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Uranium supply potential from phosphate rocks for Argentina's nuclear power fleet

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ABSTRACT

Argentina's nuclear reactor fleet provides about 10% of the country's electricity, and it is foreseen to increase nuclear power production in the future. Although most Argentinians accept nuclear power generation, public opinion is not in favor of uranium mining and all uranium needs are presently met by uranium imports at costs above international market prices (both spot and long-term contracts). Argentina also imports considerable amounts of phosphate rock and phosphate fertilizer to supply its agricultural industry. It is well-known that phosphate rocks and phosphate fertilizers can contain elevated amounts of associated uranium that is dissipated on agricultural soils if it is not recovered during fertilizer production. In this work, we estimate the amount of uranium that can be recovered from imported phosphate rock, determine the amount of uranium that could theoretically be recovered from all phosphate fertilizers used in Argentina and discuss potential uranium recovery from identified domestic phosphate rock resources.

1. Introduction

Nuclear energy accounts for some 10% of electricity produced in Argentina today (WNA, 2019) and additional reactors are foreseen (Di Sbroiavacca et al., 2014). Given the present nuclear growth scenarios, Argentina will double its uranium requirements by 2030 (WNA, 2019). Though Argentina mined uranium in the past, all uranium used for nuclear fuel production today is imported. In 1992, following the low world market prices of uranium, Argentina started the import of uranium concentrates from South Africa, a situation that gradually led to the closure of local production in 1997. Since then, uranium production ceased in Argentina and domestic uranium requirements for the operating nuclear power plants were met by raw material imports from Uzbekistan, the Czech Republic and lately Kazakhstan and Canada (Ministerio de Energía y Minería, 2016). Fig. 1 provides a brief overview of Argentina's uranium imports from 2008 to 2015 by exporting country.

Argentina has significant domestic uranium deposits. The main geological types of these uranium deposits are intrusive, granite-related, volcanic-related, sandstone, surficial and phosphate (IAEA, 2017; López and Cuney, 2014). In 2017, the National Atomic Energy Commission (CNEA) reported about 19,000 t uranium as identified resources (Reasonably Assured Resources and Inferred Resources) for the production cost category < 130 USD/kg uranium (NEA/IAEA, 2016). Approximately, 18,000 t uranium of Canadian National Instrument 43–101 (NI 43–101) certified resources have been reported in recent years by public mining companies, namely U_3O_8 Corporation (Coffey Mining Pty Limited, 2011; U3O8 Corp, 2018), Blue Sky Corporation (Blue Sky, 2018) and a private mining company named UrAmerica Limited (UrAmerica, 2018). The total uranium resources of Argentina can thus be estimated to be 37,370 t uranium in the aforementioned identified resource category and belong to six projects whose main characteristics are described in Table 1. It can be highlighted that if the higher production cost category of < 260 USD/kg uranium is considered there is no substantial variation and identified resources account for 38,420 t uranium (NEA/IAEA, 2016). According to the United Nations Framework Classification for Resources (UNFC), the reasonably

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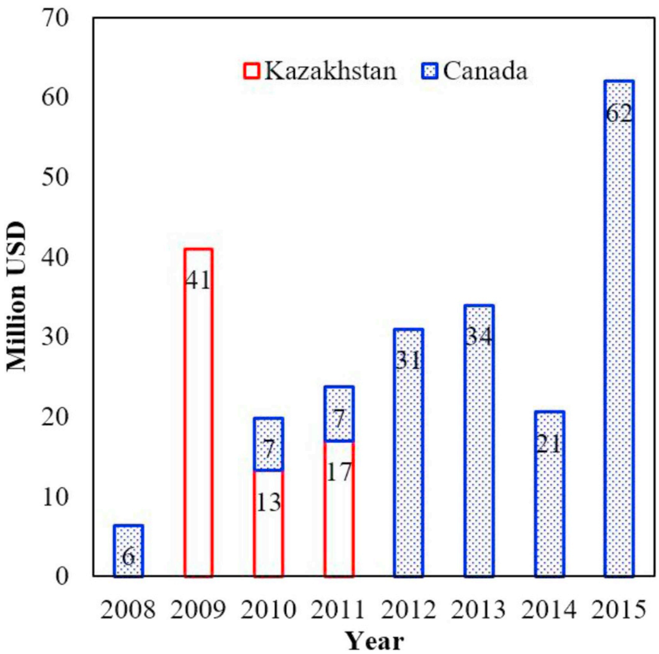

Fig. 1. Argentina's uranium imports by exporting country from 2008 to 2015.

assured resources in Table 1 can be classified as “commercial projects”, and the inferred resources can be classified as “potentially commercial projects” (UNECE, 2017).

According to the International Atomic Energy Agency (IAEA), the 38,420 t identified uranium resources can be used to produce some 40.10 EJ (EJ) of energy in Argentina (IAEA, 2018). Country-specific data (IAEA, 2018), depicted in Fig. 2 shows that this represents more than half (53%) of the total available energy and nearly all (98%) of the available low-carbon energy in Argentina.

Argentina's Mining Code, in force since 1997, considers uranium and thorium as nuclear minerals. Their associated resources belong to the Provincial States under the provisions of the National Constitution (InfoLEG, 1997). As indicated in Fig. 3, eight of the 23 Argentine provinces have legislation in place that restrict metal mining. The currently identified uranium resources are mostly located in the provinces of Chubut and Mendoza, where legislation restrict uranium production altogether. In Chubut Province, open-pit mining is not allowed, and projects need to wait for the implementation of provincial territory zoning provisions of Law 5001/2003, as well as the introduction of a mining regulatory framework for this jurisdiction (InfoLEG, 2003).

In addition to conventional uranium resources, Argentina also possesses unconventional uranium resources that are for instance associated with phosphate rocks. Phosphate rock, pre-concentrated phosphate ore, is predominantly used for fertilizer production. Argentina has a large agricultural sector that is dependent on phosphate fertilizers produced from phosphate rocks. Domestic production takes place at one fertilizer plant in Buenos Aires Province.

It is well known that phosphate rocks can contain considerable amounts of associated uranium and rare earth elements (REEs) (Chen and Graedel, 2015; Emsbo et al., 2015; Ramos et al., 2016; Schnug and Haneklaus, 2014; Wu et al., 2018) that can be recovered during wet phosphoric acid fertilizer production if this is desired. Techniques to recover uranium from phosphate rocks are historically based on solvent extraction or precipitation. These technologies were used for uranium recovery during wet phosphoric acid production at many pilot plants as well as commercial fertilizer plants in the United States and abroad from the 1980s to the mid-1990s (Astley and Stana, 2014; IAEA, 1989) until decreasing uranium prices made this practice uneconomic. During wet-phosphoric acid production phosphate rock is digested (usually with sulfuric acid) to phosphoric acid and phosphogypsum. Most of the uranium transfers to the phosphoric acid from which it can then be recovered while most of the REEs transfer to the phosphogypsum (Rutherford et al., 1994). Fig. 4 provides a brief overview of the wet-phosphoric acid process (Valdez Salas et al., 2017) indicating the fate of natural uranium (U) associated with phosphate rocks.

If uranium is recovered during wet-phosphoric acid production it will usually be recovered from the phosphoric acid right after filtration though alternative routes are imaginable (Al-Khaledi et al., 2019; Guzmán et al., 1995). Excellent reviews on the proven technologies used for uranium recovery in the past were compiled by Bunus (2000) and more recently Beltrami et al. (2014) as well as Singh et al. (2016). It is worth noting that uranium recovery units can be integrated without much effort in operating phosphoric acid plants (Haneklaus et al., 2017). Increased environmental awareness with regards to the radiotoxic uranium content in fertilizers, energy independence and volatile uranium market prices lead to renewed interest in the recovery of uranium from phosphoric acid (Haneklaus et al., 2016). Phosphate rock is to date the only unconventional uranium resource from which significant amounts of uranium have been recovered economically. Recovery of uranium is possible since a large share of the costs for excavation, mining, etc. is born by the phosphate industry (Reitsma et al., 2018). Most uranium (approximately 80%) is traded through long-term, multi-annual contracts based on estimated utility requirements (Grancea, 2018). UxC, a leading global nuclear industry market research analysis company, reported a spot market price of US$ 26 per pound U_3O_8 and long-term prices of US$ 39 per pound U_3O_8 in 2016. In the same year, Kim et al. (2016) estimated that in the United States, industrial proven solvent extraction technology could recover natural uranium at costs of US$ 44–61 per pound U_3O_8 and improved ion-exchange technology that is tested at pilot plant scale, promises uranium recovery at costs of US$ 33–54 per pound U_3O_8.

Costs for uranium recovery from phosphate rocks in Argentina may be different from the presented estimates in the same way that regional uranium prizes in Argentina are very different from the global spot and long-term prices reported by UxC. The free on board (FOB) prices that Argentina has paid for the purchase of yellowcake over the past years were considerably higher than the reported global spot or long-term prices. In 2015, for example, Argentina paid a FOB average price of USD 66 per pound U_3O_8 (Ministerio de Energía y Minería, 2016), while the uranium price at the spot market was USD 37 per pound U_3O_8 and long-term prices averaged at USD 46 per pound U_3O_8. Fig. 5 compares the FOB prices Argentina paid from 2008 to 2015 with the uranium spot and long-term prices for these years as reported by UxC. We averaged UxC month-end prices over one year. FOB prices for Argentina were taken as reported by the Ministerio de Energía y Minería.

López (2018) suggests that the high prices are a result of increased transportation charges, insurance premium and taxes. The elevated local prices for uranium in Argentina, the large agricultural industry that consumes considerable amounts of phosphate fertilizer and the strict regulations on uranium mining in Argentina may favor uranium recovery from phosphate rocks.

Recent studies, by Gabriel et al. (2013a, 2013b) and Ulrich et al. (2014) estimated that the amount of uranium that can theoretically be recovered during phosphate fertilizer production worldwide could provide slightly more than 15% of the uranium required for the present global nuclear power fleet. Additional studies were conducted for the United States (Kim et al., 2016), Europe (Sun et al., 2016; Tulsidas et al., 2019) and China (Ye et al., 2019). The objective of this work is to look into the amount of unconventional uranium associated with imported and domestic phosphates that could theoretically be recovered in Argentina and elaborate on the relevance of these results for the Argentinian nuclear power fleet.

2. Methods

Argentina imports all phosphates required by its fertilizer industry.

Table 1
Uranium resources in Argentina.

Deposit (ownership)	Type	Reasonably assured resources, RAR (tU ≤ USD 130 kg/U)[a]	Inferred resources, IR (tU ≤ USD 130/kgU)[b]
Amarillo Grande (Blue Sky Uranium Corp)	Sandstone/surficial	–	7360
Cerro Solo (CNEA)	Sandstone	4420	3760 (4810)*
Don Otto (CNEA)	Sandstone	180	250
Laguna Colorada (CNEA)	Volcanic-related	100	60
Laguna Salada (U_3O_8 Corp)	Surficial	2420	1460
Meseta Central (UrAmericaLtd)	Sandstone	–	7350
Sierra Pintada (CNEA)	Volcanic related	3900	6110
Sub total		11,020	26,350 (27,400)*
Total		**37,370 (38,420)***	

*tU for production cost category of < 260 USD/kgU.
[a] UNFC Commercial and Potentially Commercial Projects (E1F1G1,2) and (E2F2G1,2).
[b] UNFC Potentially Commercial Projects (E2F2G3).

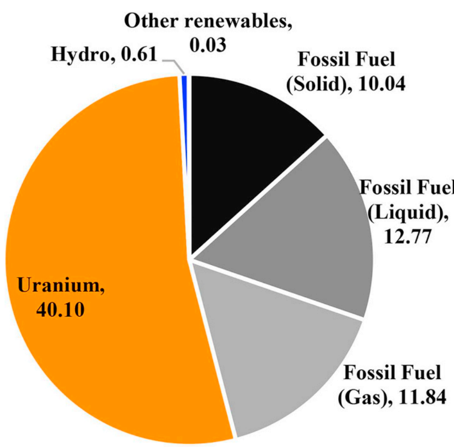

Fig. 2. Estimated energy availability (in EJ) in Argentina by fuel source using determined uranium resources and country-specific data from IAEA (2018).

Phosphates are either imported as phosphate rocks (roughly ¼ of the total requirements) and processed to Single Superphosphate (SSP) at the Bunge fertilizer plant near Buenos Aires or directly imported as mineral fertilizers (roughly ¾ of the total requirements). Data describing the amount and origin of the imported phosphates was taken from UN Comtrade. The associated quantities of uranium were estimated using recent data from Bech et al. (2010) that corresponded well with the comprehensive work done previously by Van Kauwenbergh (1997). Industrial scale, proven, solvent extraction technologies achieve recovery rates exceeding 90–95% (Hore-Lacy, 2016). For the estimates here, we assume that 90% of the uranium in the phosphate rocks transfers to phosphoric acid and that this uranium can be recovered at a recovery rate of 90%. Equation (1) summarizes these assumptions with the total amount of uranium (U) using country-specific uranium concentrations (c) in phosphate rock and quantities of imported phosphate rock (p).

$$\text{total } U = 0.9 * 0.9 * \text{sum}(c_i * p_i) \quad (1)$$

The potential uranium supply from imported fertilizers and the potential uranium supply from domestic phosphate rocks was estimated using available data from own analysis or as referenced.

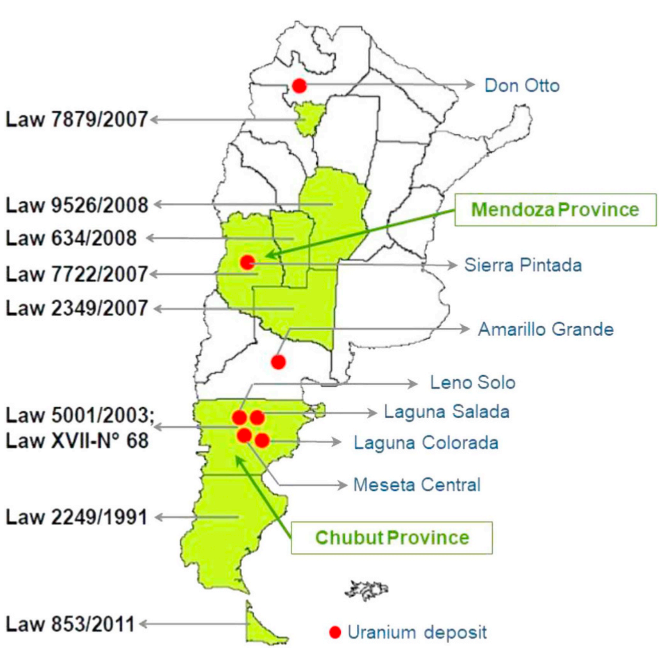

Fig. 3. Argentina's uranium deposits and the Provincial States with legislation in place that restrict metal mining.

3. Results and discussion

3.1. Present and near term uranium demand in Argentina

Argentina has three heavy water reactors: Atucha 1 with a gross electrical power of 362 MWe that is fueled with slightly enriched uranium (SEU) (0.85% ^{235}U), Embalse and Atucha 2, both based on natural uranium fuel with gross electrical capacities of 648 MWe and 745 MWe respectively (WNA, 2018). At present, Atucha 1 and Atucha 2, located in Buenos Aires Province, are in commercial operation, while Embalse, located in the province of Cordoba, has been out of the generation system for two years for refurbishment tasks designed to extend its lifetime for a term of 30 years. This includes an increase in its power production by an additional 35 MWe to reach 683 MWe (Nucleoelectrica Argentina, 2018). As part of the nuclear development in Argentina, China and Argentina are pursuing an agreement for the installation of a fourth nuclear reactor, a CANDU Pressurized Heavy Water Reactor (PHWR) and a fifth reactor, a Hualong One Pressurized Water Reactor (PWR) (WNA, 2018).

Besides, the Argentine prototype small modular reactor CAREM (27 MWe net/32 MWe gross) is under construction at the Atucha site and is planned to come into operation in 2020–2022. It is further planned to increase the scale of the unit to a higher capacity of possibly 120 MWe (Magan et al., 2011; CNEA, 2018). Table 2 provides an overview of the present and foreseen large commercial nuclear power plants in Argentina taking into consideration a scenario with two new reactors by 2030.

Argentina's uranium requirement in 2017 was 195 t since Embalse was offline to undergo the lifetime extension program. Usually, the expected uranium requirement would range from 220 to 250 t per year. Based on various nuclear growth scenarios (WNA, 2019), we estimate a generation capacity of some 3.470 GWe, for the low case, and about 4.070 GWe, for the high case by 2030. The raw material needs would consist of 525 t to 620 t natural uranium per year in the respective

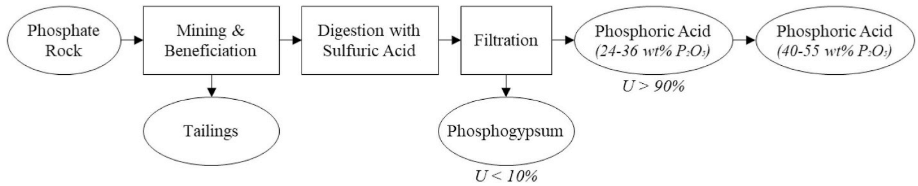

Fig. 4. Phosphoric acid production with uranium recovery by the wet-phosphoric acid process.

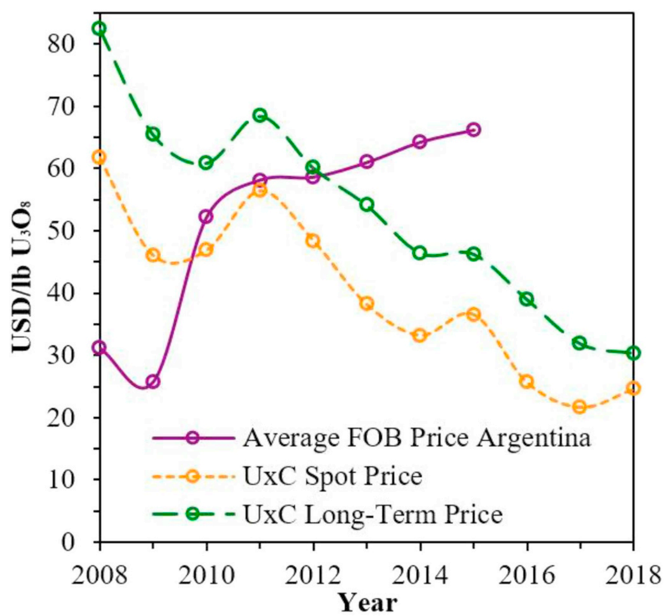

Fig. 5. Free on board (FOB) prices Argentina paid for uranium from 2008 to 2015 and uranium spot market and long-term prices at this time as reported by UxC.

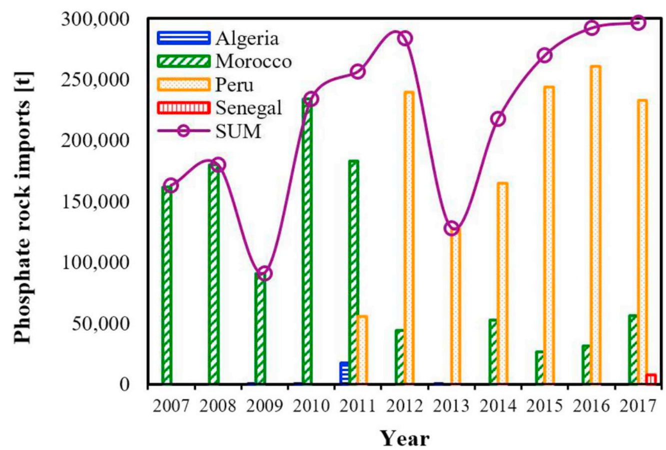

Fig. 6. Argentina's phosphate rock imports by weight from 2007 to 2017.

Table 2
Present and foreseen large commercial nuclear power plants in Argentina.

Reactor	First power	Location	Model	Gross MWe
Atucha 1	1974	Lima, Buenos Aires	PHWR (Siemens)	362
Embalse	1983	Embalse, Cordoba	PHWR (CANDU-6)	683
Atucha 2	2014	Lima, Buenos Aires	PHWR (Siemens)	745
Atucha 3	*~2030*[a]	*Lima, Buenos Aires*	*PHWR (CANDU-6)*	*750*
Atucha 4	*~2030*[a]	*Lima, Buenos Aires*	*PWR (Huolong-1)*	*1150*

[a] Possible scenarios presently discussed.

scenarios. This is a bit larger than double the current consumption since the presently employed PHWRs that use natural uranium (Embalse and Atucha 2) or SEU (Atucha 1) and generate more electricity per ton natural uranium than the foreseen PWR that uses enriched uranium. This brief analysis also does not consider possible changes to the nuclear fuel cycle in a way that thorium is introduced as fuel or spent nuclear fuel is recycled. Table 3 provides an overview of the anticipated present and future uranium requirements in Argentina.

3.2. Potential uranium supply from imported phosphate rocks

Argentina imports all phosphate rocks used for domestic fertilizer

Table 3
Anticipated present and future uranium requirements in Argentina.

Time	Estimated uranium requirements
2017–2030	220-250 t
After 2030	525-620 t

production at the Bunge fertilizer plant in Buenos Aires Province. In 2017 the vast majority (78.4%) of phosphate rock processed was imported from Peru. Additional phosphate rock was imported from Morocco (19.0%) and Senegal (2.7%). Fig. 6 depicts Argentina's phosphate rock imports by weight from 2007 to 2017.

In total, the amount of phosphate rock imported, gradually increased from about 160,000 t in 2007 to nearly 300,000 t in 2017 with two sharp drops in 2009 and 2013. The significant decrease in phosphate rock imports in 2009 is a result of a dramatic global, 352% price spike for phosphate rock from 2007 to 2008 triggered by market policies in India, the largest phosphate fertilizer and phosphate rock importer in the world (Khabarov and Obersteiner, 2017). The second sharp drop in 2013 can be explained by the shortage of foreign currency, in particular, USD in Argentina (The Economist, 2012). These two drops in 2009 and 2013 can also be identified in Fig. 7 that depicts Argentina's phosphate rock imports by value from 2007 to 2017. The value of imported phosphate rock is heavily dependent on fluctuating phosphate rock prices. Since Argentina started importing more and more phosphate rock from Peru instead of Morocco, the total value decreased despite increased quantities of phosphate rock imported.

With the average uranium concentration in Morocco (121.5 mg/kg phosphate rock), Peru (70.3 mg/kg phosphate rock) and Senegal (67.9 mg/kg phosphate rock) provided by Bech et al. (2010), the quantity of associated uranium with phosphate rock imports into Argentina can be estimated. Table 3 provides an overview of the total amount of phosphate rock shipped to Argentina by exporting country. Units for uranium recovery can be integrated into existing wet-acid fertilizer plants without much effort. It is not uncommon that countries import phosphate rock and process it domestically as examples from India, Pakistan, and the Philippines (Haneklaus et al., 2015) illustrate. All phosphate rocks imported into Argentina in 2017 have a relatively high uranium content (> 60 mg/kg) if compared to igneous phosphate rocks from Russia or South Africa that show lower uranium concentrations (usually < 30 mg/kg). In total, 19.2 t uranium could have theoretically been recovered during domestic phosphate rock production in Argentina. This amount (19.2 t uranium) could cover 7.7–8.7% of the current uranium demand or 3.1–3.7% of the uranium demand expected after 2030.

About 75% of global phosphate rock resources are found in Morocco

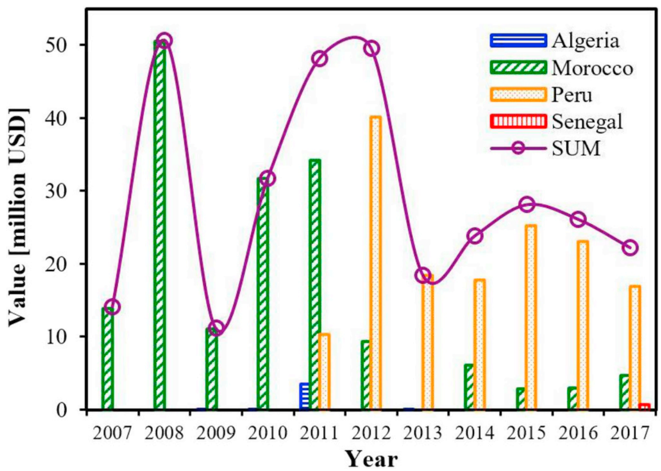

Fig. 7. Argentina's phosphate rock imports by value from 2007 to 2017.

(Cooper et al., 2011; Geissler et al., 2018) and it is not unlikely that almost all future phosphate rock exports may originate from here (Walan et al., 2014). Argentina might thus import substantially larger quantities of phosphate rock from Morocco in the future. That is interesting for this study since the average uranium concentrations in Moroccan phosphate rock is much higher (nearly double) than the uranium concentration in phosphate rock from Peru that presently constitutes the largest source. If for instance all phosphate rock in 2017 would have been purchased from Morocco, 29.2 t uranium could have theoretically been recovered assuming an average uranium content of 121.5 mg/kg. This amount of uranium corresponds to 11.7–13.3% of the current and 4.7–5.6% of the future domestic uranium demand in Argentina.

Besides phosphate rock, other countries such as India, import considerable amounts of phosphoric acid from which uranium can theoretically still be recovered if this has not already been done in the exporting country. Argentina imported 14–25 t of phosphoric acid in 2017 so that an additional uranium recovery from imported phosphoric acid could also be considered.

It is worth noting that Argentina needs some 1.2 million t phosphate fertilizer per year of which only 25% is produced domestically by the phosphate rock processing plant in Buenos Aires Province (Tan, 2018). The countries fertilizer demand is increasing at a rate above 4% since 1990 (BCR, 2019) so that erecting additional domestic phosphate fertilizer plants is reasonable to decrease foreign dependencies, reduce costs for fertilizers and subsequently food.

Table 4 provides an idea of how much uranium could be recovered if all phosphate fertilizer required in Argentina would be produced domestically. For this estimate, we assume that phosphate rock is imported as done in 2017, e.g. 19.0% from Morocco, 78.4% from Peru and 2.7% from Senegal.

The estimates in Table 4 underline that considerable amounts of uranium, relevant for Argentina's energy security, could be recovered from phosphoric acid if all mineral fertilizers required would be produced in Argentina. Three scenarios are considered in Table 4: a low scenario, an average scenario and a high scenario. The three scenarios correspond to the different P_2O_5 ranges provided for the different fertilizer types that result in different amounts of phosphate rock needed for fertilizer production and thus different amounts of accompanying uranium that can be recovered. In the average case, 93.3 t uranium could theoretically be recovered during phosphate rock processing in Argentina. With the additional 19.2 t uranium that could be recovered from present phosphate rock processing in Argentina, this would amount to a total of 112.5 t uranium. This amount would cover 45.0–51.1% of the current uranium demand in Argentina and 18.1–21.4% of the uranium demand expected after 2030.

3.3. Potential uranium supply from domestic phosphate rocks

Although Argentina is presently importing all required phosphate rock for fertilizer production, domestic phosphate rock resources exist. Systematic prospecting studies of phosphates in sedimentary basins were carried out during the 1970s by the Argentine Geological Survey ("Plan Fosforitas"). Eighteen areas in several marine basins with phosphate potential, about 640,000 km^2, were later documented (Leanza et al., 1989). From the 1980s to the present day, a research group of the Department of Geology of the University of Buenos Aires, looked into additional areas, focusing on the prospection, genesis and sedimentation environment of phosphate deposits in different basins (Duperron et al., 2018; Fazio et al., 2013, 2007; Medina et al., 2016; Moya et al., 2012; Rubinstein et al., 2017; Scasso and Castro, 1999a,b).

New data, together with published information on phosphates was compiled, and principal phosphate occurrences and their correlation with the global phosphogenetic events (Cambrian, Ordovician, Jurassic-Cretaceous, Cretaceous-Paleocene, Miocene and Modern) were defined by Castro et al. (2009).

The potential new mining areas include: (1) the Subandean Ranges and Eastern Cordillera (Jujuy and Salta provinces), (2) the Neuquén Basin (Neuquén and Mendoza provinces) and (3) the deposits in Extraandean Patagonia (Chubut and Santa Cruz province), and are shown in Fig. 8.

Fig. 9 provides an overview of the global phosphogenic events and the resulting global P_2O_5 abundance. The three regions currently investigated for phosphate rock mining in Argentina are also indicated.

Based on data from Castro et al. (2009) and other previous studies (Fazio et al., 2007; Leanza et al., 1989; Scasso and Castro, 1999a,b) the geological inferred amount of uranium has been estimated for the three areas currently investigated for prospective mining using an average phosphate rock density of 1.76 t/m^3 (Aqua-Calc, 2018). The results of this estimate and a brief characterization of the deposits are summarized in Table 5.

It is important to note that most of these estimated resources are unlikely to be mined economically due to the very low average P_2O_5 content and uranium concentration. Egypt, for example, is actively looking into uranium recovery from phosphate rock during wet phosphoric acid fertilizer production. The phosphate rock considered shows uranium concentrations of 90 mg/kg (Montaser, 2016). Given the relatively low uranium market prices in recent years, recovering uranium during phosphate rock processing in Egypt will only be monetarily

Table 4
The estimated quantity of uranium imported with phosphate rock into Argentina by exporting country in 2017.

Phosphate rock exporting country	Phosphate rock imported into Argentina in 2017		Average uranium content in mined phosphate rock [mg/kg]	Estimated amount of uranium imported into Argentina with phosphate rock in 2017		Estimated recoverable amount of uranium in 2017 [t]
	[t]	[%]		[t]	[%]	
Morocco	56,280.0	19.0	121.5	6.8	28.8	5.5
Peru	232,571.1	78.4	70.3	16.3	68.9	13.2
Senegal	7874.0	2.7	67.9	0.5	2.3	0.4
					SUM	19.2

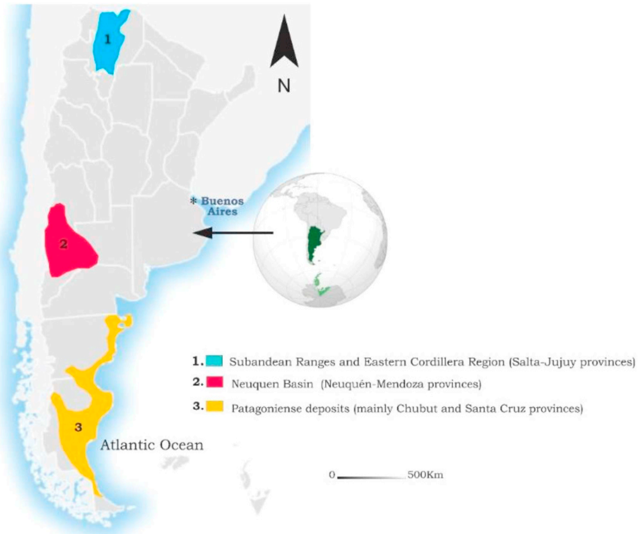

Fig. 8. Regions currently investigated for phosphate rock mining in Argentina: (1) the Subandean Ranges and Eastern Cordillera (Jujuy and Salta provinces), (2) the Neuquén Basin (Neuquén and Mendoza provinces) and (3) the deposits in Patagonia (mainly Chubut and Santa Cruz provinces).

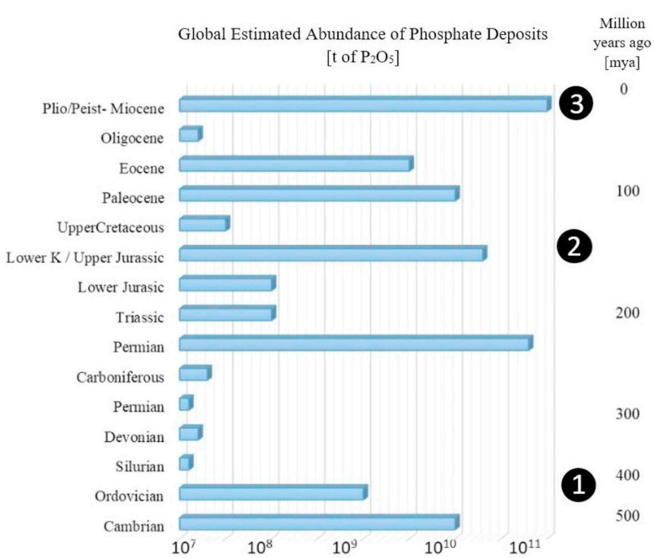

Fig. 9. Global phosphogenic events and resulting global P_2O_5 abundance with the three areas currently investigated for phosphate rock mining in Argentina indicated: (1) the Subandean Ranges and Eastern Cordillera (Jujuy and Salta provinces), (2) the Neuquén Basin (Neuquén and Mendoza provinces) and (3) the deposits in Patagonia (mainly Chubut and Santa Cruz provinces).

profitable if phosphate fertilizer is produced and the fertilizer business supports a large portion of the costs associated with uranium recovery. It is also important to note that local concentrations in the P_2O_5 and uranium content in Argentina's phosphate rocks can be much higher than the average concentrations shown in Table 5.

Local geologic characterization within the Miocene deposits in Patagonia, for instance, indicate concentrations of 16–27% P_2O_5 and 46–135 mg/kg uranium (López et al., 2018). Characterization of nine samples in the Northwestern Basin (Jujuy and Salta Province) showed concentrations of up to 23% P_2O_5 (obtained using XRF), 39 mg/kg uranium (obtained using neutron activation analysis) as well as elevated concentrations of many rare earth- and other monetarily valuable elements. Fig. 10 depicts the obtained trace element concentrations in the nine samples in comparison to the PAAS average shale concentration (black line).

The elevated concentrations are promising. Further investigations are, however, required to better understand the extent to which these elements can be recovered economically, and thus justify potential investments.

5. Conclusions

Today Argentina needs some 1.2 million t phosphate fertilizer per year of which approximately ¼ is produced domestically from imported phosphate rock at a plant near Buenos Aires. If uranium would be recovered during domestic phosphate rock processing, some 19.2 t uranium, equivalent to 8–9% of the current uranium demand or 3–4% of the anticipated future uranium demand could be substituted. If uranium would be recovered from all phosphate rock products used in Argentina more than half (45–51%) of the present and roughly one fifth (18–21%) of the foreseen future uranium demand could be substituted. Argentina has relevant uranium resources that are not developed due to a lack of public acceptance. Recovering uranium from phosphate rocks during fertilizer production and thus largely stopping the dissipation of this uranium on agricultural soils with fertilizer may find public acceptance. This practice would also reduce foreign dependencies as well as the increased costs for nuclear fuel due to higher than market value costs of uranium imports.

Argentina also has considerable amounts of uranium associated with domestic phosphate rock deposits. The majority of these deposits are low-grade phosphate rocks (1–5 wt% P_2O_5) and low-grade uranium (4–9 mg/kg) deposits so that economically mining them seems to be unlikely despite the favorable domestic market situation.

Local occurrences with relevant phosphate rock (16–27 wt% P_2O_5 and up to 23 wt% P_2O_5) could, however, be identified. The uranium content in these occurrences ranges from 39 to 135 mg/kg, so that unconventional uranium by-product recovery may be economically feasible. Further investigations of these occurrences are required. Besides, the potentially favorable market situation for domestic phosphate rock and uranium production in Argentina that can reduce

Table 5
The estimated quantity of uranium associated with phosphate fertilizers imported by Argentina in 2017.

Fertilizer Type	Usage in Argentina in 2017[a]	P_2O_5 range	Phosphate rock equivalent [t]			Estimated amount of recoverable uranium [t]		
			Low	Average	High	Low	Average	High
MAP	500,000	48–61%[b]	782,915	888,935	994,955	50.8	57.6	64.5
DAP	250,00	46%[c]	375,147			24.3		
TSP	90,000	44–52%[d]	156,583	176,156	195,729	10.2	11.4	12.7
SUM						85.3	93.3	101.5

Fertilizer types: MAP (monoammonium phosphate); DAP (diammonium phosphate); TSP (triple super phosphate).
[a] Tan (2018).
[b] IPNI (2010).
[c] IPNI (2012).
[d] NPTEL (2018).

Table 6
Characteristics, phosphogenic events, prospecting area, average P_2O_5 and uranium content as well as geological inferred resources of uranium for the (1) the Subandean Ranges and Eastern Cordillera (Jujuy and Salta provinces), (2) the Neuquén Basin (Neuquén and Mendoza provinces) and (3) the deposits in Patagonia (Chubut and Santa Cruz provinces) currently investigated for mining in Argentina.

Sedimentary Basin	Characteristics	Phosphogenic Event	Surficial prospecting Area [km^2]	Accumulated thickness of the Phosphatic Level [m][b]	Average P_2O_5 Content [wt%]	Average Uranium Content [mg/kg]	Geological Uranium Resources [kt][a]
Subandean Ranges and Eastern Cordillera (Jujuy and Salta provinces)	Intercalated discontinuous lenses from 10 to 60 cm thick of lingula-bearing coquinas. These sequences are strongly folded and faulted.	Ordovician	49,500	4	6	7	2439
Neuquén Basin (Neuquén and Mendoza provinces)	Phosphatic limestones, calcareous phosphatic sandstones and mudstones.	Uppermost Jurassic - Lowermost Cretaceous	6200	5	3	4	218
Deposits in Patagonia (Chubut and Santa Cruz provinces)	Phosphatic levels with in-situ concretions and reworked and winnowed with phosphatic concretions, ooids, vertebral bones, teeth and shells.	Miocene	130,000	1	3	8.5	1945

[a] UNFC categories E3.3, F4 and G4.
[b] With P_2O_5 content above 2 wt%.

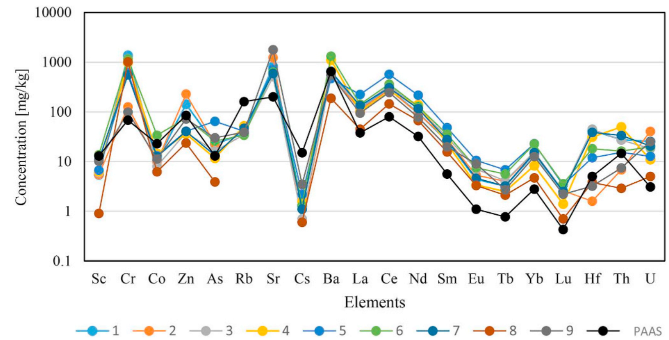

Fig. 10. Trace element concentrations of nine samples from the Eastern Cordillera (Jujuy and Salta provinces): 1. Severino Ravine -Floresta Formation, 2. Alto de la Sierra, 3. Mojotoro Range 4. Las Maderas Range, 5. Near Las Madera Dam, 6. Portezuelo, 7. Chato Hill, 8. Gallinato Ravine, 9. El Arenal Ravine and the PAAS average shale concentration in comparison.

foreign dependencies also needs to be better understood.

Declaration of interests

None.

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