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## URANIUM DEPOSITS IN VOLCANIC ROCKS

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URANIUM OCCURRENCES  
IN THE VOLCANIC ROCKS  
OF NORTHWESTERN ARGENTINA

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Abstract

URANIUM OCCURRENCES IN THE VOLCANIC ROCKS OF NORTHWESTERN ARGENTINA.

Rich uranium ore bodies were located at Macusani (14°S, Peru) and several occurrences in Bolivia (19°S, Sevaruyo district) and the Argentinian Puna (23°S) along 1800 km of the Cenozoic Volcanic Belt of the Central Andes of Peru, Bolivia and northern Argentina and Chile. The presence in the Argentinian Puna of several favourable factors for uranium accumulations in volcanic environments led to the development of a multidisciplinary project devoted to identifying the most favourable areas for further exploration. The project will comprise geological research on a 1:250 000 scale covering the most interesting areas of the Argentinian Puna, using interactive digital analysis of LANDSAT imagery and computer processing techniques. Ground-truth studies and laboratory support will complete the project, in which some 15 geoscientists will participate for about 1 year.

1. INTRODUCTION

Rich uranium bodies are located at Macusani (14°S, Peru) and several occurrences in Bolivia (19°S, Sevaruyo district) and in the Argentinian Puna (23°S, Cerro Galán of Jujuy, Aguiliri, etc.) along 1800 km of the Cenozoic Volcanic Belt of the Central Andes of Peru, Bolivia and northern Argentina and Chile.

Exploration work carried out in the Volcanic Belt has been limited, but the uranium potential could be considered very promising because several favourable uraniumiferous factors have been found throughout the entire belt environment.

For the purpose of defining the uranium potential of the Argentinian sector of the Volcanic Belt, a project will be carried out by the Comisión Nacional de Energía Atómica, in co-operation with the Comisión Nacional de Investigaciones Espaciales and the Universidad Nacional de Salta. Some 15 geoscientists will participate in the project, which will comprise geological research on a 1:250 000 scale, covering the most interesting sectors in an area of 35 000 km<sup>2</sup> of the total of 120 000 km<sup>2</sup> of the entire Argentinian Puna. The project will be performed using interactive digital analysis of LANDSAT imagery and computer processing techniques. Ground-truth studies and laboratory support (analytical, mineralogical, petrological and geochronological dating) will complete the project.

For comparison purposes, the satellite imagery interpretation will be extended in the Volcanic Belt to include the uraniumiferous districts of Sevaruyo (Bolivia) and Macusani (Peru).

## 2. GEOLOGY AND STRUCTURE OF THE ANDEAN CENOZOIC VOLCANIC BELT BETWEEN 14°S AND 28°S

The continental-internal Cenozoic Volcanic Belt develops almost continuously between 14°S and 28°S of the Central Andes of Peru, Bolivia, and northern Argentina and Chile (Fig.1) and is mainly located within the geostructural units of the Cordillera Occidental (Western Cordillera), the Altiplano and the Puna [1].

Eastwards, the Volcanic Belt is separated from the Cordilleras Orientales (Eastern Cordilleras) of Peru, Bolivia and northern Argentina, as well as from the northern sector of the Sierras Pampeanas (Pampean hills), by an important fault front. However, the volcanism also penetrates slightly eastwards of the fault zone, as in Macusani (Peru), Sevaruyo, Cerro Rico de Potosí and Chorolque (Bolivia), Acay and Farallón Negro (Argentina).

The western borders of the Volcanic Belt are the Depresiones Costeras (coastal depressions) of southern Peru and the Valle Central (Central Valley) of northern Chile, although the Domeyko Cordillera appears to the south [2, 3].

The Volcanic Belt disappears south of 28°; new isolated occurrences are known at 34°S, but it again takes importance south of 35°S [1, 4].

Superimposed magmatic arc systems developed during Mesozoic-Cenozoic times in the Central Andes; they were controlled by oceanic (Pacific) crust subducting under the South American continent. Every subsequent magmatic arc is related to a diastrophic phase [5, 6].

Five diastrophic phases, identified from Middle Eocene to Lower Pleistocene, make it possible to set the limits of and approximately correlate the effusive and sedimentary events produced within the Volcanic Belt, but not throughout the entire volcanic chain. This chain developed mainly after the Fase Incaica (Middle Eocene-Early Oligocene), but other volcanic events had already taken place. Other diastrophic phases are indicated in Fig.2 [7-11].

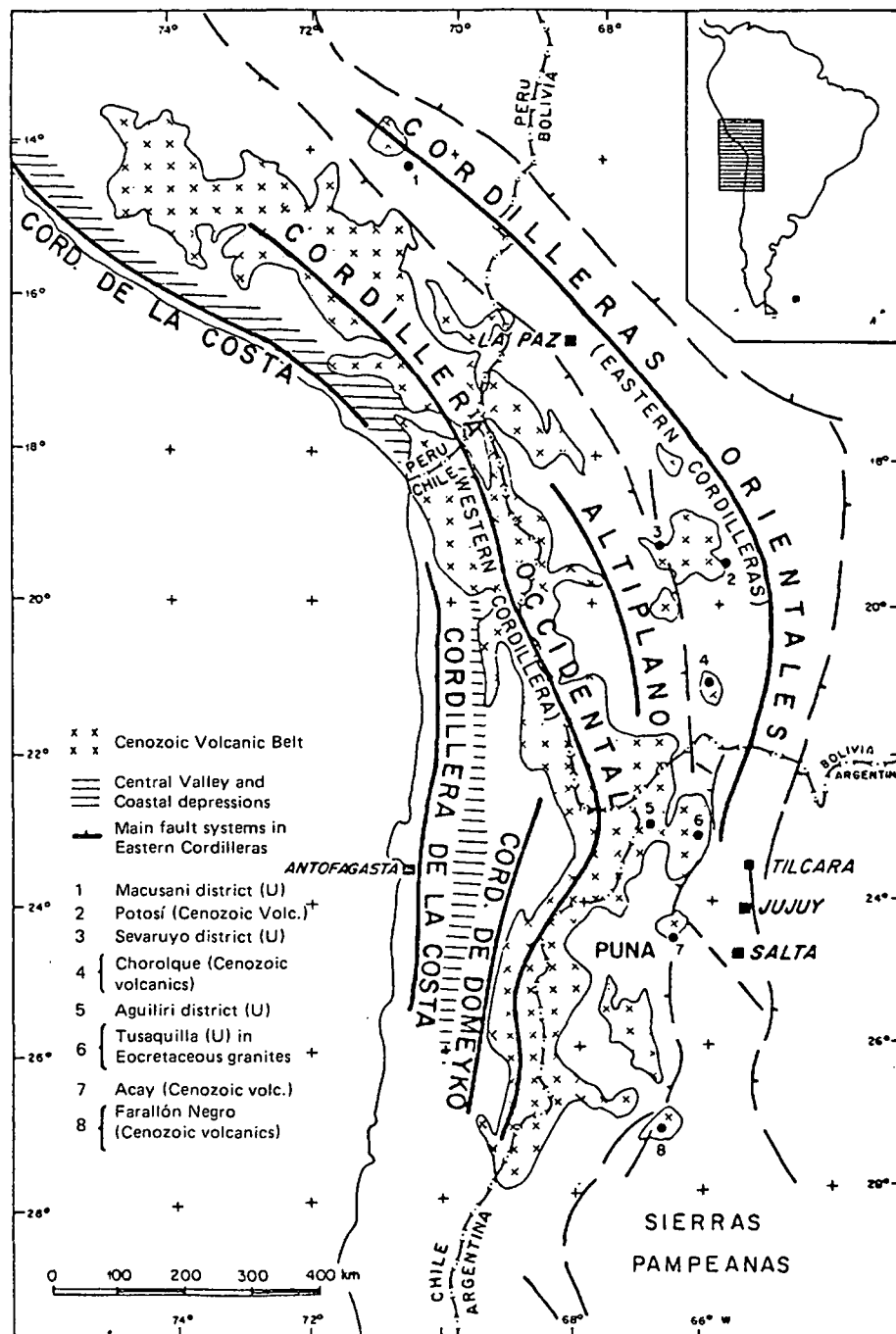


FIG.1. The Cenozoic Volcanic Belt of the South American Central Andes.

	SEDIMENTARY ROCKS	VOLCANIC ROCKS	INTRUSIVE AND SUBVOLC. ROCKS	URANIUM OCCURENC.
<b>HOLOCENE</b>	Detritus, alluvium, dunes, evaporites			
<b>PLEISTOCENE</b>	0.1 SUP Terraced deposits (congl. conglc.-sands, sands, tuffs & ignm. interc.)	Travertines Feno-bas., and., andt-bas., shoshanitic bas. ( $\pm 0.2$ ) Andt-flaws, andt-bas. (0.7-0.2) Rhyot. & andt. ignm. (1.2-0.7) Pyrocl. depts. ( $\pm 1.2$ )		Socampa
	0.7 INF			
<b>PLIOCENE</b>	2.0 Conglc.-sands, sands, calc.-limst., limst., travc. limst., tuffs, tuffites.	Rhyodac. & andt-latit. ignm. ( $\pm 2.5$ ) Rhya-dact. ignm. (4) And. & bast-and. (5-2) Tuffs & rhyot. & latiandt. aggl. & tuffs		Aquiliri Torrejo Paicone Coranzuli Peña Blanca Qda. del Torrejo
	6.0 LATE QUECHUA PHASE			
<b>MIOCENE</b>	10 Congl., sands, tuffites, calc.-sands, limst., tuffs & ignm.	Dact., rhyodot. & andt. ignm. (9.0) Fenoandt. flows, andt. brec., latit. & dact. and. (9) Latit-andt. flows & tuffs interc., dact-rhyodact. ignm., andt. tuffs, bre. & volc. aggl. ( $\pm 10$ )		
	15 REDDISH CONGL. & SANDS, red shales & siltst., with andt. volcanoclastic rocks in upper levels Violet sands. & congl. & interc. of red siltst. & brown shales		Rhyodt., dact., andt.-dact. porphyres (10-15)	
	22 PEHUENCHE PHASE			
<b>OLIGOCENE</b>			Andt. porphyre, monzonitic stock (22-26)	
<b>EOCENE</b>				
<b>PALAEOCENE</b>	Red & green claystones, yellow congl. limst., red argil.-sands, sands, siltst. & congl.			
<b>CRETACEOUS</b>			Granites	Tusoquilla

FIG.2. The Puna Post-Cretaceous stratigraphic sequence. Aggl. = agglomerate; and. = andesite; andt. = andesitic; argil. = argillaceous; bas. = basalt; bast. = basaltic; brec. = breccia; calc. = calcareous; congl. = conglomerate; conglc. = conglomeratic; dact. = dacitic; depts. = deposits; feno-bas. = fenobasalt; feno-andt. = fenoandesitic; ignm. = ignimbrite; interc. = intercalations; latit. = latitic; latiand. = latitic-andesite; limst. = limestone; pyrocl. = pyroclastic; rhyodac. = rhyodacite; rhyodact. = rhyodacitic; rhyot. = rhyolitic; sands. = sandstone; siltst. = siltstone; travc. = travertine; volc. = volcanic.

For practical reasons, Prediaguitic volcanism shall be known as 'Tertiary volcanism' (the Rhyolitic Formation of Pichler and Zeil [12]) and the Post-diaguitic as 'Quaternary volcanism' (Andesitic Formation of the same authors).

Rhyolitic, rhyodacitic and dacitic subvolcanic bodies, lava flow and ash-flow sheets characterize Tertiary volcanism. Acidic tuffs and ignimbrites of the Macusani uraniumiferous district (Peru) include abundant andalusite crystals. Postdiaguitic volcanism is mainly of andesitic character, as in the stratovolcanoes or the Western Cordillera and western parts of the Altiplano and Puna, but also acidic tuffs and ignimbrites are well developed from Peru to northern Argentina and Chile [13]. These volcanic rocks show a high  $^{87}\text{Sr}:$  $^{86}\text{Sr}$  ratio [4, 12, 14–16], which suggests crust contamination of a magma originally derived from the mantle [4, 16] or an anatectic nature of the magma [17]. Two different associations are sometimes recognized in Postdiaguitic volcanic rocks: the occidental, calc-alkalic, and the oriental, shoshonitic [16, 18].

### 3. GEOLOGY AND STRUCTURE OF THE ARGENTINIAN PUNA

Considering the objectives of this study, 'basement' shall include all geological formations older than the Fase Incaica; therefore, the following main units can be identified: 'basement': Tertiary sediments (continental, Post-Fase Incaica); 'Tertiary volcanic rocks' (effusive); 'Quaternary volcanic rocks' (effusive); and Quaternary deposits (valley sediments, evaporites).

The Postincaic stratigraphic sequence of the Puna is summarized In Fig.2 [5, 7, 9, 10, 16, 19].

The 'basement' is mainly composed of marine Ordovician sediments with thick contemporaneous intercalations of rhyolitic-rhyodacitic tuffs and ignimbrites, rhyodacitic and dacitic lava flows, andesites, etc. in the eastern sector [20, 21]. Most of the sediments were related to a 'Silurian eruptive belt', which also includes plutonic rocks [22]. Subordinated 'basement' terrains belong to Devonian, Carboniferous, Permian, Cretaceous-Eotertiary sediments and to a Precambrian pluton [21, 23, 24]. Lower Cretaceous granites are of special interest because some show uranium occurrences (Tusaquillas) or thorium deposits (Rangel) in the Argentinian Puna.

The Puna structure was considered relatively simple [22, 24] but new interpretations indicate a more complex pattern. A first in toto depression of the entire Puna block took place between Eocene and Oligocene, along the main N-S fault system of its western and eastern borders. From that time, the internal block structure of the Puna developed, and its final uplift began in Late Pliocene and was completed during Pleistocene [22].

The internal block structure shows a main system of long and narrow horsts and grabens produced by a compressional Tertiary tectonism throughout N-S and NNE-SSW inverse faults of high to moderate angles [25]. New satellite imagery

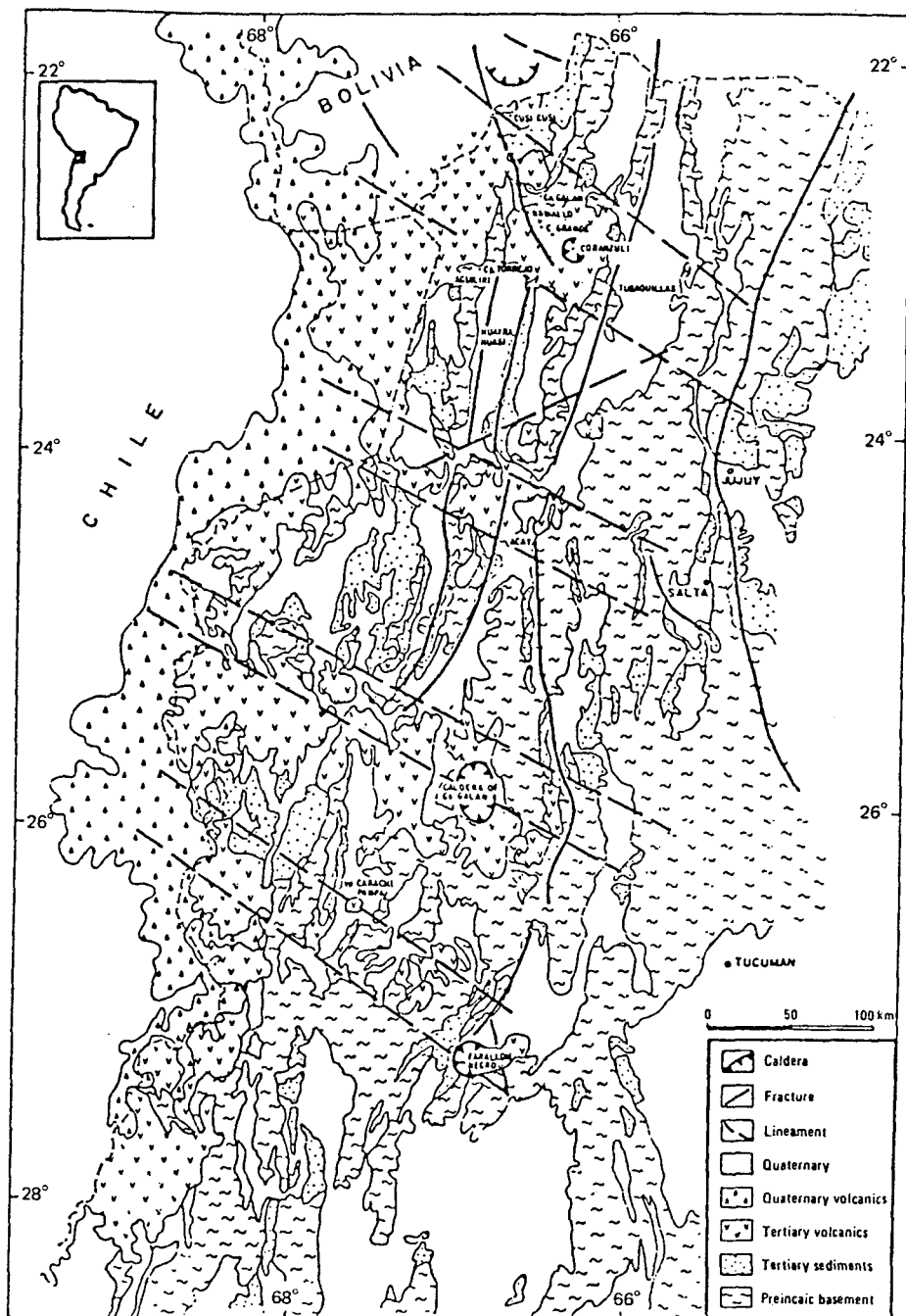


FIG.3. Geology and main structural lineaments of the Argentinian Puna.

interpretation pointed out that two other structural lineaments have also affected the 'basement' (Fig.3). One has a NW direction but the most important one, with a WNW trend, created structural sills in this direction, which enabled the formation of independent basins within the main original depressed N-S grabens [20, 26].

After this compressional tectonism, subordinated distensional compensatory fracturing took place [27–29], causing huge Tertiary volcanism which is mainly located in the intersections of the WNW-ESE and N-S fault systems. During the Quaternary age new distensional fracturing caused the great volcanism along the N-S Western Cordillera.

Within the block structure of the Puna, the horsts are composed of folded Ordovician sediments intruded by Lower Palaeozoic plutons [22], and grabens and partial basins were filled during Tertiary times with detrital materials from the Eastern Cordillera and the Sierras Pampeanas. Some of the materials produced by Tertiary volcanism have invaded the adjoining basins, alternating or interfingering with the sedimentary deposits, or covering them. However, the deposits of each of the partial basins are quite different in composition and did not allow for their respective strict correlation.

Tertiary deposits are faulted and folded but the Quaternary ones are only faulted.

No Postincaic volcanism is recorded in the Eastern Cordillera at the Domeyko Cordillera, where tectonism only had a clear compressional character.

In the few cases where Tertiary volcanic rocks intruded Tertiary sediments, small subvolcanic bodies resulted (dacitic-andesitic porphyres), located along N-S lineaments (Pan de Azúcar, Cerro Galán of Jujuy, Aguiliri, etc.); some bear Pb, Ag, Zn, Sn and U mineralization of Intramiocene age, defined by isotopic dating [5, 30] as similar to that of the Bolivian stanniferous belt. On the other hand, a similar mineralizing process recorded at the Macusani and Cotage districts is related to Pliocene-Pleistocene subvolcanic bodies.

After the Diaguitic phase, a Quaternary volcanic arc was installed along the western border of the Puna and Western Cordillera, as well as in some of the structural lineaments which controlled the former Tertiary volcanic rocks. However, the Quaternary arc, essentially related to N-S structures, shows a different spatial distribution to that of the Tertiary arc. Interpretation of seismological data, geostructural analysis and magnetic-teluric sampling suggests that the aforesaid spatial disconformity between the two volcanic arcs was produced by fragmentation of the subducted Nazca plate in two transduction blocks, known as the Calchaqui and Incaico Triangles. The above-mentioned events point out the important role of the Diaguitic phase [6, 31–33].

The Quaternary volcanic chain shows mainly stratovolcanoes composed of andesitic and basaltic lava flows and subordinated acidic and intermediate ignimbrites; small and isolated basalt occurrences are also present.

Late Pliocene diastrophism has mainly controlled the Puna geomorphological pattern, but its present general altitude was completed by Quaternary uplifts.

Pleistocene sedimentation took place within the partially depressed blocks, including valley products, evaporitic bodies in large, close basins and ignimbrites and tuffs, which have reached the maximum thickness.

At present the Puna has a closed drainage system because in spite of the Quaternary uplifts it still corresponds to a depressed block between the higher Eastern and Western Cordilleras.

#### 4. FAVOURABLE FACTORS FOR URANIUM ACCUMULATIONS RECOGNIZED IN THE PUNA VOLCANIC BELT

The following favourable factors for uranium accumulations have been recognized in the Cenozoic Volcanic Belt of the Argentinian Puna.

##### 4.1. Geotectonic spatial position of the Volcanic Belt

Because of its distal position with respect to the front of subduction of the Nazca plate, the Volcanic Belt offers good conditions for uranium accumulations on its eastern border. In such a direction the increase of alkali, silica, uranium, thorium, etc. contents in the corresponding magma favoured the formation of:

- (1) High syngenetic disseminated uranium contents in volcanic rocks, especially in tuffs and ignimbrites (as source rocks)
- (2) Hydrothermal or pneumatolitic uranium accumulations produced by late phases of magmatic differentiation.

After their formation, these abnormal uranium contents were preserved or eroded and, in the latter case, new secondary accumulations may have been formed under favourable circumstances.

The Macusani, Sevaruyo and Aguiliri uraniumiferous districts are located in the above-mentioned distal position in relation to the front of subduction.

##### 4.2. Uranium sources

- (1) The Volcanic Belt includes abundant rhyolitic, rhyodacitic and dacitic ignimbrites and tuffs (see Fig.2), which have been recognized as the most favourable uranium source rocks [34]. Commonly, these volcanic rocks are vitro-crystallines, with 50 to 60% glass, reproducing the favourable conditions mentioned by Zielinsky [34].

In this regard, in several places tuffs and ignimbrites have high uranium contents, as in the Cerro Galán of Jujuy and Corral Grande (15 ppm U), Turi Lari (10 ppm U), Ramallo (35 ppm U), Cusi Cusi (31 ppm U) and Pairiqui Chico (21 ppm U).

(2) Polymetallic mineralizations (Pb, Sn, Hg, Sb, etc.) produced by late volcanic hydrothermalism are frequent and, in some, uranium minerals are present, as in the dacitic neck of the Cerro Torrejo [35].

Joints and amygdaloids of the Socompa travertines (Quaternary) are filled with uranium minerals (autunite?) carried by late volcanic aqueous phases [35].

Small hydrothermal veins, located near Paicone in the tectonic contact between Ordovician and Tertiary sediments, include limonite, chalcopyrite and pyrite, and also show high radioactivity, up to 4000 counts/s [35].<sup>1</sup>

At Peña Blanca (near the Piriquitas Mine), small hydrothermal veins, contained in Quaternary altered tuffs, show silicification and are filled with radioactive haematite, with values up to 1000 counts/s.<sup>1</sup> This case is very similar to the Los Diques uranium occurrences of the Sevaruyo district (Bolivia).

At Aguiliri (5 km east of the Jamma volcano), a Pliocene-Pleistocene dacitic neck intrudes Tertiary red beds and an interesting uranium mineralization (autunite) was found on its northeastern border (recognized along 200 m, with a thickness of 10 m and a grade of 0.1% U). It is believed that this mineralization was produced by exhalative late volcanic phases, using the altered and crushed borders of the dacitic neck as host rocks.

#### 4.3. Alteration of source rocks – uranium leaching and mobilization

(1) Alteration of rocks has been produced in the Puna either by weathering (strong oxidation and daily changes of temperature; alternating dry and wet seasons) or by surficial and underground waters, commonly alkaline, with a pH of 7.4 to 8.2.

(2) The alteration, favoured by the high glass content, consists of advanced devitrification of tuffs and ignimbrites, with argillization and the formation of cristobalite, alkaline-phosphates, zeolites, chalcedony, etc.

The degree of devitrification (alteration) is clearly defined in satellite imagery because of the difference in reflectance between altered and fresh ignimbrites (white for altered rocks, and grey for fresh ones; analysis of band 7 complemented with band 5 in LANDSAT IV imagery).

(3) Another type of alteration is produced by hydrothermal and exhalative (CO<sub>2</sub> and H<sub>2</sub>S) volcanic processes, with silicification, argillization, deferrization (alteration of biotites), colouring by iron oxides (yellow, pink) and formation of pumpellite.

A good example of hydrothermal alteration is found at the Jama strato-volcano (4 km west of the Aguiliri uranium deposit), where a typical iron cap was produced; Mn-hydrothermal mineralization appears in the nearby volcanic plateau, with a high radioactive background (400 counts/s).

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<sup>1</sup> Measured with a SPP2 scintillometer.

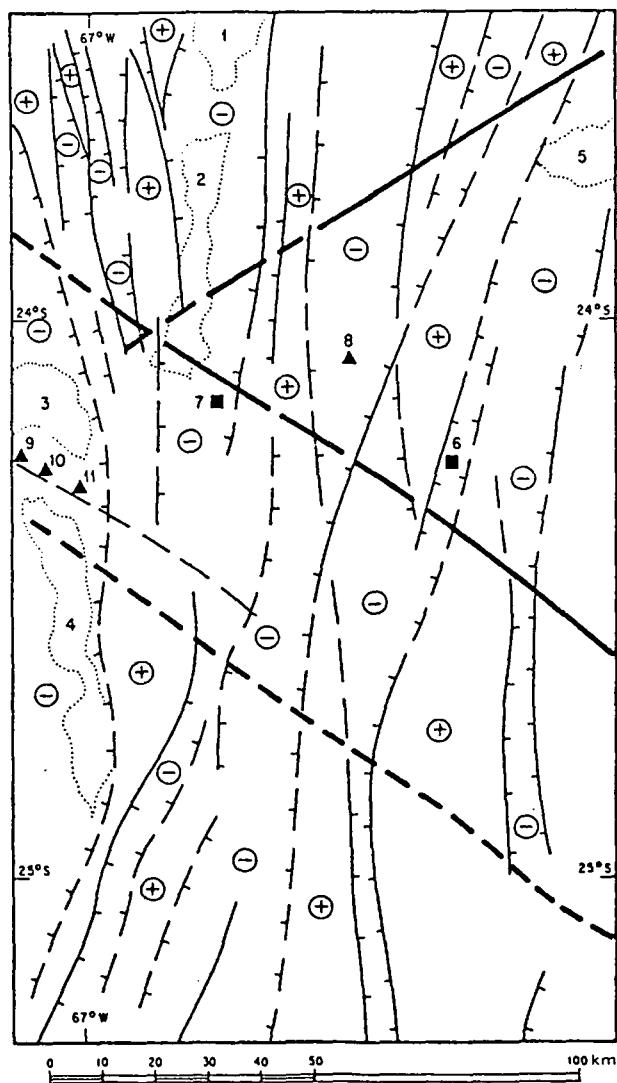


FIG. 4. The fault-block structural system in the Argentinian Puna (preliminary interpretation on LANDSAT IV imagery). (1) Salar Olaroz; (2) Salar de Cauchari; (3) Salar del Rincón; (4) Salar Pocitos; (5) Salinas Grandes; (6) San Antonio de los Cobres; (7) Estación Olacapato; (8) Cerro Tuzgle; (9) Cerro Tul-Tul; (10) Cerro del Medio; (11) Cerro Pocitos.

- (4) A third type of alteration was recognized but the process concerned, which produced the alteration of apatite, has not been identified.
- (5) Because of the alteration of the rock, strong leaching and the subsequent mobilization of several elements (including uranium) took place in the Argentinian Puna during Cenozoic times, especially favoured by the coalescence of neotectonic movements and the abundance of water during the interglacial Pleistocene stage.

#### 4.4. Deposition of mobilized uranium

The above-mentioned leached elements (including uranium) might have concentrated when the respective loaded solutions found favourable physical-chemical conditions in the course of their mobilization. Some of these conditions have been identified in the Puna environment.

- (1) Large caldera structures, such as those of the Cerro Galán in Catamarca (40 km Ø), Coranzulí and Farallón Negro (filled with tuffs and ignimbrites) have been recognized using satellite imagery. Intracaldera structures are considered one of the best environments for uranium source [34]; they also offer good conditions for uranium leaching and precipitation.
- (2) Large fault-block structures are present in the Puna; they resulted in a horst-graben system (Fig.4) which gave place to a structural pattern similar to that of Macusani, where such a pattern has participated in the distribution and concentration of the mobilized uranium [36].

In several cases, the N-S grabens have resulted in closed basins filled with thick tuffs, ignimbrites and sediments, reproducing the physico-chemical conditions of the caldera environments.

Strong evaporation of the loaded solutions in the basins resulted in the formation of important boron deposits and alkali-metal-rich brines, as in the salars Olaroz, de Cauchari, Incahuasi, del Hombre Muerto, etc. [37, 38]. In the same way, in the Salar de Río Grande, the uranium concentration reaches 50 ppm U.

Horizons of haematite and uranium minerals, produced by oscillation of the water-table, are included in altered subhorizontal tuffs on the western border of the Olaroz graben. A similar condition is recorded 10 km north of Coranzulí, where kaolinic alterations of subhorizontal tuffs include iron oxides with high radioactivity (up to 1500 counts/s).

- (3) Hydrosulphuric volcanic exhalations, normally moving through fissures, have produced uranium precipitation from loaded solutions, as in some occurrences of the Sevaruyo district (Bolivia). Hydrothermal exhalations are frequent in the Argentinian Puna, but no examples of related uranium precipitation have yet been identified.

## 5. CONCLUSIONS

The uranium possibilities of the Cenozoic Volcanic Belt of the Argentinian Puna should be considered in relation to the uranium potential of the whole Volcanic Belt of the South American Central Andes (covering approximately 300 000 km<sup>2</sup>) but especially of other similar geological environments in the world, such as those in China, Mexico, the USSR and the United States of America, where important uranium deposits have already been found.

In this regard, the identification in the Argentinian Puna of several factors favourable to uranium accumulations, which have been recognized in the above-mentioned areas, justify detailed analysis of the Argentinian Volcanic Belt through a multidisciplinary project.

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