounder Mine Region (630-539 Ma), is represented by: (i) the Saghro Group (SG) sedimentary successions and coeval mafic to intermediate units deposited at around 630 to 600 Ma (Abati et al., 2010); (ii) large felsic plutons, subvolcanic formations, along with coeval pyroclastic rocks referred to as the Ouarzazate Group (600 Ma - 539 Ma (Thomas et al., 2002).

We present new whole-rock geochemistry, and Sm-Nd isotopes for the Ediacaran successions of the Zgounder Mine Region. The aims are 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

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the lower Ediacaran magmatism and challenge the source of the Saghro Group's sedimentary units, hence, refining existing geodynamic models.

2 Geological setting

2.1 The Anti-Atlas belt

The Anti-Atlas Mountains, 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 orogenies.

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; Ennih and Liégeois, 2008; Gasquet et al., 2008, 2005; Thomas et al., 2002; Walsh et al., 2002; Aït Malek et al., 1998). Overlying these terranes, is the carbonate and quartzite succession of the Taghdout Group deposited in a passive margin (Errami et al., 2021a; Álvaro et al., 2014; Abati et al., 2010; Thomas et al., 2004). U-Pb ages on a quartzite sample from the Taghdout Group provided ages spanning from 2182 to 1987 Ma (Walsh et al., 2012). Moreover, undeformed Doleritic dikes intrude the Taghdout Group in the Ighrem and Zenaga inliers, and were dated between 1710 and 1630 Ma by Ikenne et al., (2017), and Ait Lahna et al., (2020), respectively. Overall, this implies that the Taghdout Group is in fact of Paleoproterozoic in age (Ikenne et al., 2017; Abati et al., 2010).

The Neoproterozoic episode known as the Pan-African orogeny is well established in the Central and Eastern Anti-Atlas (ca. 760 to 550 Ma) in numerous studies (Bouougri et al., 2020; Soulaimani et al., 2018; Triantafyllou et al., 2016; Karaoui et al., 2015; Blein et al., 2014; Álvaro et al., 2014; Hefferan et al., 2014; Walsh et al., 2012; El Hadi et al., 2010; Errami et al., 2009; Michard et al., 2008; Gasquet et al., 2008, 2005; Ennih and Liégeois 2008, 2001; Thomas et al., 2004, 2002). These Pan-African successions start with an early Tonian–Cryogenian syn-rift units, consisting of carbonates and quartzites known as the Jbel Lkst Group (Kerdous inlier), the Tachdamt Group (Zenaga inlier), and the Bleida quartzites (Bou-Azzer-El Graara inlier) (Álvaro et al., 2014). The rifting process is evidenced by the formation of oceanic basement now preserved as ophiolitic sequences in the Bou-Azzer and Sirwa inliers (Thomas et al., 2002, 2004). Concurrently, a long-lived island arc complex formed north of the WAC (Admou et al., 2012; D'Lemos et al., 2006; Thomas et al., 2002, 2004). This arc is now preserved as the 743 ± 14 Ma Iriri Arc in the Sirwa inlier (Thomas et al., 2002), and its equivalent, the Tazigzaout-Bougmane Complex in the Bou-Azzer inlier, dated at $752 \pm ^{1}_{2}$ Ma (D'Lemos et al., 2006). Following this, and as the north dipping subduction ceased, these latter terranes were subsequently deformed and obducted to the northern margin of the WAC around 650 Ma during the main Pan-African orogeny (Hefferan et al., 2014, and references therein; Thomas et al., 2002). Further, widespread calc-alkaline magmatic intrusions and regional metamorphism affected the Anti-Atlas belt (Hefferan et al., 2014, and references therein), with several syn-orogenic granitoids dated between 680 and 640 Ma (Hefferan et al., 2012; Walsh et al., 2012; El Hadi et al., 2010; Inglis et al., 2005; Thomas et al., 2002).

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In the northeastern domain of the Anti-Atlas, the Ediacaran stratigraphy (630 – 539 Ma) comprises an early Ediacaran basement of Saghro Group, consisting of folded meta-sedimentary units under greenschist facies conditions, and covered by a late-Ediacaran Ouarzazate Group sequence 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). The transition from volcanic dominated successions of the Ouarzazate Group to the establishment of a stable platform series is recorded during the Ediacaran – Cambrian transition, with the deposition of the Taroudante and Tata groups in an anorogenic setting (Álvaro et al., 2014).

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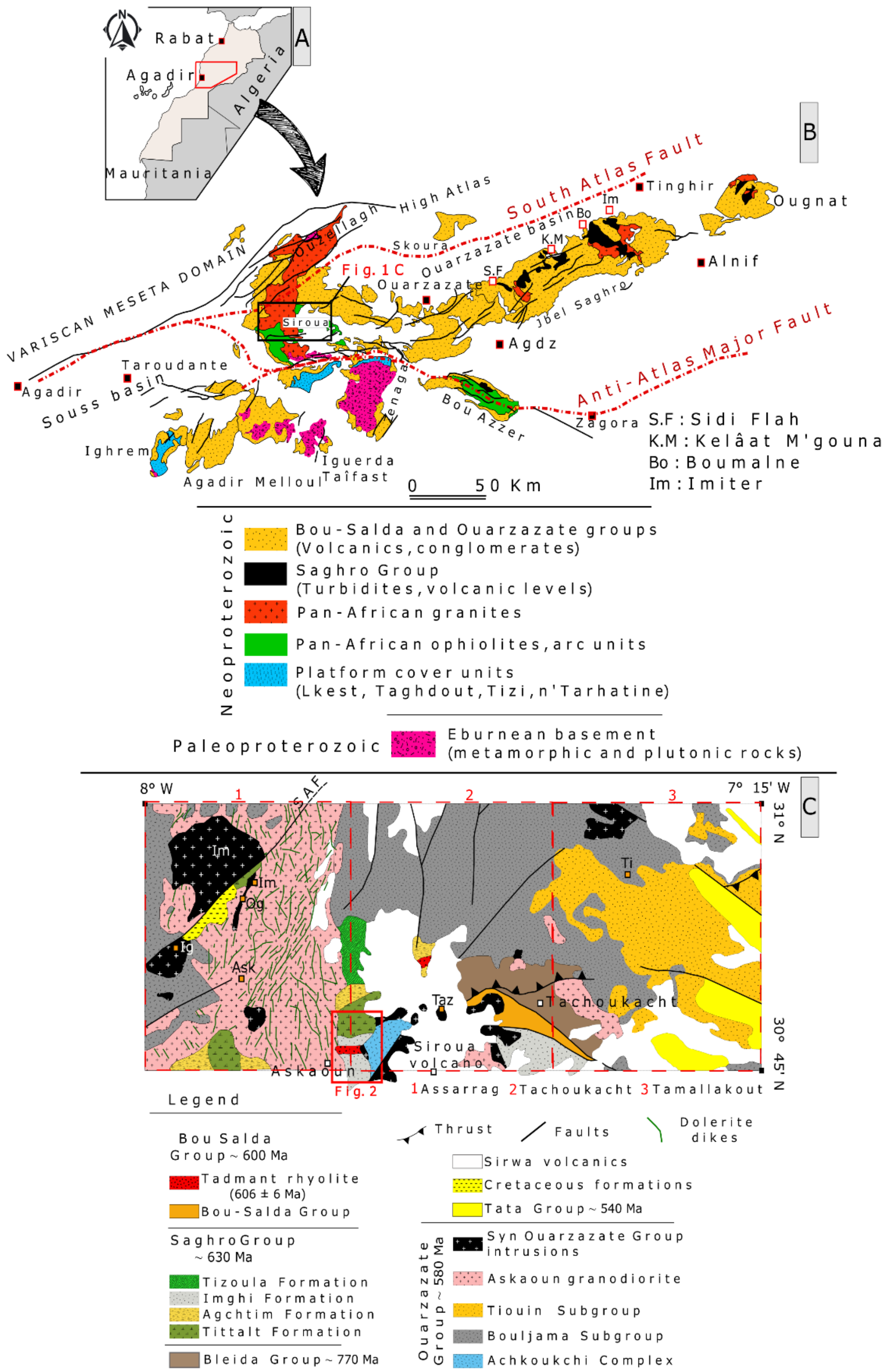

Figure 1: (A) Sketch map locating the Anti-Atlas belt in respect to Morocco (Saadi, 1985). (B): geological map of the Central and Eastern Anti-Atlas Proterozoic inliers (redrawn and modified after Michard et al., (2017)). (C): Schematic representation of the geology of the Sirwa massif (compiled and redrawn after Thomas et al., (2002)); location of the Zgounder Mine Region in red square (see Fig. 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).

2.2 Sirwa inlier

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 inlier into various groups (Thomas et al., 2000a; De Beer et al., 2000; Gresse et al., 2000).

Paleoproterozoic rocks are the oldest in the Sirwa inlier, mainly composed of altered iron-rich gneiss and schist fragments from the Zenaga Complex (Thomas et al., 2002). The Tachdamt Group's sedimentary and volcanic rocks were deposited after Rodinia's breakup (Thomas et al., 2002). Interbedded Tachdamt Group volcaniclastic deposits date to ca. 883 Ma (Bouougri et al., 2020). This Group is overlain by the Khzama Complex, which includes the Tasriwine ophiolite, the Iriri Migmatite, and Tachoukacht schists formed during island arc development and associated back-arc oceanic crust (Thomas et al., 2002).

The Saghro Group, as defined by Thomas et al., (2002), is a thick, ~8000 m pile of deformed sedimentary, volcanoclastic, and volcanic rocks with a calc-alkaline composition and greenschist-facies metamorphism. It includes six lithostratigraphic formations: Tittalt, Agchtim, Tizoula, Imghi, Azarwas, and Tafiat. The lower sequence features greywacke/turbidites with volcanic rocks, while the upper formations consist of coarse-grained clastic rocks (Thomas et al., 2002). The age of the Saghro Group has been constrained by Liégeois et al., (2006) and Abati et al., (2010) using U-Pb dating on detrital zircons from both the Sirwa and Saghro massifs. These studies established a maximum depositional age at approximately 610 Ma. More recent data from the Eastern Saghro massif reported by Errami et al., (2021a), provided slightly younger detrital ages clustering around 607 ± 6 Ma and 604 ± 5 Ma. In addition, the entire Saghro series was intruded by syn-tectonic granitoids dated at 603 ± 6 Ma and 600 ± 3 Ma (Errami et al., 2021a). Crucially, in the Sirwa inlier, the Saghro Group is significantly older as it is intruded by the Mzil granite dated at 614 Ma (Thomas et al., 2002, 2004).

The Bou Salda Group is a thick volcano-sedimentary succession from 610 to 580 Ma (Belkacim et al, 2017; Gasquet et al., 2008), interpreted as basin infills of grabens and pull-apart basins within the AAMF (Errami et al., 2021a; Gasquet et al., 2008; Thomas et al., 2002). In the Sirwa inlier, it mainly comprises the Lmakhzene and Ighil members (Thomas et al., 2002). The Lmakhzene Member features arkosic gritstones, sandstones, and conglomerates, while the volcanic Ighil Member includes basalt, rhyolite, and andesite. Ages for the Bou Salda Group in the Sirwa inlier are 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, 603 ± 13, and 625 ± 12 Ma, suggesting a maximum age for quartzite clasts in a conglomerate and, hence for the Bou Salda Group.

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The Ouarzazate Group sequences (580-539 Ma; Blein et al., 2014b; Toummite et al., 2013; Thomas et al., 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 Ouarzazate Group is subdivided into four subgroups (Fig. 1C for relevant groups) (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 Ouarzazate Group (Thomas et al., 2002) (Fig. 1C).

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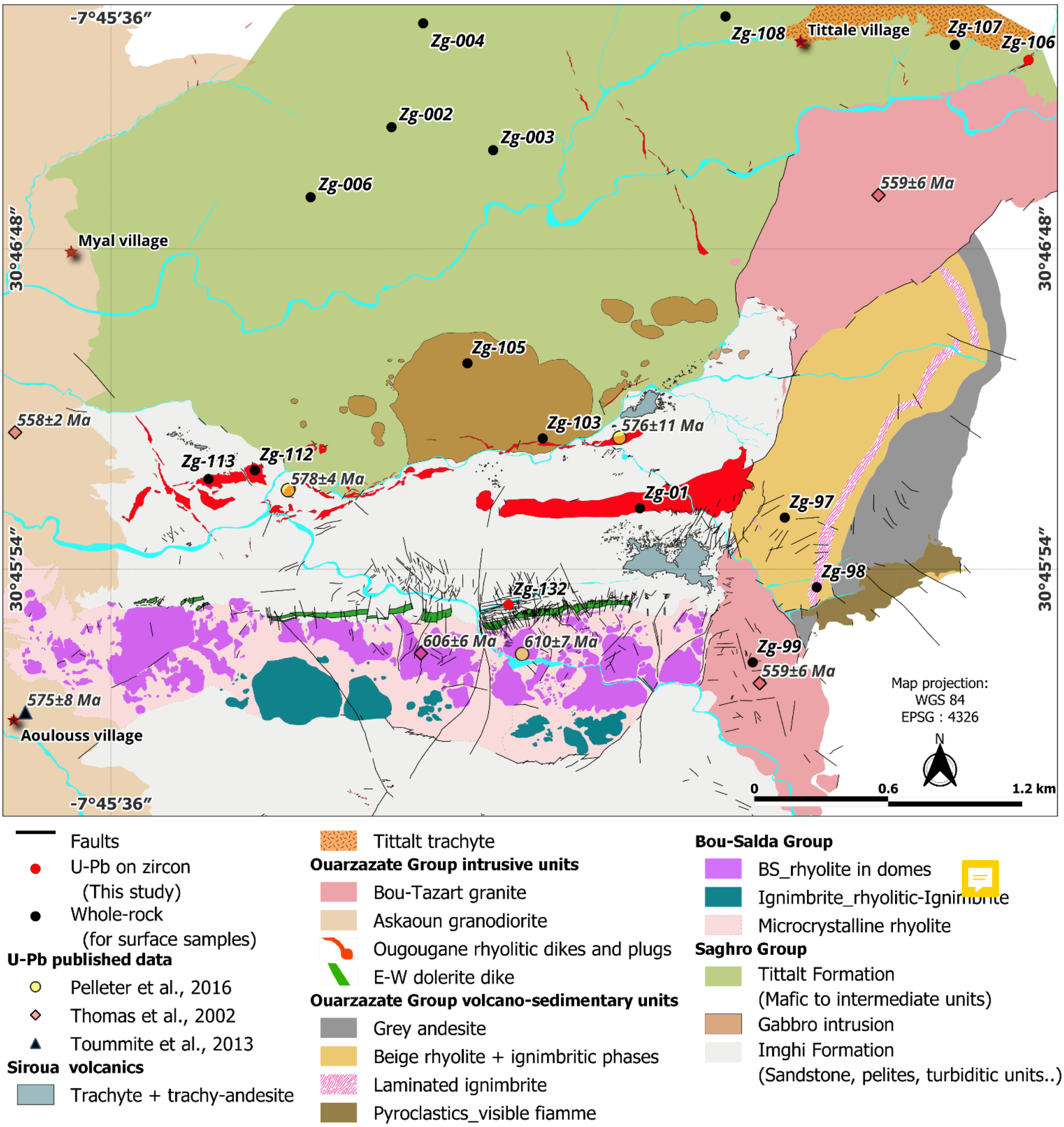

150 **Figure 2: Detailed geological map of the Zgounder Mine Region (this study). Locations of surface samples are indicated on the map. Underground samples (e.g. Mine levels, drill holes) including the dated Zg-119 are not represented on the map.**

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3 Data and methodology

3.1 U-Pb zircon geochronology

Three samples from the Zgounder Mine Region (Zg-106; Zg-119; Zg-132) were selected for U-Pb zircon geochronology (see 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) (refer to table 1 in supplementary data 1). 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 5.

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 Zgounder Mine Region. Crushing and powdering of the rock samples were performed at the facilities of the Zgounder Millennium Silver Mining Company (ZMSM). For each sample, lithostratigraphic position, sample type, drill core name and depth, short description and analytical methods applied are reported in supplementary table 3. Further details on the analytical procedures are given as supplementary data 2.

4 Results

4.1 Petrography

4.1.1 The Saghro Group rocks

- The Saghro Group is mainly represented by fine to medium-grained, and dark to olive green mafic volcanic rocks. They contain fine-grained plagioclase and clinopyroxene phenocrysts dispersed in the groundmass (Fig. 3). A medium- to coarse-grained equigranular and dark green gabbroic facies is also present, and shows heavily altered pyroxenes and amphiboles (Fig. 3a). Dolerite sample (Fig. 3b) have an intergranular texture, with lath shaped plagioclase, primary Fe-Ti oxides, and clinopyroxene aggregates. Sample Zg-108 is andesitic in composition (Fig. 3c), and shows a medium-grained intergranular texture. The texture is microlitic to microlitic-porphyritic for basalt and basaltic-andesite samples (Fig. 3d).
- The dated sandstone sample (Zg-132), displays 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). Such alternating patterns 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.

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4.1.2 The Ouarzazate Group 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. Plagioclase crystals, locally transformed to albite are moderately sericitized and rarely altered to epidote, with equant opaque grains enclosed in the primary minerals (plagioclase, pyroxene). A dolerite sample (Zg-14) collected next to the mineralized zone have an intergranular texture in which laths of black oxidized plagioclase were included in pyroxene crystals (Fig. 3h). The plagioclase crystals are strongly altered and replaced by a mixture of blue chlorite, weak and sparse grains of epidote. Clinopyroxene is mainly replaced by hornblende and actinolite, and partially by pyrite. 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. Sericite and clay minerals replace lath-shaped plagioclase phenocrysts, and are associated with chlorite and iron oxides (Fig. 3g). Chlorite replaces biotite, which locally substitutes hornblende crystals. Opaque minerals are enclosed in hornblende, biotite and plagioclase. Granite is medium- to locally fine-grained; it is distinguished from the granodiorite and quartz-diorite by its white to pink color (Fig. 3k).

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Lithology	Sample code	Texture	Primary minerals and accessory phases (size + %)	Alteration minerals
Saghro Group rocks				
Gabbro	Zg-103 Zg-105	medium to coarse-grained/ locally equigranular	Olivine (<0,1mm; <2%); Pyroxene (up to 0,25mm; less than 5%); hornblende;(5-13%); Ca-rich plagioclase (20-35%); Fe-Ti oxides (up to 9%); accessory sulfides (pyrite); <2%)	Secondary Amphibole; Green Chlorite as patches (10%); Sericite (up to 15%); epidote (2%)
Dolerite	Zg-107	intergranular	Clinopyroxene, up to 0,5mm; up to 15%); Plagioclase (20-35%); primary Fe-Ti oxides (up to 12%).	Chlorite; minor epidote; rare albite; minor sericite (green schist alteration package)/ secondary amphibole,
Andesite	Zg-108	Medium-grained intergranular	Primary Fe-Ti oxides (up to 10%); Pyroxene (up to 0,2mm; less than 5%); Plagioclase (up to 35%)	Minor sericite, oxides.
Basaltic-andesite	Zg-002	Microlitic-porphyritic	Clinopyroxenes as fine aggregates (0,1mm; up to 10%); Automorphic plagioclase as micro and phenocrysts locally zoned (0,4 - up 1,4 mm; up to 40%); Opaque minerals (<5%)	Chlorite (micro-patches); Sericite (13%); Argillic alteration, minor kaolinite in plagioclase, oxides altering plagioclase.
	Zg-003 Zg-004		Micro and local phenocrysts of Pyroxene (0,1 – to up to 1 mm; up to 13%); Plagioclase as micro and phenocrysts locally zoned (0,4 - up to 1,4 mm; 35%); oxides altering plagioclase phenocrysts; rare apatite	Chlorite; dispersed calcite (up to 5%), oxide orioles surrounding pyroxenes; Sericite (14%);
Basalt	Zg-006	Microlitic-porphyritic	Pyroxene (0,1 - 0,8 mm; less than 10%); Micro plagioclase in the mesostasis + phenocrysts (0,2-1,5mm; 30-38%); Fe-Ti oxides.	Abundant calcite, secondary quartz (amygdales); Sericite.
Sandstone	Zg-132	Fine to medium-grained	Compositional variation for darker/lighter laminations: Quartz (0,2-0,4mm; up to 70%); muscovite flakes (10 to 30 %); chlorite (10 to 25 % or more); feldspar (up to 0,3mm); iron oxides (7%).	
Ouarzazate Group rocks				
Rhyolite	Zg-04 Zg-06 Zg-117	Cryptocrystalline, locally glassy with visible fiamme	Quartz (0, 2-0,4mm; up to 30%); Plagioclase (0, 15-0,6mm; 20-30%); K-feldspar (0, 15-0,8mm; up to 55%); Biotite (~0,1mm; less than 4%); Primary opaque minerals; Zircon (<1%) + xenoliths (1-2mm; 6%)	Slight albitization; Chlorite/muscovite (micro-patches); Sericite;
Rhyolitic-ignimbrite	Zg-05 Zg-111	vitroclastic to cryptocrystalline texture, locally fluidal	Quartz (0,1-1,8 mm; up to 30%); Plagioclase (up to 2,2mm); K-feldspar (0,8-1,9mm); Fe-Ti oxides (less than 4%); + xenoliths (meta-sedimentary facies)	Sericite (4-8%)
Porphyritic rhyolite	Zg-110	porphyritic	Quartz in phenocrysts (1-4,5mm; 18-28%); K-feldspar (up to 4,5 mm); Plagioclase (up to 4,3 mm); Opaque minerals (Less than 5%); + visible xenoliths (up to 2,6mm)	Sericite (3-6%); Muscovite (1-2%)
Quartz-diorite	Zg-07	medium to coarse-grained	Amphibole (0, 15-1mm; 2-8%) ; Biotite (0,25-2mm ; 4-9%) ; Plagioclase (1,3 – 3.4 mm; 32-60%); K-feldspar (up to 1,6m ; up to 8%) ;	Chlorite (5-8%); Muscovite (3%); Epidote (<2%)

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			interstitial quartz (0.2 -1.2 mm; up to 25 %); Primary opaque minerals (inclusion in amphibole crystals; <6%); Zircon (<1%)	Sericite (10-15%); Kaolinite and Clay minerals (2%); Oxides (6%);
Granodiorite	Zg-08 Zg-09	medium to coarse-grained, isogranular texture	Hornblende (0,15-1,2mm ; 6-10%) ; minor Biotite (0,25-2mm ; 4-18%) ; Plagioclase phenocrysts (0.25 – 2.6 mm; 45-55%); Orthoclase (1-2,2m ; 20-35%) ; Quartz (0.4 -2.5 mm; 10-30 %); +xenoliths ; Primary + secondary opaque minerals ; Zircon in biotite (<1%)	Chlorite (less than 10%); Sericite (up to 25%); Epidote (2%);; Clay minerals (2%); Kaolinite (<2%); Oxides (4%)
Dolerite	Zg-13 Zg-15	intergranular	Clinopyroxene (augite) (0,1mm; up to 6%); brown hornblende (up to 14%); automorphic plagioclase (0,4 - less than 1,4 mm; up to 43%); Biotite (<4%); secondary Quartz (0,1-0,4mm; <4%); Primary opaque minerals (<5%); accessory sulfides (pyrite); <2%)	Intense Chlorite (patches); Sericite (20%); Muscovite (up to 2%)
Diabase	Zg-14	intergranular	Pyroxene (0,03-0,1mm; less than 10%); Plagioclase (0,25-2,5mm; 35-40%); Fe-Ti oxides (magnetite+ilmenite prisms, <6%)	Patches of blue chlorite (0,25-1,1 mm; up to 38%); sericite (up to 8%); clay minerals (<6%); Secondary amphibole
Ignimbrite	Zg-97 Zg-98	eutaxitic texture with visible fiamme	Quartz (less than 0,7mm; 45-60%); Plagioclase; K-feldspar (sanidine; up to 23%, 0,4mm); Opaque minerals (euhedral to subhedral) (5-10%); + Xenoliths (anhedral); Zircon in inclusion in k-feldspar crystals (<1%)	Sericite (less than 5%); Scarce chlorite (2%); Kaolinite (5%)
Granophyre	Zg-99	coarse grained	Amphibole; sub-automorphic Biotite (0,4-0,9mm) ; Plagioclase (up to 8%; 0,5–1mm) ; K-feldspar (microcline) ; Quartz (rounded and eye-shaped (0,4-3,2mm)); Magnetite + apatite+ Zircon (<2%) (; +xenoliths (mafic)	Chlorite; Sericite ; Muscovite
Rhyolite	Zg-106	Microcrystalline, locally fluidal	Quartz (0,2-0,4mm) ; K-feldspar (up to 0,3mm); Plagioclase (< 0,4mm); + rare xenoliths (mafic to intermediate). Mesostasis forms more than 85% of the rock.	Albite; Chlorite (3-5%); Sericite (up to 25%); Calcite (veinlets) (2%)
Granite	Zg-115 Zg-119	medium to fine-grained, equigranular	Amphibole (rare 2% (<0,2mm); Biotite (up to 2%); Microcline with visible twinning (20-30% (0,5 to 1,2 mm)); Plagioclase (6-10% (=0,7mm)); Quartz (35-45% (0,4 to 1,3 mm)) ; +metasedimentary xenoliths (0,5-1cm; 3%) ; Opaque minerals; Zircon (<2%);	Chlorite (moderate); Actinolite (less amount); Sericite (15%); Muscovite (less than 4%)
Rhyolite	Zg-01 Zg-112 Zg-113	microcrystalline porphyritic texture,	Quartz phenocrysts (0,4-0,9mm); Plagioclase; K-feldspar; rare biotite Opaque minerals + rare xenoliths	Muscovite rare micro-patches; Sericite (up to 12%)
Micro-granite	Zg-02 Zg-03	fine to medium-grained texture	Amphibole (0,1-0,4mm; rare: less than 3%); Biotite (<0,9mm; 2-4%); Quartz (0,4-3,2mm; less than 40%); K-feldspar (up to 32%); Plagioclase (1-2,9mm; up to 20%); Opaque minerals (<4%); + xenoliths (up to 4,5mm)	Abundant Sericite (up to 10%); chlorite (<3%); rare epidote (<1%)
	Zg-109	fine grained texture	Amphibole (0,1-0,4mm; rare: less than 3%); Biotite (<0,5mm; 2-4%); Quartz (0,4-0,9mm; less	Abundant Sericite (up to 10%); chlorite (<3%); rare epidote (<1%)

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			than 48%); K-feldspar (up to 30%); Plagioclase (0,5-1,4mm; up to 22%); Opaque minerals (<4%)	

Table 1: Mineralogical compositions of the studied rocks of the Saghro Group and Ouarzazate Group from the Sirwa massif (Zgounder Mine Region; 33 samples), refer to Fig. 2 for surface sample's locations.

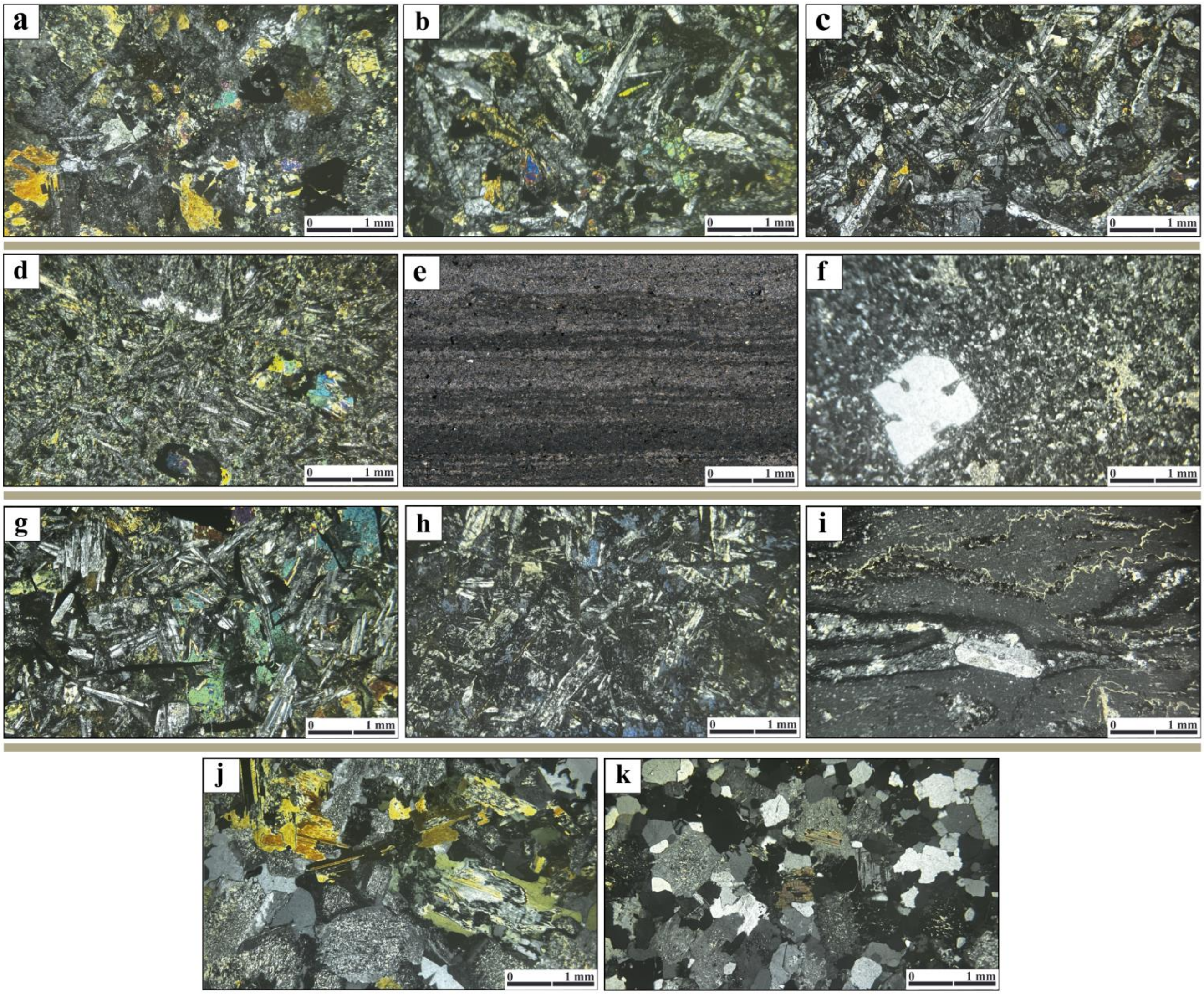

Figure 3: Photomicrographs (all in cross-polarized light) of the studied Saghro Group and Ouarzazate Group rocks. (a) Gabbro sample showcasing a medium to coarse-grained locally equigranular texture. (b) An intergranular texture for dolerite. (c) Andesite with a medium-grained intergranular texture. (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.

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

4.2.1 Tittalt rhyolite (Zg-106)

The rhyolite sample Zg-106 was taken from the Tittalt Formation as the lower unit that represents the Saghro Group in the Sirwa massif (Thomas et al., 2002, 2004). For context, this rhyolite is represented as a compact and homogenous body of approximately 46 m length, and 4 to 5 m thick. On the field, it corresponds to a rhyolitic dike crosscutting the mafic to intermediate units of the Tittalt Formation (Fig. 2). Admittedly, similar subvolcanic activity represented by E-W-trending rhyolitic dikes and related plugs was previously reported in the Zgounder Mine Region by Pelleter et al., (2016), and attributed to the Assarrag suite of Thomas et al., (2002). On the outcrop, it has a light pink to brownish taint with visible laminations. U-Th ratios range between 0.3 and 1. Most of the zircon crystals in this sample are euhedral and moderate in size. CL images reveal that zircon grains exhibit typical oscillatory zoning with rare and limited dark rim overgrowths (Fig. 4-1a), with no indication of inherited zircon grains. For filtering the data, only zircons with 95% to 105% concordance were used for age calculation (Fig. 4-1b). Thus, the weighted mean age for this sample gave 575 ± 3 Ma (MSWD = 1.5; n = 21/40), which is interpreted as the crystallization age (Fig.4-1c).

4.2.2 Granite (Zg-119)

The sample Zg-119 was sampled from the diamond drill hole (DDH) ZG-20-21 (interval in meters: 555,30m –to- 568,50m), representing the Zgounder Mine exploration program from 2020, and referred to as the ‘Deep Intrusion’ (Mine terminology). On hand, the sample corresponds to a fine to medium-grained light grey granite with pink passes. Zircon grains from this sample are homogenous in size, mostly euhedral to subhedral with some rounded zircon grains. CL images show visible oscillatory zoning with local moderately fractured zircons showing dark overgrowths (Fig. 4-2a). The discordance filter used for this sample was the same as for Zg-106; thus, zircons falling outside 95% to 105% concordance were omitted from the age calculation. A total of high-quality zircon analyses yielded a reliable concordia age of 564 ± 2 Ma (MSWD = 1.6; n = 34/37). We also calculated a 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. 4-2b). However, the zircon U-Pb are quite complicated and seem to spread over ~80 Ma which is likely due to the combined effects of Pb loss and inheritance (Fig. 4. 2-b). Hence both were omitted from the age calculation. We interpret the youngest tail of ages (~ 520 Ma) which are clearly outside of the main population reflecting analysis that have been affected by Pb loss (Sharman and Malkowski, 2024). Whilst oldest zircons are probably inherited (~ 620 Ma), and referring to a detrital signature. However, the analyzed detrital sample (Zg-132), that represents the sedimentary succession in which this granite is intruded has no zircons of this age (see supplementary table 5 for Zg-132). Moreover, the inheritance signature cannot be supported as no xenocrystic zircons were observed in the CL images. Overall, as both ages are statistically identical, we interpret the 564 ± 2 Ma as the robust crystallization age for the granite (Fig. 4-2c).

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4.2.3 Sandstone (Zg-132)

This sample was collected from the Ag-Hg hosting sedimentary units from the Imghi Formation of Saghro Group near the Zgounder Mine entrance (Fig. 2). It is a fine to medium-grained greenish sandstone. On the outcrop, it follows the E-W-trending direction of the Imghi Formation, dipping at 70° to the south. For Thomas et al., (2002), the Imghi Formation represents the lower thick beds of greywacke/turbiditic section of Saghro Group, 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. Most zircons from this sample are uniformly rounded and fragmented. They are distinguishable by their low CL signal with some being preferentially zoned (Fig. 4-3a). The age calculation utilized a filtered dataset, specifically incorporating only zircons that fell within the 95% to 105% concordance range. A total of 139 analyses were obtained on zircons from this sample, of which 91 are concordant (Fig. 4-3b). The ages distribution is dominated by one single population. For the detrital zircons, one uniform peak at around 2100 Ma, with one zircon recording an age at 3700 Ma (Fig. 4-3c).

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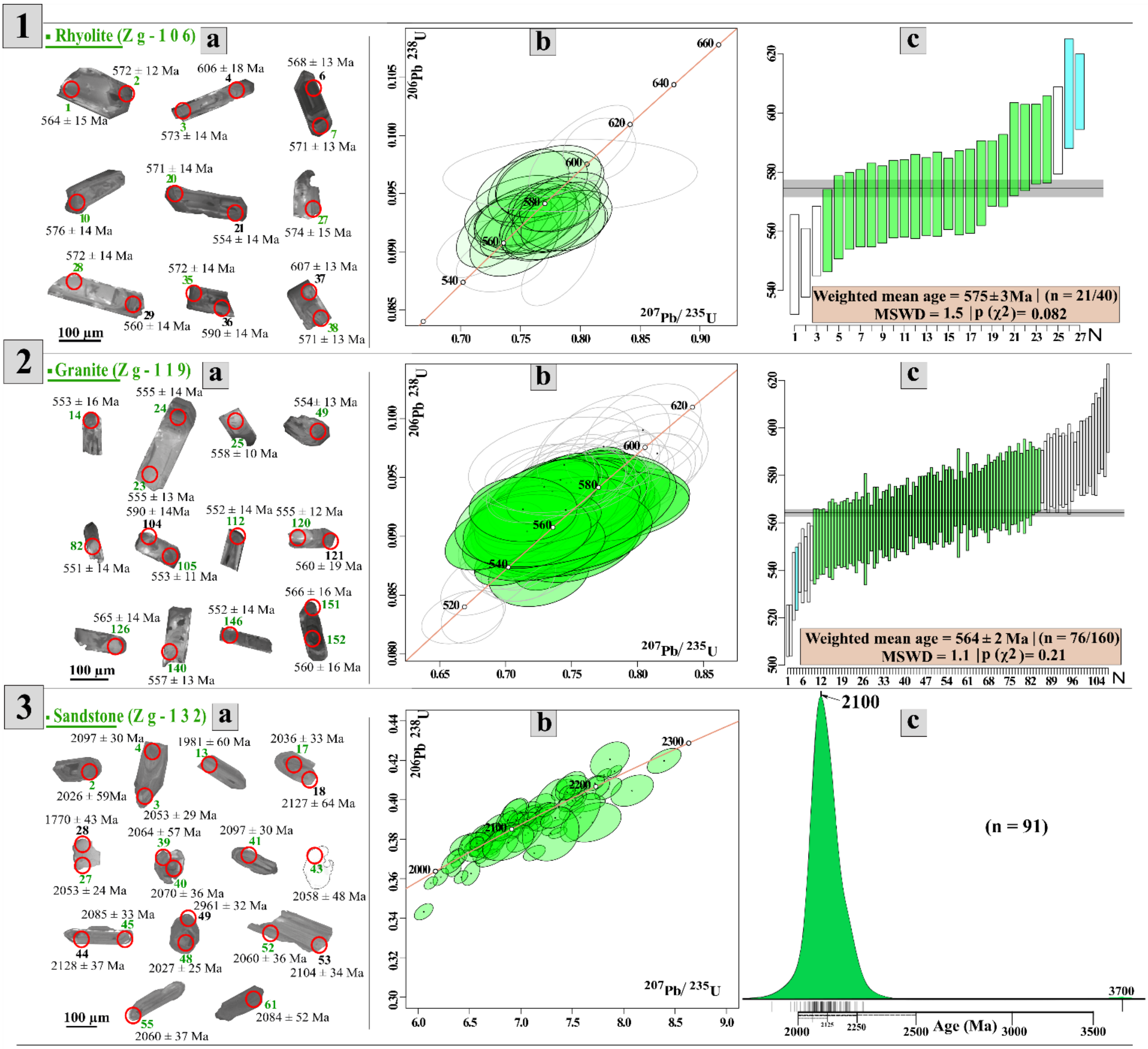

Figure 4: Cathodoluminescence (CL) images for selected zircons, U-Pb concordia and Pb^{206} / U^{238} weighted mean diagrams for samples (1) Zg-106 (rhyolite), and (2) Zg-119 (granite); along with U-Pb concordia diagram and KDE for (3) Zg-132 (sandstone). Error ellipses are plotted at 2σ. Ages were calculated using Isoplot R 1.0 (Vermeesch, 2018).

4.3 Whole-rock geochemistry

Due to samples distribution and geological diversity, the selected samples are organized in respect to their lithostratigraphic position~~, and hence treated accordingly~~. The whole-rock data for 32 samples are listed in supplementary table 4. For a start, we assessed the behavior of mobile elements and how it relates with the formed alteration minerals, using the diagram of Large

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et al., (2001); and samples are plotted in (Fig. 5). The rock material loss of ignition (LOI) at 1100 °C is low for most samples (less than 2 wt. %), except for the mafic and intermediate terms of Saghro Group where it is close to 4 wt. % (e.g. basalt, gabbro and andesite samples). On plotting our data in this diagram, a homogenous hydrothermal trend is clearly defined for all samples except for sample (Zg-106). Its trend is more directed towards sericite alteration, typical of a distal ore environment (Large et al., 2001). Overall, the plot confirms that most of our samples plot in the domain of ‘‘‘Least altered rocks’’’.

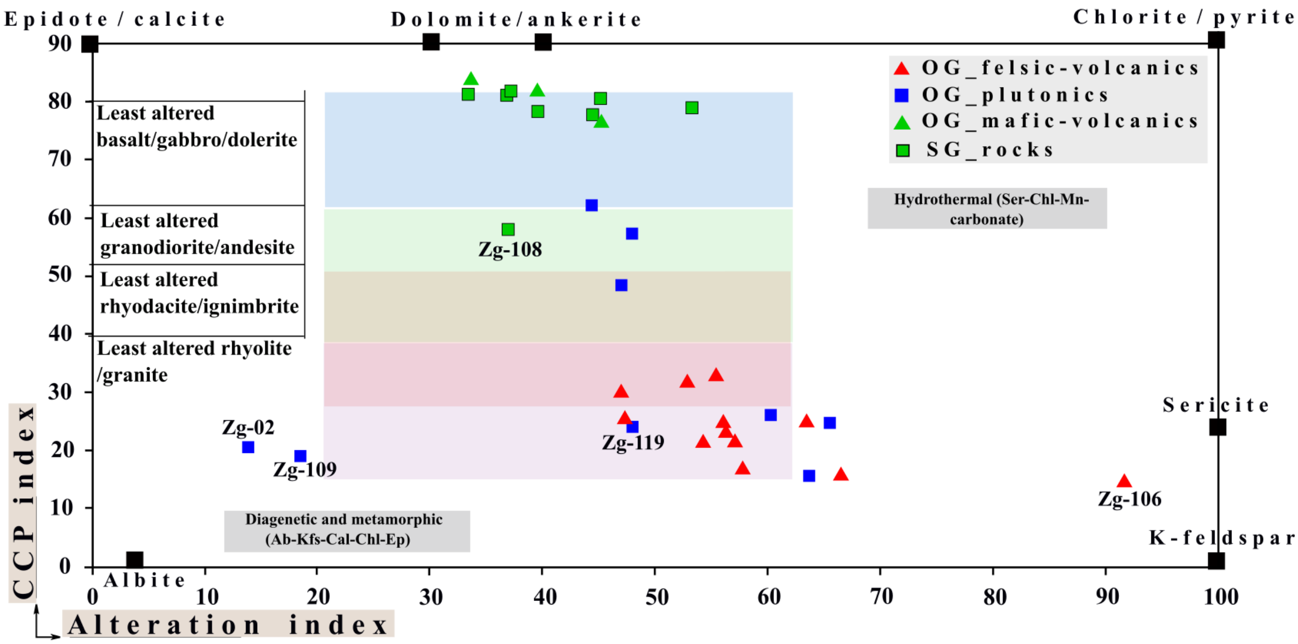

Figure 5: Plots of the studied rocks on the alteration box diagram (Large et al., 2001). Alteration Index (AI) = 100 x (K_2O + MgO) / (K_2O + MgO + Na_2O + CaO), Chlorite-carbonate-pyrite index (CCPI) = 100 x (MgO + FeO) / (MgO + FeO + Na_2O + K_2O).

4.3.1 The Saghro Group rocks

The analyzed Saghro Group rocks belong to the Tittalt Formation of the Saghro Group in the study area (Fig. 1C; Fig. 2; Thomas et al., 2002, 2004). 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 Nb/Y vs Zr/TiO_2 diagram (Fig. 6a), except for one sample (Zg-108) with andesitic composition, all samples plot within a sub-alkaline basalt; similar to contemporaneous mafic-intermediate rocks from the Saghro (Errami et al., 2009) and Sirwa inliers (Thomas et al., 2002). Most rocks are metaluminous except for one sample (Zg-006) which is peraluminous (Fig. 6b). In addition, the Saghro Group rocks display a calc-alkaline signature (Fig. 6c).

Using rare earth elements (REE) (Fig. 6d), the Saghro Group samples show a total REE varying between 60.94 to 231.77 ppm with coherent patterns characterized by a slight LREEs enrichments and HREE depletion with $(La/Yb)_N$ ratios ranging from 1.83 to 6.42. Almost all samples have slight/no important negative Eu anomalies (δEu = 0.88–0.98) to less positive anomaly

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for ~~one sample of~~ gabbro (Zg-105; Eu/Eu*)N = 1.28; Fig. 6d). For the multi-elements diagram (Fig. 6e), the Saghro Group rocks exhibit an enrichment of large ion lithophile elements (LILE, like Rb, Ba, K) over high field strength elements (HFSE) with negative anomalies in Nb, Ta, and a prominent positive Pb anomaly. They do compare in the most part with basaltic rocks from the Saghro Group of Kelâat M'gouna inlier (Benziane et al., 2008; Fekkak et al., 2001), and the early gabbro sample from Sirwa (Touil et al., 2008; Fig. 6d).

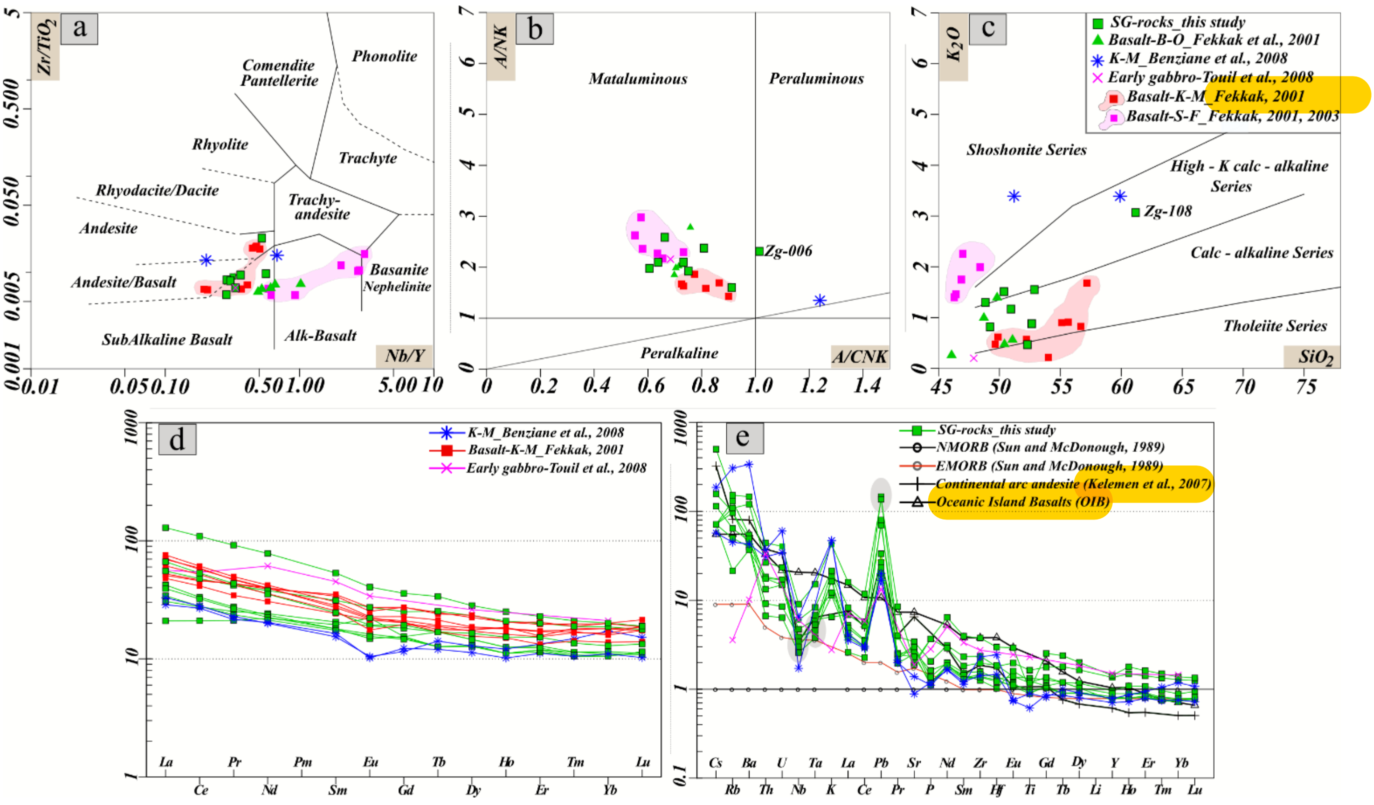

Figure 6: Saghro Group:(a) Nb/Y versus Zr/TiO2 (Winchester and Floyd, 1977). (b) Plot of A/NK vs. A/CNK [A/CNK = molar ratio Al_2O_3 / (CaO + Na_2O + K_2O) and A/NK = molar ratio Al2O3 / (Na_2O + K_2O)](Shand, 1943). (c) K_2O versus SiO_2. (d) Chondrite-normalized REE diagram of Boynton, (1984). (e) NMORB normalized diagram; normalization values are sourced from Sun and McDonough, (1989). SG samples are plotted against reference rocks from the literature. Abbreviations: B-O : Boumalne; K-M: Kelâat M'gouna; S-F: Sidi Flah.

4.3.2 The Ouarzazate Group rocks

The studied samples representing the Ouarzazate Group are composed of both volcanic and plutonic rocks. The felsic volcanic and plutonic samples have high contents ~~in~~ SiO_2 (79.89 – 61.16 wt.%), Al_2O_3 (15.18 – 10.83 wt.%), and CaO (4.42 – 0.1 wt.%) and low MgO (2.83 – 0.06 wt.%), Ni (60 - 20 ppm) and Co content (19 - 1 ppm), except for one granite (Zg-119) that have relatively high Co content of 109 ppm. Moreover, they have a $Na_2O + K_2O$ = 8.97 to 6.31 with a K_2O/Na_2O ratio of 20.75 to 0.14. Rock types for felsic volcanics are as follows: ignimbrites are represented as rhyodacite and dacite, while rhyolites and rhyolitic-ignimbrites plot inside the rhyolite field (Fig. 7a). Furthermore, the plutonic rocks occupy the granite field, with three

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distinctive granodiorites (not shown). The whole set consist of high-K calc-alkaline to shoshonitic rocks (Fig. 7b), and are peraluminous, except for the granodiorite samples that exhibit a metaluminous character (Fig. 7c). Overall, all samples plot within the calc-alkaline and alkali-calcic slightly migrating towards alkaline field (Fig.7d).

Mafic volcanics (e.g. dolerite) have moderate SiO_2 contents of (51.56 – 50.58 wt.%), Al_2O_3 (14.69 – 13.9 wt.%), moderate CaO (7.67 – 5.61 wt.%) and moderate MgO (5.3 – 4.56 wt.%). K_2O/Na_2O ratio values are 0.73 to 0.26, along with Na_2O+K_2O ratio = 5.64 to 3.58 (supplementary table 4). They are sub-alkaline basalts (Fig. 7a), with a calc-alkaline signature (Fig. 7b), and a metaluminous character (Fig. 7c).

In the REE diagram (Fig. 7e), all felsic volcanic and plutonic samples show homogeneous patterns, with enriched LREEs over HREEs. $(La/Yb)_N$ ratio varies between 17.93 and 2.1, except for one rhyolitic sample Zg-106 with $(La/Yb)_N$ of 0.89. All samples have high Eu negative anomaly (Eu/Eu* = 0.61 – 0.34, except for the same Zg-106 sample, that exhibits a prominent Eu anomaly with Eu/Eu* = 0.04, controlled by advanced plagioclase crystallization. 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. 7f). 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.

For the mafic volcanics, the REE normalized to chondrite (Fig. 7e) show moderate LREE enrichments over HREE with less fractional patterns ($(La/Yb)_N$ = 6.22 to 5.94) and very low/absent Eu anomaly (Eu/Eu* = 0.98 to 0.88). However, our dolerites are distinguished by their homogenous pattern with a prominent Pb enrichment, with less significant Sr anomaly (Fig. 7f). Our dolerites resemble those of the Tifnout Valley (TV), Group A and B, and Zaghar mafic dikes from the Sirwa massif by Belkacim et al., (2017); Touil et al., (1999); Toummite et al., (2013), respectively. Even so, minor differences related to prominent negative Nb and Ti anomaly are observed for reference samples compared to our dolerites' positive Ti anomaly (Fig. 7f). However, they differ from the Bas Drâa inlier mafic-intermediate bodies, which lack Pb enrichment and Sr depletion Karaoui et al., (2014).

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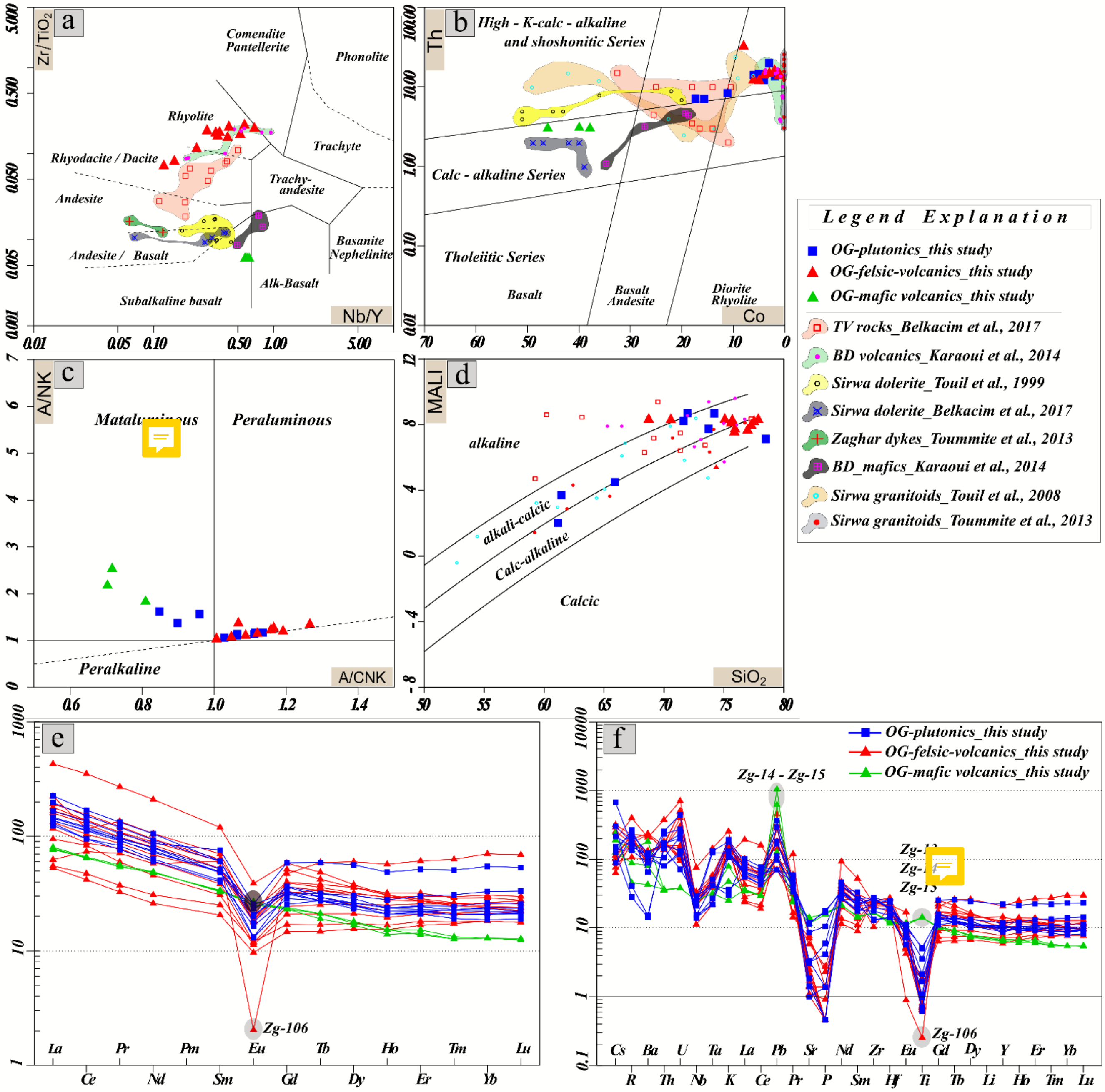

Figure 7: Ouarzazate Group: (a) Nb/Y versus Zr/TiO₂ (Winchester and Floyd, 1977). (b) Th vs Co plot of Hastie et al., (2007). (c) Plot of A/NK vs. A/CNK of Shand, (1943). (d) MALI diagram of Frost et al., (2001). (e) Chondrite-normalized REE diagram of Boynton, (1984). (f) Primitive mantle normalized diagram of Sun and McDonough, (1989). OG samples are plotted against reference rocks from the literature. Abbreviations: TV: Tifnoute Valley; BD: Bas Draâ.

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4.4 Significance of Sm-Nd isotopic data

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 538 Ma evolution of the Anti-Atlas belt post-Bou Azzer-Sirwa ophiolite accretion. Results are listed in table 2.

Lithology	Sample code	Sm (ppm)	Nd (ppm)	147Sm/144Nd	143Nd/144Nd	± 2 SE	ƐNd(0)	ƐNd(570)	TDM (Goldstein) Ma	TDM Ga
Ouarzazate Group rocks										
Granodiorite	Zg-09	10.23	50.70	0.1220	0.512414	0.000005	- 4,4	+ 1,1	1252,8	1,24
Dolerite	Zg-14	6.518	28.99	0.1359	0.512390	0.000010	- 4,8	- 0,4	1526,7	1,51
Rhyolite	Zg-106	11.50	32.75	0.2124	0.512693	0.000007	+ 1,1	- 0,1	0	N/A
Rhyolite	Zg-117	10.69	50.59	0.1278	0.512332	0.000011	- 6,0	- 0,9	1483,7	1,47
Granite	Zg-119	9.106	42.92	0.1283	0.512381	0.000009	- 5,0	0,0	1404,8	1,39
Saghro Group rocks										
Gabbro	Zg-105	3.739	13.27	0.1704	0.512762	0.000011	+ 2,4	+ 4,5	1431,6	N/A
Andesite	Zg-108	8.943	40.03	0.1351	0.512550	0.000007	- 1,7	+ 3,2	1197,3	1,19

Table 2: Sm-Nd isotopic data for the analyzed Saghro Group and Ouarzazate Group rocks. TDM is the Depleted Mantle Age in Ga calculated using the linear model of Goldstein et al., (1984); and is not calculated for samples with 147Sm/144Nd ratios greater than 0.145 (e.g. Zg-106, Zg-105). Abbreviations: ± 2 SE: Standard Errors (Uncertainty in Nd isotopic composition); N/A : Not Available.

Based on field relationships, An angular unconformity (Errami et al., 2009; Thomas et al., 2002), ~~and~~ a significant sedimentary/magmatic gap exist between the 630 - 600 Ma Saghro Group and the overlaying 570 - 538 Ma Ouarzazate Group (Errami et al., 2021a). We have used the 620 Ma as a reference age for εNd analyses of Saghro Group samples (Zg-105, and Zg-108). They show narrow (^{143}Nd /^{144}Nd) 620 Ma ratios~~, from~~ 0.512~~001 to 0.512070~~, and positive εNd (at 620 Ma) values ~~between~~ + 3.2 ~~to~~ + 4.5. Additionally, the TDM model ages (Fig. 8a), ~~ranging from~~ 1431 ~~–~~ 1197 Ma, exceed the individual maximum depositional ages of 630 to 600 Ma, and the crystallization ages of ~~pre~~ to contemporaneous igneous intrusions found elsewhere in the Anti-Atlas belt that fall within the bracket of 640 Ma to 580 Ma~~, respectively~~ (Errami et al., 2021a; O'Connor et al., 2010; Liégeois et al., 2006; Gasquet et al., 2005; Mrini, 1993). Overall, the Saghro Group samples show a mixed origin with εNd (620 Ma) ranging from + 3.2 to + 4.5, indicating a blend of mantle-derived magma and moderate contribution of an old crust (Paleoproterozoic ?). This contrasts the basaltic rocks studied in the Saghro region by Errami et al., (2009), for which εNd (at 640 Ma) vary between + 7.6~~3~~ to + 8.~~08~~, suggesting a juvenile source, with no ~~Paleoproterozoic~~ influence. Consequently, authors argued that the Saghro Group's sedimentary and volcanic deposits attest to an active back-arc basin, with the arc itself located north of the Saghro mountains in the Saghro inlier (Errami et al., 2009).

Ouarzazate Group rocks exhibit a mostly uniform distribution with (^{143}Nd/^{144}Nd) 570 Ma values from 0.511~~855~~ to 0.51~~1958~~. These ratios are close to or slightly lower than the Chondritic Uniform Reservoir (CHUR) values~~. Moreover, for all samples, the~~ εNd570 ~~values range from~~ - 0.9 to + 1.1. Volcanic rocks show negative εNd570 values: -0.9 (Tadmant rhyolite), - 0.1 (Ouarzazate Group rhyolite), and - 0.4 (dolerite). Granitoids have εNd570 values of + 0.0 ~~to~~ + 1.1 for Zg-119 and Zg-09, respectively. This range in values suggests mixing or variable degrees of interaction between a mantle source and an older

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crustal component. In addition, the TDM model ages for all of these samples range from 1526 to 1252 Ma (Fig. 8c), indicating a Mesoproterozoic affinity, even though the effect is limited. Admitting that Mesoproterozoic rocks are scarce to absent in the Anti-Atlas, these Proterozoic TDM ages, in conjunction with the mixed (near zero) εNd (570 Ma) values for both volcanic and plutonic rocks, strongly suggest that the magma for the Ouarzazate Group are likely to represent mixed values involving a Pan-African juvenile mantle together with moderate but discernible contribution from an older crustal material of Mesoproterozoic in age, which itself incorporated some even older (Paleoproterozoic ?) material (Baidada et al., 2017; El Bahat et al., 2017; Blein et al., 2014b; Gasquet et al., 2005; Thomas et al., 2002) (Fig. 8d). All in all, these results do confirm the presence of an old cratonic basement beneath the Central Anti-Atlas.

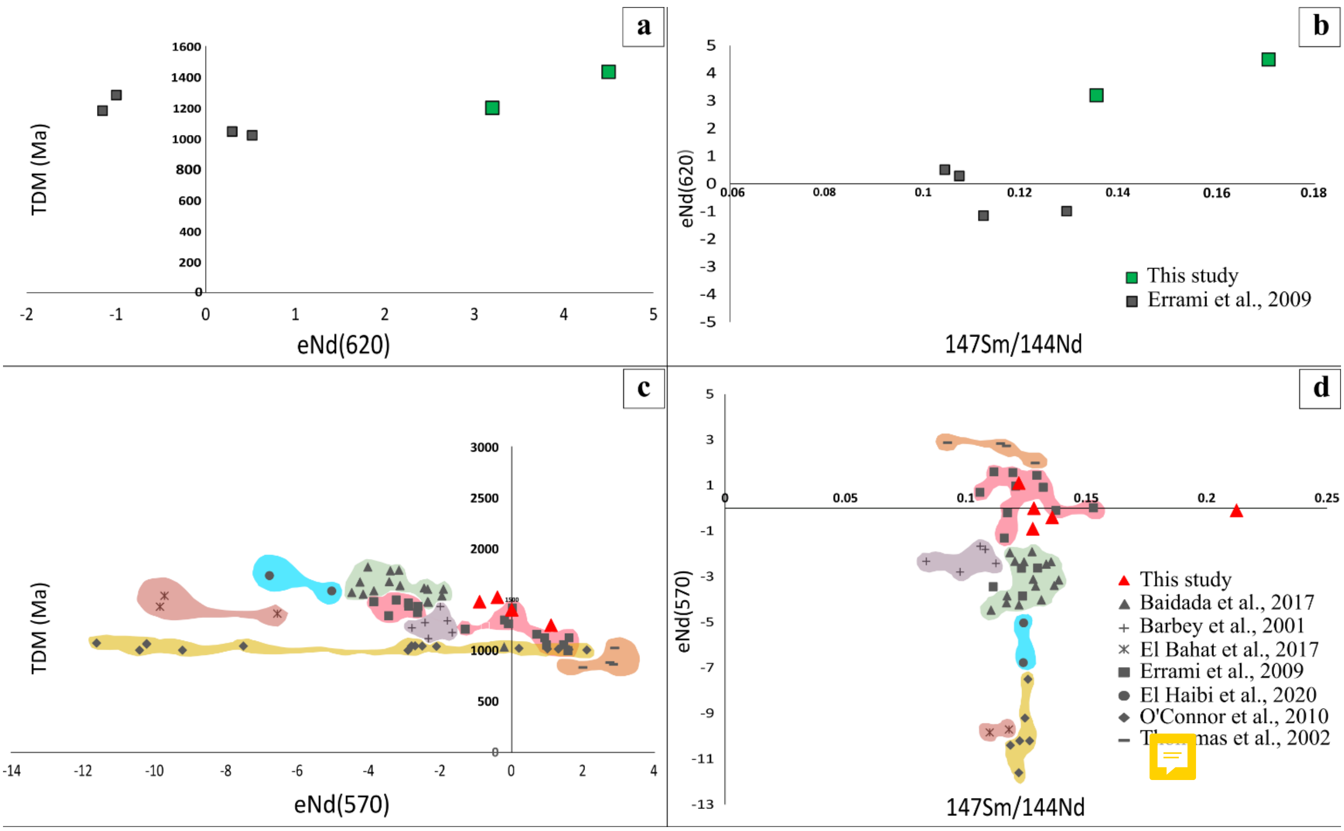

Figure 8: (a) εNd_{620} vs TDM model ages for SG. (b) εNd_{620} vs $^{147}Sm/^{144}Nd$ diagram for SG. (c) εNd_{570} vs TDM model ages for OG. (d) εNd_{570} vs $^{147}Sm/^{144}Nd$ diagram for OG rocks. All samples are compared with selected and available reference rocks from the literature.

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5 Discussions

5.1 Petrogenesis

5.1.1 The Saghro Group rocks

The Saghro Group rocks consist of basaltic lava flows interbedded with marine, low-grade metasediments. The geochemical fingerprint of the mafic rocks is well-suited for investigating the orogenic processes involved in magma genesis (Pearce, 1983; Wood, 1980). However, it is crucial to evaluate the effects of alteration, metamorphism, and crustal contamination before exploring the magmatic evolution.

- **Alteration effect**

The analyzed samples exhibit loss on ignition (LOI) values of 2 to 4 wt.%, implying major elements and LILE mobility during alteration process (supplementary table 4). Saghro Group basalt samples display scattered large-ion lithophile elements (LILEs; e.g., K, Rb, Na, Sr, Pb) vs. Zr, suggesting alteration variances. In contrast, binary plots of high-field-strength elements (HFSEs; e.g., Nb, Ta, Ti, Hf) and rare earth elements (REEs) against Zr exhibit consistent linear trends, reflecting their immobile nature (Pearce, 1996; supplementary table 4). All samples from this Group are classified as minimally altered basalts (Large et al., 2001) (Fig. 5).

- **Fractional crystallization and crustal contamination**

The analyzed samples predominantly consist of basalts displaying negative correlations for Al_2O_3, CaO, MgO, Fe_2O_3, and TiO_2 vs. Zr, and a positive correlation for P_2O_5, indicating fractional crystallization during magma evolution. The Mg# values (12.13 to 43.26), reflect early fractionation of ferromagnesian minerals, and suggest that the Saghro Group samples are not derived from a primitive melt. Furthermore, the absence of a significant Eu anomaly (δEu = 0.88–1.28) indicates limited plagioclase fractionation (Fig. 6d). The lack of a negative Eu anomaly, despite the evolved nature of the magmas (low Mg#), is likely due to the mixing of evolved basaltic magmas (low Mg#), with more primitive magmas that lacked plagioclase fractionation.

In a contamination-sensitive trace element diagram (Th/Ce and Th/La) (Fig. 9a), our samples show ratios of 0.047 to 0.080 and 0.115 to 0.172, respectively. The trend suggest that crustal contamination played a significant role in magma genesis (Taylor and McLennan, 1995). Additionally, the low Ce/Pb ratio (~ 4.3) further highlights continental crustal influence (Hofmann et al., 1986; supplementary table 4 for calculation). Further, a binary mixing model with Nd isotopic data (supplementary table 4 for calculation; De Paolo, 1981), interprets the Saghro Group basalts as formed from the mixing of a magmatic melt contaminated by 17 – 18% Paleoproterozoic continental crust (εNd_{620} = - 16; Ennih and Liégeois, 2008) and 82 – 83% primitive mantle (εNd_{620} = + 8; Errami et al., 2009). This is further supported by the negative correlation of εNd values with SiO_2, and relatively low εNd values (+ 3.2 to + 4.5), compared to contemporary mantle-derived Saghro inlier basalts (εNd = + 8; Errami et al., 2009).

However, the observed enrichment may stem from either continental crust contamination or mantle source enrichment. The Th/Ce and Th/La ratios for our samples plot linearly near the MORB reservoir, far from the upper continental crust (UCC)

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field, suggesting limited direct crustal input (Fig. 9a). Moreover, ratios such as (Sm/Yb)N versus (Nb/La)N (Safonova et al., 2016), sensitive to the nature of the mantle source, range from 1.64 to 2.74 and 0.50 to 0.91, respectively. These values place the Saghro Group samples in a transitional domain between MORB and IAB, closer to the field of back-arc basalts (BAB) (Fig. 9b). Similarly, Th/Nb and Ta/Nd ratios (0.12 – 0.30 and 0.03 – 0.06, respectively) indicate a transitional composition between MORB and the mafic lower continental crust (MLCC) (Aldanmaz et al., 2008; Fig. 9c), in alignment with the source diagram (Laurent et al., 2014; Fig. 9d), where all the Saghro Group rocks derived from fractional crystallization and contamination/assimilation of primary mafic lithologies straddling the boundary between high-K to low-K mafic rocks. Overall, the Saghro Group samples originate from the melting of an enriched source transitional between MORB and IAB, followed by fractional crystallization involving ferromagnesian minerals and assimilation of lower Paleoproterozoic continental crust.

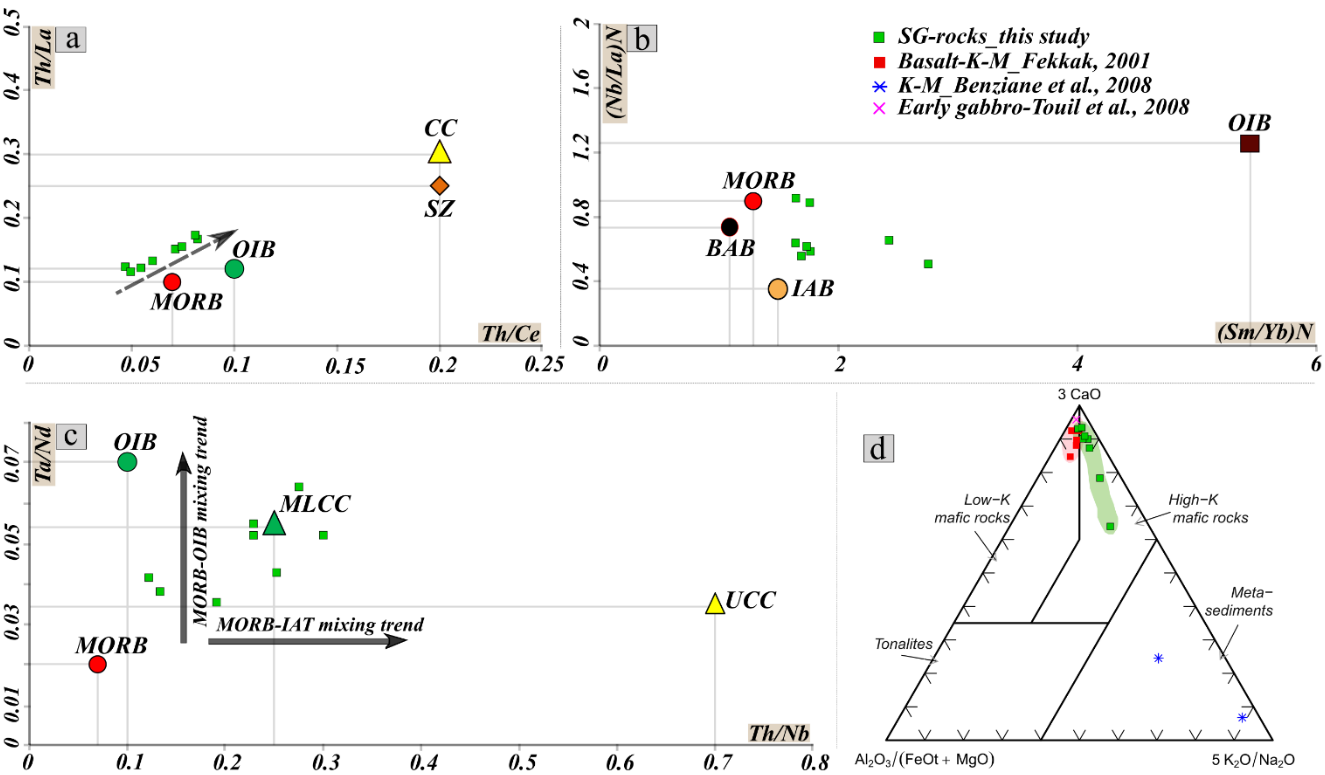

Figure 9: Saghro Group: (a) Th/Ce vs Th/La ratios for SG (Taylor and Mc Lennan, 1995). (b) plot of (Sm/Yb)N vs (Nb/La)N (Safonova et al., 2016). (c) Th/Nb vs Ta/Nd plot (Aldanmaz et al., 2008). (d) The source diagram of Laurent et al., (2014). Abbreviations: K-M: Kelâat M'gouna.

5.1.2 The Ouarzazate Group rocks

- **Fractional crystallization and crustal contamination**

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The Ouarzazate Group's volcanic and plutonic rocks exhibit chemical evolution that can be explained by fractional crystallization, with decreasing Al2O3, Fe2O3, MgO, CaO, TiO2, and P2O5 vs. rising SiO2. Major elements vs. Zr show no significant correlations (not shown: see supplementary table 4). Selected trace elements, such as Sr, decrease with rising SiO2, typical of plagioclase crystallization. Interestingly, Some trace elements (e.g. Cr, Ni, Ba, Rb, Zr) show disruptions in their patterns with increasing SiO2. Ni uniformly declines then sharply increases, Cr rises steadily then increases, while Ba, Zr, and Rb rise then decline, particularly at 70 wt.% SiO2 (Fig. 10a). These patterns are likely due to a magma recharge event affecting pre-magma’s crystallization (Fig. 10a).

Felsic volcanics and plutonics ~~compensate for~~ Sr and P depletion due to plagioclase and apatite fractionation (Fig. 7f). A prominent negative Eu anomaly in rhyolite Zg-106 indicates early calcic phase crystallization, while the absence of an Eu anomaly in dolerites suggests limited plagioclase involvement (Fig. 7e). Additionally, their Pb enrichment indicates crust assimilation (Fig. 7f). The high La (16.4 to 133 ppm) and Ce (33.8 to 284 ppm) values in the Ouarzazate Group samples suggest interaction between parental magma (s) and crust material, indicating enrichment due to either assimilation of continental crust or a combination of assimilation and fractional crystallization during magma ascent (De Paolo, 1981). Further, fractional crystallization relates to correlations between Zr and Th/Nb ratios (Fig. 10b), as most of the Ouarzazate Group felsic volcanics and plutonics show similar Th/Nb and Zr trends, indicating significant assimilation and fractional crystallization in magma evolution. Some plutonics, however, show a limited Th/Nb range, suggesting bulk assimilation control (Fig. 10b). This is supported by the La/Sm versus La diagram (Fig. 10c) indicating source heterogeneity, despite fractional crystallization's dominance. The Y/Nb versus SiO2 wt.% (Fig. 10d) confirms a crustal source with varying differentiation. Depletions in P, Nb, and Ti in Ouarzazate Group rocks (Fig. 7f) suggest crustal contamination and hydrous metasomatism, with P anomalies linked to Nb and Ti depletions (Campbell et al., 1994). In addition, the depletion of HFSEs like Nb and Ti might also indicate magmatic arc signatures and possible crustal contamination during magma processes (Wilson, 1989). All samples show slight K enrichments (Fig. 7f), likely related to fluids from subducted sediments (Beraaouz et al., 2004).

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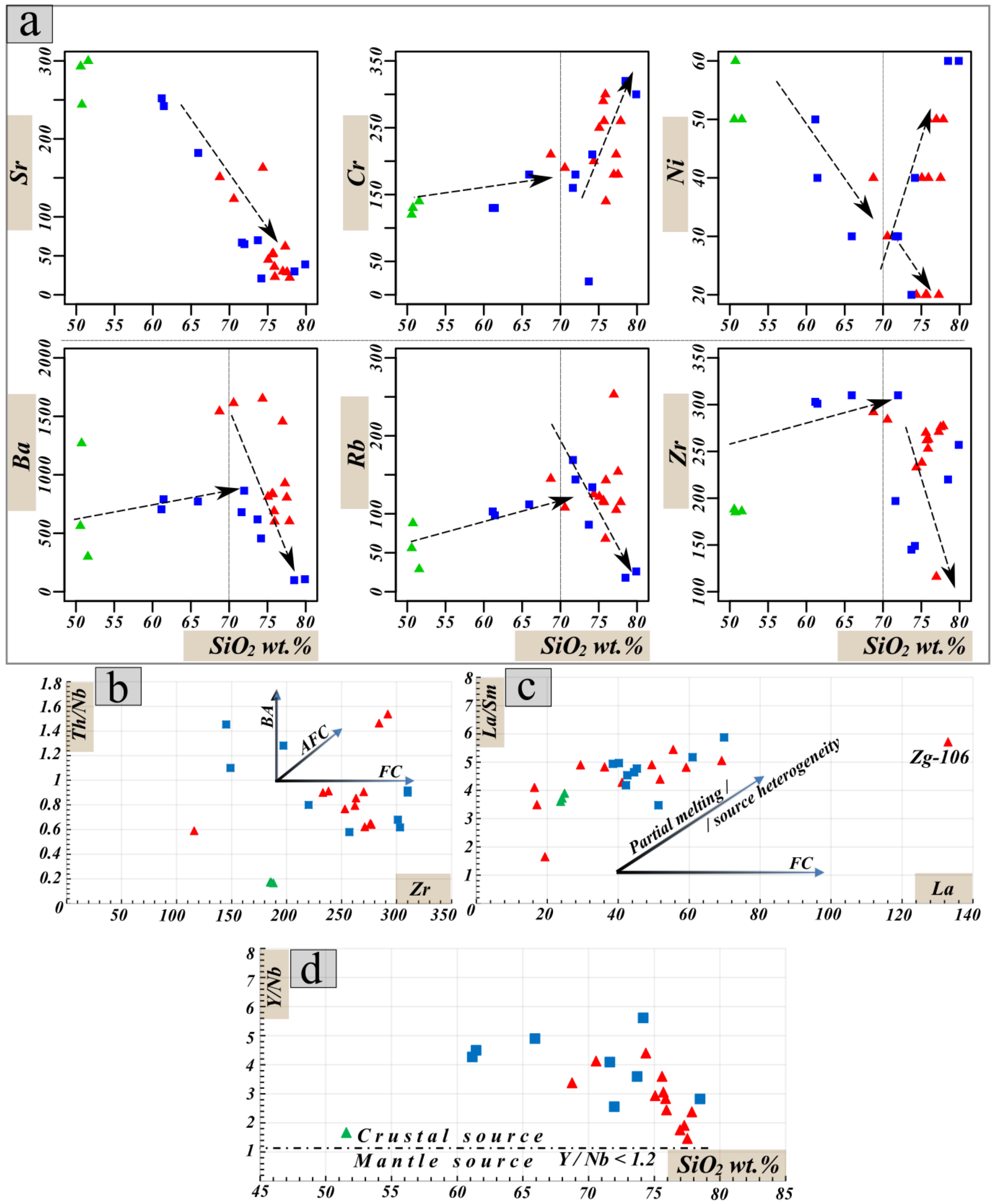

Figure 10: Ouarzazate Group: (a) Harker variation diagrams for selected trace elements (e.g. Sr, Cr, Ni, Ba, Rb, Zr) for the OG rocks. (b) plot of Th/Nb vs Zr. (c) La/Sm vs La plot. (d) Y/Nb vs ~~increasing~~ SiO_2, (Eby, 1990) for the Y/Nb =1.2 discriminating value. Abbreviations: BA: Bulk Assimilation; AFC: Assimilation and Fractional Crystallization; FC: Fractional Crystallization.

- **Magma types and source characteristics**

The coherent negative anomalies in Nb, P, and Ti in the Ouarzazate Group samples might suggest an exclusive crustal origin, with minor discrepancies due to advanced degrees of differentiation. These features may also arise from low partial melting

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of metasomatized mantle contaminated by continental material (O'Reilly and Griffin, 2013), as supported by εNd values (- 0.9 to + 1.1) indicating juvenile magma contributions. Indeed, trace elements and isotopic compositions can clarify subduction input versus crustal contamination. The Ouarzazate Group rocks show significant LILE and LREE enrichment with Nb-Ta depletion, indicating a metasomatized lithospheric mantle from subduction or assimilation of enriched continental crust (Fig. 7-f). Furthermore, the Th/Yb versus Ta/Yb diagram suggests that the magma source originated from an E-MORB-type mantle, evolving through contamination and Assimilation-Fractional Crystallization, as evidenced by the trend of the samples toward the average upper continental crust (Fig. 12a). This interpretation is consistent with the moderate εNd values and TDM ages that reflect contributions from both mantle and continental crustal components, highlighting the importance of crustal contribution over sediment zone enrichment (Fig. 12b). All in all, the primary magma responsible for the genesis of the Ouarzazate Group rocks sourced from an enriched continental lithospheric mantle, previously underwent metasomatism by fluids from ~~former~~ Neoproterozoic subduction.

5.2 Geodynamic implications and regional correlations

5.2.1 The Saghro Group

Previously, the Saghro Group 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 Saghro Group sediments in the Sirwa and Saghro inliers suggest its deposition, 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).

Basaltic samples from the Sirwa inlier (this study) show enrichment in ~~large ion lithophile elements~~ (LILE~~)~~ and ~~light rare earth elements (~~LREE~~)~~ relative to ~~high field strength elements (~~HFSE~~)~~ and ~~heavy rare earth elements (~~HREE~~)~~. They also exhibit pronounced negative anomalies in Nb, Ta, and Ti, suggesting a subduction zone fluids influence (Wilson, 1989). Despite this, the basalts feature high Zr and relatively low Y concentrations, classifying them as within-plate basalts (WPB) (Fig. 11a). This dual geochemical signature, blending within-plate and active margin characteristics, is further evidenced by their Ti/Y and Zr/Y ratios which plot in transitional field in the geotectonic discrimination diagram (Ti/Y versus Zr/Y; Pearce and Gale, (1977), not shown). Indeed, the coexistence of geotectonic signatures from both active continental margins and within-plate settings is characteristic of magmas generated during back-arc extension (Shinjo and Kato, 2000).

In this context, the subduction-related signature is acquired through mantle metasomatism by sediment/fluid-derived components during arc activity, while the within-plate signature emerges later during back-arc extension processes. This interpretation aligns with the geochemical characteristics of the Saghro Group basalts, which plot within the fields of mid-ocean ridge basalt (MORB) and back-arc basin basalt (BABB) (Fig. 11b). Moreover, the active margin signature is supported by high Th/Nb and low U/Th ratios in the Saghro Group basalts (refer to supplementary table 4). Further, the influence of

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subduction-related components is further highlighted by the ThN vs NbN ratios, with the basalts plotting above the MORB-OIB array (Fig. 11c). This pattern indicates a mantle source enriched during continental arc processes (Pearce, 1983).

At a regional scale, basaltic flows have been described as interbedded within the sediments of the Saghro Group 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, while those from the Kelâat M'gouna (KM) inlier are Nb-depleted. In contrast, the Anou N'Izem basalts in the Boumalne (BO) inlier possess typical Mid-Ocean Ridge Basalt (MORB) signatures. U-Pb dating of detrital zircons from the Saghro Group 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) (Fig. 13A). This geochemical variation may reflect a single geodynamic event. Specifically, during the evolution of a back-arc basin, the earliest magmas generated often exhibit magmatic arc characteristics due to the proximity of the back-arc to the arc itself. As the back-arc basin evolves and the magma source becomes further removed from the metasomatised mantle, the magmas acquire within-plate geochemical signatures (Vasey et al., 2021; Saunders and Tarney, 1984). Overall, basaltic magmatism in the Saghro Group fits this evolutionary framework. For instance, calc-alkaline basalts from the Sirwa inlier (Thomas et al., 2002; This study), reflect initial stages in back-arc formation. Conversely, and higher in the stratigraphy; IRT, OIB, and MORB-type basalts indicate later stages in back-arc evolution. This interpretation is consistent with sediment geochemistry suggesting back-arc basin deposition (Ouguir et al., 1996). Furthermore, this scenario aligns with the paleogeographic position of the Anti-Atlas during the Ediacaran. During that time, the Anti-Atlas region was dissected in a northward direction (present coordinates) due to south-dipping Cadomian subduction (Fig. 13) (Rojo-Pérez et al., 2024; Stern, 2024; Errami et al., 2021a; Linneman et al., 2014).

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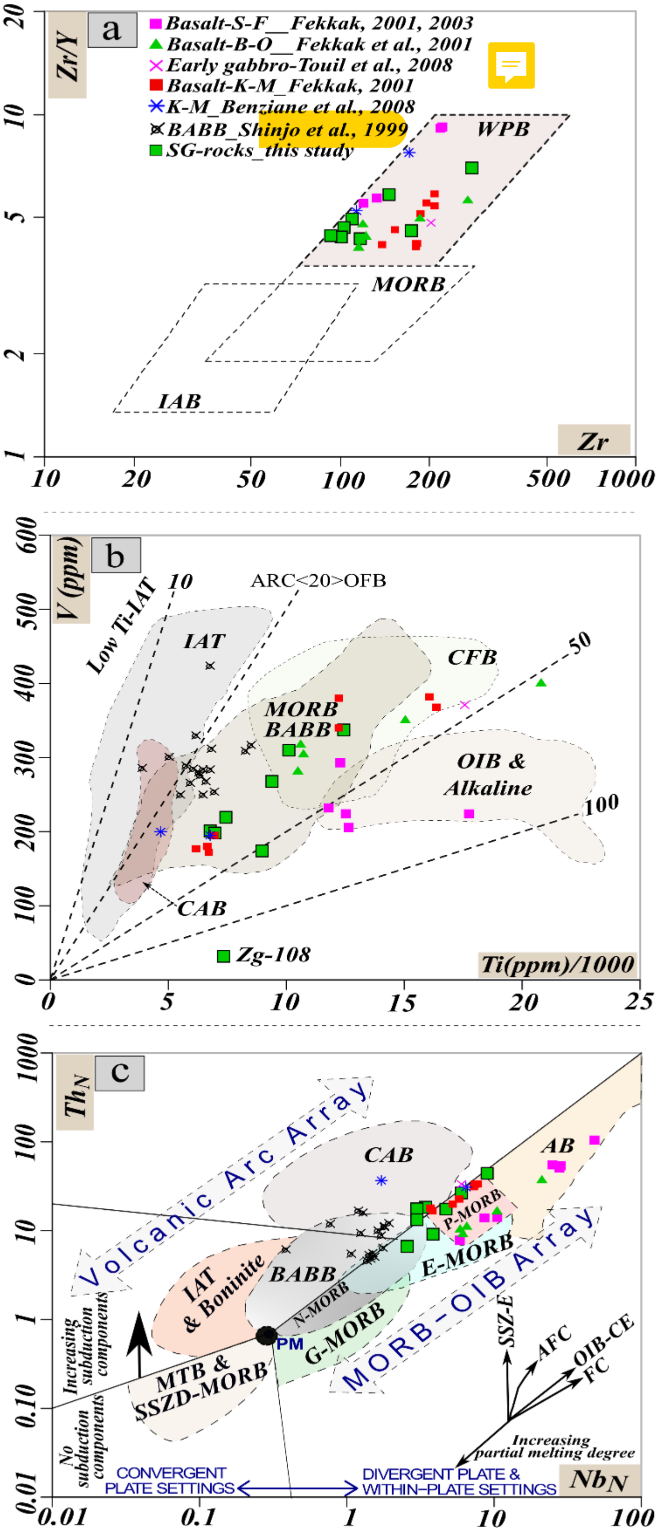

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Figure 11: Saghro Group: (a) Zr/Y vs Zr plot for basalts of SG (Pearce and Norry, 1979). (b) V vs Ti/1000 plot (Shervais, 1982). (c) plot of Th_N vs Nb_N ratios (Saccani, 2015). Abbreviations: B-O : Boumalne; K-M: Kelâat M'gouna; S-F: Sidi Flah; BABB: Back-arc basin basalts.

5.2.2 The Ouarzazate Group

On the tectonic discrimination diagrams (Fig. 12b-c), the Ouarzazate Group rocks display geochemical characteristics ranging from dominating within-plate to minor active continental margins (oceanic island arcs). Plus, the high Th/Yb ratios > 1 for all rocks refer to a metasomatised mantle source in subduction zone and/or crustal contamination. All in all, the whole accounts for a post-collisional setting (Fig. 12c), involving partial melting of a pre-existing lithospheric source, either a mantle or crust. Hence, controlling the recharge in K_2O and LILE (e.g. Rb, Ba) contents for the majority of our samples (Fig. 11a). Additionally, the alkali-calcic to high-K calc-alkaline signature of our samples is in fact typical to post-collisional events (Liégeois et al., 1998, and reference therein).

The Ediacaran magmatism of the Ouarzazate Group is still debated as being fully post-collisional and linked to asthenospheric rise (upwelling) beneath the WAC during its metacratonic evolution (Belkacim et al., 2017; 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). Nonetheless, subduction-related features can arise in a non-subduction settings without coeval subduction (Morris et al., 2000; M'arquez et al., 1999; Cousens, 1996; Hooper et al., 1995).

Regional correlations with similar magmatism lead us to attribute the Ouarzazate Group to a post-collisional event also exemplified in numerous inliers of the Anti-Atlas (Fig. 13C-D) (Yajioui et al., 2020; Karaoui et al., 2015; Linneman et al., 2014; Toummite et al., 2013; Walsh et al., 2012; Gasquet et al., 2005, 2004; Thomas et al., 2002).

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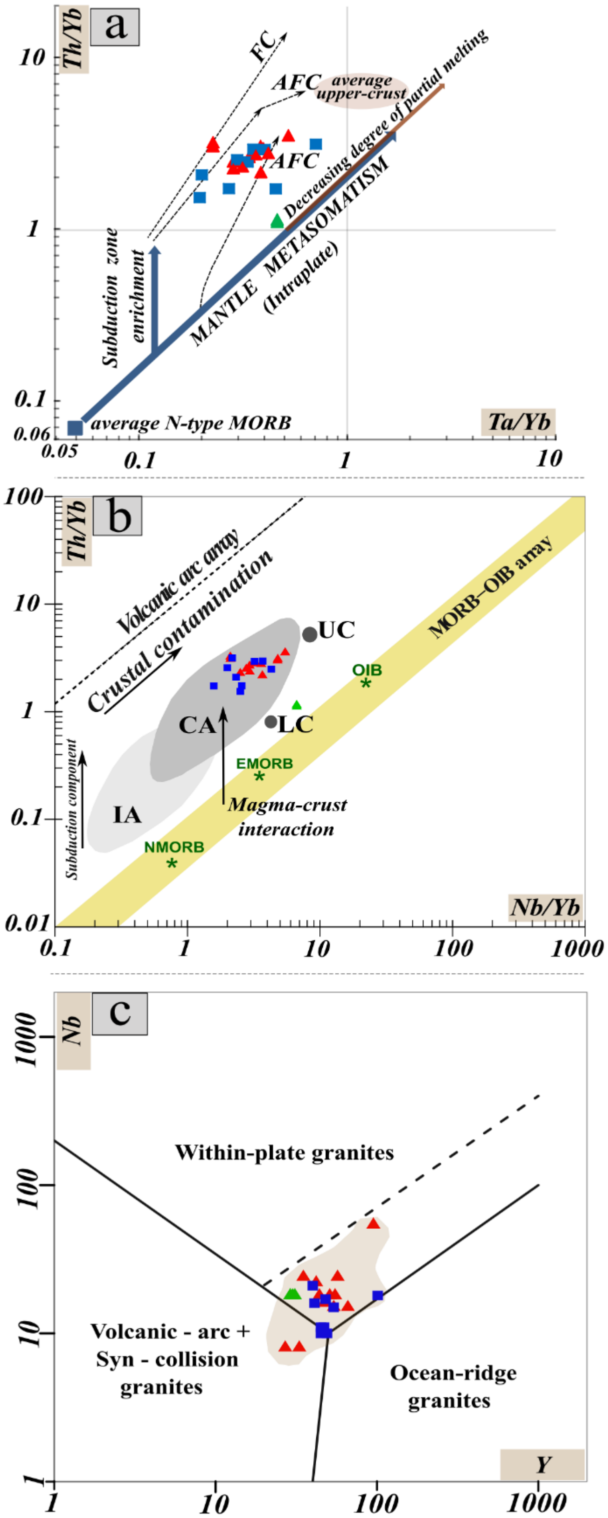

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Figure 12: (a) Th/Yb vs Ta/Yb plot for OG rocks. (b) Nb/Yb vs Th/Yb diagram of Pearce, (2008). (c) Nb versus Y diagram (Pearce et al., 1984) depicting evolution from volcanic arc granite to within-plate granite.

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

5.3.1 U-Pb zircon age record on magmatic rocks of the OG

~~Reliable n~~ew U-Pb zircon ~~ages~~ on two magmatic samples (Zg-106, and Zg-119; Fig. 4), representing the Ouarzazate Group from the Sirwa massif returned ages of 575 ± 3 Ma and the 564 ± 2 Ma, respectively. These ages are consistent with a lower Ouarzazate Group affinity, and represent the extension of the Ediacaran magmatism previously described in numerous inliers of the Anti-Atlas belt (Yajioui et al., 2020; Karaoui et al., 2015; Hefferan et al., 2014, and references therein; Toummite et al., 2013; Walsh et al., 2012; Gasquet et al., 2005, 2004; Thomas et al., 2002).

Indeed, in the Zgounder Mine Region, 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). F~~or the rhyolite (Zg-106);~~ Pelleter et al., (2016) reported mean age of 578 ± 4 Ma from the Zgounder Mine for the rhyolitic dikes and plugs using the 207Pb/206Pb 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 ~~proposed~~ 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 ~~analytically~~ identical within errors to the ages of these rocks, ~~thus inferring~~ a rapid sequence of intrusive events ~~that~~ occurred within a ~~span of a~~ few million years.

For the granite sample (Zg-119); the obtained age of 564 ± 2 Ma is also identical within ~~a margin of~~ error to the ages of the neighbouring Imourkhssen granite dated respectively at 561 ± 3 Ma, and 562 ± 5 Ma by Toummite et al., (2013), and Thomas et al., (2002) (Fig. 1C). The Imourkhssen granite on its turn intrudes the lower and older part of the Ouarzazate Group in the Sirwa massif (Thomas et al., 2002). Additionally, in the Sirwa massif, numerous syn- to late-Ouarzazate Group granites with a sub-alkaline-calcic composition provided ages of c. 560 Ma, making them the Ouarzazate Group's youngest components. According to Thomas et al., (2002), these granites belong to the Achkoukchi Complex (Fig. 1C), and grouped into the Amassine Suite (e.g., Bou-Tazart, Aït Nabdas, and Tikitar granites, and the Tazoult Quartz-porphyry at 559 ± 6 Ma).

Significant inherited Paleoproterozoic zircon population ~~are~~ previously reported for the Ouarzazate Group rocks all over the Anti-Atlas. For instance, Baidada et al., (2019) reported inherited Paleoproterozoic signature for the Saghro massif granitoids. Blein et al., 2014b proved the existence of Paleoproterozoic inherited zircon in ignimbrite of the Ouarzazate Group in the Agadir Melloul area. Finally, Thomas et al., (2002) highlighted Paleoproterozoic inherited zircons in syn-Ouarzazate Group granites in the Sirwa massif.

Indeed, the Ouarzazate Group's thick successions of volcano-sedimentary series are dominated by acidic 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). Their depositional environment as pull-apart basins with strike-slip faulting ~~conditions~~ and sub-vertical movements favored a high variability in thickness (Walsh et al.,

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2012, and references therein). Nevertheless, a contemporaneous magmatic activity spanned the 630 to 538 Ma time frame; (Table 1 in Hefferan et al., (2014) for reported precision ages from selected inliers of the Anti-Atlas Mountains). All in all, this activity indicates a prolonged tectono-magmatic event emplaced over multiple pulses over the whole Anti-Atlas belt (Tuduri et al., 2018). In regard to this, Schulte et al., (2022), considered the Ouarzazate Group in the Central and Eastern Anti-Atlas as the relicts of an Ediacaran silicic large igneous province (SLIP) deposited in a strictly continental environment. These huge volumes of mostly felsic magma were emplaced by multiple pulses and occur as a result of a long-lived magmatic event evolving from high-K calc-alkaline at 575–550 Ma to alkaline affinity at 550–540 Ma (Schulte et al., 2022; Blein et al., 2014b; Gasquet et al., 2008). This magmatism is considered to belong to a continental silicic large igneous province (SLIP), referred to as the Ouarzazate Silicic Large Igneous Province (OSLIP), and emplaced over multiple periods at ca. 575 Ma, ca. 560 Ma, and ca. 550 Ma (Tuduri et al., 2018; Blein et al., 2014b). Consequently, the last two pulses at the final stage of the Pan-African orogeny (560 to 550 Ma) appear linked to widespread pervasive hydrothermal activity across the whole Anti-Atlas (Tuduri et al., 2018). Regional correlations can be drawn to the extent of the Cadomian orogeny (Linnemann et al., 2014, and references therein). Hence, our samples fall within the age range of 580 to 550 Ma of the Cadomian arc magmatism extended to Iberia (Chichorro et al., 2022, and references therein).

5.3.2 The Saghro Group detrital age: depositional style and material source

Whether or not the Paleoproterozoic basement exists in the Sirwa massif north of the AAMF, and by consequence the northern margin of the WAC is still debated (Ennih and Liégeois, 2008). Outcrops of this Paleoproterozoic basement have been regarded as being present exclusively in the westernmost part of the Anti-Atlas belt (Choubert, 1963). However, new studies based on TDM ages support the hypothesis that Paleoproterozoic rocks may also be found in both the Central and Eastern segments of the Anti-Atlas (Baidada et al., 2019; Blein et al., 2014; Toummite et al., 2013; Liégeois et al., 2013; Abati et al., 2010; Gasquet et al., 2008; Thomas et al., 2002). Moreover, this hypothesis can be extended to Western Meseta (Pereira et al., 2015, and references therein; Tahiri et al., 2010; Baudin et al., 2003).

During the last decade, the northern boundary of the WAC is considered to be marked by the northernmost outcrops of highly deformed rocks in the southern part of the Bou-Azzer inlier, particularly the Tazagzaout migmatites and gneisses, based on similarities in lithology and deformation degree with the Zenaga Complex in the Western Anti-Atlas (Leblanc and Lancelot, 1980). However, this view has been changed owing to the new U-Pb precision dating obtained from the Tazagzaout gneisses (752 ± 1-2 Ma; D'Lemos et al., (2006), and the Oumlil granite 741 ± 9 Ma; El Hadi et al., (2010)). Furthermore, the positive Nd values of (+ 4.9 to + 6) for the Tazagzaout Complex refer to a juvenile depleted mantle source, not akin to the 2 Ga Eburnean WAC basement (D'Lemos et al., 2006). Consequently, the presence of a WAC basement beneath the Central Anti-Atlas, especially in the Sirwa massif is not clear. Published geochronological data indicate that both the Saghro and Bou Salda groups were deposited approximately 630 to 610 Ma. This deposition occurred during a period of tectonic convergence of the Cadomian arc upon the WAC Iriri-Tazagzaout Complex (Errami et al., 2021a; Walsh et al., 2012; El Hadi et al., 2010). Yet, the precise location of the suture zone marking this collision remains ambiguous. Current interpretations suggest the suture

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likely corresponds to the Anti-Atlas Major Fault (AAMF) (Hefferan et al., 2014), potentially extending north along the South Atlas Fault (SAF) (Ennih and Liégeois, 2001, 2008).

Detrital zircon age from our study provides new insights into the basement beneath the Sirwa massif. Sample (Zg-132) from the Imghi Formation of the Saghro Group returned exclusively Paleoproterozoic ages, with a prominent peak at ca. 2100 Ma (Fig. 4-3). Interestingly, no ages younger than 1600 Ma were found in our sample~~, nor were any zircons dating to the local Pan-African magmatic period in the Anti-Atlas identified~~. ~~These~~ 883 - 640 Ma Pan-African ~~younger~~ zircons, which are common in outcrops of the Sirwa inlier and have been consistently reported in Saghro Group sediments (Letsch et al., 2018; Abati et al., 2010) are absent ~~in our sample. Indeed, this~~ Paleoproterozoic peak goes in line with the ~~inherited signature from the analyzed~~ zircon population of sediments of the Saghro and Bou Salda groups from the Sirwa massif, for which the obtained maximum depositional ages cluster around 620 – 610 Ma (Abati et al., 2010). ~~Arguably, the~~ authors argued in favor of an exposure of cratonic basement (Paleoproterozoic-?) based on the relatively high proportion of the ~~610 Ma zircons in regard to~~ Paleoproterozoic zircons in the upper levels of the stratigraphy sequence. ~~Therefore,~~ this suggests that the source of the 610 Ma was eroded favoring the enrichment in Paleoproterozoic ages. Admittedly, the subsequent erosion of the underlying Neoproterozoic rocks (notably synchronous magmatic rocks, and Saghro and Bou Salda groups) might be the source for the prominent 610 Ma peak in the Iberian massif (Chichorro et al., 2022); (Fig. 13A).

The mono-peak at 2.1 Ga can only be accepted to strictly represent Paleoproterozoic. It can be interpreted as representing the material source for the Saghro Group sedimentary units only in the study area (Fig. 13A). Indeed, the returned mono zircon population may reflect insufficient sampling of detrital zircons. However, the number of analyzed zircons (~~up to~~ 139; see supplementary table 5) is considered adequate to address paleogeographic questions and sediment source areas. In this context, we interpret the Paleoproterozoic mono-peak in our sample to reflect local exposure of Paleoproterozoic basement rocks along the basin margins of the Saghro Group ~~in the study area~~ (Fig. 13A). Consequently, most sediments were derived exclusively from the erosion of these basement rocks in a possible mono Paleoproterozoic paleo-relief without interaction with ~~Cryogenian~~ sediments.

Overall, this evidence argues that during Ediacaran times, the Paleoproterozoic basement was in fact totally or locally exposed in the Sirwa inlier (Fig. 13A). This interpretation is further corroborated by Nd model ages of Ediacaran magmatism from this study ~~(see section Sm-Nd), which yield TDM age of Mesoproterozoic values~~, indicating a mixing/recycling of older Paleoproterozoic crust with juvenile Ediacaran magma. All in all, and based on these findings, the WAC crust extends beneath the Sirwa massif and ~~likely~~ 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 ~~given~~ age of 2050.6 ± 3 Ma (Pereira et al., 2015). These findings do support the ~~extension~~ of the WAC Paleoproterozoic crust northward beyond the AAMF, which was previously considered the northern margin of the craton.

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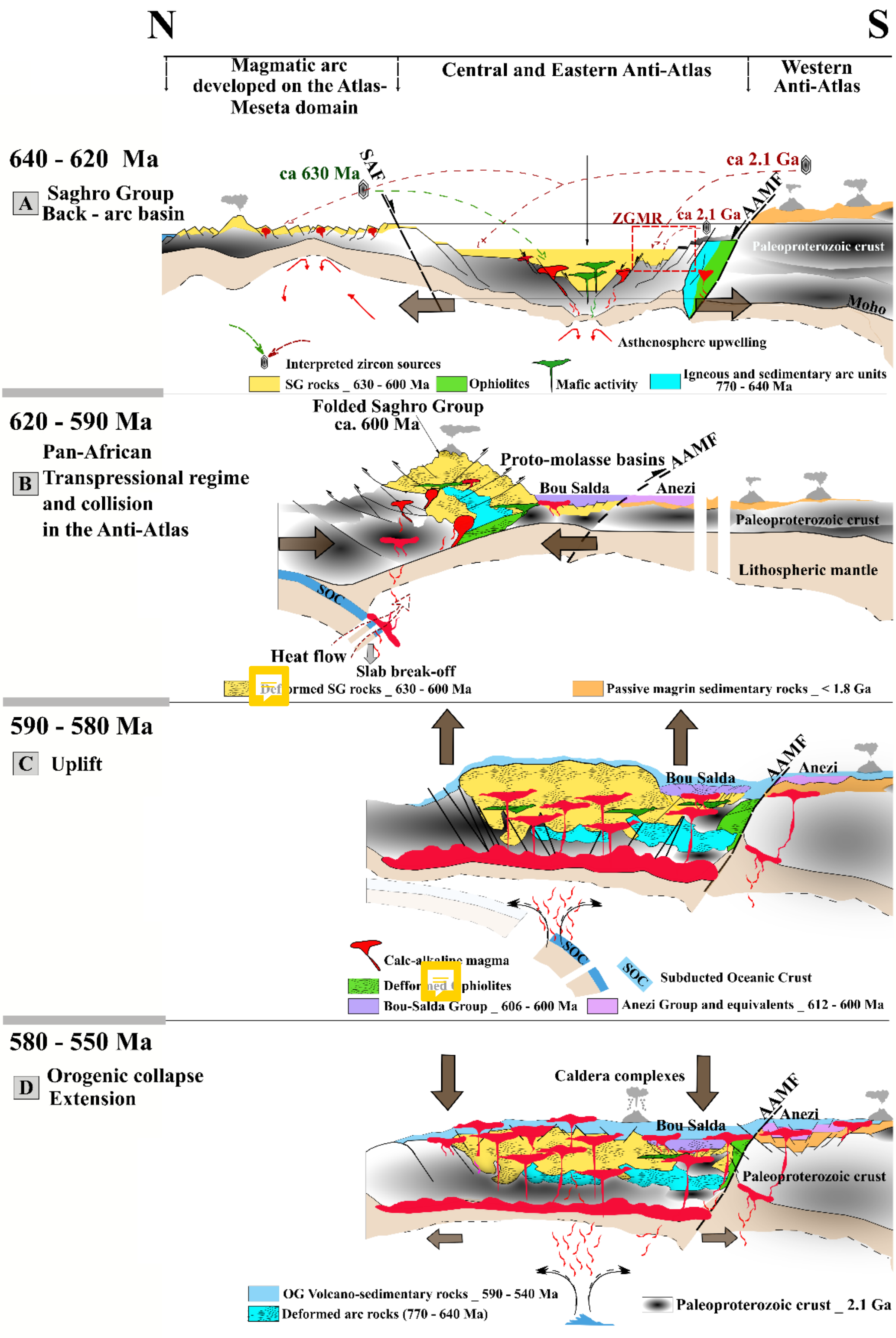

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Figure 13: Reconstruction of the geotectonic setting of Saghro Group and Ouarzazate Group during Ediacaran times. (~~resembled and~~ modified after El Kabouri et al., 2025; Chichorro et al., 2022; Errami et al., 2021a; Abati et al., 2010; Thomas et al., 2002). (A): Saghro Group deposition in a back-arc basin (This study; Ouguir et al., 1996), implying local exposure of the 2.1 Ga Paleoproterozoic crust in the Zgounder Mine Region (This study). (B): Pan-African transpressional regime and collision in the Anti-Atlas, resulting in Saghro Group folding, injection of the 600 Ma calc-alkaline magma (Errami et al., 2021a), and proto molasses basin formation (Thomas et al., 2002). (C): General uplift in the Anti-Atlas. (D): Orogenic collapse favoring the thick Ouarzazate Group sedimentation (e.g. post-tectonic molasse deposition and calc-alkaline magmatism, with coeval acidic rocks).

6 Conclusions

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

i. Based on geochemical proxies (major and trace elements), the Saghro Group rocks exhibit both active continental margins and within-plate characteristics. ~~A~~ dual signature characteristic of magmas generated during back-arc extension. Therefore, the ~~recognized~~ subduction-related signature ~~on~~ our samples ~~is~~ acquired through mantle metasomatism by sediment-derived components during arc activity, while the within-plate signature emerges~~, later~~ during back-arc extension processes.

ii. The Saghro Group rocks were emplaced at ~~the~~ early stages of back-arc basin opening, testified by their calc-alkaline affinity, geochemical characteristics and regional correlations. They were derived from ~~contaminated~~ mantle source with an old continental crust. Further, their εNd (at 620 Ma) = + 3.2 to + 4.5, and TDM ages of 1431 – 1197 Ma reflect~~s~~ a mixed origin, combining mostly mantle-derived magma with limited proportion of older crustal material. Thus admitting the existence of an old Paleoproterozoic to ~~even~~ Mesoproterozoic crust ~~under the Saghro Group~~.

iii. For the Ouarzazate Group rocks, the evolution in chemical compositions for the suite of high-K calc-alkaline to shoshonitic rocks ~~is~~ controlled in the most part by fractional crystallization and crustal contamination. They were deposited in a post-collisional setting, and their ~~primary~~ magma was sourced from an enriched continental lithospheric mantle~~, previously~~ underwent metasomatism by fluids ~~from former~~ Neoproterozoic subduction. Further, their εNd (at 570 Ma) = - 0.9 to + 1.1, and TDM ages of 1526 to 1252 Ma ~~refer to a Mesoproterozoic (and Paleoproterozoic) affinity,~~ imply~~ing~~ recycling of Paleoproterozoic material during Ediacaran times.

iv. LA-ICP-MS U-Pb zircon ages on magmatic rocks evince an expression of a post-collisional syn-orogenic magmatism (WACadomian arc), during the emplacement of its first and second pulses at ca. 575 to 560 Ma. This period of magmatism ~~is concordant~~ with a Silicic Large Igneous Province (SLIP) recognized all over the Anti-Atlas.

Code, data, or code and data availability

Data will be made available upon request.

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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. **David Lalonde:** Resources, Financing, Collaboration. Review, and validation.

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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