

Uranium exploration through the integration of Multispectral Imagery, Radar and Field Radiometry at the Laguna Sirven Project, Province of Santa Cruz

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Resumen: *EXPLORACIÓN DE URANIO MEDIANTE LA INTEGRACIÓN DE IMÁGENES MULTIESPECTRALES, RADAR Y RADIOMETRÍA DE CAMPO EN EL PROYECTO LAGUNA SIRVEN, PROVINCIA DE SANTA CRUZ.* En la presente publicación se detallan los trabajos realizados para la delimitación de anomalías uraníferas en el Proyecto Laguna Sirven, al norte de la Provincia de Santa Cruz. En la década del 70 la CNEA realizó estudios orientados a la definición de sectores con potencialidad de mineralización de uranio en las provincias de Santa Cruz y Chubut, entre los que se encontraba este Proyecto. Se trata de un depósito sedimentario formado por precipitaciones ricas en uranio cerca de la interfaz del nivel freático, generando calcretes de gran extensión y forma típicamente tabular. En la mayoría de estos depósitos, el uranio proviene de la meteorización de rocas volcánicas, las cuales podrían ser yacimientos secundarios de uranio. La solubilidad del uranio está estrechamente ligada al potencial de oxidación, por lo cual bajo condiciones oxidantes el uranio se encuentra como catión U^{6+} , altamente soluble y por ende muy móvil. Sin embargo, en un ambiente reductor, el ion U^{6+} se convierte a la forma insoluble U^{4+} . Así, el uranio en solución circula a través de estratos permeables hasta que se topa con condiciones reductoras y precipita. Geoquímicamente, el uranio es un elemento incompatible, lo cual genera que este elemento sea de los últimos en cristalizar a partir de un fluido magmático. Por consiguiente, se concentra en las rocas ácidas formadas en las últimas etapas de la diferenciación magmática. En el modelo del yacimiento se estima que la fuente primaria de uranio corresponde a las piroclastitas cretácicas de las formaciones Castillo, Bajo Barreal y Laguna Palacios, pertenecientes al Grupo Chubut, y en menor medida las piroclastitas jurásicas del Grupo Bahía Laura. Los estudios realizados mediante sensores remotos se basaron en imágenes multiespectrales LandSat 7 ETM+, ASTER, y Modelos de Elevación Digital a partir de imágenes SRTM. A partir de este set de imágenes se generaron diferentes productos orientados a la delimitación de anomalías minerales y térmicas, patrones de escorrentía, zonas de aporte y deposición. Luego, se realizaron trabajos de campo en la zona, los cuales incluyeron un relevamiento terrestre de radioespectrometría gamma y toma de muestras para análisis geobotánicos. La integración del conjunto de información obtenida en un Sistema de Información Geográfica permitió avanzar con los trabajos exploratorios de uranio en este Proyecto.

Abstract: The present publication details the works carried out for the delimitation of uranium anomalies in the Laguna Sirven Project, north of Santa Cruz Province. During the 70s the CNEA conducted studies aimed at defining areas with potential for uranium mineralization in the provinces of Santa Cruz and Chubut, including this Project. This site corresponds to a sedimentary deposit formed by rich uranium precipitations at the water table interface, creating calcretes of a large extent and typically tabular form. In most of these deposits, uranium comes from the weathering of volcanic rocks, which could be secondary uranium deposits. Uranium solubility is closely linked to oxidation potential, whereby under oxidizing conditions uranium is found as U^{6+} cation, highly soluble and therefore very mobile. However, in a reducing environment, the U^{6+} ion is converted into the insoluble form U^{4+} . Thus, the uranium in solution flows through permeable strata until it meets reducing conditions and precipitates. Geochemically, uranium is an incompatible element, which causes it to be one of the latest elements in crystallizing from a magmatic fluid. Therefore, it concentrates in acid rocks formed at the final stages of magmatic differentiation. It is estimated that, in the deposit

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model, the primary source of uranium is the Cretaceous pyroclastites from Castillo, Bajo Barreal and Laguna Palacios formations, belonging to the Chubut Group, and to a lesser extent the Jurassic pyroclastites from Bahía Laura Group. The studies conducted through remote sensing were based on LandSat 7 ETM+ and ASTER multispectral images, and Digital Elevation Models from SRTM images. Many products were generated from this image data set oriented to the delimitation of mineral and thermal anomalies, runoff patterns, source and deposition areas. Afterward, fieldwork was performed in the area, including a gamma radiospectrometry terrestrial survey and geobotanical sampling. The integration of all the information obtained into a Geographic Information System allowed us to move forward in exploratory works in this Project.

Key words: Uranium. Laguna Sirven. Satellite imagery. Gamma radiospectrometry.

Palabras clave: Uranio. Laguna Sirven. Imágenes satelitales. Radioespectrometría gamma.

Introduction

The Laguna Sirven Project is located in the North of Santa Cruz Province. It is a uranium deposit where the mineralization is concentrated in calcrete levels within the lake sediments of the Laguna Sirven. As it happens with numerous geological resources, until now there is no technique for direct identification of minerals or uranium deposits, neither is an adequate spectral description of the element. For such reasons, exploratory approach of this kind of deposits is carried out in an indirect way.

Exploration works were focused in the identification of the possible source rocks or areas of origin of the element, its transportation zone, and its deposition zone. Remote sensing allowed the delimitation of each of these zones by its spectral, topographic and sedimentological characteristics.

Inside the Earth crust, uranium is mainly found in acid igneous rocks, whether as uranium primary minerals, inside the accessory minerals or inside the major minerals under the form of inclusions (Rankama, 1962). Changes of these element primary sources allows the hexavalent uranium liberation, stable in aqueous solution inside a wide range of pH. After its displacement, it is likely to be syngenetically deposited with certain sediments, and to be epigenetically fixed with any kind of rocks, even in sedimentary formations which are not consolidated or precipitated yet. Soils are important fixing materials due to the content of clay minerals, organic

matter, iron hydroxides, manganese or aluminum hydroxides (Cordani, 1981).

These previously described geochemical characteristics are the ones that validate the use of spectral techniques in uranium deposits exploration. The use of remote sensing allows the identification of the acid volcanic rocks that conform this element source. Through the integration of optical and radar imagery, it was possible to map the water systems that drain the volcanic sequences. Likewise, through data sets of different electromagnetic ranges (VNIR, SWIR and TIR), numerous mineral and thermal anomalies could be determined with prospective purposes.

Location

The Laguna Sirven Project is located in the North of Santa Cruz Province (figure 1).

The Project can be reached by car by a 210 km paved road from the city of Comodoro Rivadavia- the largest urban center in the region- to the town of Las Heras and then, through approximately 50 km of local dirt roads southward of the latter. The project area has multiple access points due to the fact that there are many oil and gas companies developing their activities in the area.

Regional geology

Laguna Sirven is located in the San Jorge Gulf Basin. This basin covers a wide region located in the Central Patagonia. It includes the

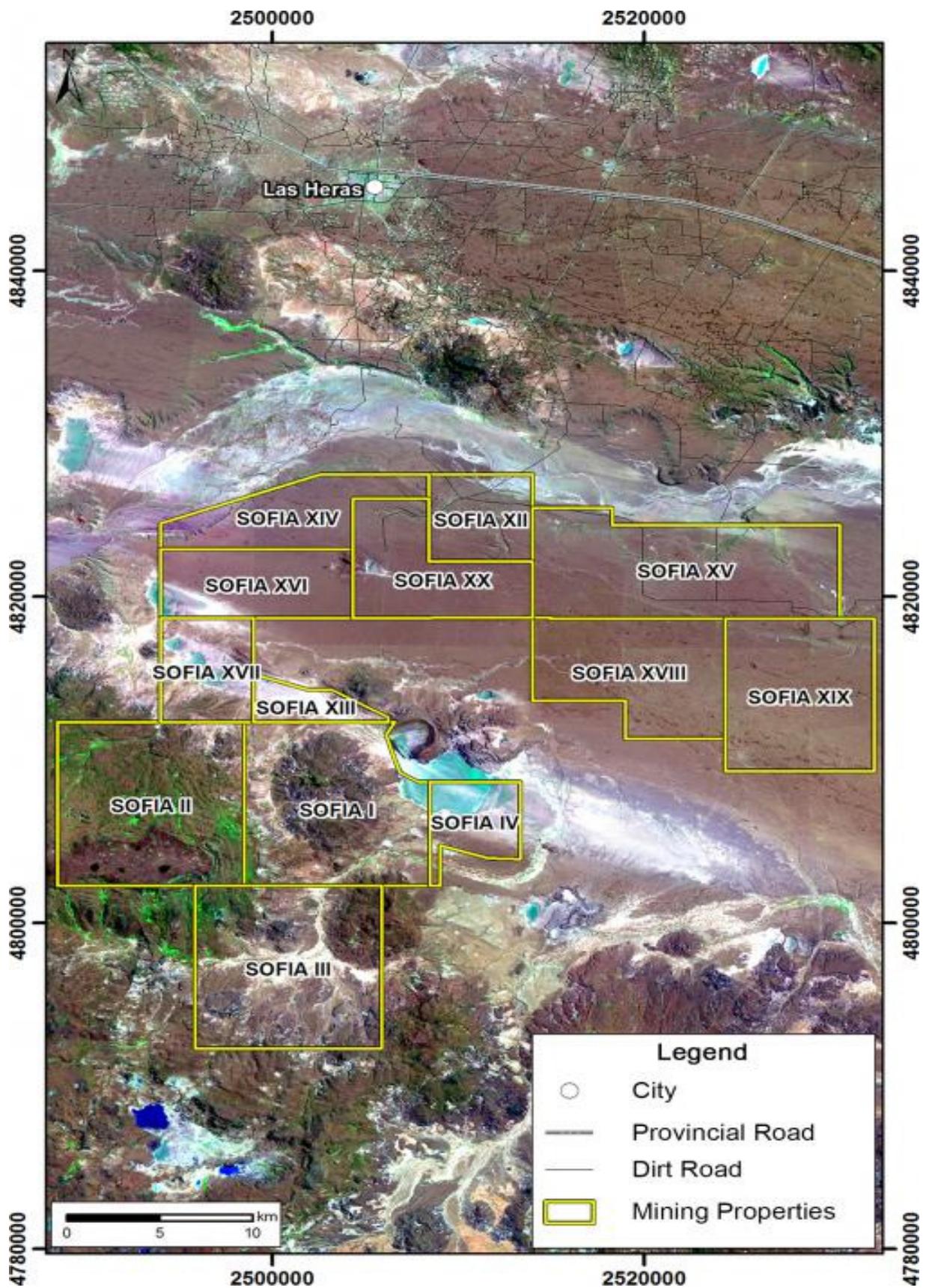


Figure 1. Laguna Sirven Project location. / **Figura 1.** Ubicación del Proyecto Laguna Sirven.

southern zone of the Chubut Province, the north of Santa Cruz Province and a part of the Argentinian Continental Platform in the San Jorge Gulf. The area of this basin is 65% onshore and 35% offshore.

The uranium metallogenesis associated to the project area is intimately related to the geological history and to the tectonic evolution of the South American continental margins.

From a regional point of view, the Uranium District of Laguna Sirven is comprised within the structural context of the retroarc Cretaceous Basins and specifically the San Jorge Gulf Basin, where the uranium deposits are principally associated with the volcano-sedimentary deposits of the Chubut Group.

Great part of the sedimentary filling of the San Jorge Gulf Basin, particularly the deposits of the Chubut Group, are comprised by material of volcanic origin. This material would have had its generation in the eruptive centers of the Pacific volcanic arc (Feruglio, 1949). The volcanic material is related to the convergent plates over the South American Pacific margin during the Cretaceous (Legarreta *et al.*, 1990).

Deposit geological model

Inside the Earth crust, uranium is mainly found in acid igneous rocks, whether as uranium primary minerals inside accessory minerals, under the form of isomorphic additions or inside major minerals, under the form of inclusions (Rankama, 1962).

The pyroclastic materials of the Castillo, Bajo Barreal and Laguna Palacios formations of the Chubut Group are the uranium main sources. The Chon Aike Formation of the Bahía Laura Group (Jurassic) can also be indicated as a uranium source. The rocks of this formation are mainly tuffs and vitroclastic chonites that contain uranium in its vitreous phase.

Based on these uranium sources, two deposit models can be proposed. One being the vulcanites outcrops themselves and a second one corresponding to sedimentary deposits generated by the weathering and epigenetic alte-

ration processes undergone by such vulcanites. As these rocks are easily altered by exogenous agents, the uranium content present in the volcanic glass is thus liberated to the surrounding hydric environment.

It is necessary to take into account the complexity of the factors for the formation of a uranium deposit in the Project area. Certain conditions for the precipitation and the preservation of uranium in the ores are needed for both the primary deposit model associated in a direct or indirect way to magmatic or hydrothermal processes and for the epigenetically originated deposit one. Such conditions are mainly related to the reducing and oxidizing properties of the mineral depositional environment.

Uranium is geochemically defined as an incompatible element. This means that it is within the last ones to crystallize when the magmatic fluid cools off. Therefore, it is concentrated in the acid rocks formed during the last stages of magmatic differentiation such as granite or in volcanic ashes.

In most sedimentary uranium deposits, uranium is originated in altered tuffs as well as in granitic plutons. Tuffs are rocks made of volcanic ash, which is unstable on the surface. Weathering alters tuffs and granites into clays and siltstones. Alteration processes liberate the uranium present in these rocks into underground waters.

Uranium solubility is closely linked to the oxidation potential. Under oxidizing conditions, uranium is found as U^{6+} cation, highly soluble and as a consequence, very mobile. However, in a reducing environment, the U^{6+} ion turns into the insoluble form U^{4+} . Therefore, insoluble uranium flows through permeable strata until it comes across with reducing conditions.

Thus, a uranium-rich precipitate is generated near the oxidation potential interface. Generally, this interface migrates in the phreatic fluids direction, which is the reason why the mineral concentrates in widely extended bodies with a typically tabular form. It is important to mention that not all tabular uranium deposits are generated by this mechanism. Frequently,

these strata are associated to dark organic matter in siltstones or adjacent shales and also to organic remains concentrations in sandstones.

Uranium deposits can present characteristic oxidized zones which contain uranium oxides usually perceived in the field as black or intense yellow anomalies.

Mineralization model

In the sedimentary sequence or uranium mineralization model hosted in sediments, the Atomic Energy National Commission (CNEA, in Spanish "Comisión Nacional de Energía Atómica") defined an inferior fluvial member (Lower Cretaceous) in which the well-known Cerro Solo deposit is located and a superior fluvial member that hosts deposits such as Sierra Cuadrada (Upper Cretaceous).

Studies made by CNEA confirmed the existence of uranium deposits and anomalies linked to tuffitic horizons. This type of mineralization model is related to epithermal and supergenic episodes occurred during the Tertiary.

A third mineralization model proposed by CNEA is the uranium mineralization linked to subsurface levels of caliche (hardened calcium carbonate deposit) and evaporitic sequences. This model is characterized by presenting uranium mineralization (mainly carnotite) few centimeters from the surface and distributed in wide areas.

According to the available information, the uranium mineralization model in caliche (sedimentary uranium) is the more relevant one in the project area. The second model of significance there is the mineralization linked to the uraniumiferous tuffs of the Bajo Barreal and Laguna Palacio formations.

Previous works

In the late 70s, CNEA defined an area of more than 100.000 km² with various potential uranium mineralization zones in Santa Cruz and Chubut Provinces, based on an aerial radiometric survey and fieldwork in

which the Laguna Sirven Project was included (figure 2).

Material and methodology

In order to cover the area of interest, two (2) Landsat-7 ETM+ images were obtained from the United States Geological Survey (USGS). The pre-processing of these images basically consisted on their correction by the application of spatial and spectral enhancements and different digital filters.

A daytime ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) image was also obtained. This image was acquired on January 30th, 2008 and processed at a 1B processing level, with radiometric (radiance values on the sensor) and geometric corrections, and snow or cloud coverage.

The selected images were originally projected according to the UTM System with the WGS 84 19S Zone Datum. In order to improve their adjustment, they were later georeferenced according to the POSGAR 1994, Faja 2 System.

The ASTER image was then separated and assembled according to the VNIR-SWIR bands on one hand, and TIR bands on the other. They were stacked with a 30 m resolution and a 90 m resolution respectively.

Data sets were then cropped following a buffer greater than 2 km around the Project area. These cropped scenes were subsequently masked with the purpose of eliminating water bodies which saturate certain spectral bands.

The data set belonging to the thermal infrared section was converted to superficial emissivity values. This was made by means of the normalization from values taken of global maps with surface properties, generated by the Surface and Atmospheric Radiation Budget (SARB) that is part of the Nubes Mission and the Sistema de Energía Radiante Terrestre (CERES) of NASA's Langley Investigation Center.

The treatment of images in laboratory consisted in enhancements application over various band compositions, in bands arithmetics and their statistical analysis and in the prepara-

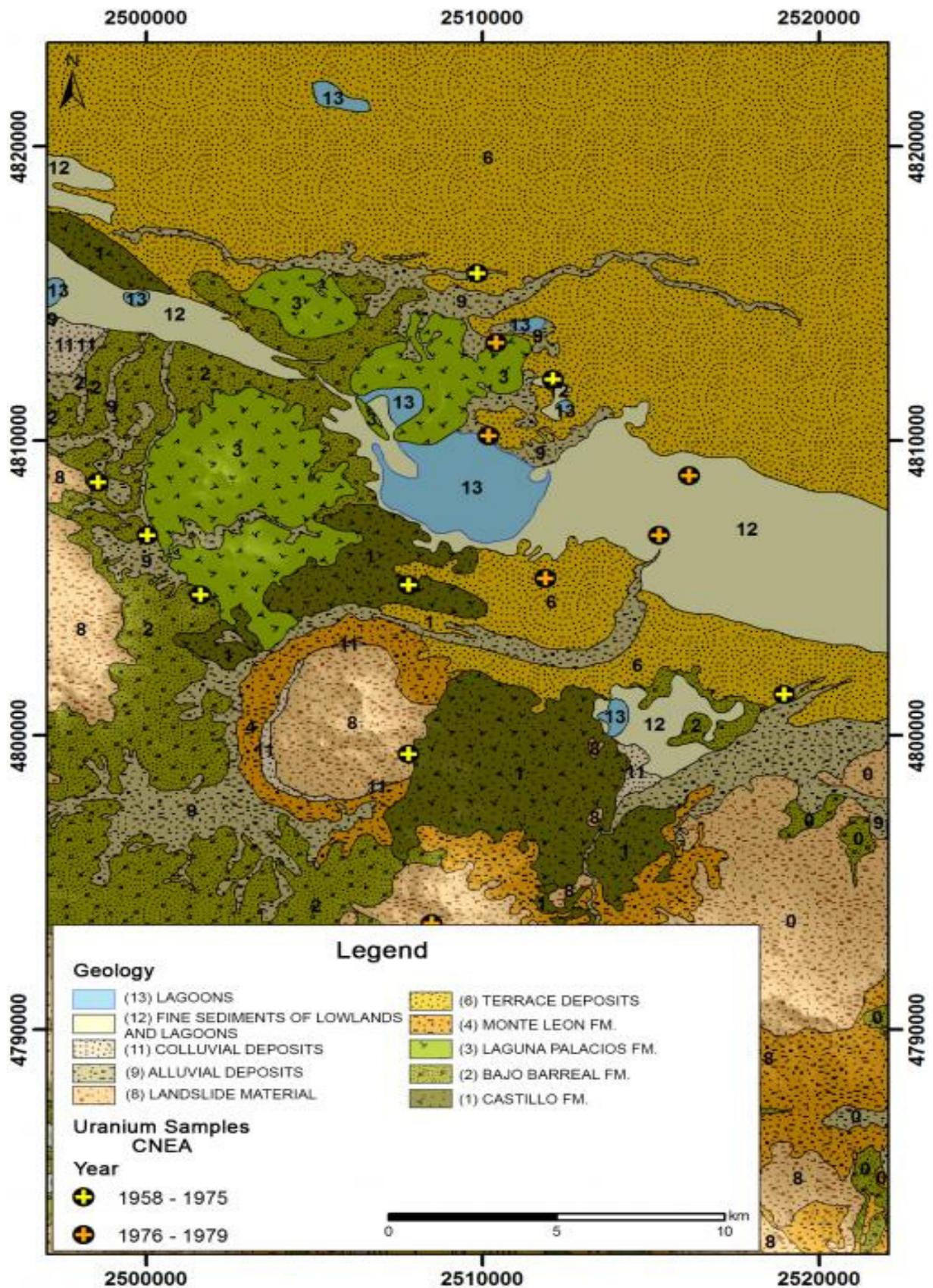


Figure 2. Geological map and CNEA sample location from survey carried out between 1958 and 1975 (from Panza, 2011). / Figura 2. Mapa geológico con el muestreo realizado por la CNEA entre 1958 y 1975 (a partir de Panza, 2011).

tion of transformations and classifications.

Typical band combinations were used, such as the false color composite to highlight geological units of different composition (table 1).

was necessary to saturate them. The enhancement technique used was a Saturation Stretch.

On the other hand, abundance indexes for various minerals were obtained through the appli

Región del Espectro	Canal Rojo	Canal Verde	Canal Azul
VNIR	3	2	1
VNIR-SWIR	1	3	4
	1	4	8
	7	3	1
SWIR	8	6	4
TIR	13	12	10
	14	12	10

Table 1. Band combinations to highlight geological units. / **Tabla 1.** Combinaciones de bandas para resaltar unidades geológicas.

Decorrelation Stretch is a process that improves the color display in highly correlated band sets. The process executes a transformation of the principal components over the input set, applies a contrast widening to the resulting components and finally reverses the transformation.

When the output band sets are displayed in red, green and blue, each band tone is generally similar to the original one, but the intensity increases. Therefore, this enhancement exaggerates the spectral properties of the different materials present on surface.

In the case of TIR images that generally have little contrast in between their values, it

was necessary to saturate them. The enhancement technique used was a Saturation Stretch. On the other hand, abundance indexes for various minerals were obtained through the appli

cation of simple mathematic relations between bands. These mineral indexes have the advantage of normalizing the data, reducing the effect on the ground variations and the illumination differences.

The mineral indexes used were described by Ninomiya (2004) and Ninomiya *et al.* (2012), (table 2). A field gamma - radiometric survey was carried out using an RS-230 BGO Super-SPEC.

These data was downloaded using the GEORADiS RSAnalyst Software, version 0.107, and exported to Microsoft Excel™ tables that allowed the subsequently analysis.

At the same time, vegetation and soils samples were taken for geochemical analysis

Región del Espectro	Índice Mineral	Aritmética de Bandas
VNIR	Óxido Férrico	2/1
VNIR-SWIR	Óxido Ferroso	5/3
SWIR	Carbonato/Clorita/Epidoto	(7+9)/8
	Dolomita	(6+8)/7
	Sericita/Muscovita/Ililita/Esmectita	(5+7)/6
	Alunita/Caolinita/Pirofilita	(4+6)/5
	Caolinita	7/5
TIR	Carbonato	13/14
	SiO ₂	13/12

Table 2. Mineral abundance indexes. / **Tabla 2.** Índices de abundancia de distintos minerales.

using the ICP-MS (Inductively Coupled Plasma Mass Spectrometry) technique.

Results

Initially, products obtained from LandSat ETM+ and ASTER scenes were interpreted: false color and natural color band composites with histogram adjustment, saturation and de-correlation enhancements and principal components rotation.

The analysis of these products was the first approach to the comprehension of the geology of the area through remote sensing.

The ASTER 14-12-10 bands composition (figure 3) clearly highlights the spatial contacts between different geological units. Also, it allows a limited discrimination of the outcropping lithology according to its acidity: basalts are observed in dark colors while the acid volcanites present light-to-reddish colors.

Likewise, the directional filtering of LandSat - 7 ETM + bands (figure 4) was useful to detect geological structures at regional level.

On the other hand, radar data (figure 5) was very useful for analyzing the region geofoms through digital terrain models.

Lithological discrimination was done through ASTER products such as mineral abundance indexes prepared from bands mathematics (RBD, RBP and K index), statistical analysis (PCA and tasseled cap) and physical parameters (ATI and brightness temperature).

For example, sandstones and specially tuffs are highlighted in the silica index (figure 6). Then, sandstones and tuffs can be differentiated using iron oxides indexes: generally, sandstones show high values while tuffs show low values (figure 7).

As expected, in the majority of the alteration indexes, tuffs, sandstones and altered siltstones are highlighted. However, the altered tuffs show a strong correlation with the kaolinite index, while altered sandstones and siltstones can be linked to smectites. The altered volcanites can be mapped with the alunite index.

Through the different band combinations generated with ASTER and LandSat ETM+ images, the discrimination by means of mineral indexes, the outcrops textures observed in radar images and the geological sheets at 1:250.000 scale, 4769-I El Puma (Cobos and Panza, 2003), 4769-III Destacamento La María (Panza and Cobos, 2001), 4769-IV Monumento Natural Bosque Petrificado (Panza, 2001), a geological map at 1:100.000 scale was generated for the project zone.

The gamma radiospectrometry survey was carried out with a guidance purpose. It intended to cover most of the project area and at the same time to establish in an expedited way the general gamma tendencies in order to determine areas to perform geochemical sampling.

Conclusions

The information obtained through the interpretation process allowed the evaluation of the presence and orientation of regional and local fractures, as well as the identification of the outcropping lithology.

The use of ASTER thermal bands made it possible the identification of acid rocks zones within the Massif. The Silica Index highlighted the volcanic Cretaceous rocks of the Chubut Group and the alluvial deposits formed by the exogenous processes that affect the outcrops of such units.

The existence of clearly anomalous areas, which present an important wide superficial extension was determined. These uranium anomalies are consistent along most part of the plateau and usually are more outstanding in the low topographic levels. This data was validated by means of field radiogamma spectrometric analysis and geochemical analysis.

The presence of subsurface caliche levels was detected approximately 50 cm deep, outcropping occasionally in the margins of the roads. It was observed that over some of the stream profiles, the caliche level serves as cement to a polyimictic conglomerate matrix. In the caliche, it was possible to evidence the presence of ura-

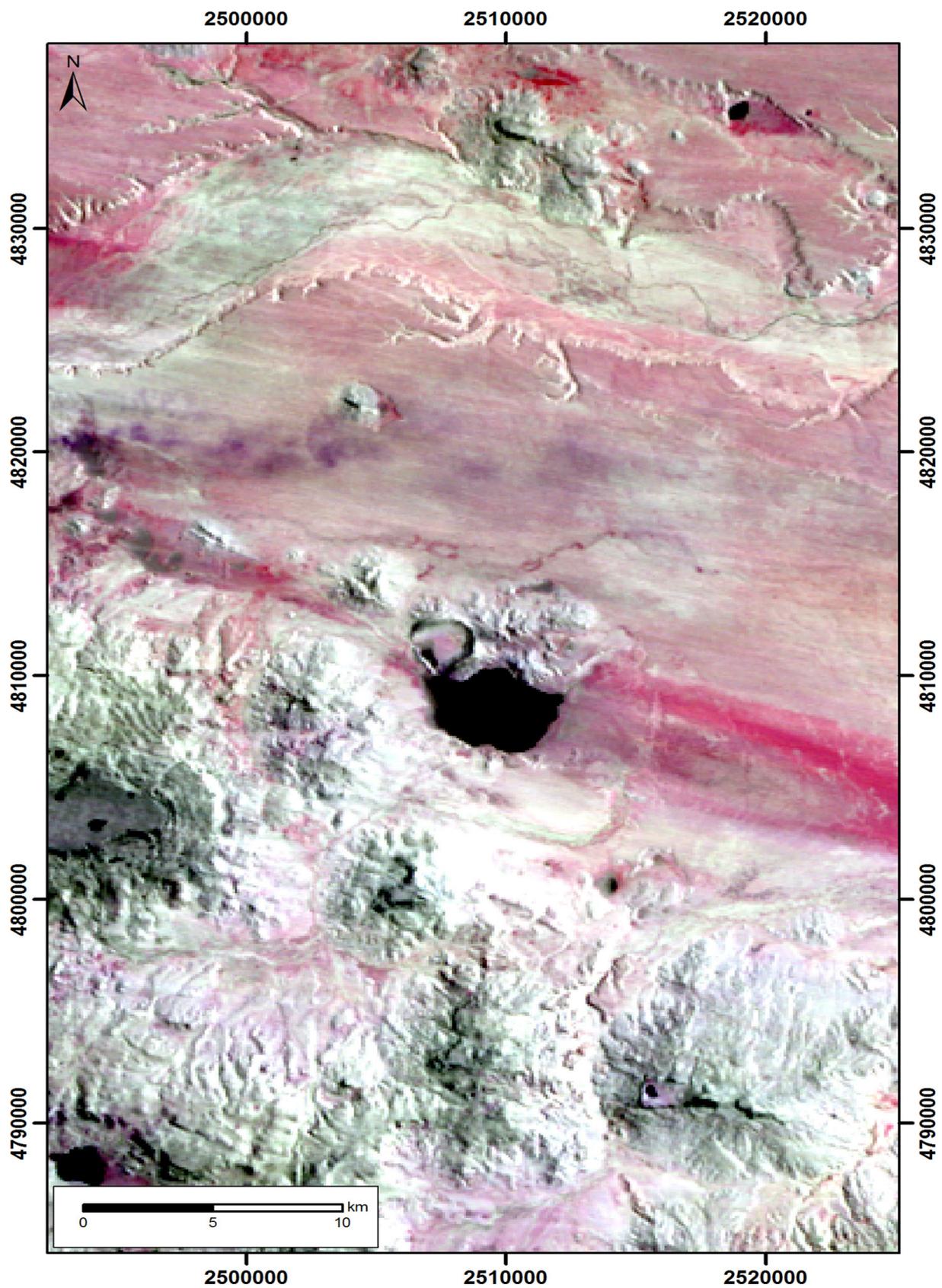


Figure 3. Colour composites of bands 14-12-10. In this combination of bands regional structures are clearly observed, as well as the presence of acidic rocks in pink. / **Figura 3.** En la combinación en falso color de bandas 14-12-10 se observan claramente las estructuras regionales, como así también la presencia de rocas ácidas en tonos rosados.

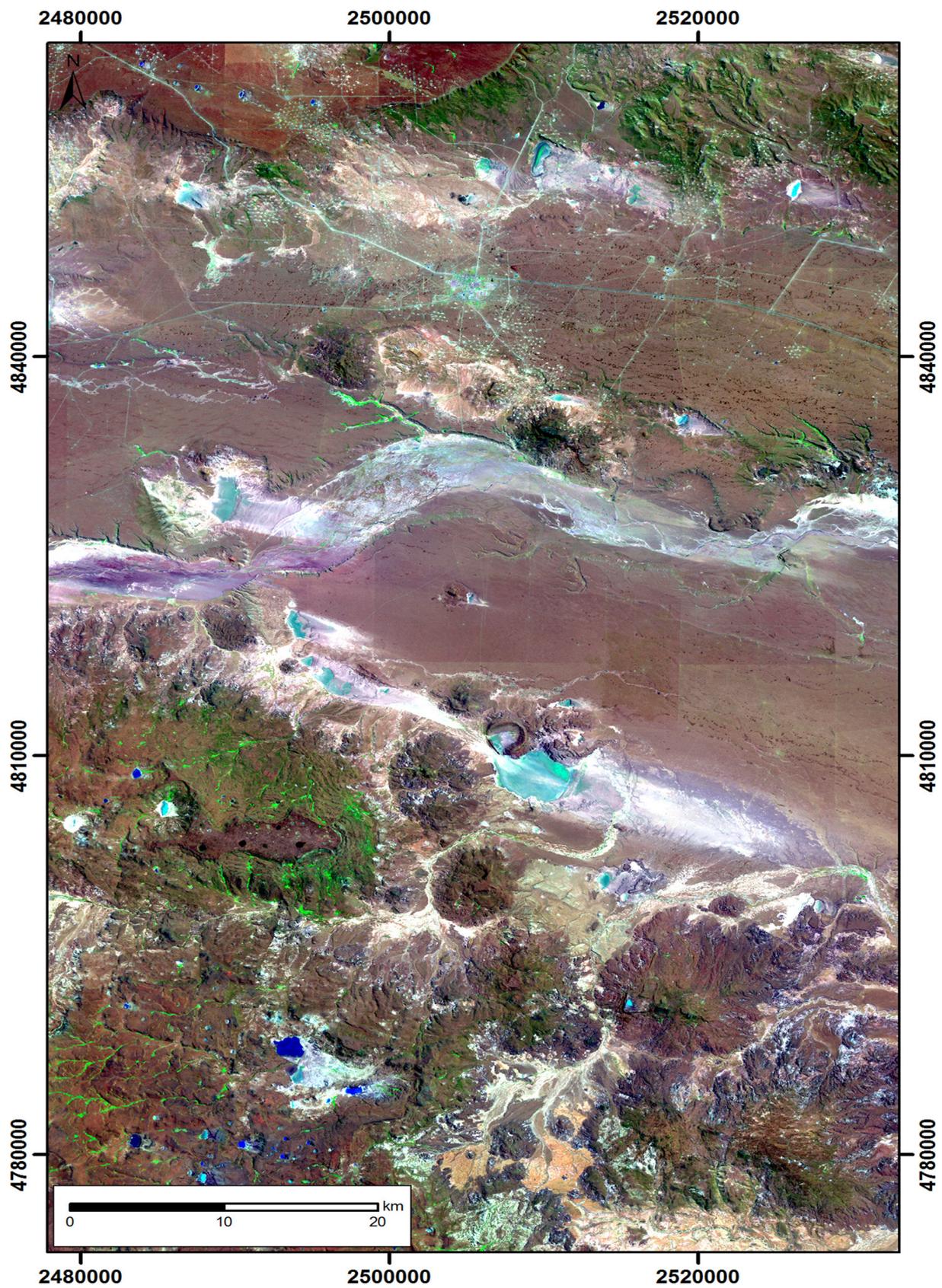


Figure 4. Colour Composite with 30° directional filter in 7-4-2 bands, shows structural NEN – SWS lineaments. /
Figura 4. Composición en falso color con filtro direccional según 30° aplicado a las bandas 7-4-2. Evidencia lineamientos estructurales en la dirección NNE-SSO.

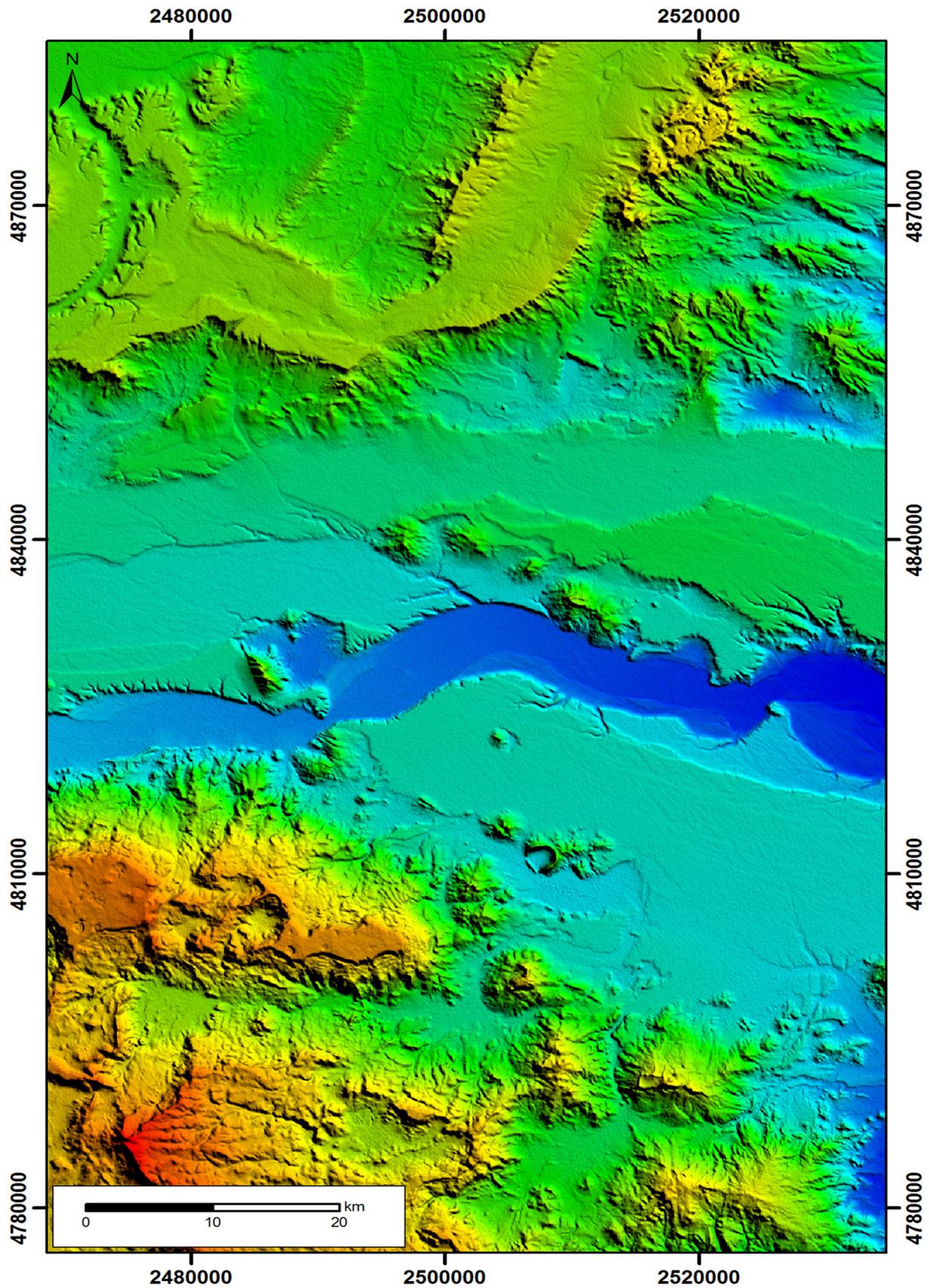


Figure 5. Colour Shaded Relief. This image shows DEM data, according to a chromatic scale, with an increase in elevation from a blue to green, yellow, brown and then finally red. Also, shades are shown according to a simulated relief. / **Figura 5.** Relieve Coloreado y Sombreado. Esta imagen ilustra los datos del DEM, de acuerdo a una escala cromática, con un incremento de la elevación que va desde un azul hacia el verde, amarillo, luego castaño y finalmente rojo. Adicionalmente, se observan sombreados acordes a un relieve simulado.

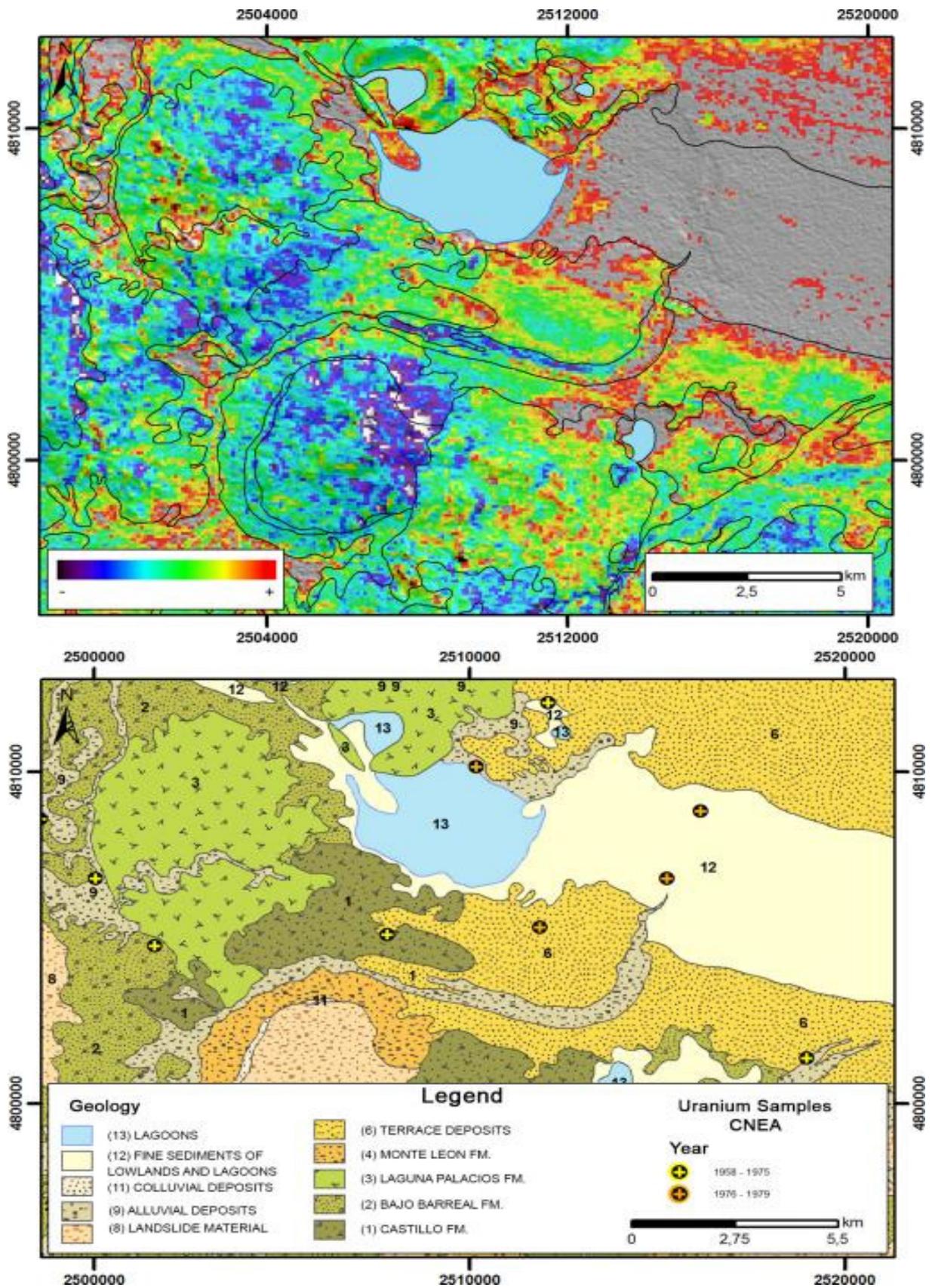


Figure 6. A) Silica Index. B) Geological map (from Panza, 2011). / Figura 6. A) Índice de Sílice. B) Mapa geológico (a partir de Panza, 2011).

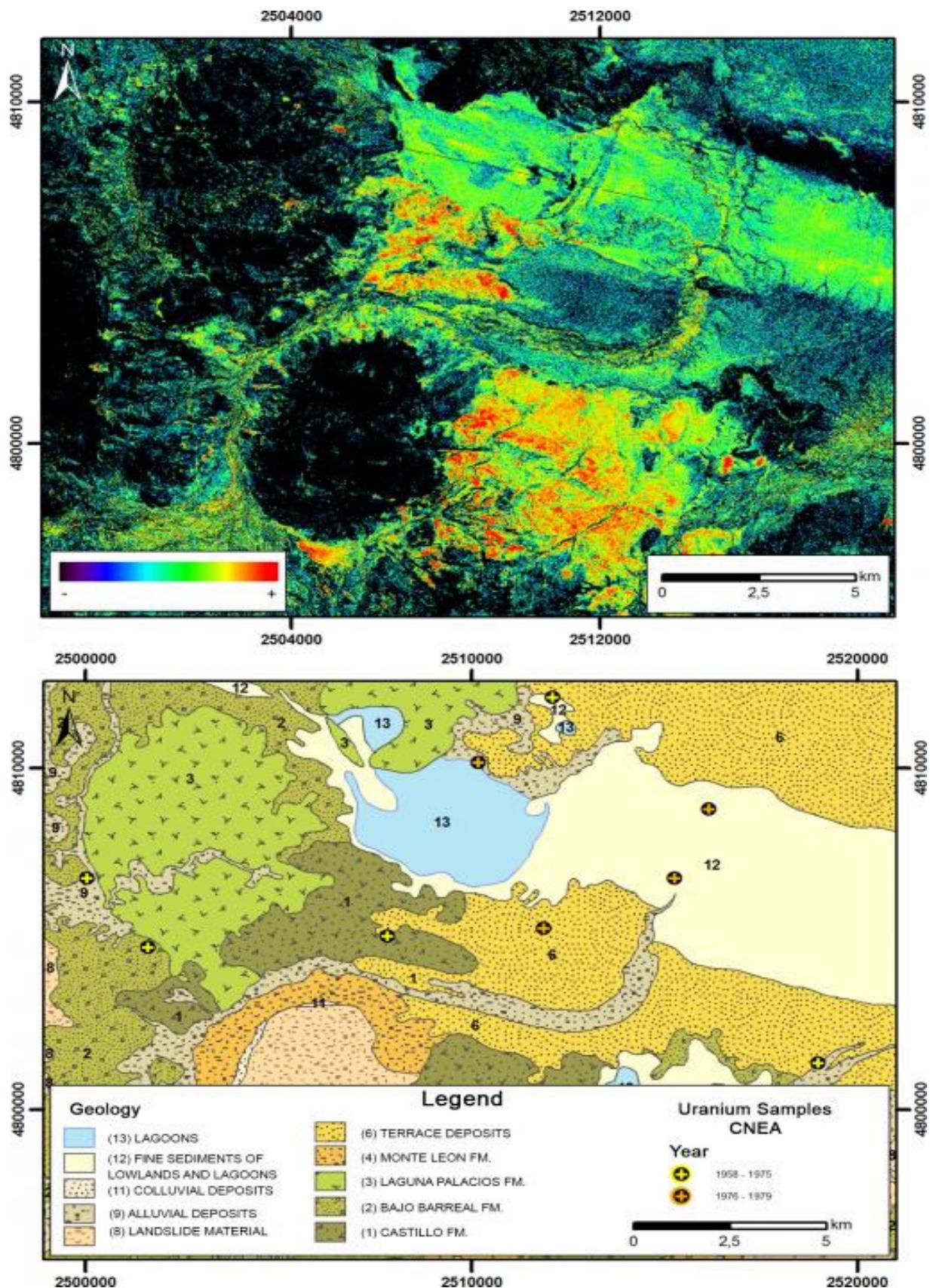


Figure 7. A) Iron Oxides Index. B) Geological map (from Panza, 2011). / Figura 7. A) Índice de Oxido Ferroso. B) Mapa geológico (a partir de Panza, 2011).

nium minerals that would probably correspond to carnotite, due to its intense yellow color and its earthy texture.

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