LITHOLOGICAL AND MINERALOGICAL MAPPING OF DEVONIAN CERRO ÁSPERO BATHOLITH, EASTERN SIERRAS PAMPEANAS, ARGENTINA, USING ASTER IMAGES

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ABSTRACT
The present study evaluates ASTER image processing as a technique to assist the lithological and mineralogical mapping of large granitic bodies and associated hydrothermal alteration assemblages related to the Cerro Áspero batholith, in Sierra de Comechingones, Argentina. This batholith was formed by the successive emplacement of several sub circular, high-level crust plutons that intruded, in the Upper Devonian, to metamorphic sequences of high to medium grade reworked by shear zones. Each of these plutons developed internal, external and roof units, and dyke swarms. Internal units are composed by porphyritic biotite monzogranites and external, roof units and dyke swarms are dominated by two-mica and muscovite leucocratic monzogranites to quartz-rich alkali-feldspar granites. The main associated mineralizations are W-Mo magmatic-hydrothermal deposits and postbatholith epithermal fluorite deposits of cretaceous age. Supervised classification, principal component analyses and emissivity calculations were made to identify lithological composition and variations within the different plutons that comprise the Cerro Áspero batholith. This methodology allowed us to have a better and precise mapping of the study area as well as the contacts between the different plutons that comprise the Cerro Áspero batholith. The classification with spectral angle mapper methods allowed to identify the different sectors with hydrothermal alteration (argillic and silicification). The argillic alteration is mainly associated with epithermal fluorite deposits.

Keywords: Lithological mapping, ASTER, batholith, hydrothermal alteration

INTRODUCTION
The mapping of large granitic bodies can be a time-consuming challenge for petrologists. Some difficulties typically involving this kind of mapping are: identification of different plutons, textural and mineralogical variations and discrimination of gradual contacts between internal facies within plutons, among others. At present, orbital remote sensing techniques allow scientists to perform very
detailed lithological mapping, and also to identify hydrothermal alteration assemblages in mineralized areas. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a 15-channel imaging instrument operating on NASA’s Earth Observing Terra orbital platform. ASTER has three separate subsystems to measure and record the reflected and emitted electromagnetic radiation. These subsystems work in different wavelength regions: the visible and near infrared (VNIR) between 0.52 and 0.86 μm, short wave infrared (SWIR) between 1.6 and 2.43 μm, and thermal infrared (TIR) between 8.125 and 11.65 μm. ASTER data consists of 15 spectral bands: three in the VNIR and an additional backward-looking band for stereo, six in the SWIR, and five in the TIR with 15, 30, and 90 m of spatial resolution, respectively. The band positions of ASTER are designed to allow the identification of mineral groups such as clays, carbonates, silicates, and iron oxides (Kalinowski and Oliver 2004). The presence of quartz and the bulk silica content is determined by using the TIR bands. The VNIR, SWIR and TIR wavelength regions provide complementary data for lithological mapping. The ASTER sensor has been successfully applied for lithological mapping (Ninomiya et al. 2005, Gad and Kusky 2007, Amer et al. 2010, Duuring et al. 2012, Pournamadi et al. 2014, Son et al. 2014, Witt et al. 2014) and for hydrothermal alteration mapping (Crosta et al. 2003, Ducart et al. 2006, Mars and Rowan 2006, Marchionni and Schalamuk 2010). ASTER thermal infrared bands (TIR) were used by Demartis et al. (2011) for regional mapping of granitic and quartz-rich pegmatites of the Sierra de Comechingones (Eastern Sierras Pampeanas). However, there are not enough studies using ASTER imagery for mapping large granitic batholiths emplaced in metamorphic terranes and related hydrothermal alteration zones in the eastern Sierras Pampeanas.

The Cerro Áspero batholith, in Córdoba province, Argentina, is a remarkable example of multistage emplacement of granitic bodies that have grown by three major successive intrusions (Figs. 1a, b). This magmatic event began with the emplacement of a small-volume intrusion, the Alpa Corral pluton (50 km²) which was followed by the largest pluton, El Talita pluton (390 km²). Finally, the intrusion of the Los Cerros pluton (5 km²) marked the culmination of the magmatism (Pinotti et al. 2002, Pinotti et al. 2014). This interpretation is based on the structural relationships between the granitic plutons. However, this voluminous magmatism is largely dominated by biotite monzogranites and some of them have been emplaced with little rheological and compositional differences. Thus, this low petro-structural contrast makes its definition in the field very difficult by conventional methods and consequently its cartography.

The present study evaluates ASTER Image Processing as a technique to assist the mapping of different granitic units of the Cerro Áspero batholiths (Fig. 2a), as well as the identification and mapping of the associated hydrothermal alteration zones that crop out at the northern part. This work is based on the petro-structural and metallogenetic studies of Pinotti et al. (2002, 2006, 2014, 2016) and Coniglio et al. (2000, 2010) and Coniglio (2006). Specially, fieldwork was carried out to redefine the boundaries between granitic units and hydrothermal alteration areas identified in the present research.

**GEOLOGICAL SETTING**

The Sierras Pampeanas expose precambrian and paleozoic metamorphic and igneous rocks of the basement of the Andes (Dalla Salda 1987). The geological evolution of this basement reflects the overprinting of successive orogenic events (González Bonorino 1950, Gordillo y Lencinas 1979, Ortiz Suárez et al. 1992, Rapela et al. 1998, Rapela et al. 1999, Oramendi et al. 2004). The Pampean Orogeny, developed between the Late Precambrian and Cambrian, was followed by the Famatinian Orogeny of Ordovician to Late Silurian age. A further contractual phase, referred to as “Achalian orogeny” (Sims et al. 1998) took place during the Upper Devonian, after Famatinian orogeny. In the Sierras Pampeanas the Achalian orogeny is characterized by the intrusion of a suite of granitoid bodies, most of them of batholithic dimensions, emplaced between 380 and 360 m.y. (Stuart-Smith et al. 1996). On the other hand, these suites of granitoid bodies were also interpreted by some authors as post-tectonic intrusions, regarding the Famatinian orogeny (Ortiz Suárez et al. 1992, Pinotti et al. 2002, Sato et al. 2003). Most of these Devonian granitoids show sub-circular shapes (Fig. 1a) and are composed by plutons that have discordant contacts with the country rocks and develop wide thermal aureoles.

In Sierras de Córdoba, the most penetrative metamorphic structure is an east dipping foliation with variable N-NW strike. This regional foliation, referred to as $S_1$ (Martino et al. 1995), was reworked within regional-scale shear zones developed at amphibolite to greenschist-facies conditions during the closing stages of the Famatinian orogeny (Martino et al. 1995, Rapela et al. 1998). These north-trending, east-dipping shear bands consistently show westward shear sense of the hanging walls. The Guacha Corral shear zone, in the Sierra de Comechingones, of up to 120 km in length and 10-20 km in width (Fig. 1b), is a crustal-scale thrust that juxtaposed Cambrian and Ordovician rocks with different metamorphic evolutions during the Ordovician to Silurian (Martino et al. 1995, Fagiano et al. 2002, Whitmeyer and Simpson 2003, Martino 2003, Radice 2015, Radice et al. 2015). The northward prolongation of the Guacha Corral shear zone has been referred to as the Tres Arboles fault zone by Whitmeyer and Simpson (2003). The Cerro Áspero batholith is intruded into the Guacha Corral shear zone (Martino, 2003). Thus, the activity of the Guacha Corral shear zone predates the Early Devonian intrusion of the Cerro Áspero batholith as evidenced by the inclusion of mylonitic xenoliths into the El Talita and the Alpa Corral plutons (Pinotti et al.
Most xenoliths have been preserved at the north-western border of the El Talita pluton, in the external unit, and are characterized by large blocks of host rock up to 30 m in length.

The successive emplacement of the plutons were controlled by the movement of major fractures developed in an extensional tectonic regime, as it is inferred from the Cerro Áspero batholith. The magma stopping mechanisms gained importance in the later stages of the batholith emplacement, and was widely favoured by the development of these master fractures and the thermal contrast between the granite and its host rocks. The decrease of the magma viscosity due to high fluorine contents also contributed to enhance the influence of the stopping mechanisms of emplacement (Pinotti et al. 2002, Coniglio et al. 2008).


The figure 1b shows the geological map of the area based on Pinotti et al. (2001), which was basically obtained by Landsat image (L5TM20081230_229_083) processing and field geological mapping. As shown in the map, the three major plutons of the Cerro Áspero batholith (Alpa Corral, El Talita, and Los Cerros pluton) are arranged in a NNW trend (Fig. 1b). The emplacement of the Cerro Áspero batholith is interpreted to have taken place during the Middle to Late Devonian. A well constrained Rb/Sr isochron allowed Pinotti et al. (2006) to establish a crystallization age of 369 ± 9 Ma for the Alpa Corral pluton. The main geological and mineralogical characteristics of the plutons are summarized in Table 1.

The magmatic event of the Cerro Áspero batholith was multi episodic, beginning with the emplacement of the Alpa Corral pluton, followed by the synchronic emplacement of two coalescent circular intrusions of the El Talita pluton and ended with the Los Cerros pluton emplacement (Pinotti et al. 2006). Each pluton of the
TABLE 1: Summary of granitic units of the Cerro Áspero batholith. Data extracted from Coniglio et al. (2000) and Pinotti et al. (2014 and references there).

<table>
<thead>
<tr>
<th>Pluton</th>
<th>Granitics</th>
<th>Description units</th>
<th>Enclaves</th>
<th>Host-rocks xenoliths</th>
<th>Surface (Km²)</th>
<th>Bigger axis, smaller axis</th>
<th>Felsic dykes</th>
<th>Late-magmatic alteration</th>
<th>Mineralization associated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpa Corral Internal</td>
<td>Prophyritic to coarse grained biotite monzogranite</td>
<td>Abundant</td>
<td>Rare</td>
<td>50</td>
<td>8 km of diameter</td>
<td>Annular dyker (scarse); radial dyker (abundant)</td>
<td>Rare</td>
<td>Rare</td>
<td></td>
</tr>
<tr>
<td>External</td>
<td>Inequigranular monzo-leucogranite</td>
<td>Rare</td>
<td>Scarcce</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sericitization greisenization (pervasive)</td>
<td></td>
</tr>
<tr>
<td>El Talita Internal</td>
<td>Porphyritic biotite monzogranite</td>
<td>Abundant</td>
<td>Rare</td>
<td>385</td>
<td>22,16 km</td>
<td>Annular dyker (abundant); radial dyker (scarse)</td>
<td>Rare</td>
<td>Wo-F</td>
<td></td>
</tr>
<tr>
<td>External</td>
<td>Coarse grained to prophyritic biotite monzogranite</td>
<td>Rare</td>
<td>Scarce</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sericitization - greisenization (pervasive)</td>
<td></td>
</tr>
<tr>
<td>Top</td>
<td>Inequigranular monzo-leucogranite</td>
<td>Rare</td>
<td>Scarce</td>
<td></td>
<td></td>
<td>Thin dyker (abundant) inside the pluton and host rock</td>
<td>Greisenization (pervasive); albitization (scarce)</td>
<td>W-Mo-F</td>
<td></td>
</tr>
<tr>
<td>Los Cerros Top</td>
<td>Coarse grained to prophyritic biotite monzogranite</td>
<td>Rare</td>
<td>Scarce</td>
<td>5</td>
<td>5,1 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Cerro Áspero batholith is associated with a particular set of dykes, which show different relative ages. Pervasive subsolid alterations are mainly related to the crystallization of the top or external units of the plutons (Pinotti et al. 2002, Coniglio et al. 2008). The dominant rock type is a porphyritic to coarse-grained equigranular biotite monzogranite characterized by large crystals of microcline (Fig. 2b, c) that are interpreted as phenocrysts (Pinotti et al. 1992). The geochemical evolution of the Cerro Áspero batholith was the result of differentiation of a high-K granitic magmatism; where the less evolved rocks are similar to the calc-alkaline granites, with SiO₂ contents between 65 and 71 % (internal units of the Alpa Corral and El Talita plutons); whereas the more evolved rocks (Los Cerros pluton) show strong geochemical affinity with A-type granites with SiO₂ contents > 76% (Coniglio 2006, King et al. 2001, Lira et al. 2012).

Regarding the rare earth elements (REE) behaviour, Pinotti et al. (2014) determined an enrichment of large-ion lithophile elements (LILE) in the internal units of the Alpa Corral and El Talita plutons. It is also important to note the F behaviour in the geochemical evolution of the Cerro Áspero batholith: considering the crystallization sequence of the batholith, F behaves as a compatible element during the earliest stages (internal units of the Alpa Corral and El Talita plutons), occupying the anion sites (OH-) in biotite structure (Coniglio 2006). During subsequent alteration of biotite and plagioclase, a subsolus muscovite-chlorite-epidote association takes place, as well as the precipitation of secondary fluorite due to F mobilization. Contrary, the more evolved granitic rocks contain accessory fluorite directly crystallized from the magma, indicating a relative low abundance of biotite. At these stages F behaves as an incompatible element and it is enriched in the residual fluids. Changes in the geochemical behaviour of F allow understanding the spatial distribution of magmatic-hydrothermal W-Mo-F deposits in the Cerro Áspero batholith, genetically linked to the Los Cerros pluton emplacement (Coniglio 2006; Coniglio et al. 2006, 2008, Pinotti et al. 2014). As a result of this hydrothermal activity, pervasive hydrothermal alteration zones (greisenization, albitization and muscovitization) can be locally observed in the granites, principally at the north of the batholith and metamorphic host rocks (Fig. 2d, e). These mineralizations constitute the Cerro Áspero mining district (Fernández Lima et al. 1963, González Díaz 1972, Coniglio et al. 2004, Mutti y González Chioza 2005, Coniglio 2006).

A post-batholith stage of mineralization (of Cretaceous age) was responsible for the formation of epithermal fluorite deposits. These deposits occur as veins uniformly distributed throughout the border zone of the Cerro Áspero batholith, and are closely related to pervasive silification and argilic alteration of the host granite (Coniglio et al. 2000 y 2010).

METHODS

An ASTER Level 1B (L1B, Registered Radiance At Sensor) image acquired on March 3, 2003 (WRS 2 229/83, upper left corner: 32°24’38.16” South; 65°2’24.15” West), was processed and analyzed with the ENVI (4.7) software. Several preprocessing techniques were applied. As the original values of data are in radiance values (float single), the first step was the IARR atmospheric correction with ENVI’s module of VNIR and SWIR bands performed on scene (Alder-Golden et al. 1998), which is similar to flat field calibration since a reference spectrum is divided into each pixel in the image to generate relative reflectance. The reference spectrum for IARR is the mean spectrum of the entire image, rather than that of user-defined samples. IARR requires no user input.

The second step for this sub sets (VNIR and SWIR) was a spatial resolution resampling of SWIR bands from 30-m to 15-m to match that of VNIR bands. The 15-m resolution SWIR and VNIR bands were combined to form a 9-band data set. The ASTER data from the VNIR and
SWIR spectral regions converted to surface reflectance using the Internal average relative reflectance IARR ENVI’s module (Alder-Golden et al. 1998), which is similar to flat field calibration since a reference spectrum is divided into each pixel in the image to generate relative reflectance. The reference spectrum for IARR is the mean spectrum of the entire image, rather than that of a user-defined ROI. IARR requires no user input. Atmospheric correction and calculation to emissivity by the normalization method were performed on thermal ASTER bands.

After pre-processing, four different processing techniques were applied to the ASTER data: (1) RGB composition with VNIR-SWIR bands; (2) Principal Component Analysis from all VNIR-SWIR and TIR bands; (3) supervised classification and (4) spectral emissivity analysis. Table 2 shows the methodological sequence developed.

RESULTS

RGB compositions
RGB color compositions were made with the VNIR-SWIR bands for lithological discrimination and visual interpretation. All possible RGB combinations were tested. The composition RGB 469 (Fig.
distinguishes the three plutons that constitute the Cerro Áspero batholith. This composition allowed a clearer segregation of the two rock types present in the basement of the Sierra de Comechingones: the igneous rocks represented by the Cerro Áspero batholith and the metamorphic host rocks (Fig. 3). The metamorphic rocks are observed in brown color and granitic rocks in light grayish colors. Furthermore, this band combination permitted discriminating the different plutons that compose the batholith. The El Talita pluton is observed in a clearer tone. To the south, the Alpa Corral pluton shows clear brown color and to the north, the Los Cerros pluton stands out with blue-gray color. This combination also highlights the radial and circular structures associated with the intrusion. The contact between the Alpa Corral pluton and the El Talita pluton is marked by the swarm of fine-grained granite dikes. The Alpa Corral pluton shows a circular shape and its internal units can be delineated. Two units that conform the El Talita pluton are visible in the RGB: 469; an external unit consisting of an inequigranular granite (Fig. 2b), grading into an internal unit of porphyritic biotite granite. The external unit of this pluton is 4 km-wide approximately, clearly observable in the south and east sector. The contact between both units is difficult to recognize in the field. These results are similar to those obtained by Amer et al. (2010) for the mapping of ophiolite and granitic rocks in the central-eastern desert of Egypt.

**Principal component analysis**

Principal component analysis (PCA) was applied to produce uncorrelated output bands, to delete noise components, and to reduce the dimensionality of data sets. This is made by finding a new set of orthogonal axes that have their origin at the data mean and that are rotated so that the data variance is maximized. It is possible to calculate the same number of output PCA bands as input spectral bands (Amer et al. 2010). PCA was applied separately, on the one hand the subset with VNIR-SWIR and on the other only with TIR. All possible RGB combinations were tested with the main components of three subsystems. The composition RGB PC1 (VNIR-SWIR) - PC1 (TIR) - PC4 (VNIR-SWIR) is the one that best represents the truth of the terrain according to the field knowledge. This composition (Fig. 4) shows in black the external units of El Talita pluton and the limits of this body with metamorphic host rocks. In addition, the top unit of El Talita pluton is observed in blue. The external unit of Alpa Corral pluton is identified by magenta.

**Supervised classification**

As a first step, homogeneous and representative areas were sampled, in terms of spectral signatures on the ASTER data (reflectance for the VNIR and SWIR subsystems resampled to 15 m). These areas are correlated with each lithological unit according to the preliminary geological map. The areas were chosen from the initial geological map and represent different lithological units. The ASTER data from each area, called training data (or endmember), corresponds to specific classes from the surface. For post classification verification, samples of same endmembers were taken. The variation coefficient for all classes for all bands which was not higher than 14%. In a second step the classification method assigns each pixel of the image to a given class. The neural network supervised classification method with defaults settings from ENVI was used in this study. The Neural Net technique uses standard back propagation for supervised learning. We selected one hidden layer that consists of a logistic activation function. Learning occurs by adjusting the weights in the node to minimize the difference between the output node activation and the output. The error is backpropagated through the network and weight adjustment is made by using a recursive method (Rumelhart and Mc Clelland 1987, Richards and Xiping 1998).

In this study we selected six regions of interest corresponding to specific classes of the surface: metamorphic rocks (Guacha Corral shear zone, migmatite), granitic igneous rocks (internal, external and top units) and vegetation. Each end-member consists of approximately 2000 selected pixels for each region of interest. Subsequently, control points from each region of interest were randomly extracted. To verify the quality of the classification map, a confusion matrix and the kappa coefficient were performed. With these data a confusion matrix provided the overall accuracy was 0.75 (11181/14908) with Kappa coefficient = 0.8214.

The results of this technique allowed distinguishing the different internal units that constitute the three plutons of the Cerro Áspero batholith, highlighting the internal, external and top units in yellow, red and blue, respectively (Fig. 5). Likewise, the internal unit of the El Talita pluton appears in yellow in the processed image (porphyritic biotite granite), while
Lithological mapping, Cerro Áspero Batholith.

The units in the El Talita pluton are gradational along 50-100 m distance, and distinction between them depends on the grade of development of the porphyritic texture. Furthermore, in the northern region of the image (Los Cerros pluton) where red colors can be observed (Fig. 5), there is evidence of increasing silica contents, characterized in the field by miorolitic pegmatites, stockworks (Fig. 2e) and greisens (Fig. 2d).

SAM methods (spectral angle mapper methods)

Spectral angle mapper (SAM) is a physically-based spectral classification that uses a n-D angle to match pixels to reference spectra (Kruse et al. 1993). The algorithm determines the spectral similarity between two spectra by calculating the angle between the spectra and treating them as vectors in a space with dimensionality equal to the number of bands. Endmember spectra, from United States Geological Survey (USGS; Clark et al. 2007) and Johns Hopkins University (JHU; Salisbury et al. 1991) spectral libraries were used here to map with the SAM method (Fig. 6a). An emissivity spectrum of quartz from JHU spectral library was used with the five TIR ASTER bands (Fig. 6b). Spectra of kaolinite and muscovite from USGS spectral library were used with the six SWIR ASTER bands (Fig. 6c). Results from the three mineral mapping were integrated in a RGB color composition, where red, green and blue represent high silica granites, muscovite-rich granites and kaolinite-rich areas, respectively (Fig. 6a). The highest concentrations of quartz and kaolinite are observed in the external unit of the El Talita pluton and in a lesser magnitude in the external unit of the Alpa Corral pluton. The kaolinite-rich areas mapped by this method in the external unit of the El Talita pluton (Fig. 6a) partially coincide with the argillic alterations associated with the epithermal fluorite deposits that are distributed throughout the border zone of the Cerro Áspero batholith, generally close to the contact with the enclosing metamorphic rocks.

Figure 3: Band color compositions for geological mapping. Color composition of bands 469 (RGB) distinguished the three plutons: ACP (Alpa Corral pluton), ETP (El Talita pluton) and LCP (Los Cerros pluton). The contacts between the El Talita pluton and the Alpa Corral pluton with the country rocks are also highlighted. In addition, the contacts between the different units that compose the El Talita and Alpa Corral plutons and the radial and circular structures associated with the intrusions are clearly observed. In the upper right of the figure is shown a sketch of the plutons that compose the Cerro Áspero batholith.
In the figure 6b and 6c we observed the reflectance and emissivity spectra extracted from points A, B and C of the ASTER image, compared with spectra from USGS and JHU spectral libraries. The spectra A and B represent the reflectance of the VNIR-SWIR ASTER bands (Fig. 6c), and C represents the emissivity spectrum of ASTER TIR bands (Fig. 6b).

**RGB composition from thermal bands**

ASTER TIR data are the best suited to show up silica-rich minerals. The greatest variability of the emissivity spectra for the study area is showed in a RGB composition with the bands 13, 12 and 10, respectively (Fig. 7; Vincent and Thomson 1972, Salisbury et al. 1991, Clark et al. 2007, Thomson and Salisbury 1993, Ramsey and Christensen 1998, Rowan et al. 2003). The spectra of mafic minerals, such as epidote and hornblende, display an emissivity minimum in ASTER band 13, whereas quartz microcline and muscovite minimums are centered in shorter wavelength bands (Ramsey and Christensen 1998).

Analysis of the TIR data was hampered by the presence of prominent stripping in the output images with all five bands. Magenta and red in this image highlight the richest quartz facies of the Cerro Áspero batholith, mainly the external and top units of the El Talita pluton, respectively. In the north of the batholith, the red color corresponds to swarm of magmatic-hidrothermal wolframite and molybdenite quartz veins associated with silicification of the granitic and metamorphic host rocks. In addition, numerous stockworks, which explain the high silica contents in these regions, were also surveyed (Fig. 2e). Likewise, the main silicification process occurs as pervasive zones, within the fault domains, with fine-grained, jasperoid-like quartz affecting mainly the external unit of the El Talita pluton, and comprises the best field evidence for fluorspar exploration (Coniglio et al. 2000).

In contrast, the green classes with some yellow and blue tones correspond to the metamorphic host rocks (Fig. 7). The result of this image processing was verified by field data. From the field knowledge of the location of the jasperoids, all possible RGB compositions were made with bands from the TIR region. As a result, it was observed...
that the composition that best emphasizes jasperoids is the RGB 13 12 10. Two hundred pixels corresponding to the jasperoids were sampled. The statistics corresponding to the emissivity values of the samples are presented in Table 3.

CONCLUSIONS

The results from variability the ASTER data processing of the study area turned out detailed information about the different plutons of the Cerro Áspero batholith. The use of several processing techniques, such as RGB composition, principal component analysis, supervised classification and emissivity analysis, combining different bands from the ASTER subsystems, is proved to be an appropriate method to assist the geological mapping of the Cerro Áspero batholith. In particular, with this methodology it has been possible to identify the boundaries between the different granitic units in a more precise and faster way, a task that is usually difficult with direct observation in the field. The results obtained with the SAM method, principal component analysis and spectral emissivity show a total correspondence with field observations, especially within those areas in which high-silica granites crop out (Fig. 7). The highest concentration value of silica and muscovite is registered in the north of the plutons (roof zones) and it mainly represents compositional variations related with the magmatic evolution. Likewise, the geochemical evolution of each pluton is mentioned in the heading Geological Setting.

Magenta and red colors in figure 7 mainly highlights outcrops of silica rich granites, with SiO$_2$ contents varying between 74.6% and 76.2% (Pinotti 1998, Coniglio 2006). The RGB composition of the RGB bands 13 12 10 highlights structurally controlled silicified zones, jasperoids, (ellipses in Fig. 7), which are diagnostic attributes for vein-type fluorite deposits exploration. The sector marked as CN in figure 7 faithfully records the location of the Cerros Negros mine, currently in production, and represents one of the main fluorite mineralization of the Cerro Áspero batholith (Coniglio et al. 2010). This silicic alteration is related with fluorite deposits and occurred with variable intensity during the entire mineralizing processes (Coniglio et al. 2000). Furthermore, the kaolinite-rich zone is distributed throughout the border zone of the Cerro Áspero batholith, and partially coincides with the silicic alteration. Both argillic and silicic alterations are products of the epithermal fluorite deposits (Coniglio et al. 2000).
Finally, ASTER images constitute a powerful tool for preliminary study of areas, providing highly accurate data that can be used as starting point for mapping of granitic bodies. Comparison between the results derived from the proposed meth-

Figure 6: a) Supervised classification by Spectral Angle Mapper Methods (SAM), using spectra of muscovite (green) and kaolinite (blue) from USGS spectral library, and quartz (red) from JHU spectral library. Yellow stars: main epithermal fluorite deposits in Cerro Áspero batholith, with kaolinite alteration; b) Emissivity spectrum extracted from point C of ASTER TIR bands (bands 10-14). A spectrum from the JHU spectral library, converted to the spectral resolution of ASTER, is also showed for comparison; c) Reflectance spectra extracted from points A and B of VNIR-SWIR ASTER bands. Spectra of muscovite and kaolinite from USGS spectral library, converted to the spectral resolution of ASTER, are showed for comparison.
Lithological mapping, Cerro Áspero Batholith.

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