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Geochemical and Mineralogical Characterization of Uranium and Thorium Deposits

Final Report of a Coordinated Research Project



IAEA

International Atomic Energy Agency

GEOCHEMICAL AND MINERALOGICAL
CHARACTERIZATION OF URANIUM
AND THORIUM DEPOSITS

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GEOCHEMICAL AND MINERALOGICAL CHARACTERIZATION OF URANIUM AND THORIUM DEPOSITS

FINAL REPORT OF A COORDINATED RESEARCH PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2020

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FOREWORD

A long term, sustainable supply of uranium (and potentially thorium in the future) is an essential part of the nuclear fuel cycle. It is also important to ensure that the mining, extraction and processing of uranium (and thorium) are efficient and environmentally friendly. Over the past few decades there have been significant advancements in geochemical techniques and geological assessment methodologies. These advancements can be used to elucidate the genesis of uranium and thorium deposits in various geographical and geological environments for enhanced resource evaluation and to characterize deposits for improvements in mining, extraction and processing.

In 2015, the IAEA launched a coordinated research project entitled Geochemical and Mineralogical Characterization of Uranium and Thorium Deposits. The goal of the project was to improve the understanding of the genesis of uranium and thorium deposits using new methodologies and geochemical techniques. The project, which involved 12 research contract holders (from Argentina, China (2), Egypt, Ghana, Islamic Republic of Iran, Kenya, Madagascar, Mongolia, the Philippines, Ukraine and the Bolivarian Republic of Venezuela), one technical contract holder (Canada) and one agreement holder (France), was concluded in October 2018.

This publication presents a summary of the research and selected papers from the project's partners. The results are expected to enhance exploration programmes, resource evaluation and sustainable supply of uranium and thorium for peaceful purposes.

The IAEA would like to acknowledge the support provided by the following partners: School of Nuclear and Allied Sciences, University of Ghana; Department of Earth Science, University of Ghana; National Nuclear Research Institute, Ghana Atomic Energy Commission; University of Lorraine-GeoRessources Laboratory-CREGU; National University of Córdoba, Argentina; United States Geological Survey, Colorado office; and National Institute of Nuclear Sciences and Techniques, Madagascar. The IAEA would also like to thank all the participants for their contributions, in particular the late K. Kyser for facilitating and hosting the second research coordination meeting. The IAEA officer responsible for this publication was A. Hanly of the Division of Nuclear Fuel Cycle and Waste Technology.

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SUMMARY

1. BACKGROUND

With increased need for uninterrupted, long-term and sustainable supply of uranium (and potentially thorium in the future), it has become important to consider further evaluation of regions for increasing the resource base, and at the same time, making the mining and extraction more efficient and environmentally friendly. A deeper understanding of the genesis of uranium and thorium deposits under various geological environments with complex mineralization processes is required. This can be obtained through technological advancements which includes the analysis of the geochemical and mineralogical characteristics of each deposit. Such information will be helpful in guiding further exploration and optimization of extraction and production, and in effective environmental management.

The objectives of the Coordinated Research Project (CRP) were accomplished through a variety of methods, some of which were project specific. The main methods comprised obtaining geochemical and mineralogical data including major, minor and trace elements; stable and radioactive isotopes; identification of major uranium, thorium and other ore minerals; scanning electron microscopy and fluid inclusion studies. The outputs are expected to assist in understanding the global distribution of uranium and thorium resources in a consistent manner and thus provide valuable inputs for exploration strategies, resource evaluation and their sustainable development.

2. OBJECTIVE

This publication is a summary of the results and an overview of activities that were carried out under the CRP, Geochemical and mineralogical characterization of uranium and thorium deposits that was launched in 2015 and terminated in 2018.

3. STRUCTURE

This publication comprises an introduction of the background and objectives of the CRP and a brief summary of the fourteen studies. An individual brief summary of all studies that were part of the CRP has been provided as not all contract holders provided a research summary paper, and papers for this publication were voluntary due to the different levels of research undertaken. The remainder of the publication consists of eight papers that are more detailed reports of research undertaken in association with the CRP.

4. SCOPE

Twelve research contracts, one agreement and one technical contract were implemented for this CRP. The Member States involved, institutions, chief investigators and title of the individual projects are outlined in Table 1. Researchers were encouraged to publish their results and some of the preliminary results were presented at the IAEA International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2018) held in Vienna, Austria, 25–29 June 2018 (see Appendix 1).

Argentina, China, and Ukraine focused on comprehensive studies of specific deposit types; broad studies of an international scope were undertaken by the researchers from Canada and France; Ghana, Madagascar, Mongolia and the Philippines focused on aspects of characterizing and evaluating national uranium resources; Kenya focused on development of analytical techniques; Egypt, the Islamic Republic of Iran, and the Bolivarian Republic of Venezuela undertook characterization and assessment of the uranium potential of phosphate type deposits.

5. CRP ACHIEVEMENTS

New geochemical and mineralogical data from the research conducted under this CRP has resulted in a better understanding of the genesis of uranium and thorium, improved the evaluation of uranium and thorium resources, and in some cases will have implications for processing and production.

Several collaborations were developed among CRP partners from a number of countries that were involved in the CRP including: Argentina, Canada, China, France, Madagascar, Ukraine, and the Bolivarian Republic of Venezuela, and one country not directly involved in the CRP (the United States of America). Collaborations were also developed amongst institutions within the countries.

A field trip, which shared some of the research conducted by the Ukraine was held in the Ukraine from 2–6 July 2018 with 25 international participants.

Twenty-eight publications (Appendix 1), and eight graduate degrees (PhD and MSc, Appendix 2) were reported in association with the CRP activities.

TABLE 1. IAEA MEMBER STATES, INSTITUTIONS, TITLE OF RESEARCH PROJECTS AND CHIEF SCIENTIFIC INVESTIGATORS FOR CRP

IAEA Member State	Institute City	Title	Chief Scientific Investigator(s)
Argentina	Comisión Nacional de Energía Atómica Buenos Aires	Metallogenesis of granite-related uranium deposits in Argentina	Mr Juan Oscar Álvarez Mr Luis López
Canada	Queens University Kingston	Geochemical and mineralogical characterization of various uranium deposits	Mr Kurt Kyser
China	Beijing Research Institute of Chemical Engineering and Metallurgy Beijing	Mineralogical characterization of sandstone uranium deposits in China	Mr Liao Weng-Sheng
China	East China University of Technology/Jiujiang University Nanchang	The relations of A-type igneous rocks to uranium mineralization in south China	Mr Liu Xiaodong
Egypt	Nuclear Materials Authority Cairo	Geochemical and mineralogical characterization of uranium and thorium in Egyptian phosphate deposits	Mr Hado Gady
France	Centre de Recherches sur la Géologie de l'Uranium (CREGU) Nancy	Geochemistry of uranium oxides; tracing the uranium deposit types	Mr Michel Cuney
Ghana	Ghana Atomic Energy Commission Accra	Geochemical and mineralogical studies of potential co-products; uranium resources in Ghana	Mr Samuel B. Dampare
Islamic Republic of Iran	Nuclear Science and Technology Research Institute Tehran	Investigation of the uranium potential of Islamic Republic of Iran's sedimentary phosphatic rocks	Mr Khoshnoodi Khalegh

TABLE 1 (Cont.). IAEA MEMBER STATES, INSTITUTIONS, TITLE OF RESEARCH PROJECTS AND CHIEF SCIENTIFIC INVESTIGATORS FOR CRP

IAEA Member State	Institute City	Title	Chief Scientific Investigator(s)
Kenya	University of Nairobi Nairobi	Multimodal spectrometric characterization of uranium and thorium bearing mineral ores from Kenya's high background radiation areas	Mr Hudson Angeyo Kalambuka
Madagascar	Office des Mines Nationales et des Industries Stratégiques Antananarivo	Morondova uranium project	Ms Dinamalala Ranaivosoana
Mongolia	Nuclear Research Center National University of Mongolia Ulaanbaatar	Elemental Characterization of Uranium Ore Deposits from Mongolia	Ms Tserenpil Shurkhuu
Philippines	Philippine Nuclear Research Institute Quezon City	Geochemical and radiometric characterization of the Cu-Mo-U occurrences in the Larap- Paracale mineralized district, Camarines Norte, Phillipines	Mr Vargas Edmondo Mr Rolando Reyes
Ukraine	M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation Kyiv	Geochemical and mineralogical characterization of Palaeoproterozoic albitite-type uranium deposits of the Ukrainian Shield	Mr Leonid Shumlyanskyy
Bolivarian Republic of Venezuela	Universidad Simon Bolivar Caracas	Geochemical and mineralogical study of the U-bearing phosphatic rocks of Navay Formation, Tachira State, Bolivarian Republic of Venezuela	Mr John Luis Manrique Mr Haydn Barros

BRIEF SYNOPSIS OF THE STUDIES CARRIED OUT UNDER THIS CRP

This section provides individual partner summaries of research objectives and key results of studies carried out under this CRP.

1. ARGENTINA

1.1. Objective

To characterize mineralogical and geochemical aspects of uranium deposits related to granites and define the felsic igneous (granitic) rocks that have played the most relevant role as uranium sources, including understanding key processes such as successive fractionation in the different magmatic complexes, magmatic uranium enrichment and hydrothermal processes, alteration and uranium mobility.

1.2. Key results

The studies allowed refinement of the metallogenetic model of uranium deposits related to granitic rocks which will also aid in formulation of guidelines to better plan exploration activities. Granites play an important role as a uranium source and hosting diverse types of uranium mineralization and the knowledge gained from this research will assist in development of new uranium prospects and resources related to granites in Argentina.

2. CANADA

2.1. Objective

To increase the understanding of the genesis of various types of uranium deposits in diverse geographical and geological environments via analyses of their geochemical and mineralogical characteristics.

2.2. Key Results

Geochemical data obtained during the first two years of the CRP were shared with the IAEA and participants in the CRP. The second research coordination meeting was held at Queen's University, Canada. The chief scientific investigator, Mr Kyser provided mentoring and advice to many of the CRP participants and organized a tour of the excellent laboratory facilities at the university.

3. CHINA

China had two projects, focusing on sandstone-type and granite-type environments, respectively.

Mineralogical characterization of sandstone uranium deposits in China

3.1. Objective

To identify additional uranium resources, develop guidelines on uranium mining and production and to enrich databases on sandstone-type uranium deposits.

3.2. Key results

Ten major sandstone-type uranium deposits in China have been studied and estimated resources were increased by 100–500 tU. The outcomes of this study will aid in the comparison of various deposits and in particular in the establishment of the relationships between permeability, uranium mineralization and uranium recovery by leaching. This will also be used to predict the leaching properties for newly discovered deposits. There is an expression of interest from organizations in China to use the outcomes of this study in order to develop a software establishing a database which relates the mineralogy of deposits with leaching methods to predict the leaching technology.

The relations of A-type igneous rocks to uranium mineralization in south China

3.3 Objective

To determine the genesis of A-type syenite and granite assemblages and sodium-metasomatic uranium deposits in the Jiling area.

3.4. Key results

Paleozoic A-type syenite and granites in the Jiling area were formed by mixing between crustal- and mantle- derived magmas. Ore forming fluid was derived from mixing between magmatic fluid and meteoric water, and the uranium was derived from the host A-type granitic rocks. The results of this programme will be used to formulate guidelines for future exploration in the area and other areas with similar lithologies.

4. EGYPT

4.1 Objective

Evaluation of P₂O₅ and uranium in El-Sebaiya and Abu-Tartur areas to determine the added value (recovery of uranium and rare earth elements (REE)) from phosphate deposits in Egypt.

4.2. Key results

The inferred phosphate resources in El-Sebaiya area are about 80 million tons with an average of 90 ppm uranium and is depleted in REE and low in thorium. The Abu-Tartur phosphate is enriched in REE with about 0.2% but poor in uranium and thorium (25 and 4 ppm respectively).

The El-Sebaiya area has the best potential for added value through recovery of uranium and Abu-Tartur through recovery of REE.

5. FRANCE

5.1 Objective

To improve the understanding of the genesis of uranium deposits by measuring and comparing the REE from a wide range of deposits from variable geological settings (from deep magmatic to surficial conditions).

5.2. Key results

It was determined that the REE patterns are specific to each deposit type and that they directly reflect the conditions of their genesis. REE patterns and associated trace elements may represent an efficient tool for: (i) constraining geological models of uranium deposits; (ii) genetically discriminating new uranium discoveries; and (iii) forensic studies (isotopic tracing of deposits). However, additional experimental work is needed to improve the interpretations.

6. GHANA

6.1. Objective

To investigate the potential of the late Devonian to early Carboniferous Takoradi Shale Formation (TSF) in Ghana to host uranium, thorium and other trace elements.

6.2. Key results

The rocks have a uranium content of 6.9 to 9.0 ppm with an average concentration of 8.3 ppm, thorium contents range from 18.1 to 22.1 ppm and total REE range between 271 ppm and 368 ppm. Thorium, zirconium, niobium, tantalum, vanadium, total REE and titanium, which are typically enriched in uraniferous black shales, are also enriched in the Takoradi Shale Formation (TSF). However, the black shales of the TSF have lower concentrations of uranium compared to typical uraniferous black shales and therefore are of limited interest as a potential source of uranium.

7. ISLAMIC REPUBLIC OF IRAN

7.1. Objective

Investigation of uranium mineralization potential of Islamic Republic of Iran's sedimentary phosphates using geochemistry and mineralogy.

7.2. Key results

The major factors controlling uranium enrichment in sedimentary phosphates include environment of formation; phosphate mineralogy; amount of organic matter; P_2O_5 grade; redox conditions, (Eh and pH) at the time of phosphate deposition; paleo-climatic conditions; and weathering. According

to the above factors, the phosphorite horizons of Pabdeh Formation have the potential for uranium enrichment. Uranium in phosphorite horizons of Sheikh Habil, Kuh-e Kumeh, Choram, Khormoj and Kuh-e Rish deposits are in a range of 88 to 108 ppm, 17 to 69 ppm, 19 to 57 ppm, 12 to 40 ppm and 10 to 41 ppm uranium, respectively. In the phosphate deposits of Pabdeh Formation, the main host of uranium is apatite.

8. KENYA

8.1. Objective

To develop and utilize machine learning to enable multimodal spectrometric methodologies for direct geochemical characterization of Kenya's high background area comprising thorium and uranium bearing rocks.

8.2. Key Results

Machine learning was developed and applied/tested to a number of techniques including: laser induced breakdown spectroscopy (LIBS) and its new extension, laser ablation molecular isotopic spectrometry (LAMIS); energy dispersive X-ray fluorescence and scattering (EDXRFS) spectrometry; laser Raman microspectrometry (LRM); laser induced fluorescence (LIF) spectroscopy; and laser scanning microscopy (LSM), to develop a multimodal protocol for direct geochemical analysis and characterization of thorium and uranium bearing mineral rocks from Kenya's alkaline-carbonatite complexes. This work will be used towards development of a multimodal protocol relevant to mineralogical and geochemical characterization of uranium and thorium, as well as to their extraction and sustainable exploitation.

9. MADAGASCAR

9.1. Objective

To find a new deposit of uranium in the Morondava sedimentary basin (Makay Formation) in Madagascar.

9.2. Key results

Due to issues with procurement of equipment required for the geochemical analyses, this work was not fully completed. However, the field work and sample collection were completed, and the analytical work will be undertaken once the equipment is received through the related IAEA Technical Cooperation project.

10. MONGOLIA

10.1. Objective

To determine elemental fingerprints including rare earth element (REE) distribution patterns of Mongolian uranium deposits.

10.2. Key results

As a result of complications to obtain UO_2 concentrates, bulk samples from the Mongolian uranium deposits were studied instead. A REE pattern with light rare earth element (LREE) enrichment was noted for Zoovh Ovoo, a sandstone-type deposit which represents a significant part of the total uranium resources of Mongolia. This geochemical signature can be used as a comparison tool for other potential deposits in Mongolia.

11. PHILIPPINES

11.1. Objective

To conduct a re-evaluation of known uranium-bearing base metal and iron deposits in Larap-Paracale mineralized district in Camarines Norte, Philippines and to verify previously identified areas with anomalous radioactivity, to assess the REE contents, and to determine if more detailed evaluations should be recommended for future studies.

11.2. Key results

The historical uranium anomalies previously delineated in the San Isidro and Capacuan area did not show anomalous uranium concentrations but showed relatively high thorium concentrations (equivalent thorium (eTh) of 1.7 to 23.2 ppm with an average of 9.9 ppm). The uranium content in the Paracale National-Sta Rosa Sur anomaly is approximately 13 ppm equivalent uranium (eU) based on radiometric data. The high uranium concentrations detected by gamma spectrometry at Nakalaya were confirmed. Data also indicated high uranium concentrations that were associated with the base metals such as copper, molybdenum, zinc, lead and iron.

12. UKRAINE

12.1. Objective

To investigate sources of the fluids and uranium for the sodium-metasomatites of the Central Ukrainian Uranium Province (CUUP) and to establish links with major crust-forming events.

12.2. Key results

The project provided a detailed mineralogical, geochemical and isotope-geochemical (Sr-Nd-Pb isotopes) characterization of the albitite-type uranium deposits. The results indicate a prevailing crustal source of the metasomatizing fluids. However, a plume-related mantle source is also important, as plume provided not only heat required for generation of hot fluids, but also contributed to elevated concentrations of a characteristic set of elements such as heavy rare earth

elements (HREE) and transitional metals (nickel, cobalt, copper, and zinc). These new results are important for the understanding of the nature and causes of sodium-metasomatism and related uranium mineralization, and for further exploration of albitite-type uranium deposits in other areas.

In association with the research conducted for this CRP, an international field trip, Uranium and Thorium Deposits of the Central Ukrainian Uranium Province was held 2–6 July 2018 with 26 researchers from nine countries (Australia; China; Ecuador; Estonia; France; India; Islamic Republic of Iran; Ukraine; and Bolivarian Republic of Venezuela attending).

13. BOLIVARIAN REPUBLIC OF VENEZUELA

13.1. Objectives

Geochemical and mineralogical characterization of the uranium-bearing phosphate rocks of the Navay deposit.

13.2. Key results

The phosphate rocks of the Navay Formation are an important source for manufacturing phosphorus fertilizer. Phosphate rocks of the Navay Formation have relatively high concentrations of uranium and yttrium and the range of total rare earth elements are higher than the average of other phosphate deposits that have been reported in the literature. As a follow up to the studies carried out under the CRP it was recommended that a more detailed study be undertaken to identify the total REE contents of individual sedimentary beds of the Navay Formation, in order to establish if the phosphate deposits could be economically mined for rare earth elements.

GRANITE-RELATED URANIUM DEPOSITS IN ARGENTINA. GEOLOGICAL CONTEXT AND NEW METALLOGENETIC STUDIES*

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*Preliminary results and some parts of this paper were presented at the IAEA International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2018). Vienna, Austria, 25-29 June 2018.

Abstract

In Argentina, Devonian-Carboniferous magmatism has played a very relevant role in uranium metallogenesis, driving magmatic and late-magmatic preconcentration processes, both within and in the periphery of the granitic massifs. This research has characterized different types and subtypes of uranium deposits linked to that fertile magmatism. These new studies on uranium minerals from uranium sites of interest have improved the metallogenetic knowledge of the granite-related uranium deposits, which in turn could aid the exploration for similar uranium deposits. It was determined that granites play an important role both as a uranium source and hosts of diverse types of uranium mineralization. Additionally, it is thought that, at the existing level of knowledge, there are prospects for the discovery and development of new uranium resources related to granites in Argentina.

1. INTRODUCTION

The National Atomic Energy Commission of Argentina (CNEA), in cooperation with the National University of Córdoba, has carried out the project entitled ‘Metallogenesis of Granite-Related Uranium Deposits in Argentina’ within the framework of an IAEA coordinated research project (CRP), entitled, ‘Geochemical and Mineralogical Characterization of Uranium and Thorium Deposits’. The project, whose main results are summarized in this paper, pursues the aim of improving the general knowledge of the granite-related uranium deposits to a better understanding of their potential to delineate new uranium resources [1].

Late Paleozoic magmatic activity is well developed in the central-western part of Argentina including San Luis, Cordoba, La Rioja, San Juan, Catamarca, Santiago del Estero and Tucuman provinces (Figure 1). This Devonian-Carboniferous magmatism has played a very relevant role in uranium metallogenesis, driving magmatic and late-magmatic preconcentration processes, both within and in the periphery of the granitic massifs. In addition, these granitic rocks are considered good sources of uranium for the formation of more recent sedimentary deposits.

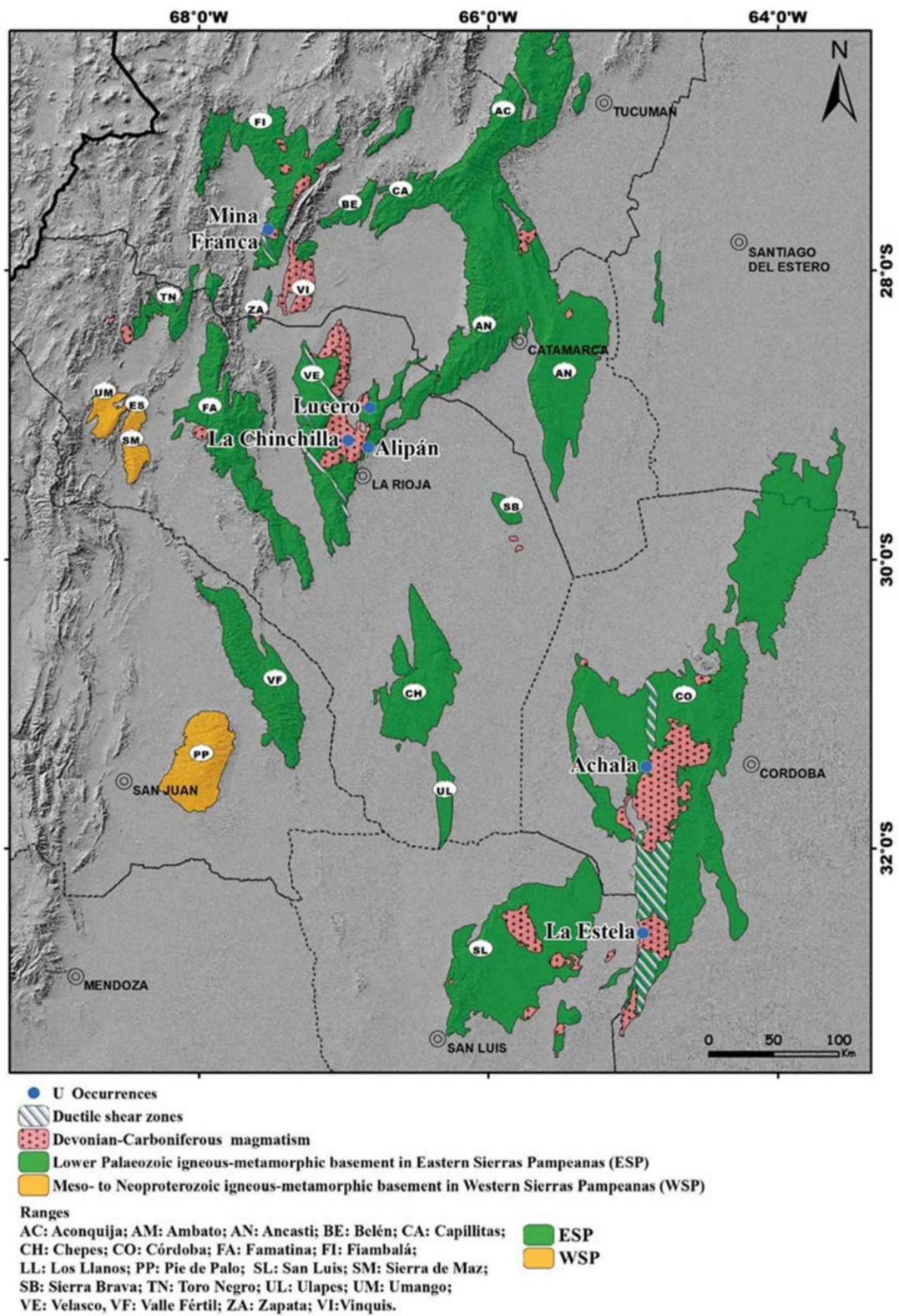


FIGURE 1. Regional geologic map of Devonian–Carboniferous magmatism in Sierras Pampeanas Range, Argentina. Modified from [2].

The voluminous magmatic activity that occurred between ca. ca. 359–322 Ma (Carboniferous magmatism) [3] and 390–365 Ma (Achalian Orogeny) [4] and consists of both batholiths and plutons that were emplaced in metamorphic or granitic complexes, some with differentiated S-type signature, whereas other have A-type characteristics.

This research allowed the characterization of different types and subtypes of uranium deposits linked to fertile magmatism. Several metallogenetic studies have been carried out in order to improve the geological, structural, geochemical and mineralogical knowledge of uranium deposits related to granites. Additionally, efforts have been made to define those felsic igneous rocks that have played the most relevant role as uranium sources and to characterize the relationship between magmatic uranium enrichment and hydrothermal deposits, alteration and uranium mobility.

Intragrantic episyenite-subtype deposits with disseminated uranium mineralisation (pitchblende, pyrite, and hexavalent uranium minerals) hosted in the peraluminous leucogranites of the Achala batholith (368 Ma) are comparable to those from the Middle European Variscian chain. The La Estela deposit corresponds to an endogranitic vein-type model and is located in the Cerro Áspero – Alpa Corral batholith (358 Ma); the mineralisation occurs as fluorite-pitchblende veins (uranophane, autunite, and gummite) hosted in high K calc-alkaline granites. There are also exposures of the perigranitic vein/stockworks subtype located in the metamorphic basement enclosing high potassium calc-alkaline granites. An example of this type of deposit is the Franca deposit, located in the periphery of the Los Ratonés granite (335–340 Ma) in the Sierra de Fiambalá (north-western Pampean Ranges). The mineralisation is mainly controlled by N to NE fracture zones to the west and northwest border of the pluton, and dominantly consists of pitchblende and hexavalent uranium minerals. This perigranitic subtype is also represented by the Alipan and Lucero deposits (sooty pitchblende, pyrite, and hexavalent uranium minerals), located in the Velasco Ranges and related to the Huaco (358–330 Ma) and Pinchas granitoids. La Chinchilla leucogranitic pluton corresponds to the intrusive type, plutonic (quartz monzonite) subtype uranium deposits with magmatic oxyuranopyrochlore-columbite-(Fe) accessory assemblage and a supergene carlosbarbosaite and uranophane low-grade disseminated mineralisation.

2. METHODOLOGY

General tasks carried out during the project include both geological field work and specific metallogenetic determinations at specialized laboratory facilities of different institutions.

Eight field trips were carried out at different sites of uranium interest in order to perform geological characterization, sampling and ground gamma-ray radiometric surveys. Geologic-structural mapping, alteration studies, systematic radiometry and complementary gamma-ray spectrometric measurements were carried out in anomalous uranium sectors.

Specific petrographic, mineralogical and chemical determinations can be summed up as follows:

- Petrographic and mineralogical studies of thin polished sections by using polarized light microscopy (transmitted and reflected light) at the CNEA laboratories
- Chalcographic studies and alpha-autoradiographies of uranium perigranitic mineralization hosted in metamorphic rocks, including different types of alteration and uranium minerals at the CNEA laboratories;

- Thin polished sections of selected unaltered minerals were analysed using a CAMECA SX100 electron microprobe (EPMA) at the GeoRessources Laboratory, Lorraine University (Nancy, France). The major elements were measured (U, Pb, Th, Ca, Si, Al, Ti, Fe, Mn, V, Na, Nb, La and Y);
- U-oxide geochemistry of selected mineralisation was determined using Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) at the GeoRessources Laboratory. For each experiment, 14 REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu), U-238, Pb total and a series of trace elements were analysed;
- Thin sections of gneisses and granites were analysed by Scanning Electron Microscopy (SEM) and electron probe microanalyser (EPMA). SEM was performed using a QUANTA FEG 450 instrument while EPMA was implemented using a JEOL JXA8900R instrument. Both instruments belong to the Denver Microbeam Laboratory, USGS, Denver;
- Mineralogical determination of perigranitic uranium mineralisation by X-Ray Diffraction (XRD) with a Philips PW 1800 instrument of the LAMARX Laboratory, National University of Córdoba was done. These samples were also analysed with a portable XRF Thermo Niton equipment at the CNEA;
- Major and minor geochemical analyses of granite, aplite and pegmatite dykes, phyllite, schist and granitic mylonite samples and determination of beta and gamma radiometric U, total chemical U, major and trace elements of U minerals were carried out at CNEA laboratories;
- Chemical analyses of granites, pegmatites and schist samples by Neutron Activation Analysis (NAA) were accomplished at the Argentine Research Reactor RA-3 (CNEA);
- Petrographic, X-Ray Diffraction, short wave infrared spectrometry (SWIR) reflectance spectrometry, portable infrared mineral analyzer (PIMA) and scanning electron microscopy studies were performed in trench samples to characterize hydrothermal/supergenic alteration belts in the metamorphic host. These studies were carried out in cooperation with the Argentine Geological Mining Survey (SEGEMAR).

Previously completed and new results have been interpreted within a general magmatic-metallogenic context and taking into consideration IAEA World Distribution of Uranium Deposits (UDEPO) criteria [5].

3. GEOLOGICAL SETTING

The Sierras Pampeanas of Argentina are elongated blocks of crystalline basement that were exposed by tilting during Cenozoic Andean tectonics. Caminos [6] was the first to recognize different groups based on lithological differences; an eastern group of sierras dominated by abundant Paleozoic granites and metasedimentary rocks (Eastern Sierras Pampeanas), and a western group characterized by ultrabasic and carbonatic rocks (Western Sierras Pampeanas) (Figure 2).

The Eastern Sierras Pampeanas are mainly made of low-to-high grade metasedimentary rocks of Paleoproterozoic to Early Ordovician age and extensive granites of Paleozoic age, including Cambrian (Pampean), Early Ordovician (Famatinian) and Devonian–Carboniferous (Achalian and Gondwanan) magmatisms. The present study is focused on the last group of igneous rocks.

Devonian to Carboniferous granitoids can be divided into two groups according to their absolute ages and geological characteristics, as follows: Middle to Upper Devonian granitoids (e.g. Achala and Cerro Áspero batholiths) and Lower Carboniferous granitoids (e.g. Huaco, Los Ratones, Pinchas and Chinchilla). These two groups of granitoids belong to different tectono-magmatic events that developed in the Eastern Sierras Pampeanas. The first group correspond to the Achalian event and the second group to an Early Gondwanan event [7, 8]. Intrusive bodies appear aligned along prominent shear zones involving ductile and brittle-ductile deformation developed during the Famatinian orogeny and was reactivated during Devonian and Carboniferous times.

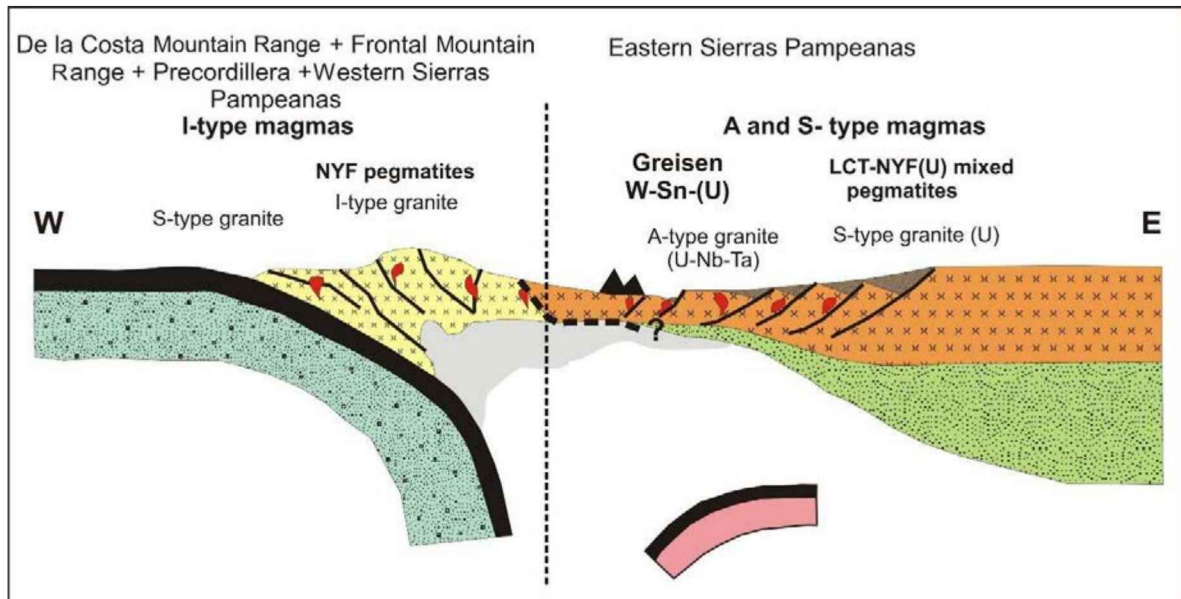


FIGURE 2. Tectonic environment of Carboniferous uranium-rich magmatism and related mineralisation events. Modified from [9].

4. STUDY AREAS

4.1. Achala batholith U District

The ‘Hercynian’ peraluminous Achala batholith (approx. 2 500 km²) located in the Sierras de Córdoba is composed of several magmatic suites and numerous facies (Figure 3) [10]. Two-mica monzogranites are the most exposed lithology. Muscovite (± almandine-rich garnet) monzogranite is the most evolved rock that occurs as marginal plutons or facies. The magmatic cycle ends with intragranitic niobium-yttrium-fluorine (NYF) or mixed family pegmatites of the beryl-columbite-phosphate subtype, enriched in Be and U and aplitic-pegmatitic dikes of simple mineralogy [11]. U-Pb dating of zircon for the most important granite type (i.e. coarse grained to porphyritic two-mica monzogranite) yielded an Upper Devonian age. Rb/Sr and K/Ar dating obtained from whole granite rock and pegmatitic muscovites, respectively, have yielded a Carboniferous age [12].

The uranium occurrences of the Achala batholith are located in the western part of the massif (Figure 3). On the one side, the batholith exhibits on its surface numerous hexavalent uranium mineralisations hosted in feldspar episyenites, which are generated by the intensive

dequartzification and sodium metasomatism of the granite. These episyenites are distributed along magmatic shear zones and host both hexavalent uranium minerals and Fe-oxyhydroxide, produced as the result of the oxidation of the pitchblende–pyrite paragenesis [13].

On the other side, in Don Alberto and Sala Grande sites, mineralisation lies in metamorphic rocks [14], where the mineral assemblage has been described as ‘cordierite-apatite-uraninite-muscovite-biotite-chlorite-feldspar-quartz’ in nodules within pegmatites penetrating gneissic roof pendants [15]. Additionally, at the Los Riojanos site, the fracture that hosts uranium mineralisation lies in muscovite granite.

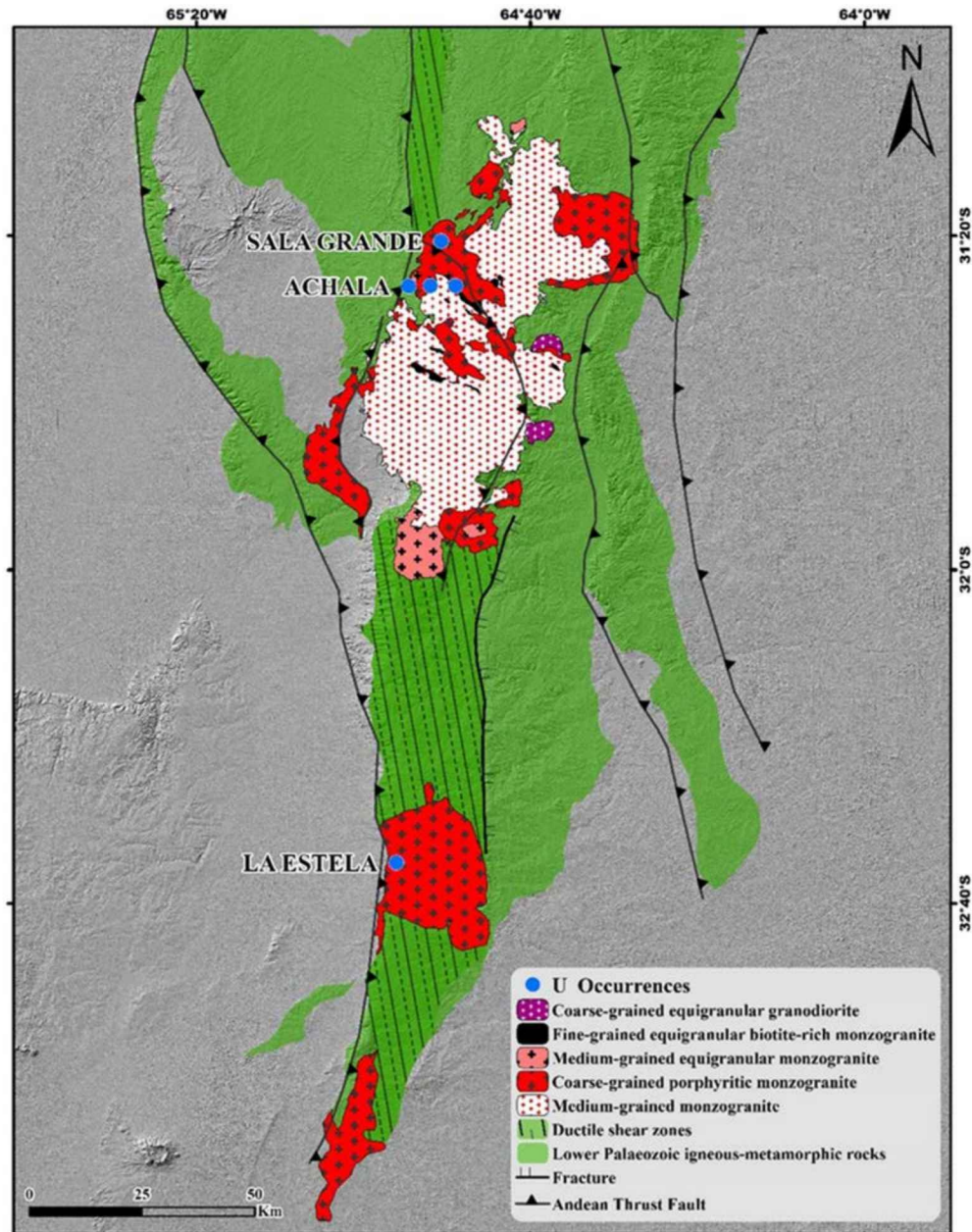


FIGURE 3. Hillshade Aster GDEM image with geological map of Achala and Cerro Áspero batholiths and pre-Devonian basement, modified from [16].

4.1.1. Don Alberto U mineralisation

Uranium mineralisation is hosted in biotite gneiss intruded by porphyritic two mica granite and later, in the contact surface, by a cordierite-bearing pegmatite body that corresponds to late-magmatic activity. Cordierite shows two textural varieties: idioblastic and xenoblastic. The latter is poikilitic with biotite, zircon, apatite and euhedral uraninite inclusions (Figures 4a, b). Also, uraninite is included in biotite and muscovite showing concentric radioactive halos and marked radial fractures (Figures 4c, d).

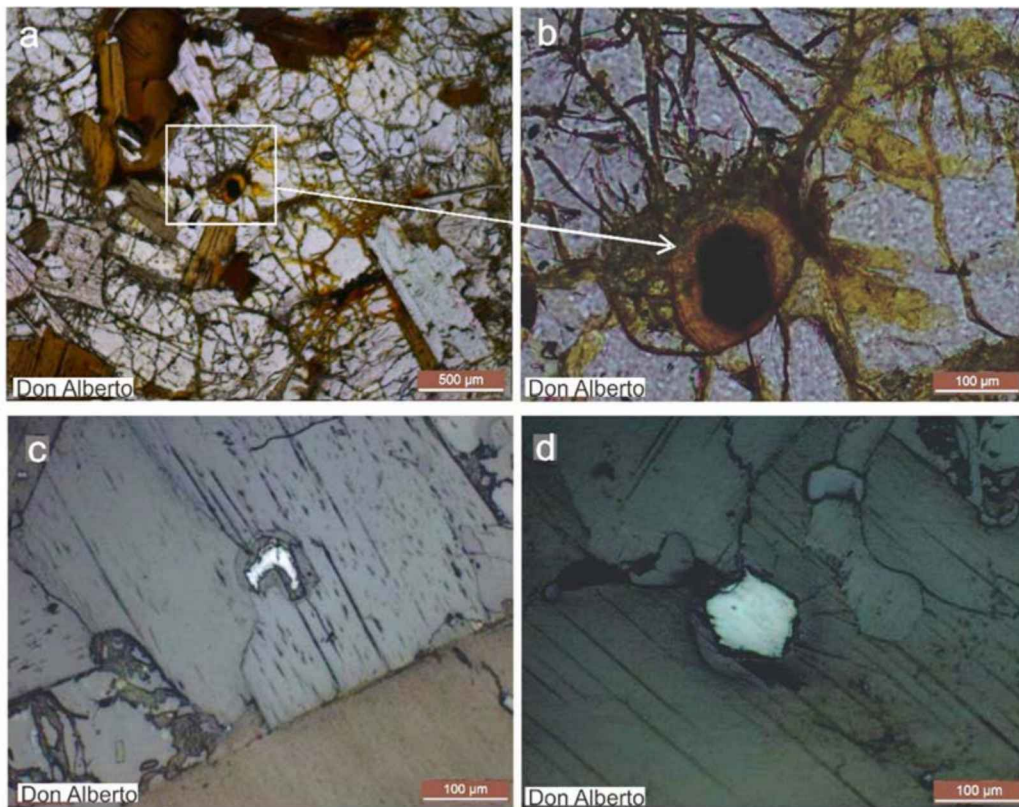


FIGURE 4. Microphotographs of euhedral uraninite: a- Gneiss texture and mineral assemblage (quartz, cordierite, biotite and plagioclase); b- Detail of uraninite with metamict halo, oxidized border and radial fractures in cordierite (transmitted light); c- Euhedral uraninite with metamictic halo and radial fractures in muscovite (reflected light); d- Radial fractures in biotite and muscovite (reflected light).

Uranium oxides from Don Alberto are euhedral uraninite grains and analyses show significant Th content (about 1 wt% ThO_2) which indicates a high temperature origin (Figure 5). They have between 2.7 and 3.8 wt% PbO corresponding to chemical ages between 255 and 325 Ma. Their yttrium content is not significantly enriched (0.07 to 1 wt% Y_2O_3), but the highest value corresponds to an altered U-oxide (characterized by the lowest UO_2 : 86.2 wt% and PbO: 0.1 wt% and the highest SiO_2 : 7.58 wt% and CaO: 3.18 wt%, compared to the other analyses).

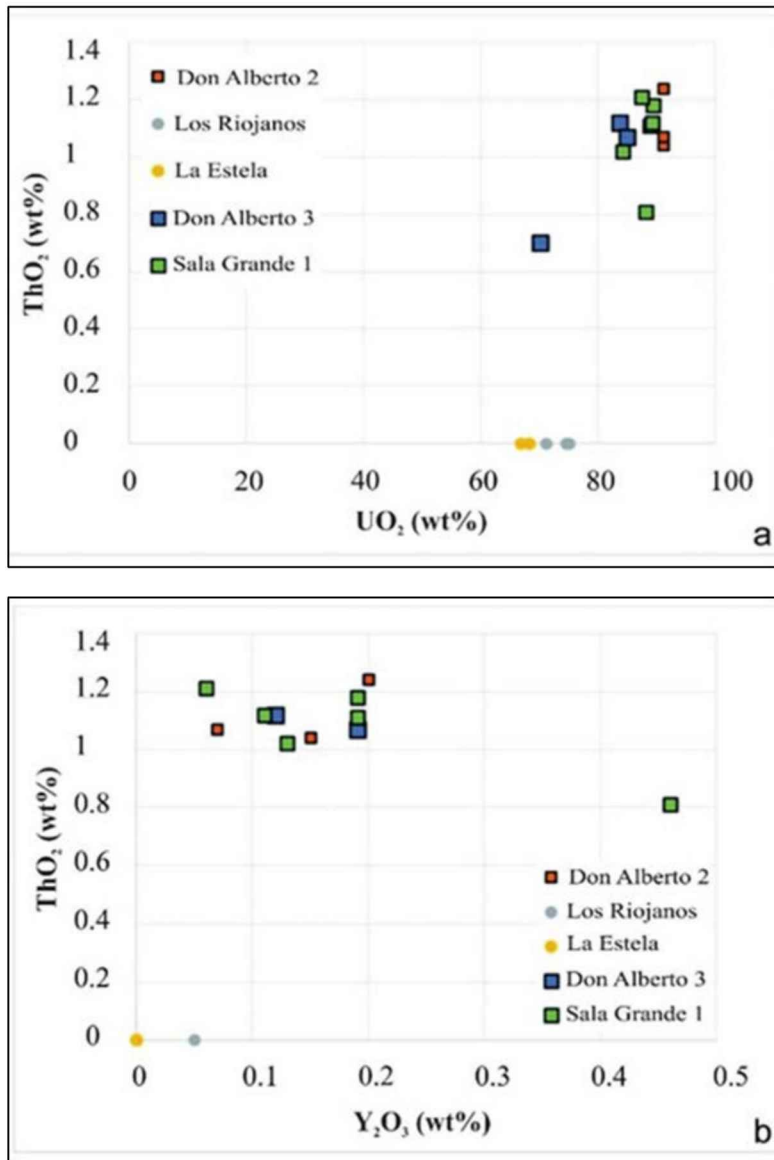


FIGURE 5. a) UO₂ vs ThO₂ and b) Y₂O₃ vs ThO₂ for the U-oxides from different sites.

The global fractionation of the REE patterns and the high REE contents of the U-oxides have been studied in two samples (Don Alberto 2 and 3). Figure 6 shows the results of sample Don Alberto 3, where points DON 3.2 and DON 3.3 are identical and only analysis of point DON 3.1 has slightly lower REE contents. These patterns are similar to those found for magmatic uraninite of the Rössing deposit in Namibia [17], but with lower total REE.

The other trace element patterns of these U-oxides are also similar, with significant enrichment in W, Zr and Mn and more limited enrichments in B, As, W, except two points sampled (DON 2.1 and DON 2.2) which are not enriched in Mo, W and Ti. They are all very poor in Nb.

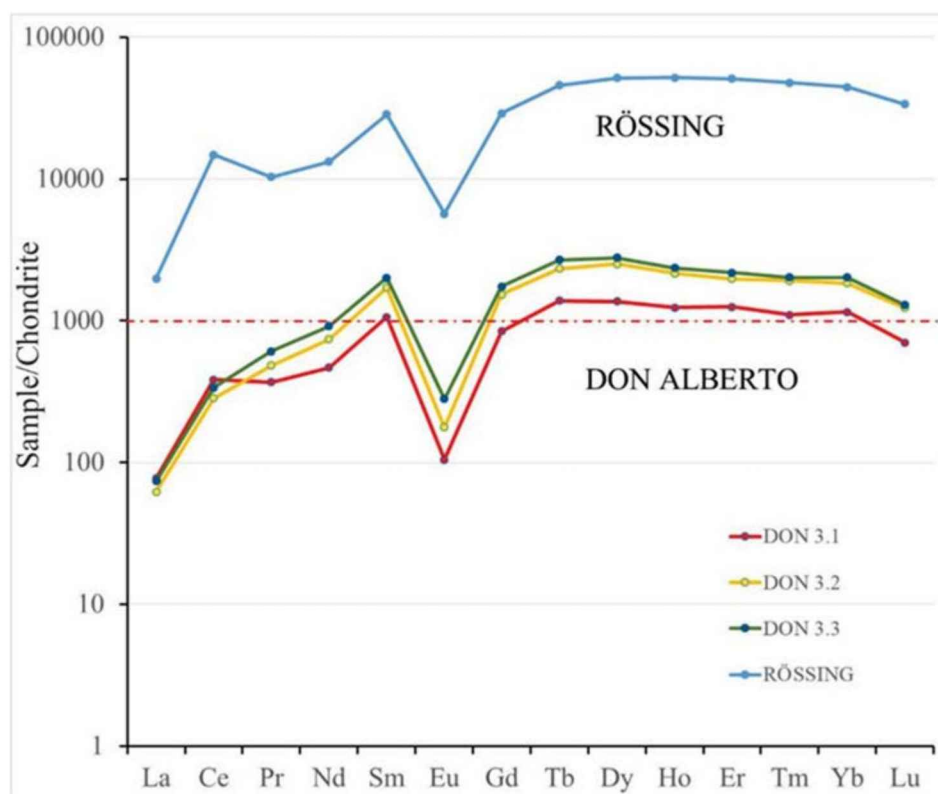


FIGURE 6. Chondrite normalized REE patterns of U-oxides from Don Alberto 3 (DON 3.1, 3.2, 3.3) and Rössing U deposit.

4.1.2. Sala Grande U mineralisation

Uranium mineralisation occurs in the subhorizontal contact between biotite ($\pm$ sillimanite) gneiss and the granitic surface of the Achala batholith. In this site, the metamorphic host is a roof relict that has been transformed by contact metamorphism to a hornfels at hornblende facies. The granitic facies in Sala Grande is a two-mica porphyry, similar to Don Alberto. The hornfels contains hexagonal-shaped uraninite and zircon inclusions, both with pleochroic halos. Uraninite is partially altered to yellow oxidized uranium mineral (possibly uranophane) (Figures 7 a, b).

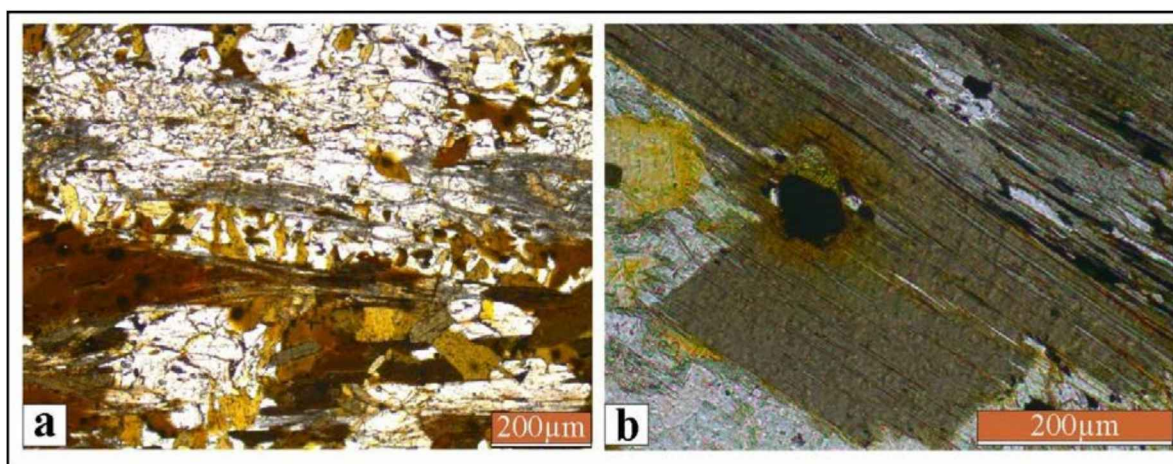


FIGURE 7. Transmitted light photomicrographs: a) spaced foliation microtexture of biotite-cordierite gneiss; b) Partially altered euhedral uraninite included in biotite.

Uranium oxides from Sala Grande 1 has a ThO_2 content of about 1% indicating high temperature uraninite (see Figure 5). REE contents are equivalent to those of Don Alberto occurrences, which indicates a similar environment and formation processes. REE patterns of the sample studied (2 analytical points) from Sala Grande are shown in Figure 8.

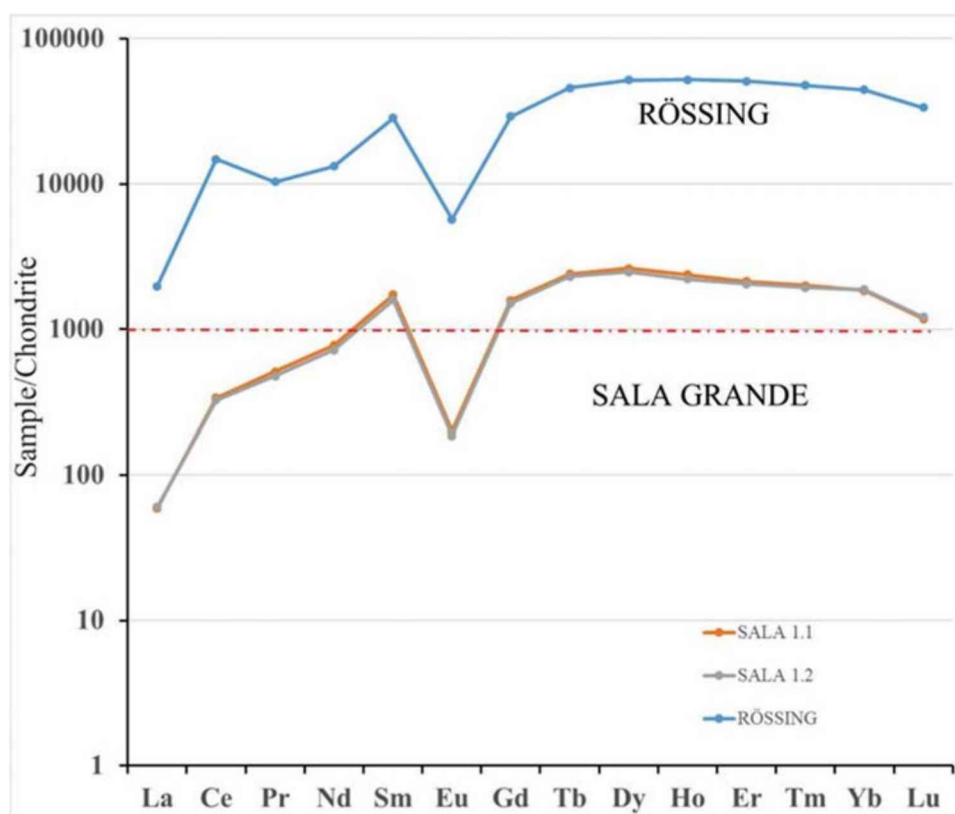


FIGURE 8. Chondrite normalized REE patterns of U-oxides from Sala Grande occurrence in comparison with Rössing U deposit.

4.1.3. Los Riojanos uranium mineralisation

The main uranium mineralisation is hosted in a cataclastic belt affecting the equigranular muscovite granite. These cataclastics are made of recrystallized fine-grained granitic matrix and low temperature hydrothermal quartz. The sample studied is from drill core (44 m depth). The uranium mineralisation occurs within a 0.5 mm thick vein, associated with pyrite and quartz (Figures 9 a, b). This vein shows a mortar texture formed by crushed and recrystallized quartz grains. Both the vein and small cavities are filled with pyrite and sooty pitchblende [18].

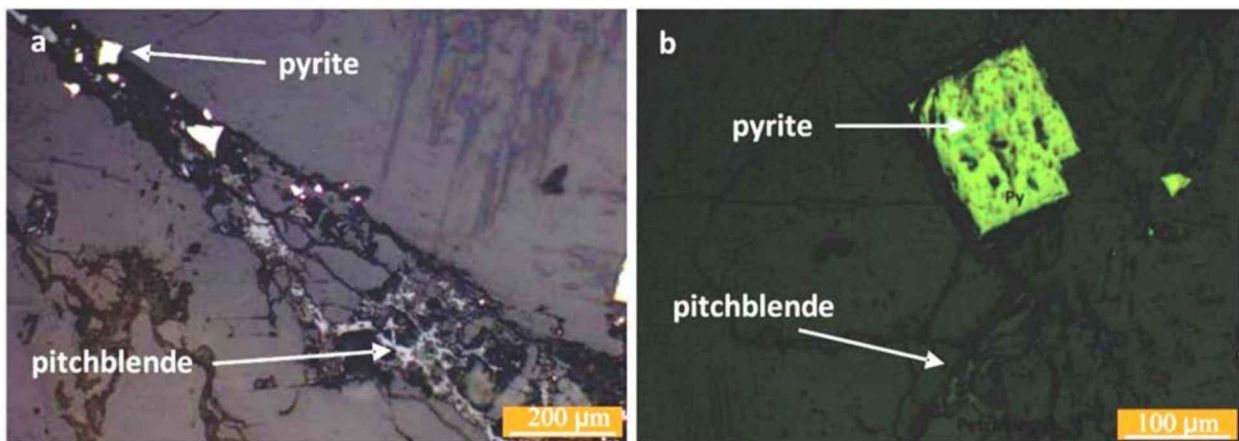


FIGURE 9. Reflected light microphotographs of mineralized fractures: a- Fissure filled with cubic pyrite and sooty pitchblende; b- Detail of cubic pyrite crystal with grey pitchblende filling micro-fractures.

Uranium oxides from Los Riojanos have no detectable thorium content but have significant yttrium (0.47–1.01 wt% Y_2O_3) and calcium (3.49–4.46 wt% CaO) concentrations with low to moderate silica contents (1.7–3.21 wt% SiO_2), indicating a low temperature hydrothermal origin.

4.2. Cerro Áspero U District

The Middle to Late Devonian Cerro Áspero batholith (440 km²) was formed by the emplacement of Alpa Corral, El Talita, and Los Cerros plutons which are aligned in a NNW direction, intruding the Guacha Corral mylonite shear zone (Lower Paleozoic). This batholith shows a geochemical evolution characterized by a progressive increase in alkalinity and aluminosity [19]. For the Alpa Corral pluton a Rb/Sr isochron established a crystallization age of 369 ± 9 Ma (Early Devonian) [20]. Granites belong to the high K series with initial $^{87}Sr/^{86}Sr$ higher than 0.704, which would suggest a cortical anatexis origin [20].

There are some 15 post-batholithic vein-type fluorite-chalcedony deposits that can also host uranium minerals. These deposits occur as veins uniformly distributed throughout the border zone of the Cerro Áspero batholith, and they are closely related to pervasive silicification and argillitic alteration of the host granite [17]. In La Estela mine, fluorite is spatially associated with pitchblende and other uranium minerals such as uranophane and meta-autunite.

4.2.1. La Estela U deposit

La Estela deposit belongs to the endogranitic model and was emplaced in the Cerro Áspero batholith in the western slope of the Sierra de Comechingones. This deposit was mined from 1953 to 1990 and produced 36 tU at an average grade of 0.07% U. Resources are estimated at 1500 tU.

The U mineralisation is linked to black fetid fluorite veins (antozonite) filling a poly-phase brecciated granite (Figures 10 a, b, c). Primary minerals include pitchblende, fluorite, pyrite and probably chalcopyrite in a silica gangue. These minerals appear in surface and in drill cores at up to 120 meters deep. Secondary uranium minerals are uranophane and to a lesser amount autunite and meta-autunite. Yellow to reddish-brown mixtures of hydrous oxides of uranium ('gummite') are associated with botryoidal pitchblende nodules (Figure 10 d). These minerals are disseminated and covered fractured areas close to the mineral body.

According to SEM studies 10 μm coffinite and pitchblende inclusions in pyrite with antozonite and second stage fluorite assemblage precipitated at 136–122°C (microthermometry of fluid inclusions) [18]. Neutron activation data also show 123 ppm U content in antozonite crystals whereas fluorite from other stages has only 0.5 ppm U. Pitchblende age according to [19] U/Pb method is 23 ± 1 Ma (early Miocene), with other pulses that give ages of 10 and 12 Ma.

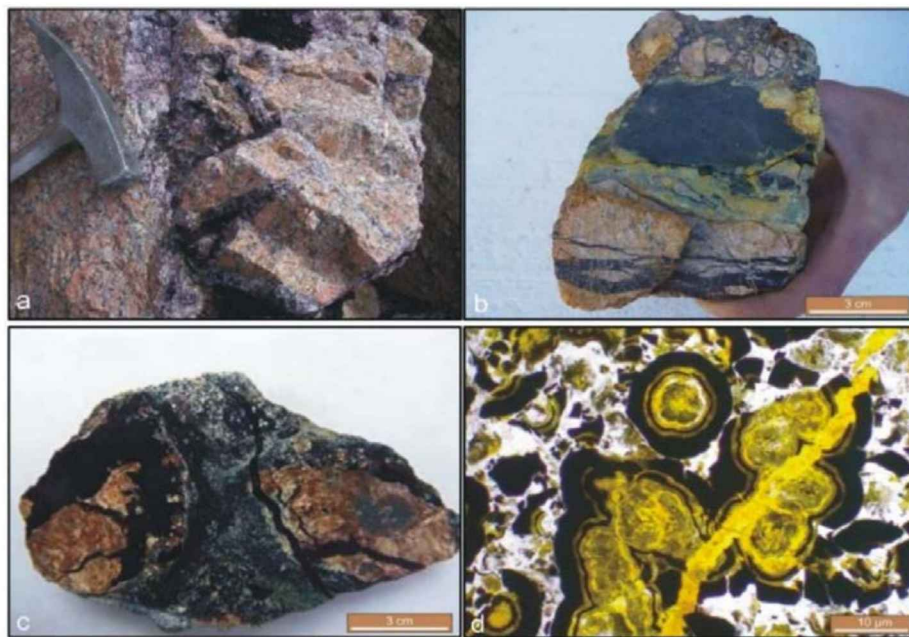


FIGURE 10. a) Outcrop showing granite with mineralized fluorite stockwork; b) Lenticular pitchblende partially altered to yellow oxidized uranium minerals and fractures with antozonite; c) Fluorite-pitchblende-pyrite breccia granite; d) Microphotograph of botryoidal pitchblende surrounded and cut by yellow hexavalent uranium minerals.

Uranium minerals from the La Estela deposit do not have detectable thorium and yttrium contents (see Figure 4) and shows relatively high Si (14.82 and 15.47 wt% SiO_2) and Ca concentrations (6.91 and 6.67 wt% CaO), corresponding to a coffinite type composition [20].

REE patterns of U-oxides are similar to deposits associated with granites, but with an important negative Ce anomaly indicating the involvement of highly oxidized conditions being able to oxidize Ce^{3+} to the weakly mobile Ce^{4+} and a very high abundance in total REE (Figure 11).

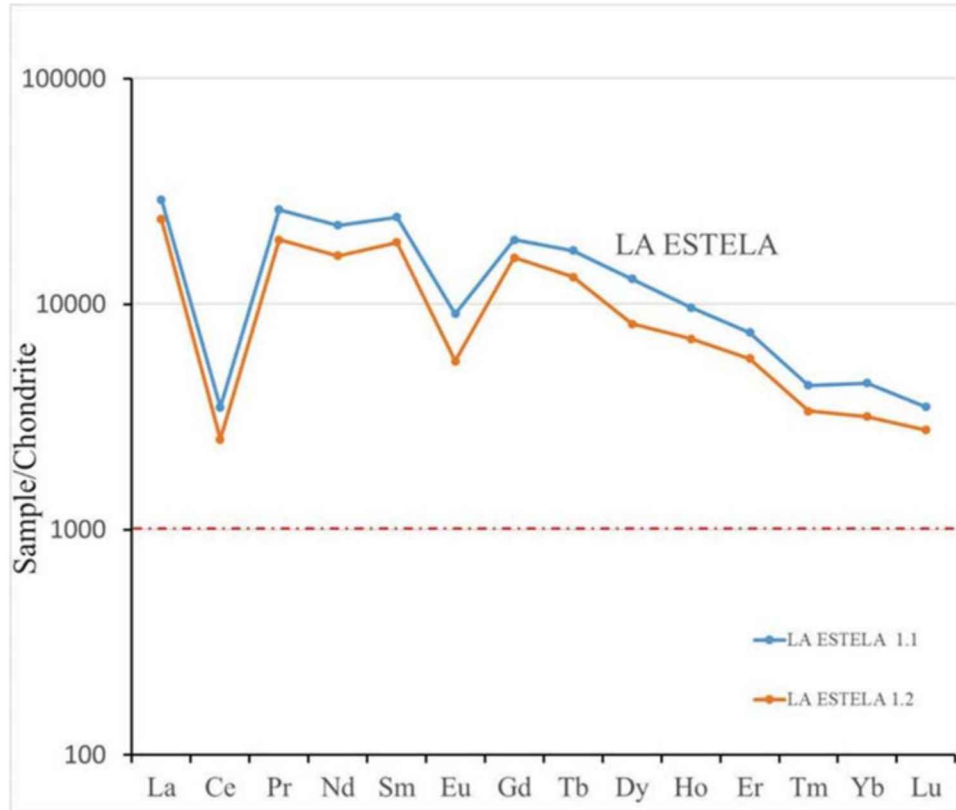


FIGURE 11. Chondrite normalized REE patterns of U-oxides from La Estela deposit.

Their trace element patterns (Figure 12) are characterized by a very high abundance of elements associated with hydrothermal granite related deposits (B, As, Mo, W, Mn) but also less mobile elements such as Ti, Nb and Zr.

Figure 13 shows primary REE and a series of other trace element contents determined by LA-ICPMS of Achala and Cerro Áspero U deposits. The procedure described in [17] has been followed, where after electron microprobe analysis only the unaltered areas of uranium oxides and with a crystal size exceeding the diameter of the ablation spot were analysed.

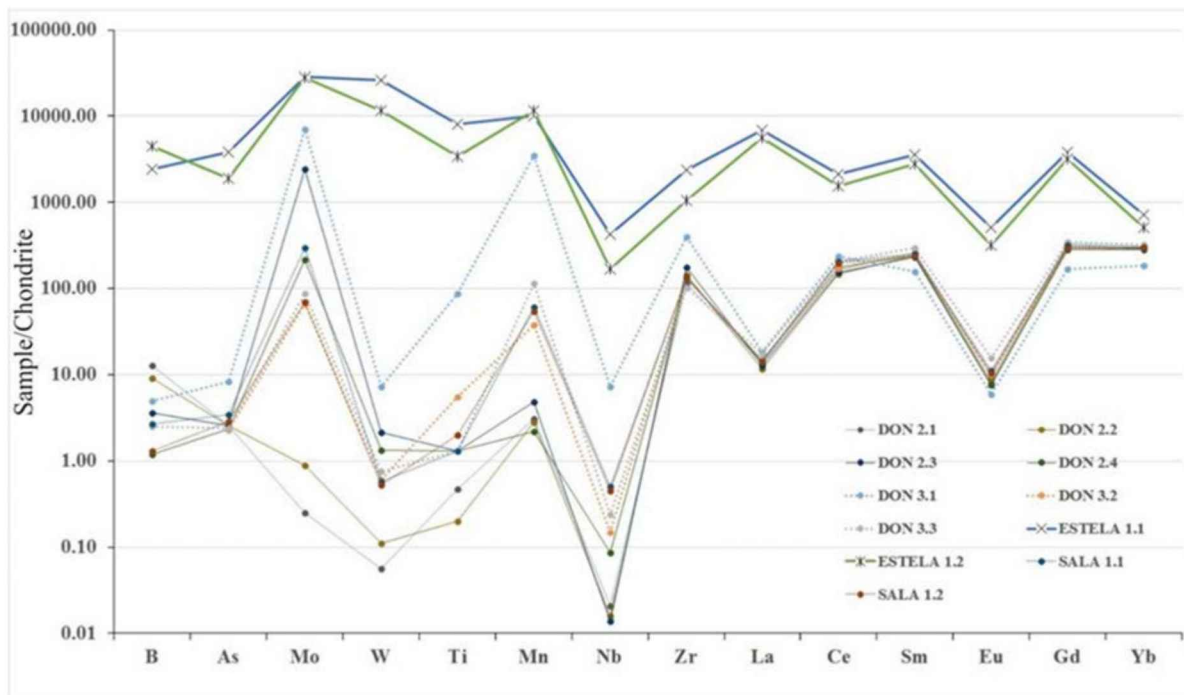


FIGURE 12. Trace element spider plots of the U-oxides from different uranium deposits from Argentina. LA-ICP-MS analyses. DON = Don Alberto 2 and 3, ESTELA = La Estella, SALA = Sala Grande.

4.3. Sierra de Velasco U District

Sierra de Velasco range extends in La Rioja province and constitutes the greatest plutonic outcrop of the Pampean Ranges [21]. Most of the plutons are made of peraluminous granites of Ordovician age generated during the Famatinian orogeny [22]. These Famatinian granites have been locally intruded by several Upper Devonian to Lower Carboniferous plutons, three of which were studied in this research: Huaco granitic complex related to the Alipan deposit; La Chinchilla pluton and Pinchas granite related to the Lucero deposit (Figure 13). Several ages have been reported for the Huaco granite: zircon U-Pb, LA-ICP-MS age of 354 ± 4 Ma [23] and monazite U-Pb, ID-TIMS ages between 350 ± 5 and 358 ± 5 Ma [24].

4.3.1. Alipan U deposit

Alipan uranium deposit is located in the eastern flank of Sierra de Velasco (Figure 14). The host rock belongs to the Ordovician basement of La Cebila metamorphic complex. This basement is in intrusive and tectonic contact with the Carboniferous Huaco granite to the west, and in tectonic or erosive contact with Tertiary piedmont deposits to the east.

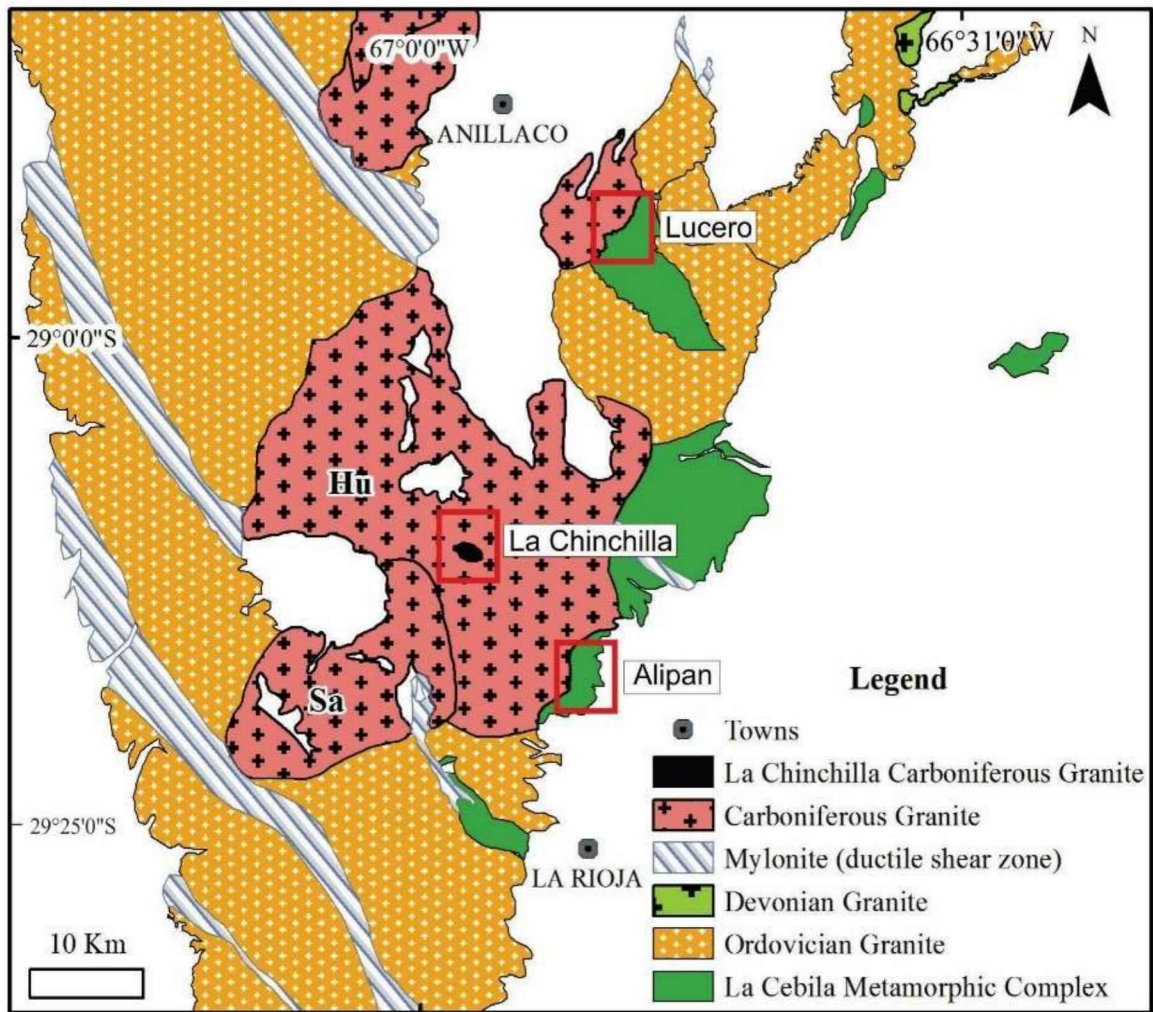


FIGURE 13. Regional geologic map of northern Velasco range with three main uranium sites: Alipan, La Chinchilla and Lucero occurrences.

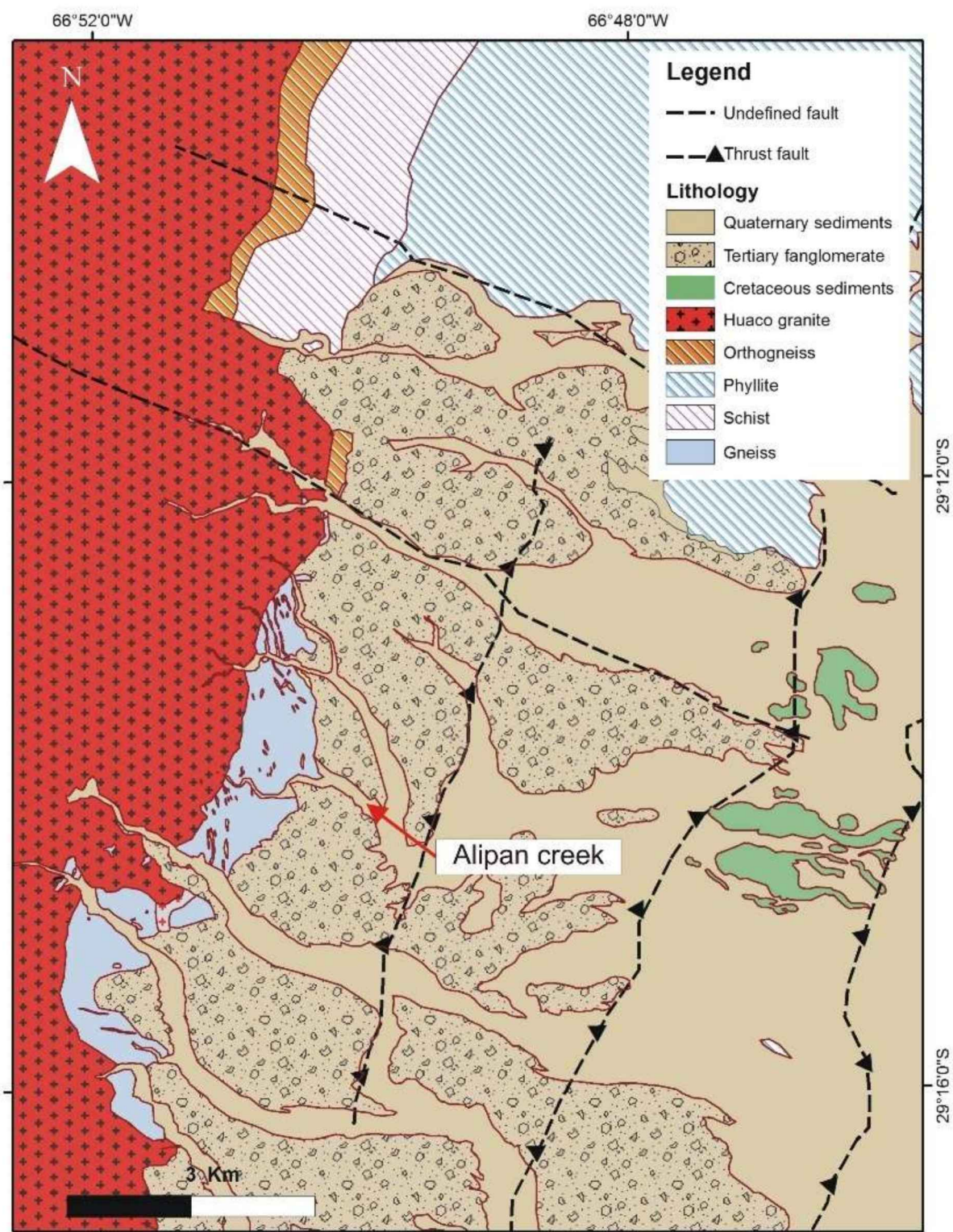


FIGURE 14. Detailed geologic map of Alipan uranium deposit.

A radioactive gamma-ray anomaly at surface is 2.5 km long and 300 m wide within a north-south discontinuous medium to high-grade metamorphic belt. Borehole information clearly defines a vertical, irregular and fault-controlled redox zone. An oxidized halo developed 30 m from surface hosts the main uranium mineralisation. Above approx. 30 m, the reduced zone contains quartz-pyrite and calcite, vertical veins that are crosscut by sooty pyrite and pitchblende in vertical fragile fissures and fractures.

Uranium minerals of the oxidized zone, such as uranophane and meta-autunite, can be observed at a macroscopic scale. They appear coating pores and fractures from 1 mm to 1 cm thick (Figure 15 a). Under the optical microscope, uranophane is present as greenish yellow crystals with micaceous or acicular habit (Figure 15 c). Meta-autunite is green, with platy habit. Samples of drill core from the reduced zone contain tetravalent uranium minerals such as pitchblende and coffinite (Figures 15 b, d) [25, 26]. Both are black minerals under transmitted light, and light grey with low reflectance under reflected light. They have a crustiform texture, filling fractures as monominerals or are associated with calcite and pyrite (Figure 15 e). Textural analysis in fractures has identified different mineralisation events, of which the most frequently observed is successive pulses of pyrite cut by veins with different amounts of silica and uranium.

There are different types of fractures. Breccia texture with euhedral grains of pyrite, plagioclase, calcite, muscovite and quartz inside a matrix are composed of different amount of silica and uranium (Figure 15 f). Furthermore, there is a zonal variation in composition with the edges being richer in pyrite and calcite and the core richer in uranium minerals. In other fractures the uranium minerals fill interstitial space between calcite crystals. These minerals are also disseminated in the rock, isolated or associated to different minerals: mica cleavage, partial or total substitution of cordierite and/or adsorbed in rutile. Pitchblende also occurs with botryoidal texture in corroded pyrite.

Chemical composition of pitchblende (average of $n=11$) is UO_2 80%, SiO_2 4.6% and CaO 3.9%, with minor amounts of Al_2O_3 (1%) and FeO (0.96%). The average chemical composition of coffinite ($n=14$) is UO_2 66.3%, SiO_2 13.3%, CaO 3.8%, Al_2O_3 2.54% and FeO 2%. There is evidence of an increase in the concentration of SiO_2 and a decrease in UO_2 , which is likely due to the process of coffinitization of pitchblende. Analysis of uranophane (average of $n=12$) UO_2 64%, SiO_2 13.8%, CaO 4.5% and minor constituents Al_2O_3 (0.4%), K_2O (1.77%) and FeO (0.4%). No appreciable radiogenic lead concentrations were found in any of the minerals.

XRD was performed on the samples with uranium minerals and uranophane was most abundant with other uranium minerals identified including, β -uranophane, meta-autunite, phurcalite and pitchblende [27]. The analysis was also performed on a fracture filled with uranium minerals obtained from a drill core sample with 2 600 cps (measured by a SPP2 type scintillometer) in which it was determined by XRD that the sample contained uraninite and quartz [28].

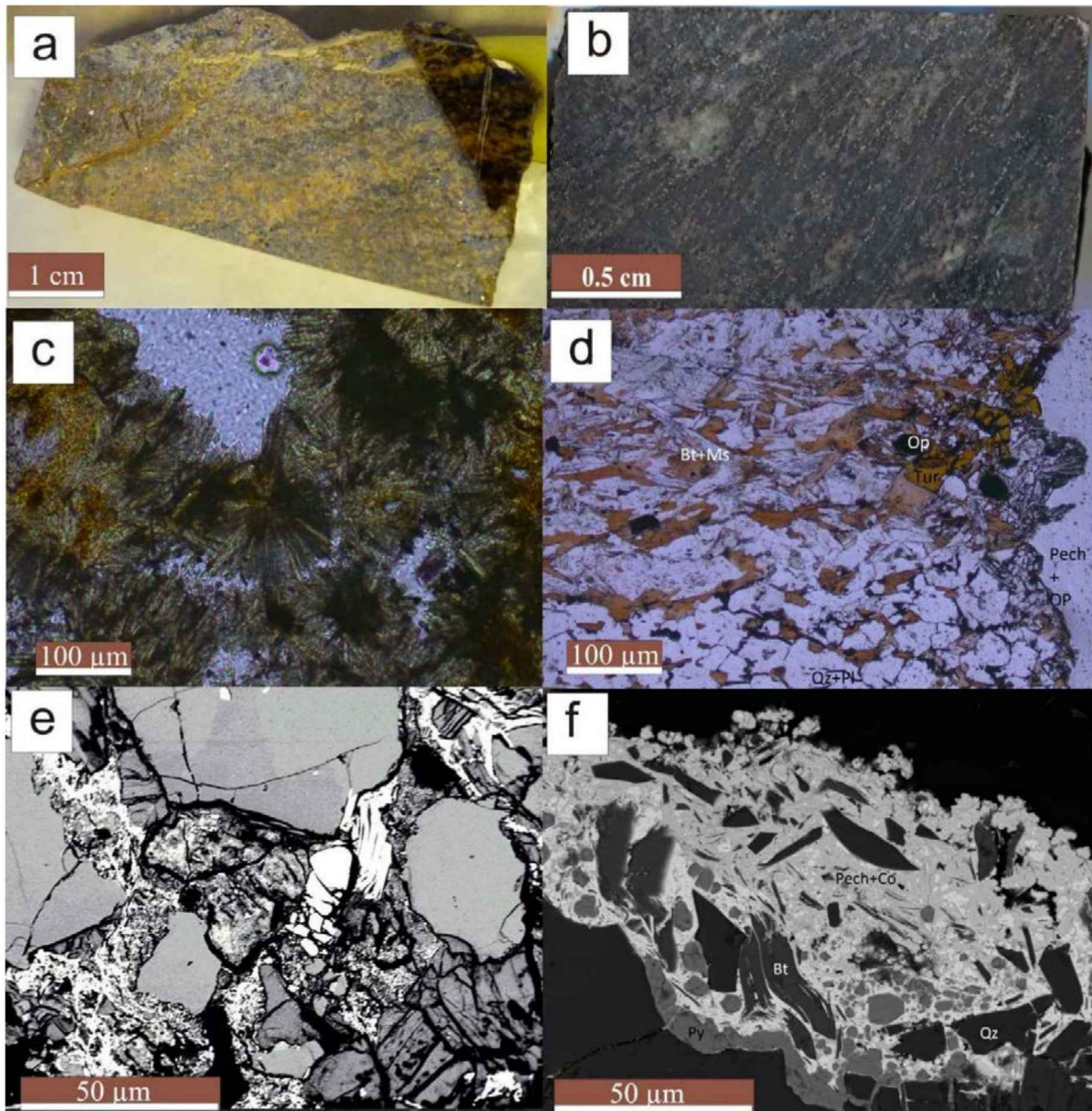


FIGURE 15. a) Photograph of mineralized gneiss with fractures filled with uranophane; b) Photograph of mineralized gneiss with pitchblende and coffinite in a reduced environment (2 cm bar); c) Radial uranophane micrograph; d) Microphotography of gneiss with pitchblende and coffinite as opaque mineral; e) Backscattered electron (BSE) image of uranophane (white) filling spaces between grains); f) Backscattered electron (BSE) image of fracture filled with a matrix of pitchblende (white) and coffinite (grey) and clasts of pyrite, biotite and quartz. Abbreviations: Pech: pitchblende; Co: coffinite; Py: pyrite; Bt: biotite; Ms: muscovite; Qz: quartz.

4.3.2. La Chinchilla U deposit

The Chinchilla pluton, located in the Sierra de Velasco Range, has been the subject of numerous investigations due to its complex and distinctive geochemistry, its varied and valuable accessory mineralogy and its high uranium content (Figure 16).

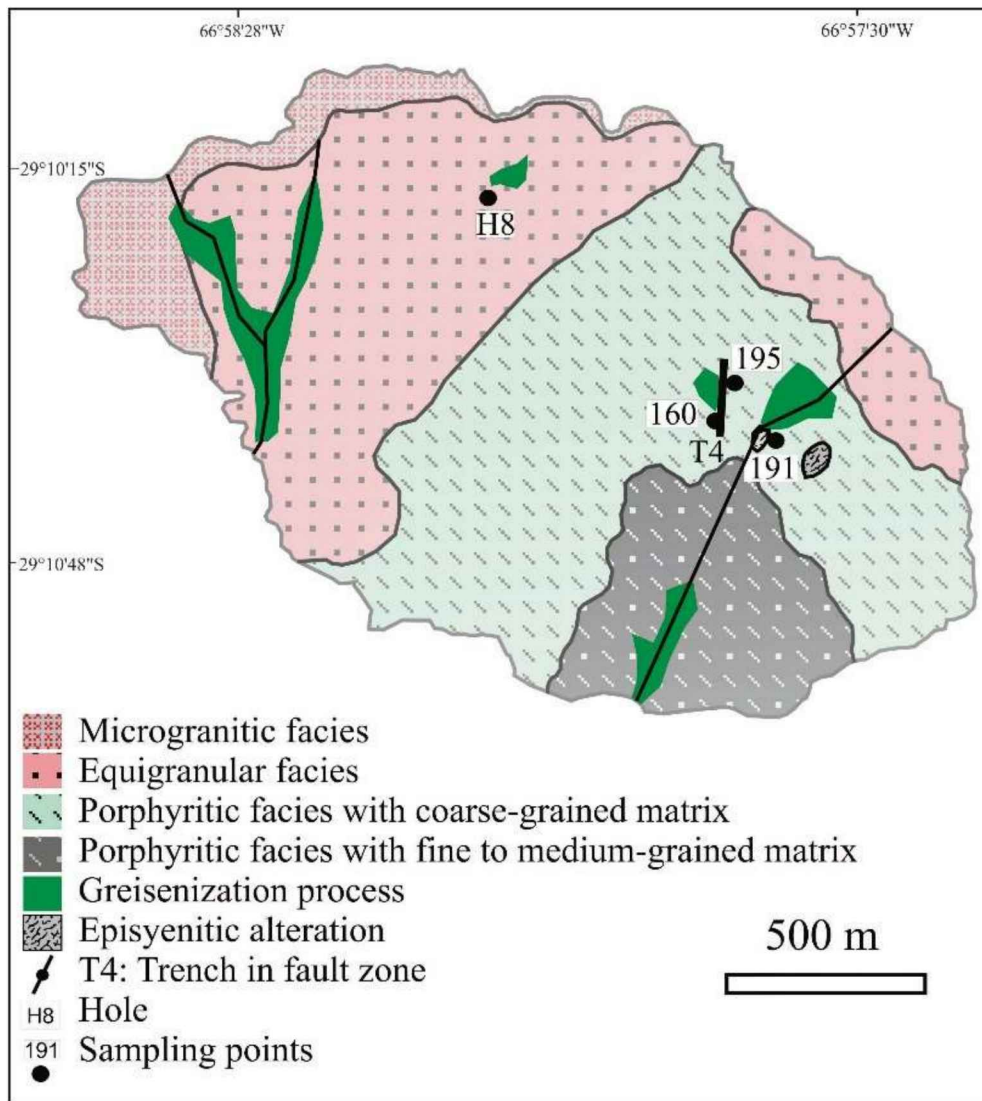


FIGURE 16. Detailed geologic-alteration map of La Chinchilla pluton [30].

La Chinchilla granite is an epizonal, sub-ellipsoidal shape intrusive body of about 3.75 km², with its major axis-oriented ESE. A 344.5 ± 1.4 Ma crystallization age was established according to U-Pb dating of monazite [24].

According to its textural and radiometric characteristics, three main granite facies have been distinguished: porphyritic (differentiated into fine and coarse matrix subfacies), equigranular and microgranite [29] (see Figure 16). The dominant equigranular and porphyritic facies corresponds to miarolitic-pegmatite and micromiarolitic granites, respectively [30].

The geochemical characteristics of the La Chinchilla granite are very distinctive. It is weakly peraluminous, rich in SiO₂, alkalis (8.4%) and F (accessory fluorite), with ferrous affinity (high Fe/Mg ratios), relatively poor in Fe₂O₃, MgO, CaO, Sr and Ba and very impoverished in P; shows enrichment in HFSE, mainly Y, Nb, Ta, Th, U, HREE and Li, Rb and Be [24]. With respect to

trace element values, although U and Th are found in high proportions in the three facies, the equigranular facies has the highest uranium and thorium contents (average: 119 ppm U and 32 ppm Th). Average Th/U ratio for equigranular facies is 0.38, 1.6 for porphyritic facies and 0.29 for microgranitic facies.

Accessory minerals of the porphyritic facies have been previously studied in detail [30]. For the current study identification of accessory minerals was carried out using BSE images and analysed by EDS and WDS. Oxyuranopyrochlore which occurs as inclusions in late smoky quartz and muscovite were investigated. EDS identified columbite-(Fe) which is commonly associated with oxyuranopyrochlore. Ilmenite has appreciable amounts of Nb that indicates a differentiated character of the intrusive. In addition to the previously mentioned minerals, xenotime and uranophane (rich in Nb, Ti and Th) inclusions in zircon have been described in drill cores.

Regarding the mineralogy of miarolitic pegmatites of equigranular facies, amazonite, beryl, oxy-calcio pyrochlore and cassiterite are identified, which reflects the NYF nature of the melt [31].

In addition, the supergene mineral carlosbarbosaite $[(\text{UO}_2)_2\text{Nb}_2\text{O}_6(\text{OH})_2 \cdot 2\text{H}_2\text{O}]$ has been identified in altered areas of granite [32] and also as secondary accessory phases disseminated in the unaltered micromiarolitic porphyritic granite. It occurs in intergranular contacts, fractures and/or cavities in aggregates of fine fibres. Microscopically it appears pale yellow to cream in colour, is slightly pleochroic from yellow to yellow greenish and EDS analysis exhibits compositions similar to those reported by Atencio et al. [33].

It is interpreted that fluids of meteoric origin affected the granite transforming the primary association oxyuranopyrochlore and columbite-(Fe) into carlosbarbosaite; no further evidence is available to establish a precise and balanced alteration reaction.

According to the level of current geological knowledge, the preliminary estimation of resources made in the equigranular facies indicates speculative resources of 990 tU @ 0.0159% U [34].

4.3.3. *Lucero U deposit*

Lucero uranium deposit is located in the northeast sector of the Sierra de Velasco range (Figure 17). The present metamorphic sequences of low to medium grade belongs to La Cébila metamorphic complex. These constitute an elongated NNE-SSW belt limited to both the ESE and WNW by syntectonic to post-tectonic granitoids. The main syntectonic unit is the Huaco granite where crystallization ages range from 481 ± 2.8 Ma dates for zircon by the SHRIMP U-Pb method [22] and 476.4 ± 1.5 to 461 ± 2.2 Ma dates from monazites by conventional U-Pb method [35]. Towards the NW of Lucero site, these units are intruded by the post-tectonic Pinchas granite, through a net and semi-circular contact. This granite is a pink to yellowish grey porphyritic to equigranular granite. Pinchas does not exhibit evidence of deformation and is assigned to the Lower Carboniferous magmatic event as well as the Huaco and the Chinchilla granites.

The Pinchas granite crops out in La Punta range and has two main facies: a pink porphyritic granite, with K-feldspar mega crystals and a light grey leucocratic equigranular granite. In addition, there is a set of aplitic and late banded pegmatitic dikes with synmagmatic contacts with the granite facies. Pegmatites emplaced in metamorphic rocks have banded texture and a varied mineralogy.

The sub circular-shaped pegmatites found in Pinchas are generally zoned, with a quartz core and quartz-albite-muscovite dominated wall zone. Well crystallized tourmaline and beryl are common in the wall zone with phengitic muscovite and Nb-Ta oxides with important U content. Geochemically, it is a peraluminous granite with an aluminium saturation index between 1.22 and 1.31 [36] and the sum of Na₂O and K₂O reaches normal to high values (7.2 to 8.0%).

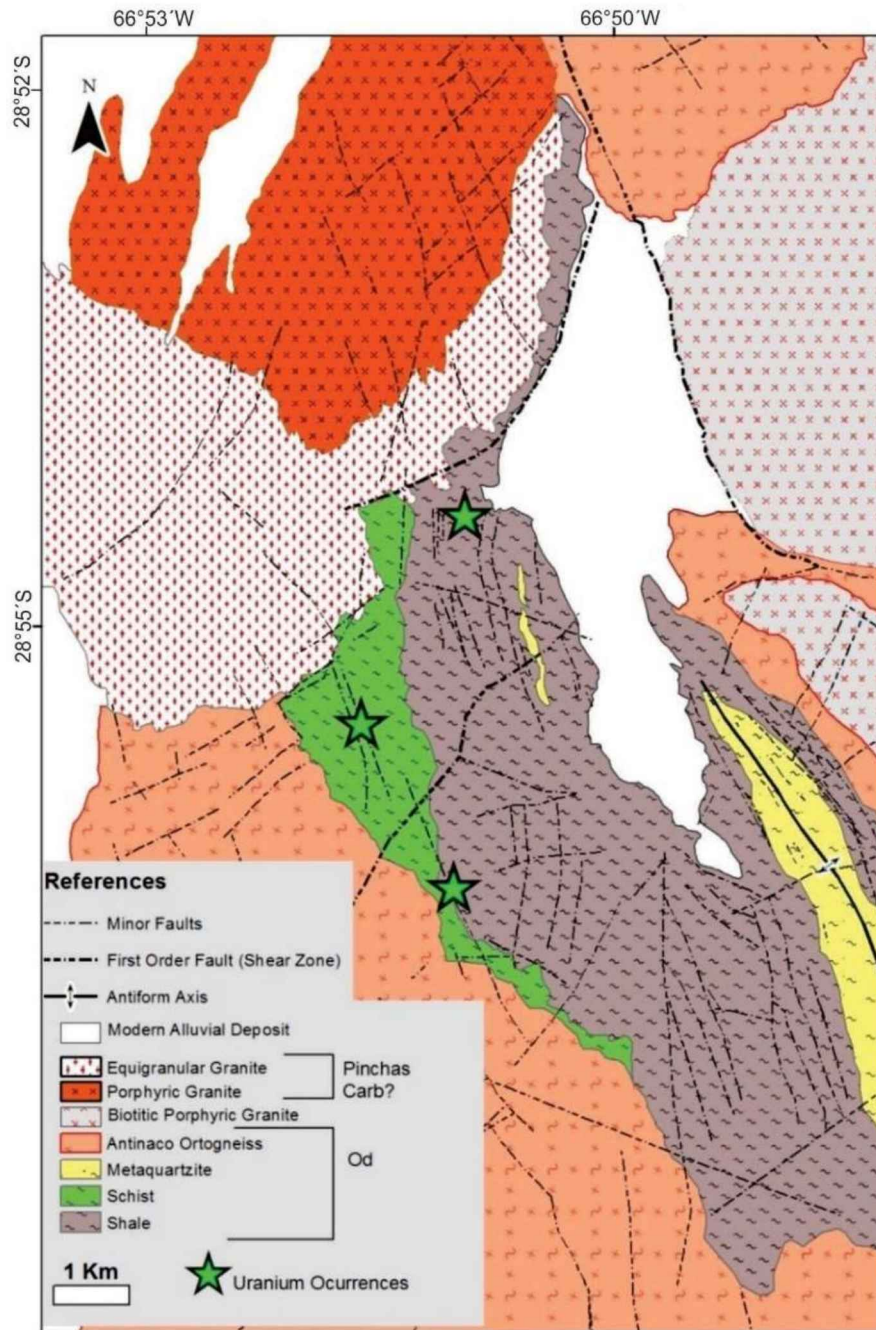


FIGURE 17. Geologic map of Pinchas granitic facies and La Cébila metamorphic complex.

There are uranium occurrences both in aplitic/pegmatitic facies of Pinchas granite and in the metamorphic rocks intruded by this granite. Pinchas granite shows albitization, which affected both the magmatic microcline and plagioclase, and the formation of secondary muscovite replacing biotite and feldspars. Phyllite and mylonitic schists of the La Cébila metamorphic complex host the most important uranium mineralisation within fractures or foliation planes. This schist displays an intense fracturing, hematite alteration and has been intruded by granite and pegmatitic dikes assigned to the Pinchas granite.

Mineralisation is composed of Na-uranospinite which has greenish-yellow, pale green and lemon-yellow colours, micaceous habit and strong green fluorescence (Figure 18 a). Phurcalite and uranophane are also present in fissures as powdery yellow-orange crusts or forming small fibrous aggregates of vitreous lustre on iron oxides (Figure 18 b).

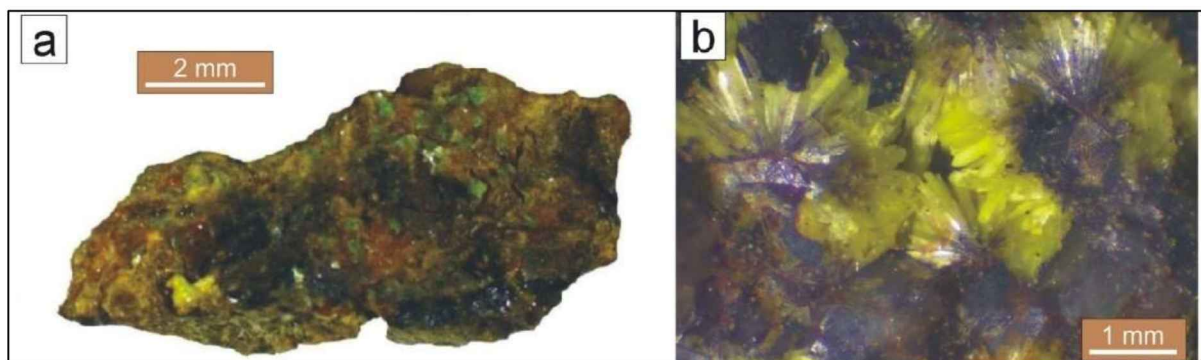


FIGURE 18. a) Sodium-uranospinite in phyllite; b) Phurcalite in quartz vein in phyllite.

Uraninite was observed as inclusion of zircon crystal in an isolated way. Both in aplites/pegmatites and porphyritic granite facies a Nb-Ta-U oxide (Figures 19 a, b) was identified which could preliminarily be classified as carlosbarbosaite [36] and/or other undefined species.

In metamorphic rocks the uranium mineralisation impregnates veins or is infilling cavities. When it is associated with tourmaline the uranium mineral is vyacheslavite $U^{4+}(PO_4)(OH) \cdot 2.5H_2O$ and is the first time that it has been identified in Argentina (Figures 19 c, d) [37].

Autunite, meta-autunite, uranophane, natrouranospinite and phurcalite appear near the contact with Pinchas Granite [36]. They are associated with quartz, fluorite veins and iron oxy-hydroxides in fragile and fragile-ductile structures.

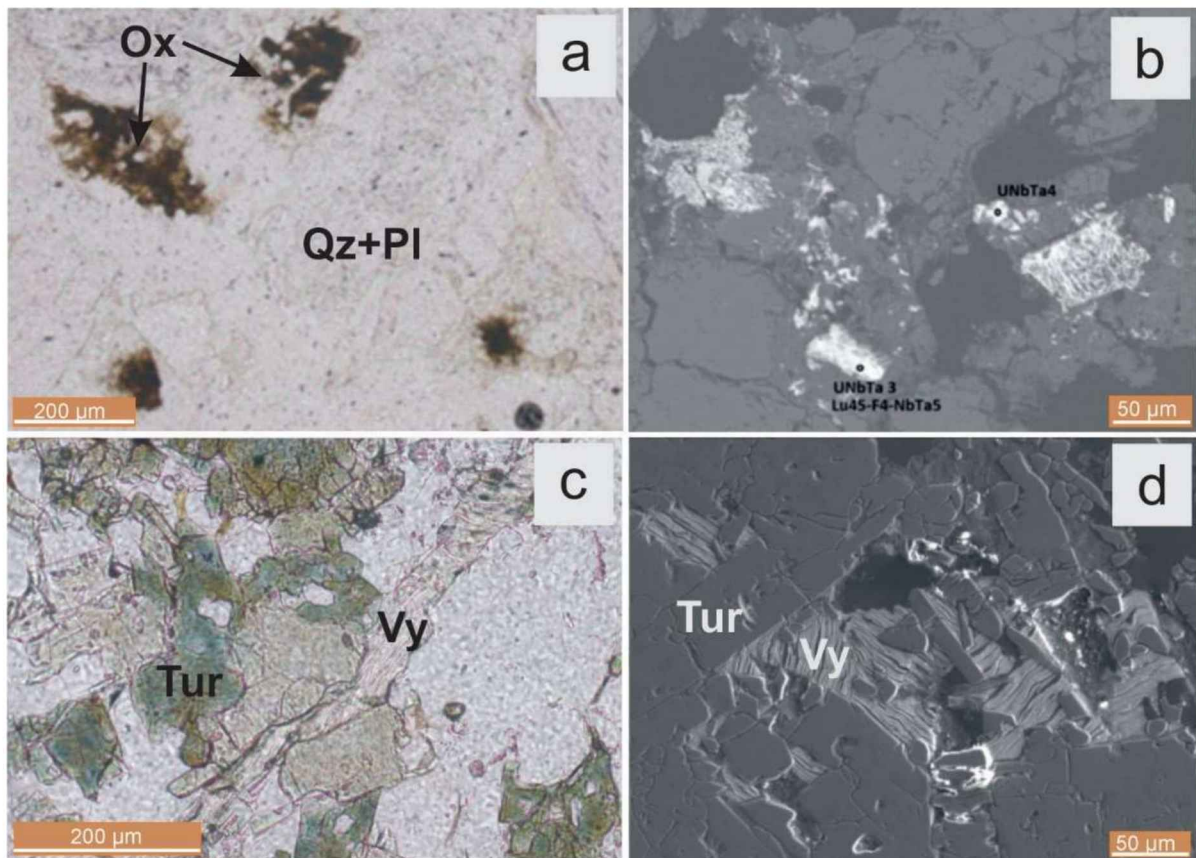


FIGURE 19. Microphotographs of: a- Nb-Ta-U $\pm$ Si oxide; b- BSE image from these oxides; c- Vyacheslavite vein in tourmalinite lenses; d- SEM relief image of Vyacheslavite. References: Ox: oxide; Qz: quartz; Pl: plagioclase; Tur: tourmaline; Vy: Vyacheslavite.

4.4. Fiambala U District

The Sierra de Fiambala is composed of a variable composition and grade of metamorphic rocks (phyllite, schist, gneiss, marble, amphibolite, meta-gabbro and migmatite). There are two large groups of intrusive rocks according to their field setting and age. One group of plutons of Neoproterozoic to Lower Palaeozoic age (545–480 Ma) [38] are deformed bodies that are generally concordant with the foliation of the metamorphites. The second group of intrusives are of Neopalaeozoic age (close to 330 Ma) [38, 39, 40]. They are discordant with the internal structure of the host rock and are located in more superficial levels than the previous group. These intrusives have been linked to different mineralisations of Sn-W-U.

4.4.1. Franca U deposit

The Franca mine area is composed of pelitic and quartz-feldspathic metasediments of Upper Precambrian to Lower Palaeozoic age. These have been intruded by the Los Ratones pluton of Carboniferous age (325 Ma in monazite) [41]. Los Ratones is a peraluminous/metaluminous granite and outcrops in the central sector of the Sierra de Fiambalá [42]. It contains two dominant facies with sharp contacts; one is porphyritic and the other is equigranular facies. Petrological characteristics of granites evolved from the high-K granite series are rich in fluorine.

There are five altered-mineralized belts in N-S direction. The largest of them is 1500 meters long and 300 meters wide. Studies of alteration carried out using a portable infrared mineral analyser (PIMA) confirm the presence of sericite, illite-smectite, montmorillonite, kaolinite, quartz, calcite and associated chlorite [43]. The altered belt has topaz, muscovite, fluorite and cassiterite indicating the presence of a greisen system that is well recognized in the sector [42, 44] (Figures 20 a–f). This greisen system affects both the metamorphic rocks and Los Ratones granite which exhibits albitization and microclinization [42].

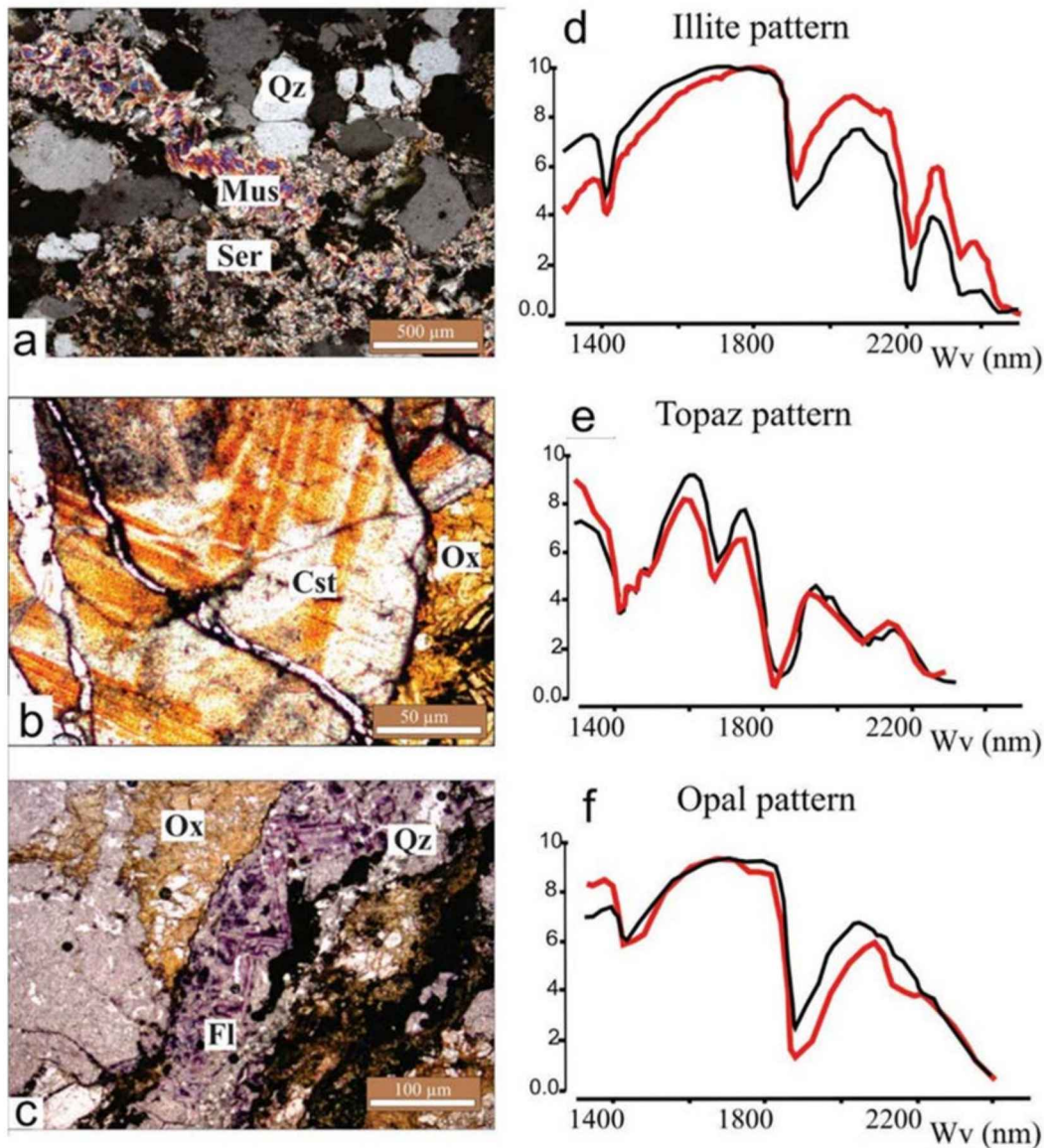


FIGURE 20. Photomicrographs : a) Argillic-sericitic alteration (Qz=quartz; Mus=muscovite; Ser=sericite); b) cassiterite (Cst) crystal, oxides (Ox); c-Fluorite (Fl) vein and associated silica (Qz) and oxides (Ox); d, e and f) infrared spectra obtained by PIMA corresponding to samples shown in adjacent photomicrographs [43].

The primary mineralisation is composed of pyrite and pitchblende associated with chalcopyrite, pyrrhotite, galena, sphalerite, electrum and subordinated cassiterite and wolframite. Based on textural and field relationships the following paragenetic sequence was established: cassiterite–wolframite; pitchblende–pyrite; chalcopyrite–pyrrhotite–melnikovite–galena–sphalerite–electrum. Sn–W mineralisation was intimately associated with the greisenization process, and mineralisation of uranium and pyrite is spatially linked to fluorite [44, 45]. The pitchblende appears in reniform masses, as spherulites of 1–4 mm in diameter, surrounded by euhedral crystals of blackish to bluish-violet fluorite. This association was replaced by a supergene paragenesis with torbernite, autunite, meta-autunite, meta-torbernite, saleeite, kasolite, coffinite, uranophane, phurcalite and parsonsite [46].

EDS and EPMA analyses were performed on oxidized samples with abundant presence of secondary uranium minerals [47]. The predominant uranium mineral is uranophane and the second most dominant one is kasolite, where the aluminium content seems to be higher (Figure 21).

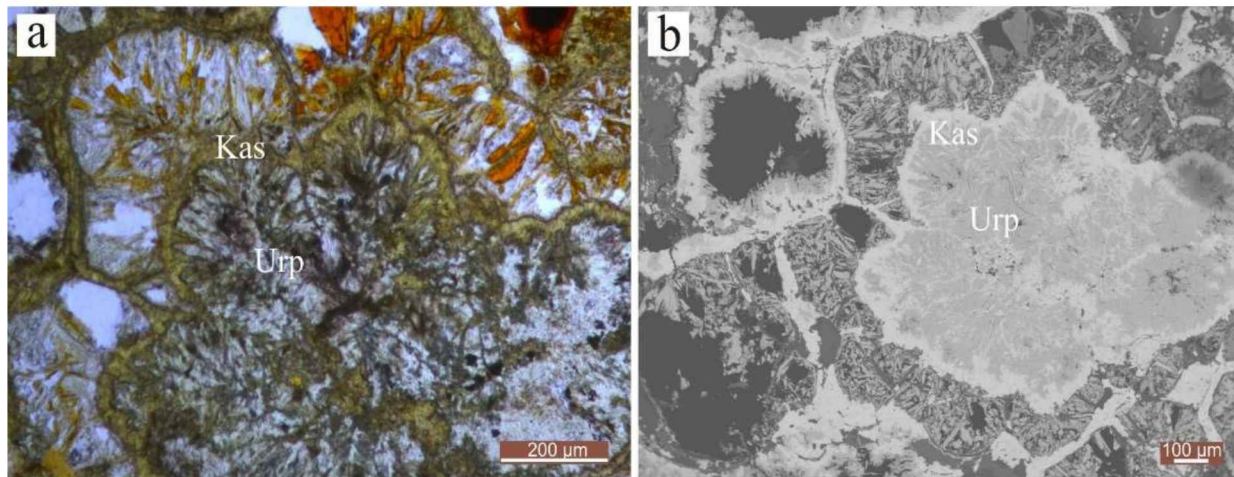


FIGURE 21. a) Photomicrography of kasolite (Kas) and uranophane (Urp); b) Backscattered electron image from the same association.

The only mineralisation age of 114–113 Ma was obtained by Morello [48]. This age was achieved by two different methods. One was by the measuring the A0 parameter of the pitchblende cell by XRD. The other age was acquired by the $\text{Pb}^{207}/\text{U}^{235}$ isotopic method which provided two ages, one of 113.6 Ma and another of 51.4 Ma.

5. MAGMATISM CHARACTERIZATION AND ASSOCIATED MINERALISATION

Data and interpretations obtained during this study in conjunction with information published by other authors, have allowed the characterization of the different magmatic uranium sources.

In an A–B chemical mineralogical diagram [49] (Figure 22), it was observed that in general all samples correspond to highly differentiated magmatism. Most of the samples (except for a set of samples corresponding to La Chinchilla) plot in the peraluminous domain. Within this domain a

high percentage of samples plot in the leucogranitic field, more specifically in field I, with predominance of muscovite over biotite. Other samples corresponding to the Cerro Áspero, Achala, Huaco and to a lesser extent Los Ratones plot in the field II with biotite > muscovite and III with biotite.

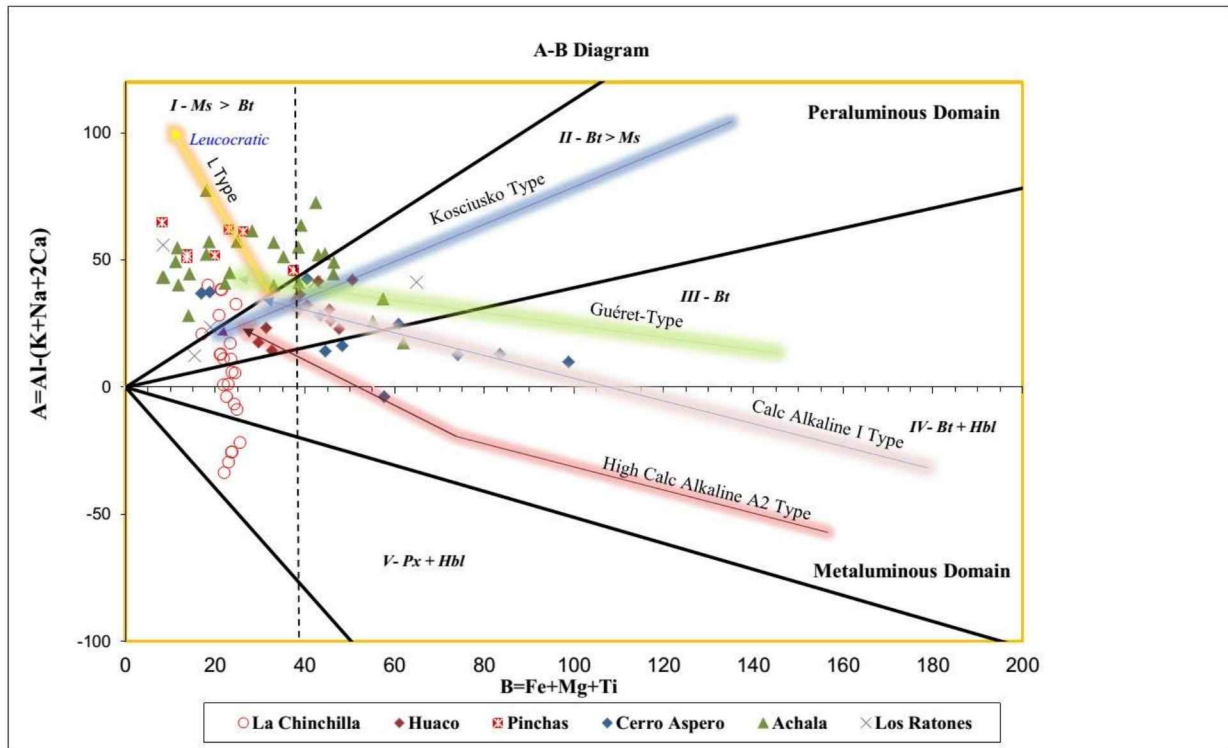


FIGURE 22. Peraluminous index ($A = Al - [Na + K + 2Ca]$) versus differentiation index ($B = Fe + Mg + Ti$) diagram of [49]. Modified from [50].

Devonian magmatism is clearly differentiated in the diagram discriminating igneous rocks (Figure 22), where the samples corresponding to Achala, plot mainly in the peraluminous field ($ASI > 1$), while those of Cerro Áspero plot in the metaluminous field ($ASI < 1$) with a slight tendency to peraluminosity. This indicates that for the middle to upper Devonian period there are two distinctive uranium fertile magmatic events; high-K calc-alkaline metaluminous to peraluminous represented by Cerro Áspero batholith and another peraluminous one represented by two-mica A- and S-type Achala batholith.

Lower Carboniferous magmatism varies from the metaluminous to slightly peraluminous fields for La Chinchilla and Huaco granites; whereas Los Ratones granite is located in the slightly peraluminous field. The Pinchas granite is clearly peraluminous and represents together with the Achala batholith, highly polymerized magmas ($ASI > 1.1$) (see Figure 23).

During this period the dominant magmatism was metaluminous to slightly peraluminous, of high-K calc-alkaline series, represented mainly by A-type plutons such as La Chinchilla, Huaco and Los Ratones. Only Pinchas represents clearly peraluminous two-mica granitoids.

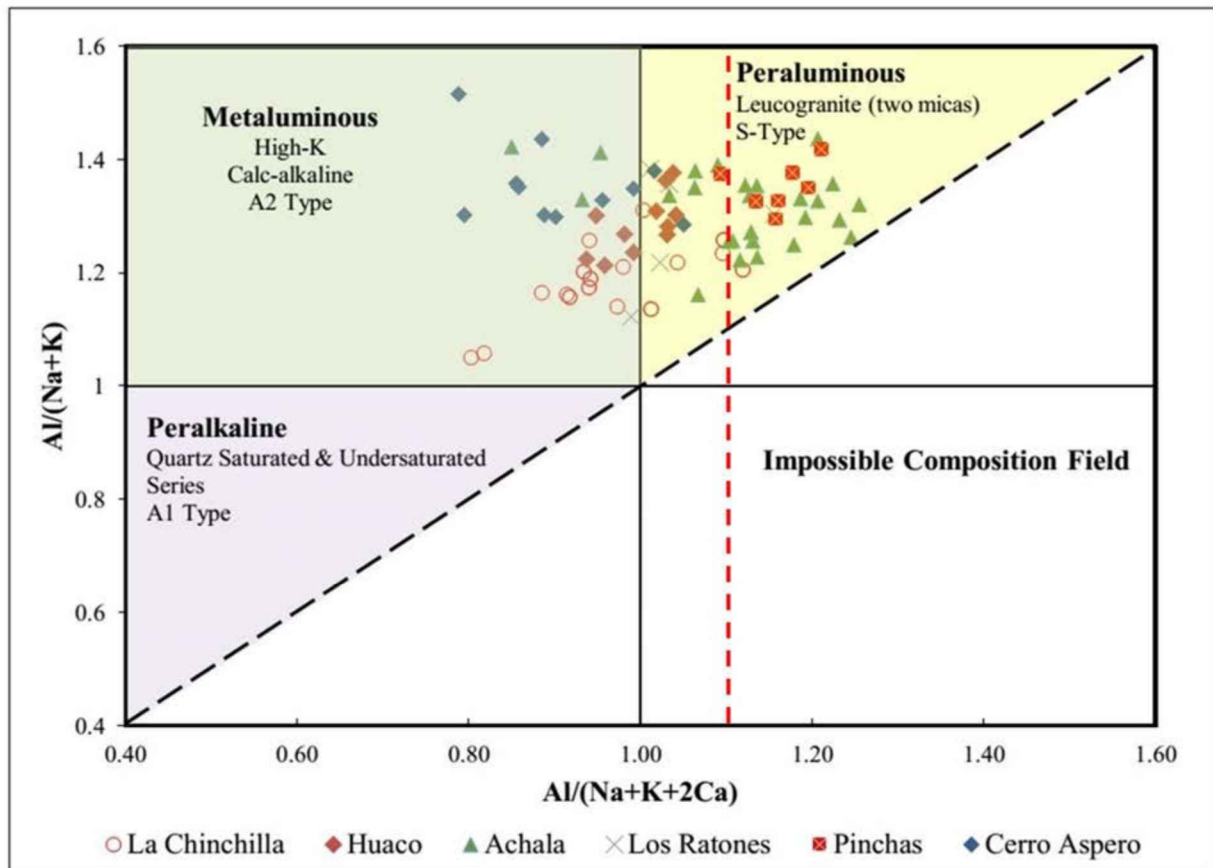


FIGURE 23. Diagram discriminating peraluminous, metaluminous and peralkaline igneous rocks. Only the uranium-rich igneous rocks have been indicated with their corresponding designation in the alphabetic classification. Red dashed line represents $ASI=1.1$. Modified from [51].

Figure 24 shows Th/U ratios for all the granitoids studied. Those with lower Th/U ratios are Pinchas and La Chinchilla, but uraninite is not observed as a common accessory mineral. Only in Pinchas granite has uraninite been found as scarce small inclusions in zircon [36].

In both granites, accessory minerals such as columbite-(Fe), tantite and oxyuranopyrochlore are common. Alteration under low temperature oxidizing conditions formed disseminated carlosbarbosaite [30], common in both granites.

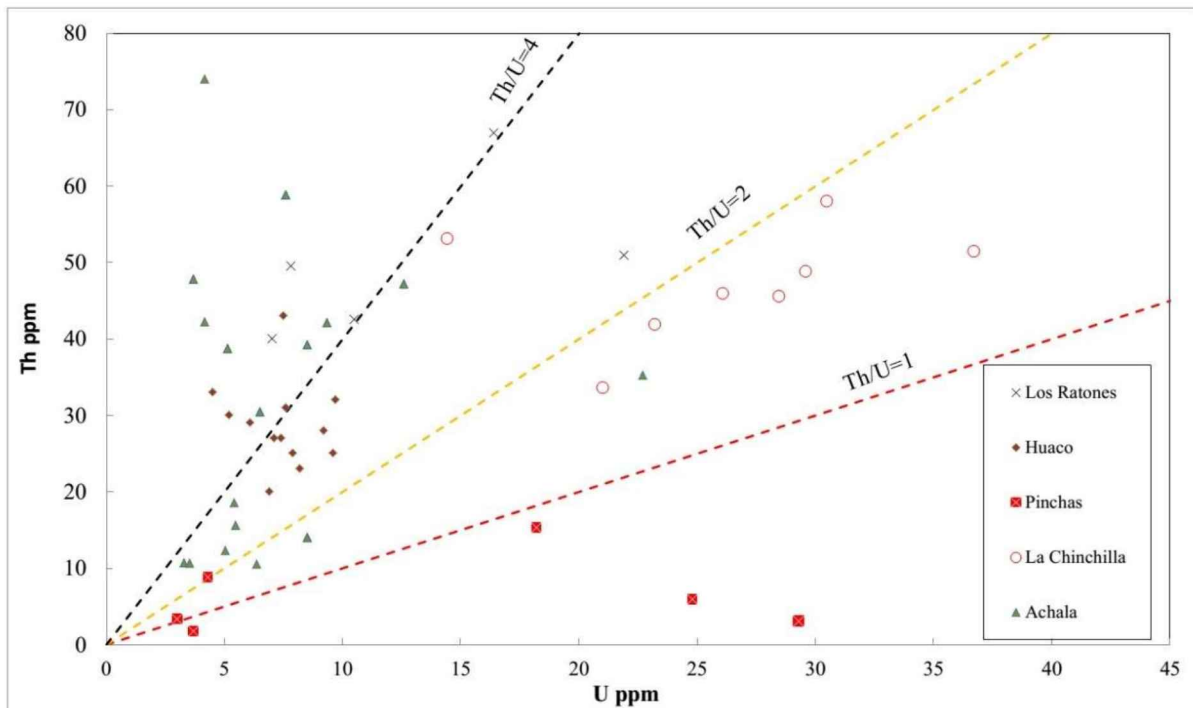


FIGURE 24. Th/U ratios from different Devonian – Carboniferous granites.

The Pinchas granite and some samples from La Chinchilla and Achala have $Nb/Ta \leq 5$ and $Zr/Hf > 18$ ratios indicating fertility and good mineralizing potential with evidence of magmatic-hydrothermal interaction processes such as secondary muscovitization and greisenization [52] (Figure 25).

Most of the samples belonging to the Pinchas granite fall in the domain of granites related to Sn-W (U) mineralisation as well as some samples of La Chinchilla and Achala granite. This is corroborated with what was observed with EDS and WDS in La Chinchilla and Pinchas, with the presence of cassiterite as an accessory phase in pegmatitic miaroles [31] and wolframite-quartz veins and accessory cassiterite included in quartz and muscovite of the equigranular facies and aplites of the Pinchas granite [53]. Some samples of Pinchas also plot in the rare metals related granite mineralisation field.

There is a set of samples from La Chinchilla and Los Ratones that plot outside established fields. Although they have values of Zr/Hf less than 25, which indicates granite fertility and association to Sn-W(U)-Be and Ta mineralisation [54], they have values of Nb/Ta between 5 and 7. However, at the level of current metallogenetic knowledge of both granites [30, 42, 55] they can be considered granites of high fertility and related to mineralisation.

The majority of the Achala and Huaco samples and two samples from Los Ratones plot in the barren granite field because of their low Ta content. There are no data available concerning the Nb/Ta and Zr/Hf ratios for the Cerro Áspero granite.

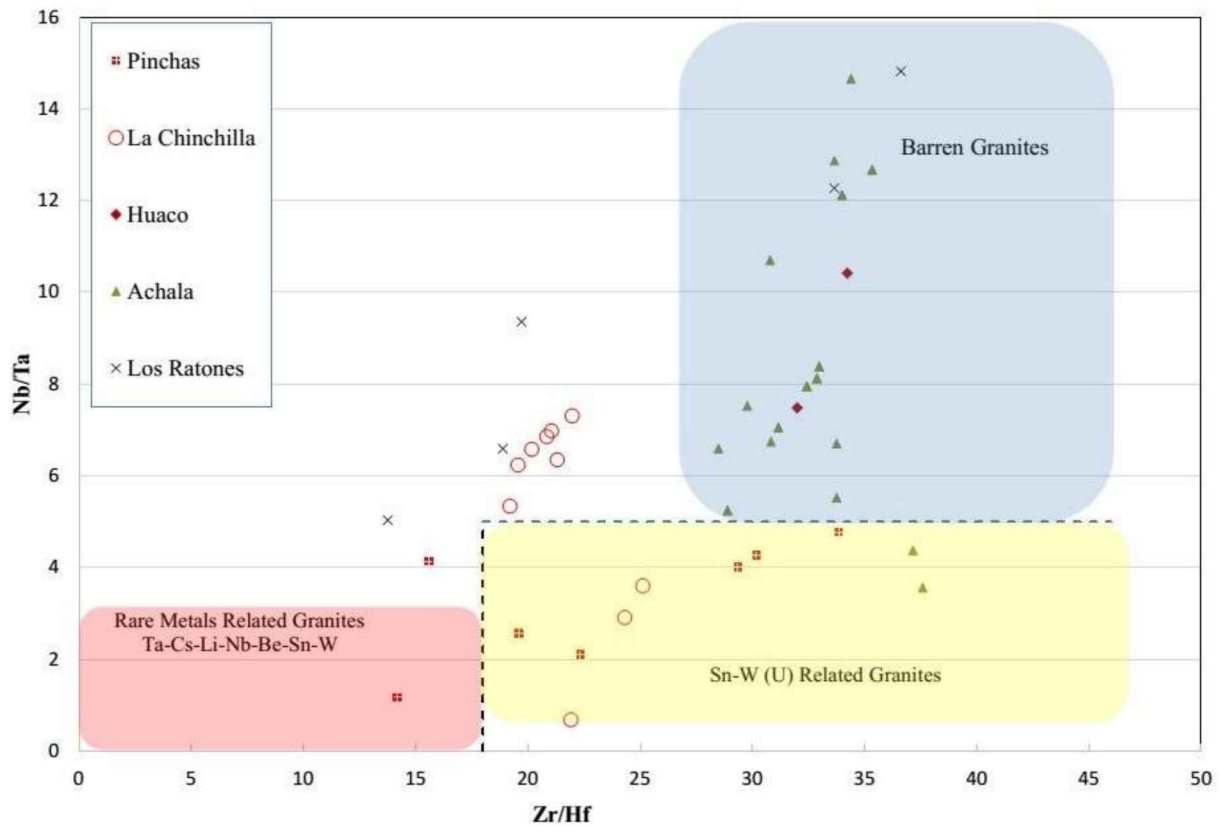


FIGURE 25. Nb/Ta versus Zr/Hf diagram differentiating barren and ore-bearing peraluminous granites. Modified from [52].

The set of granitoids studied indicates that the Devonian to Carboniferous magmatism of the Sierras Pampeanas geological province generated granites enriched in U, Sn, W, Nb, Ta, Li, Be and F. Two major types of uranium-rich igneous rock are described: metaluminous to slightly peraluminous high-K calc-alkaline granites and peraluminous (two-mica) leucogranites. The first group corresponds to La Chinchilla, Huaco, Cerro Áspero and Los Ratonés granites with $Al/(Na+K) \approx 1$. This group represents fertile U magmas especially in highly fractionated facies with a high U/Th ratio and where metamictization/alteration processes have acted on the silicates containing uranium (i.e. U-thorite, allanite, zircon). In particular, La Chinchilla has very low P_2O_5 contents with Fe-Li rich mica (phengite, zinnwaldite), $Al/(Na+K) < 1.15$ and intermediate REE, Y, Zr, Hf, Th contents that were derived from a highly fractionated melt of A-type magmas with Nb-Ta (columbite), U-Nb-Ta (oxyuranopyrochlore) and Sn (cassiterite) mineralisation.

The second group includes the peraluminous Achala and Pinchas granitoids. These represent fertile magmas and very good uranium sources with uraninite as a common accessory mineral present mainly as high P_2O_5 leucogranitic peraluminous ($Al/(Na+K) > 1.15$) facies. Evidence from new outcrops at the Achala sites (Don Alberto and Sala Grande) suggests that the uraninite from the western slope of the Sierra Grande was derived from pegmatitic melts fractionated from the Achala monzogranite. These are peraluminous pegmatite bodies (cordierite-andalusite) emplaced between the porphyritic granite and the country rock biotite-gneisses.

6. CONCLUSIONS

The interpretation of new studies on uranium minerals from several uranium sites of interest improved the metallogenic knowledge of the granite-related uranium deposits, which could in turn improve exploration guidelines.

Granites played an important role both as a uranium source and as host of diverse types of uranium mineralization. Additionally, it is thought that at the existing level of knowledge there is good potential to develop new uranium resources related to granites in Argentina.

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REFERENCES

- [1] ÁLVAREZ, J., LOPEZ, L., Annual Progress Reports for Contracts under the Coordinated Research Activities, Metallogenesis of Granite-Related Uranium Deposits in Argentina. IAEA Internal Rep., IAEA, Vienna, 2016–2018 (Unpublished internal report).
- [2] DAHLQUIST, J. A., ALASINO, P. H., BASEI, M. A., CÁMERA, M. M. M., GRANDE, M. M., NETO, M. D. C. C., Petrological, geochemical, isotopic, and geochronological constraints for the Late Devonian–Early Carboniferous magmatism in SW Gondwana (27–32° LS): an example of geodynamic switching. *International Journal of Earth Sciences* **107** 7 (2018) 2575–2603.
- [3] ALASINO, P. H., DAHLQUIST J.A., PANKHURST, R.J., GALINDO, C., CASQUET, C., RAPELA, C.W., LARROVERE, M.A., FANNING, C.M., Early Carboniferous sub-to mid-alkaline magmatism in the Eastern Sierras Pampeanas, NW Argentina: A record of crustal growth by the incorporation of mantle-derived material in an extensional setting. *Gondwana Research* **22** 3–4 (2012) 992–1008.
- [4] PANKHURST, R. J., RAPELA, C.W., The proto-Andean margin of Gondwana: an introduction. *Geological Society, London, Special Publications* 142 1 (1998): 1–9.
- [5] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA), UDEPO – World Uranium Deposits and Resources (2017) <https://infcis.iaea.org/UDEPO/Deposits>.
- [6] CAMINOS, R. Sierras Pampeanas de Tucumán, Catamarca, La Rioja y San Juan. In: TURNER, J.C. (Ed.): Segundo Simposio de Geología Regional Argentina, Academia Nacional de Ciencias, Córdoba, Argentina (1979) 41–79.

- [7] DAHLQUIST, J.A., ALASINO, P.H., EBY, G.N., GALINDO, C., CASQUET, C., Fault controlled Carboniferous A-type magmatism in the proto-Andean foreland (Sierras Pampeanas, Argentina): geochemical constraints and petrogenesis. *Lithos* **115** (2010) 65–81.
- [8] GORUSTOVICH, S., GUIDI, F., ZELAYA, A., PARRA, F., MORELLO, O., ALVAREZ, J., LÓPEZ, L., SALVATORE, M., BIANCHI, R., Depósitos de minerales nucleares del noroeste argentino. In: MURUAGA, C.M. y GROSSE, P. (Eds.), *Ciencias de la Tierra y Recursos Naturales del NOA. Relatorio del XX Congreso Geológico Argentino*, San Miguel de Tucumán (2017) 1003–1024.
- [9] ZAPPETTINI, E.O., Metalogénesis del noroeste argentino. *Relatorio del XI Congreso Argentino de Geología Económica*, Salta (2016) 41 pp.
- [10] DEMANGE, M., ALVAREZ, J.O., LOPEZ, L., ZARCO, J.L., The Achala Batholith (Córdoba, Argentina): A composite intrusion made of five independent magmatic suites: Magmatic evolution and deuteritic alteration. *International Journal of Earth Sciences* **91** 2(1996) 11–25.
- [11] GALLISKI, M. A., SFRAGULLA, J., Las pegmatitas graníticas de las sierras de Córdoba. 19° Congreso Geológico Argentino, Relatorio Asociación Geológica Argentina, Córdoba (2014): 365–388.
- [12] LIRA, R., SFRAGULLA J., El magmatismo devónico-carbonífero: el batolito de Achala y plutones menores al norte del cerro Champaquí. *Geología y Recursos Naturales de la Provincia de Córdoba*. 19° Congreso Geológico Argentino Relatorio Asociación Geológica Argentina, Córdoba (2014) 293–347.
- [13] LIRA, R., Episienitas feldespáticas y su relación con depósitos uraníferos en el Batolito de Achala, Provincia de Córdoba. *Revista Asociación Geológica Argentina* 42.3–4 (1987): 388–406.
- [14] LIRA, R., Un nuevo modelo metalogenético uranífero en el basamento cristalino de las sierras Pampeanas: uranio en metamorfitas de contacto (batolito de Achala, Provincia de Córdoba), *Boletín de la Asociación Geológica de Córdoba* **7** (1985) 438–451.
- [15] GORDILLO, C. E., SCHREYER, W., WERDING, G., ABRAHAM, K., Lithium in NaBe-cordierites from El Peñón, Sierra de Córdoba, Argentina. *Contributions to Mineralogy and Petrology* **90** 1 (1985) 93–100.
- [16] ZARCO, J. J., Geología estructural y petrología estructural del complejo granítico peraluminoso de Achala en relación con la génesis y la localización de la mineralización de Uranio (Sierras Pampeanas, Argentina). PhD. Thesis, Universidad Nacional de Salta 2006 (Unpublished internal report) 94 pp.
- [17] MERCADIER, J., CUNEY, M., LACH, P., BOIRON, M.C., BONHOURE, J., RICHARD, A., LEISEN, M., KISTER, P., Origin of uranium deposits revealed by their rare earth element signature. *Terra Nova* **23** (2011) 264–269.
- [18] LIRA, R., Manifestación Nuclear “Los Riojanos”: Estudio mineralógico de testigos de perforación, sondeo L.R. ex-15. Comisión Nacional de Energía Atómica Internal Report, CNEA, Córdoba 1983 (Unpublished internal report).
- [19] CONIGLIO, J. E., Evolución petrológica y metalogenética del batolito Cerro Áspero en relación con el ciclo geoquímico endógeno del flúor, Sierra de Comechingones, Córdoba, Argentina. PhD Thesis, Universidad Nacional de Río Cuarto 2006 (Unpublished internal report).

- [20] PINOTTI, L., TUBÍA, J.M., D'ERAMO, F., VEGAS, N., SATO, A.M., CONIGLIO, J., ARANGUREN, A., Structural interplay between plutons during the construction of a batholith (Cerro Áspero batholith, Sierras de Córdoba, Argentina). *Journal of Structural Geology* **28** 5 (2006) 834–849.
- [21] TOSELLI, A. J., DURAND, F.R., ROSSI DE TOSELLI, J.N., SAAVEDRA, J., SIAL, A.N., Granitos peraluminosos de la Zona Batolítica Central de Sierras Pampeanas (NW Argentino): Relaciones y significado geotectónico. *Memorias del XII Congreso Geológico de Bolivia* **2** (1996): 755–768.
- [22] PANKHURST, R., RAPELA, C. Y., FANNING, C., Age and origin of coeval TTG, I - and S- type granites in the Famatinian Belt of NW Argentina. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **91**(2000): 151–168.
- [23] SÖLLNER, F., VERDES, A., GROSSE, P., TOSELLI, A., U-Pb age determinations by LA-ICPMS on zircons of the Huaco granite, Sierra de Velasco (NW-Argentina): a long-term history of melt activity within an igneous body. *Proceeding 20° Colloquial, Latin American Earth Science* **1** (2007): 57–58.
- [24] GROSSE, P., SÖLLNER, F., BÁEZ, M., TOSELLI, A., ROSSI, J., DE LA ROSA, J.D., Lower Carboniferous post-orogenic granites in central eastern Sierra de Velasco, Sierras Pampeanas, Argentina: U-Pb monazite geochronology, geochemistry and Sr-Nd isotopes. *International Journal of Earth Sciences* **98** (2008) 1001–1025.
- [25] MORELLO, O., APARICIO, P., Informe preliminar: Mineralización en la Sierra de Velasco- La Rioja. Resultados DRX y SEM. Comisión Nacional de Energía Atómica Internal Report, Buenos Aires, 2010 (Unpublished internal report) 4pp.
- [26] ANZIL, P.A., SALVATORE, M.A., PARRA, F.J., SCARLATTA, L.R., MIYNO, S.S. y BELLO, F.C., Análisis textural y química mineral de la mineralización de uranio Alipán, Sierra de Velasco, La Rioja. Implicancias sobre la edad de la mineralización. 20° Congreso Geológico Argentino, Actas. San Miguel de Tucumán (2017) 2pp.
- [27] MORELLO, O., APARICIO, P., Mineralización de uranio en la Sierra de Velasco, La Rioja. *Revista de la Asociación Geológica Argentina* **70** 3 (2013): 335–340.
- [28] ANZIL, P.A., SALVATORE, M.A., Análisis por DRX de muestras mineralizadas de las áreas: Alipán, Lucero y Maggi. Comisión Nacional de Energía Atómica Internal Report, Córdoba 2018 (Unpublished internal report) 18pp.
- [29] SALVATORE, M., PARRA, F.J., SÁNCHEZ, D.L., ÁLVAREZ, J.O., BELLO, C., ZARCO AMBROSIO, J.J., Caracterización litogeoquímica del granito La Chinchilla y su relación con el uranio, Sierra de Velasco, Provincia de La Rioja. *Revista de la Asociación Geológica Argentina* **70** (2013): 341 –350.
- [30] BARDELLI, F.M., PARRA, F.J., LIRA, R., Minerales accesorios y procesos de alteración del granito La Chinchilla, sierra de Velasco, La Rioja: aspectos mineralógicos y geoquímicos en su relación con mineralización uranífera. *Revista de la Asociación Geológica Argentina* **75** 1(2018): 134–151.
- [31] LIRA, R., PARRA, F., BARDELLI, F.M., GALLISKI, M.Á. y SCARLATTA, L.R., Amazonite from miarolitic NYF-pegmatites and primary accessory minerals of the A-type La Chinchilla granite, Sierra de Velasco, La Rioja province, Argentina. 7th International Symposium on Granitic Pegmatites, PEG, Książ (2015) 40–41.
- [32] MORELLO, O., Nuevo hallazgo del óxido de uranio-niobio-tantalio en Argentina. I Reunión Latinoamericana de Cristalografía. IX Reunión Anual de la Asociación Argentina de Cristalografía **1**(2013) 2 pp.

- [33] ATENCIO, D., ROBERTS, A.C., COOPER, M.A., MENEZES FILHO, L.A.D., COUTINHO, J.M.V., STIRLING, J.A.R., VENANCE, K.E., BALL, N.A., MOFFATT, E., CHAVES, M.L.S.C., BRANDÃO, P.R.G., ROMANO, A.W., Carlosbarbosaite, ideally $(\text{UO}_2)_2\text{Nb}_2\text{O}_6(\text{OH})_2 \cdot 2\text{H}_2\text{O}$, a new hydrated uranyl niobate mineral with tunnels from Jaguaraçu, Minas Gerais, Brazil: description and crystal structure. *Mineralogical Magazine* **76** (2012) 75–90.
- [34] URQUIZA, L.A., Estimación de recursos. Cateo El Gallo. La Rioja. Comisión Nacional de Energía Atómica. Comisión Nacional de Energía Atómica Internal Report, Mendoza 2011 (Unpublished internal report) 20 pp.
- [35] DE LOS HOYOS, C., LAZO, M., ROSSI, J., Caracterización petrológica y geoquímica del Granito Señor de La Peña, sierra de Velasco, La Rioja, Argentina. 16° Congreso Geológico Argentino, La Plata. Actas publicadas en CD (2005) 8 pp.
- [36] CIMA, A., COLOMBO, F., SALVATORE, M., Caracterización petrológica y geoquímica del plutón La Punta y sus manifestaciones uraníferas asociadas (Sierra de Velasco, La Rioja). Universidad Nacional de Córdoba, Bachelor final project 2016 (Unpublished internal report) 161 pp.
- [37] ANZIL, P., MIYNO, S., SALVATORE, M., PARRA, F., SCARLATTI, L., FELKAI, E., BELLO, C., ÁLVAREZ, J., Cateo Lucero: Análisis con EDS y WDS en minerales de uranio y asociados. Comisión Nacional de Energía Atómica Internal Report, Córdoba 2018 (Unpublished internal report) 30 pp.
- [38] GRISSOM, G., DE BARI, S., SNEE, L., Geology of the Sierra de Fiambalá, northwest Argentina: implications for Early Palaeozoic Andean tectonics. In: PANKHURST, R. J., RAPELA, C. W. (Eds.), *The proto-Andean margin of Gondwana*. Geological Society, London, Special Publications **142** (1998) 291–323.
- [39] ARROSPIDE, A., Las manifestaciones de greisen de la Sierra de Fiambalá, Catamarca. *Revista de la Asociación Geológica Argentina* **40** 1–2(1985) 97–113.
- [40] ÁVILA, J.C., RUBINSTEIN, N., MORELLO, O., FOGLIATA, A.S., Edad y caracterización de una mica de litio asociada a un sistema de greisen en Mina La Rosario, Sierra de Fiambalá, Catamarca. *Revista de la Asociación Geológica Argentina* **63** 1(2008) 43–48.
- [41] GRISSOM, G.; DE BARI, S.; PAGE, S.; PAGE R.; VILLAR, L; COLLEMAN, R; VIRUEL DE RAMÍREZ, M., The deep crust of an Early Paleozoic Arc; The Sierra Fiambalá, Northwestern Argentina. In: HARMON R. S., RAPELA C.W. (Eds.): *Andean Magmatism and its Tectonic Setting*. Geological Society of America, Special Paper 265 (1991) 189–200.
- [42] FOGLIATA, A., Depósitos de greisen asociados a granitos carboníferos post-orogénicos con potencial mineralizador, Sierra de Fiambalá, Catamarca, Argentina *Boletín Geológico y Minero* **118** 4 (2008) 385–400.
- [43] CEBALLOS E., ZELAYA A., GORUSTOVICH, S., Estudios Complementarios de alteración hidrotermal en el depósito de uranio Mina Franca, Catamarca, Argentina. *Actas del XX Congreso Geológico Argentino* S9 (2017) 16–19.
- [44] RUBINSTEIN, N., MORELLO, O., BURGOS, J., El yacimiento de uranio Las Termas, Catamarca, Argentina. *Revista Asociación Geológica Argentina* **56** 1(2001) 91–98.
- [45] MORELLO, O., RUBINSTEIN, N., BURGOS, J., Nuevos avances sobre la metalogénesis de la Manifestación Las Termas-Fiambalá, Argentina. 3° Reunión de Mineralogía y Metalogenia, La Plata (1996) 153–156.
- [46] DE LA HOZ, M., Mineralización supergénica del depósito de uranio Las Termas, sierra de Fiambalá, Catamarca. *Actas del XI Congreso de Geología Económica* (2016) 4pp.

- [47] CEBALLOS E., ANZIL P.A., Mina Franca: muestras analizadas por microscopio electrónico y microsonda. Comisión Nacional de Energía Atómica Internal Report 2017 (Unpublished) 6 pp.
- [48] MORELLO, O., Edad de la mineralización de uranio. Depósito Las Termas, Fiambalá, Catamarca. Actas del 17° Congreso Geológico Argentino **2** (2008): 641–642.
- [49] DEBON, F., LE FORT, P.A., Chemical – mineralogical classification of common plutonic rocks and associations. Transactions of the Royal Society of Edinburgh: Earth Sciences **73** (1982) 135–149.
- [50] CUNEY, M., KYSER, K., Deposits related to Na-metasomatism and high-grade metamorphism. In Recent and Not-so-Recent Developments in Uranium Deposits and Implications for Exploration. Short Course Series 39. Quebec: Mineralogical Association of Canada (2008) 257 pp.
- [51] CUNEY, M., Felsic magmatism and uranium deposits. Bulletin de la Société Géologique de France **185** 2(2014) 75–92.
- [52] BALLOUARD, C., POIJOL, M., BOULVAIS, P., BRANQUET, Y., TARTÈSE, R., VIGNERESSE, J. L., Nb-Ta fractionation in peraluminous granites: A marker of the magmatic-hydrothermal transition. Geology **44** 3(2016) 231–234.
- [53] ANZIL, P.A., SALVATORE, M.A., LOPEZ PINTO, M.R., SCARLATTA, L.R., MIYNO, S.S., FELKAI, E.F., BELLO, F.C., PARRA, F.J., ÁLVAREZ, J.O., Cateo Lucero: Análisis de las rocas ígneas mineralizadas. Potenciales fuentes de uranio. Comisión Nacional de Energía Atómica Internal Report, Córdoba 2019 (Unpublished) 60 pp.
- [54] ZARAIISKY, G.P., AKSYUK, A.M., DEVYATOVA, V.N., UDORATINA, O.V., CHEVYCHELOV, V.Y., The Zr/Hf ratio as a fractionation indicator of rare-metal granites: Petrology **17** (2009) 25–45.
- [55] MORELLO, O., RUBINSTEIN, N., HONGN, F., FERREIRA, L., ANESA, J., ARIAS A., Modelo metalogenético del yacimiento de uranio Las Termas, Fiambalá, Catamarca, Argentina. Boletín Geológico y Minero **122** 3 (2011) 325–332.
- [56] ÁLVAREZ, J., LÓPEZ, L., CUNEY, M., MERCADIER, J., HANLY, A., PARRA, F., BELLO, C., LIRA, R., ANZIL, P., MIYNO, S., SALVATORE, M., SCARLATTA, L., FELKAI, E., FERREYRA, P., New Studies of the Uranium Deposits Related to Granites in Argentina. In: International Atomic Energy Agency (IAEA). International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM2018). Vienna, Austria 25–29 June 2018. Book of abstracts and extended abstracts (2018) 33–36.

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