TRACKING FLUID PATHWAYS IN A GEOTHERMAL SYSTEM USING ASTER IMAGERY BAND-RATIO COMBINATION: THE CASE OF LICANCURA FIELD, NORTHERN CHILE.

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ABSTRACT

Identification of surface hydrothermal mineralogy using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery is one of the first steps to define potential areas for geothermal exploration; being especially relevant in areas of difficult access (e.g. high-altitude), where direct sampling is logistically complicated and time consuming. In Northern Chile, there is plenty of surface evidence indicating active and fossil geothermal activity, manifested as highly altered areas, yet most of these sites are located above 3,500 meters above sea level. In this work we aim to develop a remote-sensing technique as a proxy for the identification of active or fossil fluid circulation in potential geothermal zones. As a working example, this methodology was applied to the study of the Licancura Geothermal Field. Here, we used SWIR (short wave infrared) band ratio combination of ASTER imagery to identify areas associated with advanced argillic and propylitic alterations, likely related to emplacement of acid and neutral-alkali fluids. We found a correlation between highlighted electromagnetic spectrum features and minerals formed at specific temperatures at the time of fluid emplacement. Interpreted minerals assemblages are kaolinite+alunite+pyrophyllite and chlorite-epidote+illite-smectite+calcite, which show a preferential spatial distribution and abundance. Such arrangement can be used to estimate fluid circulation and evolution patterns, with different pH and temperature constraints through time.

This remote-sensing technique is sought to be considered as a first tool in geothermal exploration and a guide to establish areas of potential interest for geothermal exploration. Ongoing research and work is focusing on X-ray diffraction analyses of samples collected in the field to validate the correlation between remotely-interpreted mineralogical assemblages and field mineral occurrence.

1. INTRODUCTION

In geothermal systems, interaction between hot water and rocks results in a temporal and spatially regular zonal pattern of new minerals, as the fluids moves through the rock (Inoue, 1995). Generation of alteration minerals depends on pH and temperature characteristics of the fluid (Reyes, 1990; White and Hedenquist, 1995). So alteration mineral identification by mean of remote sensing techniques can be used as a proxy to define areas of interest, particularly when these are of difficult access.

Alteration minerals including chlorite, epidote, calcite, illite, smectite, alunite, kaolinite and pyrophyllite have particular spectral signatures (i.e. reflectance) which are possible to identify on spectral curves of each mineral. These spectral curves can have reflectance picks in the VNIR (visible and near-infrared), SWIR (short wave infrared) and TIR (thermal infrared) portions of the electromagnetic spectrum. Nevertheless, carbonates, hydrate and hydroxide minerals can be identified in the SWIR portion (e.g. Delendatti, 2003; Rowan and Mars, 2003; Calvin *et al.*, 2014). ASTER imagery has a six band division in the SWIR (Table 1) portion, a number of bands that make possible to differentiate and identify remotely alteration minerals prior to field work, giving evidence of possible areas of fluid flow which generated the alteration minerals remotely identified.

In this work we used SWIR band ratio combination of ASTER imagery to remotely-identify different mineral geothermometers of advanced argillic (i.e. acid pH fluids) and propylitic alterations (i.e. neutral-alkaline fluids), to have a proxy of hydrothermal fluid flow at the Licancura Geothermal Field in northern Chile.

Table 1. Bands from ASTER imagery (Rowan and Mars, 2003).

Subsystem	Band number	Spectral range (µm)
VNIR	1	0.52-0.60
	2	0.63-0.69
	3N	0.78-0.89
	3B	0.78-0.86
SWIR	4	1.600-1.700
	5	2.145-2.185
	6	2.185-2.225
	7	2.235-2.285
	8	2.295-2.365
	9	2.360-2.430
TIR	10	8.125-8.475
	11	8.475-8.825
	12	8.925-9.275
	13	10.25-10.95
	14	10.95-11.65

2. GEOLOGICAL SETTING

The Licancura Geothermal Field, covering an area of about 270 km^2, is located 220 km NE of the city of Iquique in the High Andes within the U.T.M coordinates 790300N-48000E, 7876000N-49000E, between 3600-4500 m.a.s.l. (Figure 1).

The rocks outcropping in the Licancura area corresponding to volcanic products of the Andean arc, and include Upper Miocene, Upper Miocene-Pliocene andesitic lavas and andesitic to dacitic tuffs. These units overlie Miocene volcano-sedimentary deposits. The Miocene-Pliocene units are also covered by younger sedimentary deposits, identified as Holocene fluvial, colluvial, alluvial and landslide deposits (Figure 2) (Valenzuela *et al.*, 2014).

In the study area hydrothermal activity is evidenced by argillic alteration affecting volcanic and volcanosedimentary units (Valenzuela *et al.*, 2014). Also evidence of actual and past geothermal fluid circulation corresponds to the occurrence of alteration minerals such as sulfates, epidote, calcite, alunite, and clay minerals in volcanic units (Maureira, 2013).

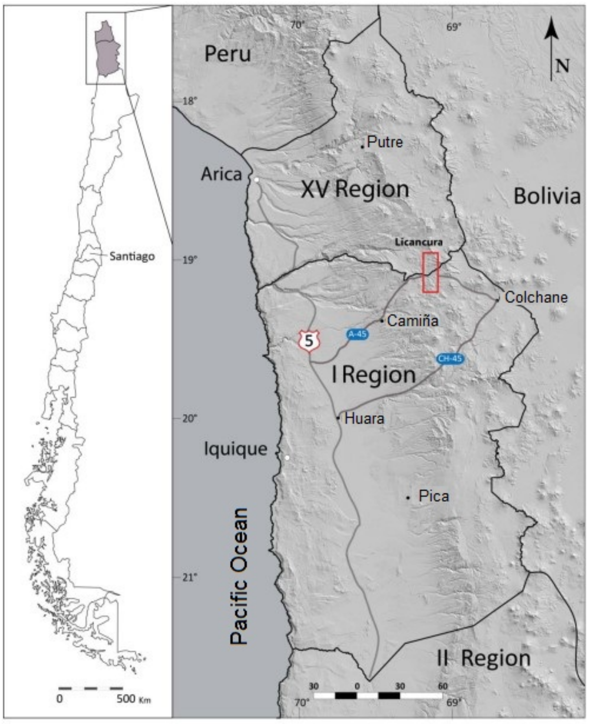

Figure 1. Location and access of Licancura Geothermal Field.

3. GEOTHERMAL WATERS AND HYDROTHERMAL ALTERATION

Chemicals composition of hydrothermal waters is one of the main factors affecting hydrothermal alteration processes (Browne, 1978). In geothermal systems is possible to find four types of waters based on major ions, which originates different types of hydrothermal alteration (Ellis and Mahon, 1977; Nicholson, 1993)

Chloride waters have a neutral pH between 4 and 11, and are typical of deep high temperature geothermal systems. Chloride ion is the main component, although sodium, potassium, silica, boron, sulfate and bicarbonate are also present. These types of water originate propylitic-argillic alteration by quartz, albite, illite, chlorite, epidote, zeolites, calcite and pyrite crystallization.

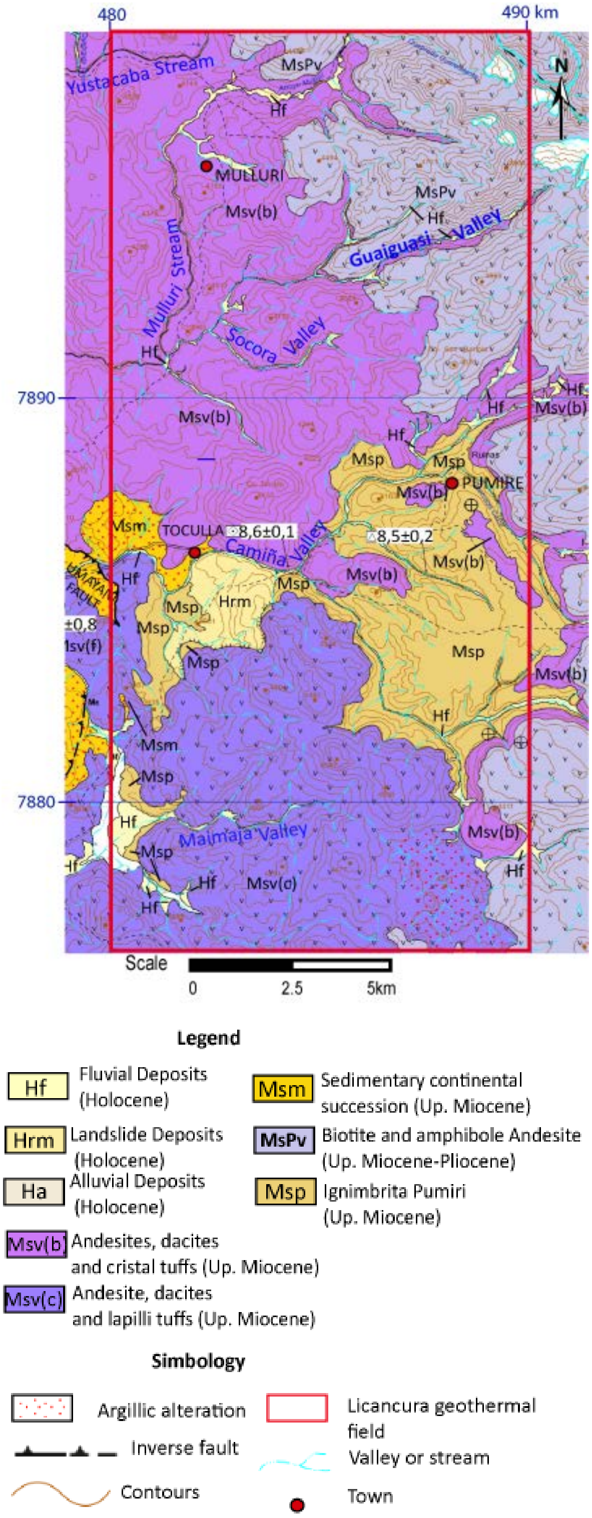

Figure 2. Licancura geological map (modified from Valenzuela *et al*., 2014).

Acid sulfate waters have acid pH, ~3. These are surficial fluids formed by geothermal gas condensation in shallow oxygenated groundwater. The gas, mainly composed by sulfate (formed by H_2S oxidation) and water vapor, is separated from deep chloride waters after a boiling process and then mixing with shallow groundwater. These types of fluids are found at the margins of the geothermal systems and generates an advanced argillic alteration, originating native sulfur, kaolinite, alunite and pyrophyllite.

Acid sulfate-chloride waters typically have pH values between 2 and 5. They typically form by mixing chloride and acid sulfate water from different depths, but also can result from discharge and oxidation of H_2S in chloride water near surface and from condensation of volcanic gases in meteoric water. This type of water can originate propylitic and advanced argillic alteration depending on the pH. The minerals formed as products of these alterations are kaolinite, cristobalite, alunite, chlorite, calcite, anhydrite and adularia.

Bicarbonate waters have near neutral pH. These waters derive from CO_2 rich steam condensing or mixing with water, although they also have variables quantities of chloride and sulfate. These types of waters are common in old geothermal waters or on the periphery of geothermal areas. Argillic alteration forms from these waters, originating kaolinite, montmorillonite and calcite crystallization.

4. PERMEABILITY

Studies on alteration in geothermal fields have recognized the important control of permeability. Extensive alteration and hydration needs more than pore water to proceed (Browne, 1978). Actually, some deposit of alteration minerals such as alunite and halloysite can develop in geothermal systems where the permeability has been naturally enhanced by faults (Ece *et al*., 2007). So this parameter must be considered in tracking of fluids pathways.

5. SPECTRAL ANALYSIS

Minerals species have the capacity to absorb and/or reflect light in different ranges of the electromagnetic spectrum, thus spectral patterns can help to distinguish between different mineral species and/or assemblages. Because most alteration minerals include an OH^- group – together with other elements such as Al, Fe or Mg – into its crystallographic structure, it is possible to identify their reflectance patterns in the SWIR zone of the electromagnetic spectrum (Delendatti, 2003; Rowan and Mars, 2003). ASTER imagery has the benefit of including a greater band division in this area (Table 1), thus providing favorable data for the remote identification of hydrothermal alteration minerals and assemblages. Identification of mineral species is then carried with the help of USGS and ASTER library tools, which help to identify particular bands associated with particular mineral species.

Figures 3 shows the spectral curves in the SWIR zone for the minerals expected to occur as main alteration assemblages in the Licancura area. Targeted mineral species show more than one pick within the SWIR zone. Nevertheless, for band ratio combination, picks must belong to different bands. The circles in Figure 2 represent the picks of each mineral species chosen for band ratio combination. These picks belong to different bands of ASTER imagery and were selected based on that their combination only represents the target mineral.

6. MINERALOGICAL DISTRIBUTION

Minerals chosen for identification were selected because they carry information about both the pH and the temperature of the fluid when the mineral species or associations crystallized (Browne, 1978; Hedenquist and Browne, 1989). We choose these minerals as their differences in temperature of crystallization might provide information about the cooling history of the fluids as these interacted with the host-rock. Thus the minerals chosen as representative of high temperatures were pyrophyllite and chlorite-epidote assemblage, whereas for intermediate to low temperatures the minerals chosen were kaolinite and illite-smectite (Reyes, 1990). Despite that both calcite and alunite mineral species show a wide range of formation temperature, their identification can still provide evidence of fluids pathways by highlighting areas of increased permeability (Browne, 1978).

6.1 Acid pH fluids

To identify alteration zones associated with acid pH fluids of high temperature, i.e. between 230-320°C, we used pyrophyllite as guide mineral (Reyes, 1990) which can be identified on the satellite imagery by using the band ratio combination B6/B5 (Figure 3). Identified zones are highlighted on Figure 4, and located mostly near the Guaiguasi Valley and, to a lesser extent, the east between Maimaja and Camiña valleys.

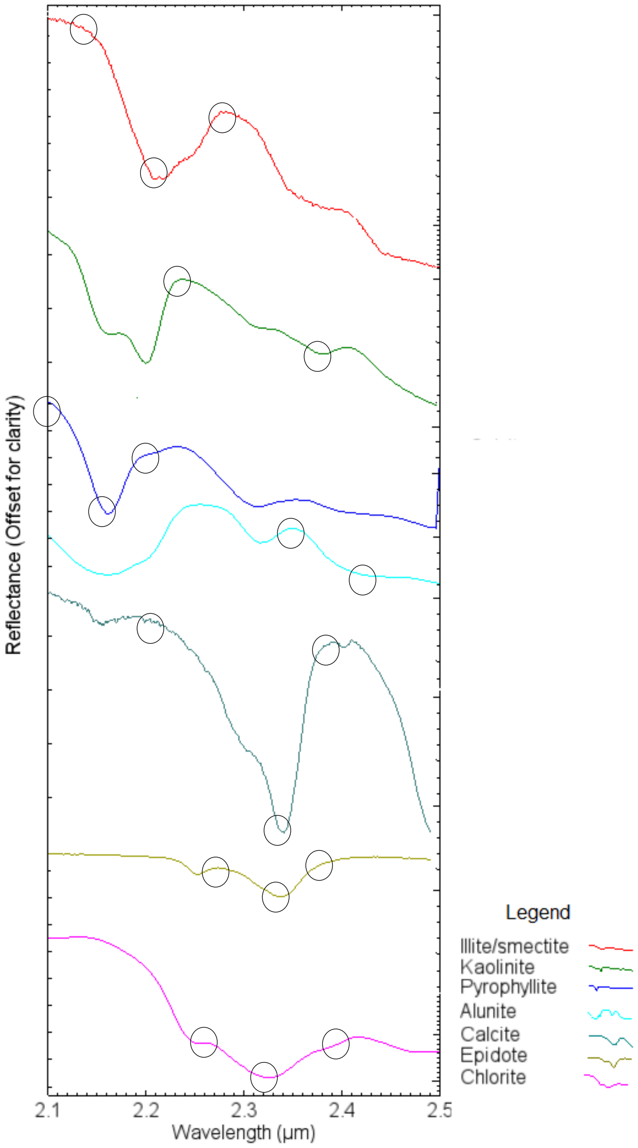

Figure 3. Spectral curves from USGS and ASTER spectral libraries, showing features in SWIR zone for alteration minerals associated with acid and neutral-alkali pH fluids. The picks used to identify each mineral are indicated by circles.

To determine zones associated with a low to intermediate temperature alteration (i.e. 100-200°C) we used kaolinite as guide mineral (Reyes, 1990). For this, we used the band ratio combination B7/B9 (see Figure 3). The resulting image (Figure 5), on were both pyrophyllite- and kaolinite-rich alteration zones were plotted, in order to identify zones with presence of alteration minerals of different temperatures, shows that the Guaiguasi Valley zone remains the same (i.e. pyrophyllite-rich alteration) whereas in the east between Maimaja and Camiña valleys alteration covers a wider area .

In order to determine other zones affected by acid pH fluid, we use alunite, as it is considered a characteristic mineral of advanced argillic alteration. Although alunite has a wide range of crystallization temperature, its presence is related to the passage of an acid fluid trough the hosting rocks.

The occurrence of alunite can be detected by using the B8/B9 (Figure 3) band ratio combination. It was plotted together with pyrophyllite- and kaolinite-rich alteration zones, observing in Figure 6 the spatial distribution of the three mineral assemblages used to identify advanced argillic alteration. Again, the zone near the Guaiguasi Valley remains the same, whereas the east between Maimaja and Camiña valleys becomes wider.

6.2 Neutral-alkaline pH fluids

To identify zones altered by fluids with temperatures between 200-340°C, we aim to identify chlorite-epidote which crystallization occurs at those temperatures (Reyes, 1990).

The band ratio combination used for chlorite-epidote- rich zones was B7+B9/B8 (Figure 3). Figure 7 shows chlorite-epidote rich zones. These zones are located north of Guaiguasi Valley and east between Maimaja and Camiña valleys, covering an area similar to that affected by the alteration minerals associated with acid pH fluids.

The mineral assemblage used as guide for tracing a low-intermediate temperature of 180-230°C fluid circulation was illite-smectite, which crystallizes between those temperatures (Reyes, 1990; Vázquez *et al.*, 2014).

Illite-smectite mineral assemblage was detected in the ASTER imagery through B5+B7/B6 (Figure 3) band ratio combination. The illite-smectite-rich zones identified by this combination were plotted together with chlorite-epidote-rich zones previously identified, in order to observe distribution of different temperature alteration minerals associated with neutral-alkali pH fluids. The resulting image is shown in Figure 8. The highlighted zones correspond, mainly, to that north of Guaiguasi Valley and east between Maimaja and Camiña valleys. Plotting together these two rich alteration zones, it is possible to observe that north of Guaiguasi Valley remain the same, whereas in the east between Maimaja and Camiña valleys the alteration becomes wider.

As calcite is another mineral associated to propylitic alteration, its presence, even when related to a wide range of temperatures, indicates a neutral-alkaline pH fluid flow in host rocks.

The occurrence of calcite was detected by using the B6+B9/B8 (Figure 3) band ratio combination. Highlighted areas made by this combination, were plotted together with chlorite-epidote+illite-smectite-rich zones previously identified. The resulting image (Figure 9) shows the zone north of Guaiguasi Valley becomes wider as well as the zone east between Maimaja and Camiña valleys.

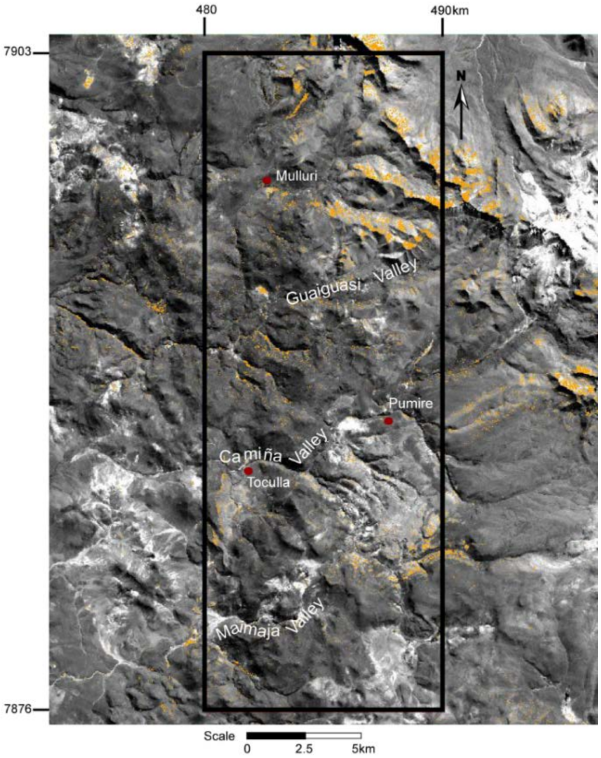

Figure 4. Spatial distribution of highlighted zones by band ratio combination B6/B5, corresponding to pyrophyllite-rich alteration. Black rectangle corresponds to Licancura area.

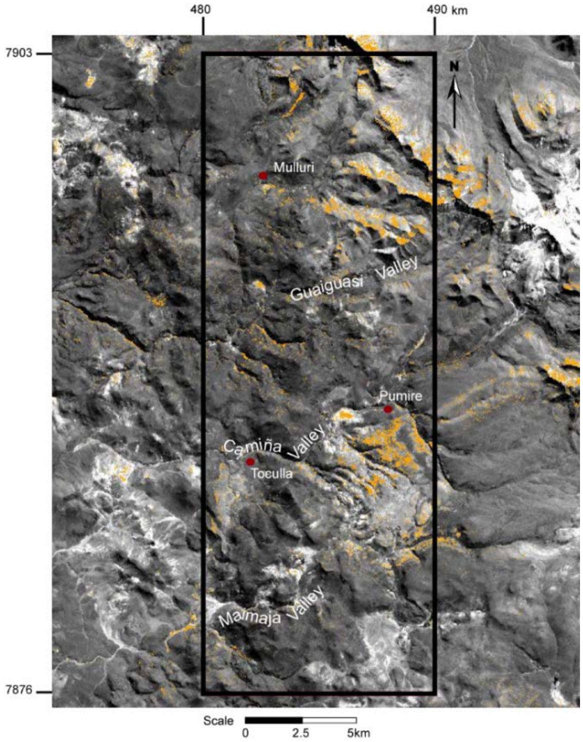

Figure 5. Spatial distribution of pyrophyllite+kaolinite-rich alteration, highlighted by B6/B5 and B7/B9 band ratio combination.

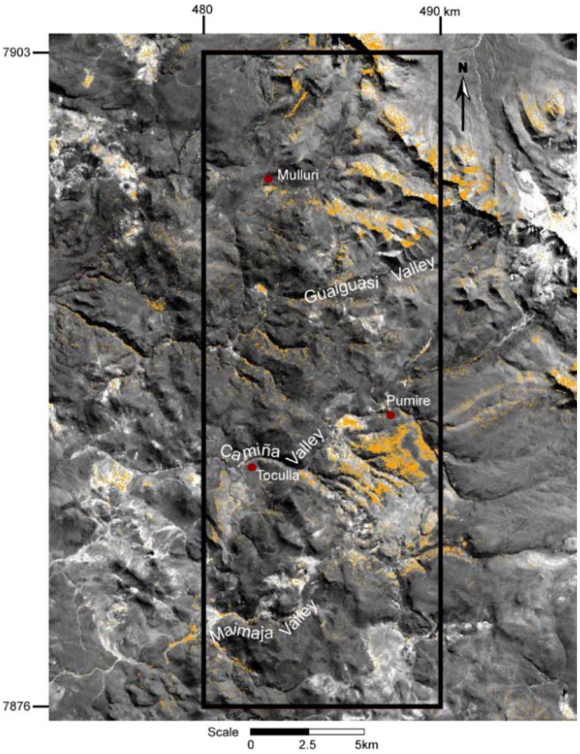

Figure 6. Spatial distribution of pyrophyllite +kaolinite+alunite-rich alteration, highlighted by plotting together B6/B5, B7/B9 and B8/B9 band ratio combination.

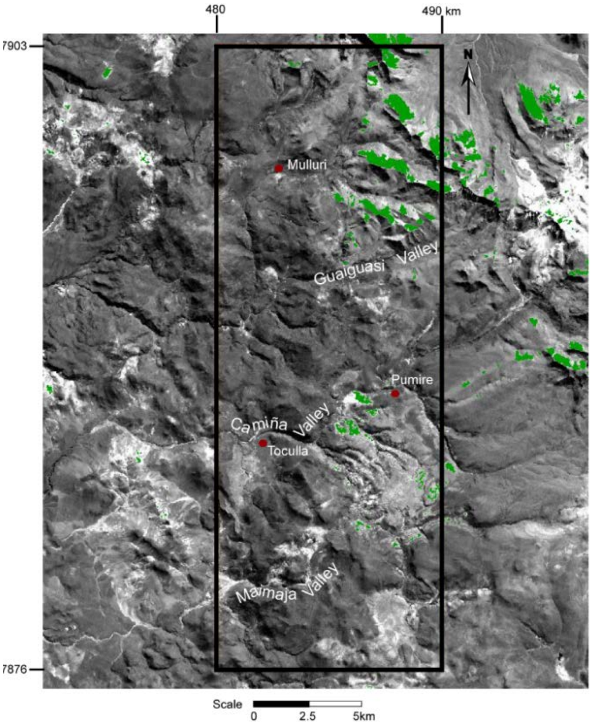

Figure 7. Spatial distribution of chlorite-epidote-rich alteration, highlighted by B7+B9/B8 band ratio combination.

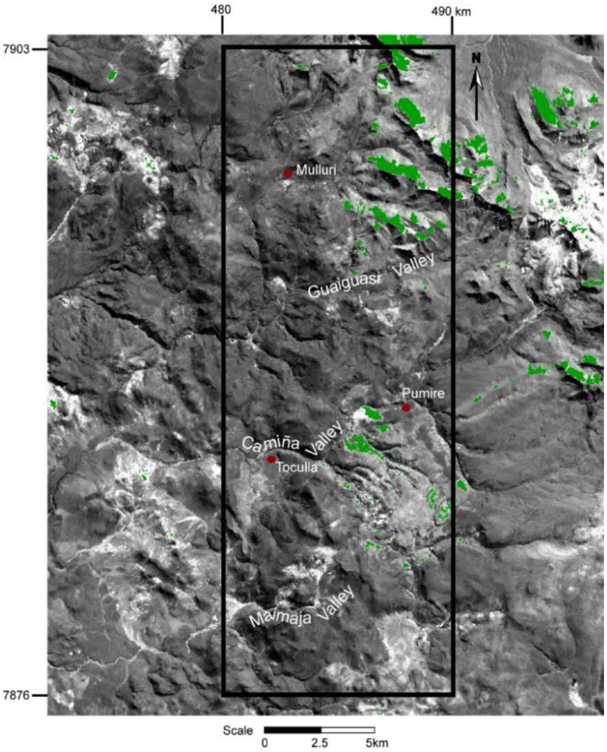

Figure 8. Spatial distribution of chlorite-epidote+illite-smectite-rich zones, highlighted by B7+B9/B8 and B5+B7/B6 band ratio combination.

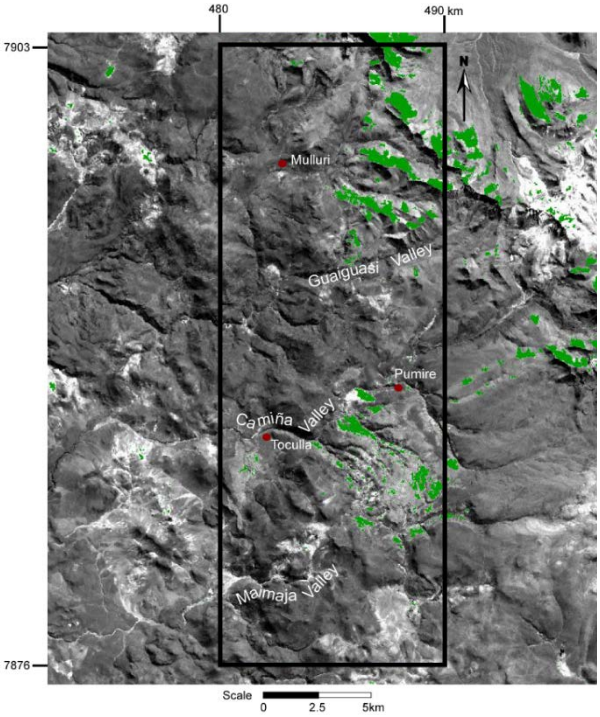

Figure 9. Spatial distribution of chlorite-epidote+illite-smectite+calcite-rich alteration zone, highlighted by B7+B9/B8, B5+B7/B6 and B6+B9/B8.

7. DISCUSSION

Targeted minerals were chosen because they represent different temperatures and pH fluid conditions. Pyrophyllite, kaolinite and alunite are representative minerals of advanced argillic alteration, formed from acid pH fluids as acid sulfate and acid sulfate-chloride waters (Ellis and Mahon, 1977; Nicholson, 1993). As indicated by Reyes (1990), pyrophyllite crystallization occurs between 230-320°C, so its identification on ASTER imagery suggest the path of a high temperature acid fluid through the highlighted zones by band ratio combination.

Crystallization of kaolinite occurs between 100-200°C (Reyes, 1990), thus the zones highlighted on ASTER imagery indicating the presence of this mineral suggest the path of a colder acid pH fluid. This fluid may correspond to the same fluid which caused pyrophyllite crystallization, that on cooling crystalized kaolinite.

Chlorite-epidote, illite-smectite and calcite minerals are considered as representative of a propylitic alteration, which can be caused by neutral-alkali fluids as chloride waters (Ellis and Mahon, 1977; Nicholson, 1993).The crystallization temperature of chlorite-epidote assemblage corresponds to 200-340°C. Thus, the highlighted zones indicates the presence of this assemblage suggests the path of a neutral-alkali fluid of high temperature. Illite-smectite crystallizes between 180-230°C, so its identification on ASTER imagery suggests a neutral-alkali fluid of less temperature, which could be the same that originated the chlorite-epidote assemblage.

The identification of both alunite and calcite, even though they do not represent temperature changes, due to their wide range of temperature crystallization, can be tracers of pathways for both, acid pH fluids as well neutral-alkali fluids. Their presence indicates zones of enhanced permeability. For both types of interpreted fluid, the zones affected by its alteration products were the north of Guaiguasi Valley and east between Maimaja and Camiña valleys. The north of Guaiguasi valley remains without changes, suggesting that the fluid has a low mobility maybe due to a lower permeability in this zone. Whereas east between Maimaja and Camiña valleys, it was possible to interpret that as the fluid cooled, the zones affected by the minerals formed as product of alteration becomes wider, possibly because of an enhanced permeability at this zone.

8. CONCLUSION

By remotely identification of targeted alteration minerals it is possible to interpret zones affected by the passage of different types of fluids.

At Licancura Geothermal Field it was possible to identify mineral assemblages that can be the product of two types of fluids; one of acid pH, which may correspond to acid sulfate waters or acid sulfate-chloride waters, and other of neutral-alkali pH which may correspond to chloride waters. These fluids may have reached high temperatures (i.e. 230-320°C, 200-340°C), originating alteration minerals as pyrophyllite and chlorite-epidote assemblage, respectively; and low to intermediate temperatures (i.e. 100-200°C, 180-230°C) originating kaolinite and illite-smectite for each type of fluid.

The remotely identification of the above named minerals, together with alunite and calcite may indicate permeable zones where the fluids was able to passage and arrest, originating the remotely identified alteration minerals. At Licancura, these zones of enhanced permeability were identified as north of Guaiguasi Valley and east between Maimaja and Camiña valleys. The first zone, probably, with reduced permeability, originating the minerals remotely detected in the same places, whereas the second with an enhanced permeability, covering wider zones as the fluid change its temperature.

This remote-sensing technique is sought to be considered as a first tool in geothermal exploration. Actual research and work is focusing on X-ray diffraction analyses of samples collected in the field to validate the correlation between remotely-interpreted mineralogical assemblages and field mineral occurrence and to validate the interpretation here proposed.

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