41° cycle - PhD in Earth Sciences - Curriculum in Geosciences

Research project

Petrogenesis of carbonatites and REE-Nb mineralization: Insights from the Oulad Dlim Massif, SW Morocco

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1 Introduction and state of the art

In recent years, the demand for critical raw materials such as Rare Earth Elements (REE) and Nb has been steadily increasing as they represent key enablers for the ongoing energy and environmental transition [1]. This is due to their optical, catalytic, magnetic, electrical and metallurgical properties, which are also commonly exploited for the creation of cutting-edge technologies in various scientific and industrial fields [2, 3]. Despite not being always associated with economic mineralization, carbonatite complexes stand out as the most prominent REE source, occasionally characterized also by Nb enrichment, which is one of the most relevant by-product [4].

Carbonatites are rare, virtually SiO_2-free to strongly SiO_2-undersaturated igneous rocks. They are defined as igneous rocks constituted by at least 50 vol% of primary magmatic carbonates and with SiO_2 <20 mass% [5, 6]. Despite their petrological relevance and strategic importance as one of the main reservoirs of critical raw metals, the petrogenesis of carbonatites remains cloudy and far from being fully understood [7, 8]. Furthermore, the definition of carbonatite itself proposed by IUGS remains vague and their mixed mineralogical-chemical classification results quite messy, a feature that led to several contrasting conclusions among different research groups [9, 10]. For this reason, a new genetic classification has been recently proposed [10], separating carbonatites into three main types: primary carbonatites, carbothermalites and pseudocarbonatites [10]. This distinction is not purely academic, as the remarkable potential to host great concentrations of REE, Nb and other critical elements is not equally shared among all carbonatite types. For this reason, the possibility to accurately distinguish the different variants could be essential both in petrological studies and in the ore geology field [9, 10].

Primary carbonatites are related to mantle partial melting either as a primary carbonatitic melts or as a carbonatitic magmas exsolved from an original CO_2-rich silicate melt [9, 10]. They are often characterised by little REE enrichment compared to other primary silicate magma, because these elements show similar distribution coefficient in the carbonatite-silicate magma systems in equilibrium with a peridotitic source [11, 12]. Strongly different from primary carbonatites, carbothermalites consist of residual or deuteric deposits formed at lower temperatures (<500 °C) from CO_2-rich carbohydrothermal fluids which encompass both the leftovers of magmatic processes and crust-derived fluids [10]. This carbonatite type is the most economically important, as it is usually characterized by strong enrichments in REE, Nb, F and P due to late-magmatic concentration and/or post-magmatic sub-solidus remobilization [10, 13]. Such processes often lead to the formation of unusual mineral phases, some of which constitute ore minerals like REE-phosphates (e.g., monazite) and REE-fluorocarbonates (e.g., bastnäsite) [9, 10]. Lastly, pseudocarbonatites are derived from different kinds of magmas with carbonatitic-like compositions as consequence of anatectic melting and/or assimilation of crustal lithologies. They are usually sterile in critical metals, as observed in typical sedimentary carbonates such as limestones and dolostones [14, 9].

Only recently, geological surveys conducted in the Moroccan Sahara by the "*Office National des Hydrocarbures et des Mines*" (ONHYM) have highlighted the presence of several carbonatite bodies scattered in SW Morocco [8, 15]. They are located inside the Oulad Dlim Massif, a Variscan nappe stack of four main gneissic units that overrides, with an eastward tectonic transport, the Archean crust of the western side of the Reguibat Shield [8; Fig. 1]. Aside from two more studied complexes – Gleibat Lafhouda and Twihinate – the majority of them has received very little to no attention at all, despite being extremely promising in terms of exploitable REE-Nb mineralization [8, 11, 16]. At the aforementioned sites, the mineralization mainly consists of monazite-(Ce), bastnäsite-(Ce), pyrochlore and/or columbite-(Fe) hosted within the main carbonatite bodies and/or their iron oxide caps. The latter have been identified as Iron-Oxides-Apatite (IOA) deposit-types and are considered the product of late-stage hydrothermal alteration, as evidenced by the rocks composition, texture and stockwork pattern [8, 11, 16; Fig. 2].

The present project proposes a thorough petrological investigation of Hdibat Dlim, Bou Lautad, Lehraycha and Lghassaliyat bodies, four of the newly discovered carbonatite complexes that are yet to be investigated with detailed petrology, mineral chemistry, geochemistry and isotope systematics. This investigation has the potential to provide fresh knowledge crucial to advance our understanding of carbonatite petrogenesis and the processes leading to the formation of REE-Nb ores. Moreover, a multidisciplinary comparison of the Moroccan carbonatites with the calcite-rich carbonatite-like rocks of Italian Intra-Apennine Province (IAP) and the carbonatites from the German Eifel Volcanic Field (EVF), is planned.

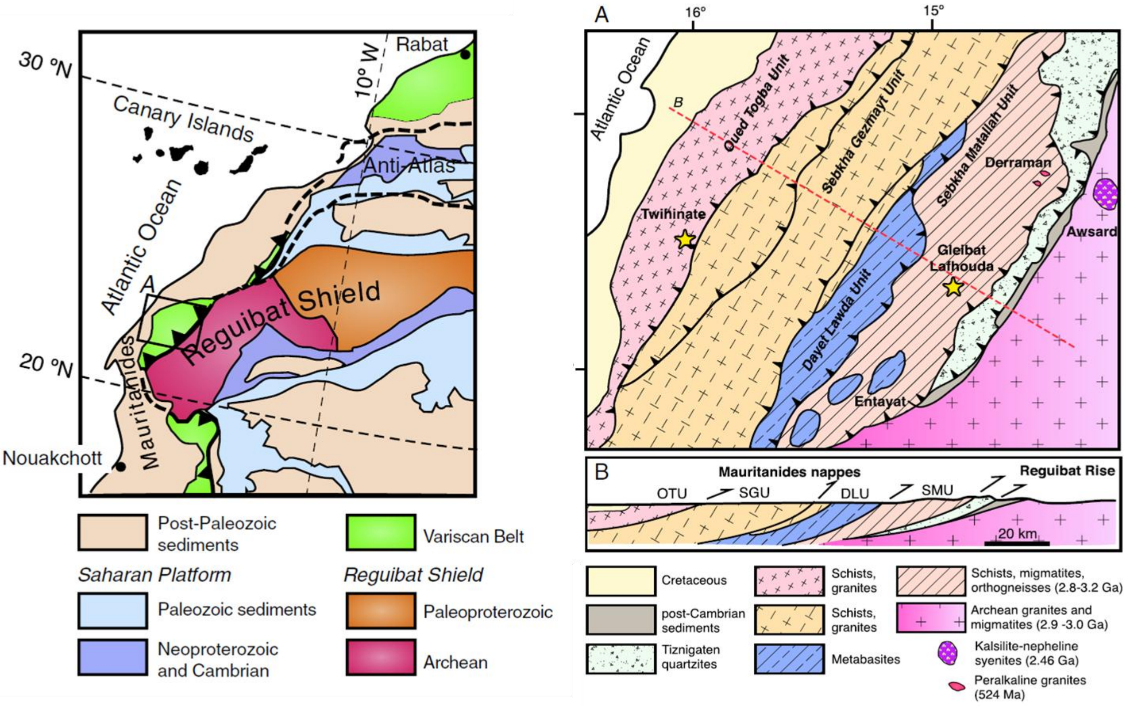

Figure 1 Main geological domains and relative ages of the Reguibat Shield and its adjacent peri-cratonic terrains. The Oulad Dlim Massif units and their tectonic relations are shown in detail "A" and profile "B", some of the major alkaline intrusions of the area are also shown. Yellow stars indicate only two of the several carbonatite outcrops of SW Morocco [15].

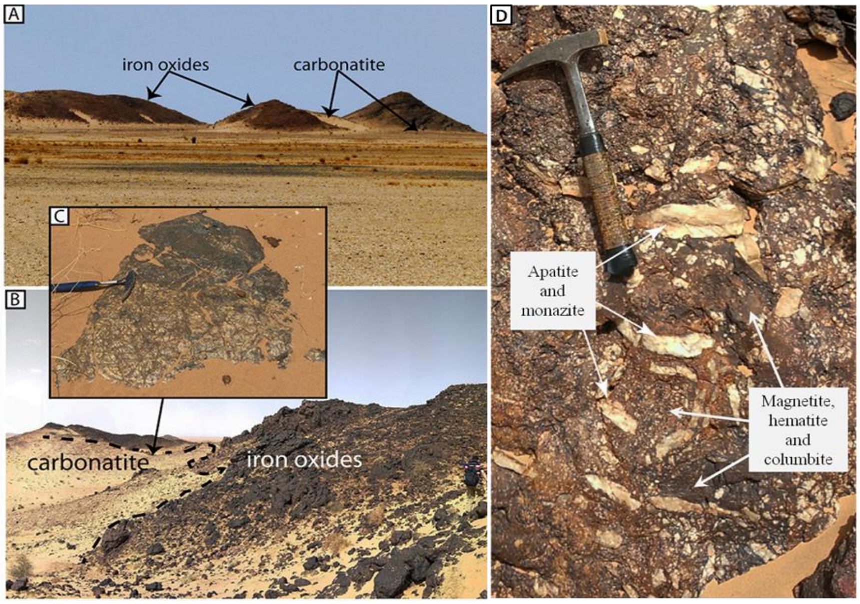

Figure 2 (A, B) Field view of Gleibat lafhouda carbonatites and REE-NB rich Iron Oxides-Apatite (IOA) epigenetic deposits. (C) IOA filled stockwork vein pattern inside the carbonatite body. (D) Close-up view of the IOA mineralization with coarse phosphates in an Fe-oxides matrix [11].

2 Aim of the work

2.1 General objective

Understanding carbonatite petrogenesis and the processes that lead to the formation of their related economic REE-Nb mineralizations in multiple geodynamic environments.

2.2 Specific Objectives

- Detailed petrographic, mineralogical, geochemical characterization and isotope dating of Hdibat Dlim, Bou Lautad, Lehraycha and Lghassaliyat carbonatites and their associated rocks.

- Development of a petrological model able to explain the source conditions and the set of processes that contributed to the genesis, the geochemical features and the deuteric/post-magmatic REE-Nb mineralisation of these four carbonatite complexes.
- Petrographic, geochemical, petrological and geodynamic comparison between the Moroccan carbonatites, the carbonatite-like rocks of the Italian Intra-Apennine Province (IAP) and the carbonatites of the Eifel Volcanic Field (EVF), Germany.

3 Implications and/or applications

An in-depth study of these newly discovered carbonatite complexes and their respective mineralization has the potential to provide new insights on carbonatite petrogenesis and help the development of future petrological models. Furthermore, these carbonatite bodies, together with the products of their weathering and/or hydrothermal alteration, might prove to be high-grade REE-Nb ores, making them promising targets for exploration and future mining.

4 Research activities and work schedule

4.1 Phase 1 (end of 2025 – autumn 2026)

After the first two months in investigating local and general literature devoted on the geodynamic evolution of Morocco and on the different hypotheses on carbonatite genesis and evolution, I will start my research by carrying out a fieldwork in the Hdibat Dlim, Bou Lautad, Lehraycha and Lghassaliyat areas. There, several samples of carbonatites and their associated rocks will be collected in collaboration with local researchers of El Jadida University (Prof. Abdelilah Fakkek), with which the Dipartimento di Scienze della Terra of Sapienza University of Rome (DST) activated an agreement on a scientific collaboration on January 2025. Should any logistic problem arise during the field-work plan on the Moroccan samples, the attention will be fully shifted towards the Eifel Volcanic Field (EVF; W Germany). About hundred samples of carbonatites from EVF have already been collected in the last years and are available at DST, ready to be studied. The main target remains the Moroccan carbonatites. The samples will be processed and analysed in the DST, starting from a detailed petrographic investigation through Optical Microscopy (OM). Then, the samples will undergo Scanning Electron Microscopy (SEM), Electron Probe Micro Analysis (EPMA). Additional Laser Ablation Microprobe Inductively Coupled Plasma Mass Spectrometry (LAM-ICP-MS) will be carried out at Rome Tre University in collaboration with Prof. Federico Rossetti. SEM investigation will grant a deeper look at the rocks texture and will help to highlight the relations and possible chemical zoning of the minerals, EPMA will be used to acquire the whole-rock chemical composition in terms of major oxides and by LAM-ICP-MS it will be possible to analyse the trace element content in the various mineral phases, to calculate also relative distribution coefficients. The whole-rock analyses will be entrusted to Activation Laboratories Ltd (Actlabs) and to the CNR Istituto di Geoscienze e Georisorse (IGG) of Pisa.

4.2 Phase 2 (autumn 2026 – spring 2027)

During this period, the research work will continue at CNR-IGG in collaboration with Dr. Samuele Agostini. During my stay in the CNR-IGG laboratories, I plan to perform trace elements measurements with ICP-MS and isotope analyses on Sr-Nd-Pb-B-C-O systems with Multicollector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS) and Isotopic Ratio Mass Spectrometry (IRMS). I plan also to define a new laboratory procedure to analyse Ca and Mg isotopic ratios in the IGG laboratories. Following that, I will also collaborate with Dr. Andrea Giuliani at Carnegie Institution for Science, Washington, DC, to perform trace elements and isotope analysis on single crystals employing the LAM-ICP-MS technique. Moreover, mica Rb-Sr, apatite U-Pb and $^{40}Ar/^{39}Ar$ isotopic dating will also be performed both in Pisa and Washington in order to estimate the crystallization age of the samples and hence the emplacement age of the various complexes and their related mineralization stages. It is under investigation the possibility to spend some time at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences in collaboration with Dr. Ming Lei to perform Si-Ce-B stable isotopic systematics on the carbonatitic rocks and associated silicate lithologies.

4.3 Phase 3 (spring 2027 – summer 2027)

Throughout the third phase, all the acquired data will be compiled and thoroughly examined. The aim is to create a working petrological model that can clarify the source conditions and the formation processes of the Hdibat Dlim, Bou Lautad, Lehraycha and Lghassaliyat carbonatites, including their associated REE-Nb mineralization, in a peri-cratonic environment.

4.4 Phase 4 (summer 2027 – autumn 2028)

The proposed petrogenetic model will be accompanied by a detailed comparative study between the Moroccan carbonatites, the calcite-rich carbonatite-like rocks of the IAP and the carbonatites of the EVF. This comparison will focus on the mineralogical, chemical and isotopic composition of these rocks to delineate differences and similarities in their features in relation to their respective geodynamic environments and genetic processes. This comparison is crucial for my research since Italy is considered to be part of a REE-rich belt, with the most important lithologies being identified in the carbonate-rich rocks of IAP [17]. Various rock specimens from the IAP and EVF have already been collected, supplementary material will be taken from literature. The final phase of this period will be dedicated to the writing my PhD thesis.

5 Milestones

- Detailed petrographic study and mineralogical characterization of Hdibat Dlim, Bou Lautad, Lehraycha and Lghassaliyat carbonatites and their associated rocks via OM, SEM and EPMA techniques (by the IV trimester of the first year).
- Compositional analyses in terms of major oxides, trace elements and isotopic ratios for rock specimens and mineral separates via EPMA, ICP-MS and LAM-ICP-MS, MC-ICP-MS and IRMS techniques (by the II trimester of the second year).
- Isotope age determination for the emplacement and the following mineralization stages of these complexes through Rb-Sr, U-Pb and $^{40}Ar/^{39}Ar$ isotopic dating of rock samples and/or mineral separates (by the II trimester of the second year).
- Data compilation and realization of a petrological model to define source composition, partial melting conditions, differentiation processes and deuteric/post-magmatic mineralisation of the Hdibat Dlim, Bou Lautad, Lehraycha and Lghassaliyat carbonatites and their associated rocks (by the IV trimester of the second year).
- Multidisciplinary comparison between the Moroccan carbonatites, the calcite-rich carbonatite-like rocks of IAP and the carbonatites from the EVF (by the II trimester of the third year).

6 International mobility

As part of an ongoing scientific cooperation between DST and Chouaib Doukkali University of El Jadida, I will travel to Morocco in January 2026 and collaborate with Prof. Abdelilah Fekkak to collect carbonatite samples from several outcrops. During the I and II trimester of the second year, I will also collaborate with dr. Andrea Giuliani from Carnegie Institution for Science in Washington, D.C. and employ a wide range of laser-based techniques to perform trace element measurements, isotope analyses and isotopic dating. I am defining the details to spend 2-4 months at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, under the supervision of dr. Ming Lei.

7 Training activities and dissemination

I will sharpen my scientific skills by attending as many relevant workshops, seminars and conferences as possible, both in Italy and abroad. Key target events include the Goldschmidt, EGU, AGU and SGI-SIMP (including SGI Be-Geo) congresses. Whenever possible, I will actively participate in these events by sharing and discussing my preliminary research findings. Furthermore, I will maintain my involvement in science communication activities, as done in the past four years. Additionally, I plan to enrol in several courses from master’s degree and PhD programs offered by Sapienza University of Rome and other scientific institutions.

8 Gantt chart

Research Activities	First year				Second year				Third year			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
Bibliographic study	X	X	X	X	X	X	X	X	X	X	X	X
Fieldwork activity	X	X										
Thin sections study		X	X			X	X					
SEM and EPMA study			X	X			X	X				
Isotope study (MC-ICP-MS / IRMS)			X	X	X							
Mineral trace element study (LAM-ICP-MS)					X	X						
Rb-Sr, Ar-Ar and U-Pb isotopic dating					X	X						
Si-Ce-B stable isotopic systematics						X	X					
Petrological model development						X	X	X				
Morocco-IAP-EVF rocks comparison								X	X	X		
Abroad period	X	X			X	X	X					
Courses and workshops	X	X	X	X	X	X	X	X	X	X	X	
Conferences	X		X	X	X		X	X	X		X	X
Publications							X	X	X	X		
PhD thesis writing										X	X	X

Figure 3 Gantt chart of all the activities (fieldwork, research, training, mobility…) planned for the PhD project. Each academic year (November-October) is subdivided in four trimesters (I = November-January, II = February-April, III = May-July and IV = August-October).

9 References

[1] IEA – Global critical minerals outlook 2025.

[2] Babaei et al. (2020) A review on plasma electrolytic oxidation (PEO) of Niobium: mechanism, properties and applications. *Surf. Int. 21, 100719*.

[3] Ben Ali et al. (2025) Efficient enrichment and selective recovery of Rare Earth Elements from igneous carbonatite ore. *Min. Eng. 229, 109374*.

[4] Chen et al. (2024) Global rare earth element resources: A concise review. *Appl. Geochem. 175, 106158*.

[5] Le Maitre (2002) Igneous rocks: A classification and glossary of terms. *Cambridge Univ. Press*.

[6] Lustrino et al. (2024) Updates on the IUGS Task Force on classification and nomenclature of igneous rocks. *Abstr. 37th IGC Busan*.

[7] Schmidt et al. (2024) The origin of carbonatites - combining the rock record with available experimental constraints. *J. Petrol. 65, 10*.

[8] Haissen et al. (2016) Carbonatites from Southernmost Morocco (Reguibat Shield, WAC): petrography, geochemistry, geochronology and economic potential. *Conference: Geological days of Morocco*.

[9] Mitchell (2005) Carbonatites and carbonatites and carbonatites. *Can. Mineral. 43, 2049-2068*.

[10] Mitchell & Gittins (2022) Carbonatites and carbothermalites: A revised classification. *Lithos 430-431, 106861*.

[11] Benaouda et al. (2020) Thorium-poor monazite and columbite-(Fe) mineralization in the Gleibat Lafhouda carbonatite and its associated iron-oxide-apatite deposit of the Ouled Dlim Massif, South Morocco. *Gondw. Res. 77, 19-39*.

[12] Martin et al. (2013) Element partitioning between immiscible carbonatite and silicate melts for dry and H_2O-bearing systems at 1-3 GPa. *J. Petrol. 54, 2301-2338*.

[13] Woolley et al. (2008) Paragenetic types of carbonatite as indicated by the diversity and relative abundances of associated silicate rocks: Evidence from a global database. *Can. Mineral. 46, 741-752*.

[14] Lentz (1999) Carbonatite genesis: A reexamination of the role of intrusion-related pneumatolytic skarn processes in limestone melting. *Geology 27, 335-338*.

[15] Montero et al. (2016) Contrasting SHRIMP U-Pb zircon ages of two carbonatite complexes from the peri-cratonic terranes of the Reguibat Shield: Implications for the lateral extension of the West African Craton. *Gondw. Res. 38, 238-250*.

[16] Benaouda et al. (2020) Discovery of high-grade REE-Nb-Fe mineralization associated with calciocarbonatite in south Morocco. *Ore Geol. Rev. 124, 103631*.

[17] Goodenough et al. (2016) Europe's rare earth element resource potential: An overview of REE metallogenetic provinces and their geodynamic setting. *Ore Geol. Rev. 72, 838-856*.