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Investigation of quartz-alunite epithermal gold deposits using PRISMA satellite imagery: examples from Goldfield, Nevada, USA and Rodalquilar, Spain

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Abstract
The PRISMA (Hyperspectral Precursor of the Application Mission) satellite of the Italian Space Agency (ASI) is in orbit since March 2019. The PRISMA satellite hyperspectral data have found applications in many disciplines including environmental monitoring, agriculture, forest and grassland mapping, land use and land cover mapping, hydrology, geology, and glaciology. In this study the PRISMA satellite hyperspectral imagery are evaluated for the characterization of the surface outcrop of quartz-alunite epithermal gold deposits occurring at Goldfield in Nevada, USA and at Rodalquilar in southeastern Spain. The Goldfield in Nevada has an arid to semiarid climate, whereas the Rodalquilar occurs in a semiarid region in southeastern Spain. The quartz-alunite gold deposits are associated with extensive alteration zones. Several important alteration minerals display distinct spectral reflectance features in the 0.4-2.5 μm wavelength region where the PRISMA sensor records. The surface reflectance PRISMA satellite hyperspectral data were analyzed using the Spectral Mixture Analysis (SMA) technique. The PRISMA mapped several key alteration minerals useful to depict the epithermal alteration zones. The study shows the applicability of PRISMA satellite hyperspectral imagery for the detection and mapping of altered rocks associated with quartz-alunite epithermal gold deposits in arid and semiarid regions.
Keywords: PRISMA, satellite, hyperspectral, epithermal gold, Goldfield, Rodalquilar

Investigação de depósitos de ouro epitermais de quartzo-alunito usando imagens de satélite PRISMA: exemplos de Goldfield, Nevada, EUA e Rodalquilar, Espanha

O satélite PRISMA (Hyperspectral Precursor of the Application Mission) da Agência Espacial Italiana (ASI) está em órbita desde março de 2019. Os dados hiperespectrais do satélite PRISMA encontraram aplicações em muitas disciplinas, incluindo monitoramento ambiental, agricultura, mapeamento de florestas e pastagens, uso da terra e mapeamento da cobertura da terra, hidrologia, geologia e glaciologia. Neste estudo, as imagens hiperespectrais do satélite PRISMA são avaliadas para a caracterização do afloramento superficial de depósitos de ouro epitérmicos de quartzo-alunito ocorrendo em Goldfield em Nevada, EUA e em Rodalquilar no sudeste da Espanha. O Goldfield em Nevada tem um clima árido a semiárido, enquanto o Rodalquilar ocorre em uma região semiárida no sudeste da Espanha. Os depósitos de ouro de quartzo-alunito estão associados a extensas zonas de alteração. Vários minerais de alteração importantes exibem características distintas de refletância espectral na região de comprimento de onda de 0,4-2,5 μm onde o sensor PRISMA registra. Os dados hiperespectrais do satélite PRISMA de refletância de superfície foram analisados usando a técnica Spectral Mixture Analysis (SMA). O PRISMA mapeou vários minerais de alteração importantes, úteis para representar as zonas de alteração epitermais. O estudo mostra a aplicabilidade das imagens hiperespectrais do satélite PRISMA para a detecção e mapeamento de rochas alteradas associadas a depósitos de ouro epitermais de quartzo-alunito em regiões áridas e semiáridas.
Palavras-chave: PRISMA, satélite, hiperespectral, ouro epitérmico, Goldfield, Rodalquilar

1. Introduction

The PRISMA (Hyperspectral Precursor of the Application Mission) satellite of the Italian Space Agency (ASI) was launched into orbit on March 22, 2019. The hyperspectral imaging technology acquires images in hundreds of registered, contiguous spectral bands such that for each picture element of an image it is possible to derive a complete reflectance or emissivity spectrum (Kruse, 2012). The PRISMA records hyperspectral data in the 0.4-2.5 μm wavelength region of the electromagnetic spectrum at a spatial resolution of 30 m (Pignatti et al., 2013). The PRISMA satellite hyperspectral data are used in environmental monitoring, agriculture, forest and grassland mapping, land use and land cover mapping, hydrology, geology, glaciology etc. (e.g., Pepe et al., 2020; Bedini and Chen, 2020; Guanter et al., 2021; Heller Pearlshtien et al., 2021; Vangi et al., 2021; Bresciani et al., 2022; Bohn et al., 2022; Tagliabue et al., 2022).

Gold epithermal systems are associated with characteristic mineral alteration assemblages (Hedenquist and Arribas, 2022). Molecular vibrational features, occurring between 1.4-2.5 μm, are diagnostic of minerals containing anion groups such as Al–OH, Mg–OH, Fe–OH, CO_3, and SO_4 (Clark, 1999). A number of alteration minerals display distinct spectral features in the visible to short wave infrared wavelength region. The use of airborne hyperspectral images and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite multispectral data to investigate the gold epithermal alteration systems is reported in a number of studies (e.g., van der Meer and Baker, 1997; Crosta et al., 2003; Kruse et al., 2006; Bedini et al., 2009; Pour and Hashim, 2012; van der Meer et al., 2012; Bedini, 2017).

This study applies PRISMA imagery to the analysis of the hydrothermal alteration system of two characteristic epithermal gold deposits occurring at Goldfield in Nevada, USA and at Rodalquilar in southeastern Spain. The Goldfield in Nevada has an arid to semiarid climate, whereas the Rodalquilar occurs in a semiarid region in southeastern Spain. In the study areas the gold epithermal deposits are associated with extensive quartz-alunite alteration type (Ransome, 1907; Ashley, 1974; Arribas et al., 1995). The study has potential to evaluate the application of PRISMA imagery for the localization and mapping of alteration assemblages associated with epithermal gold deposits.

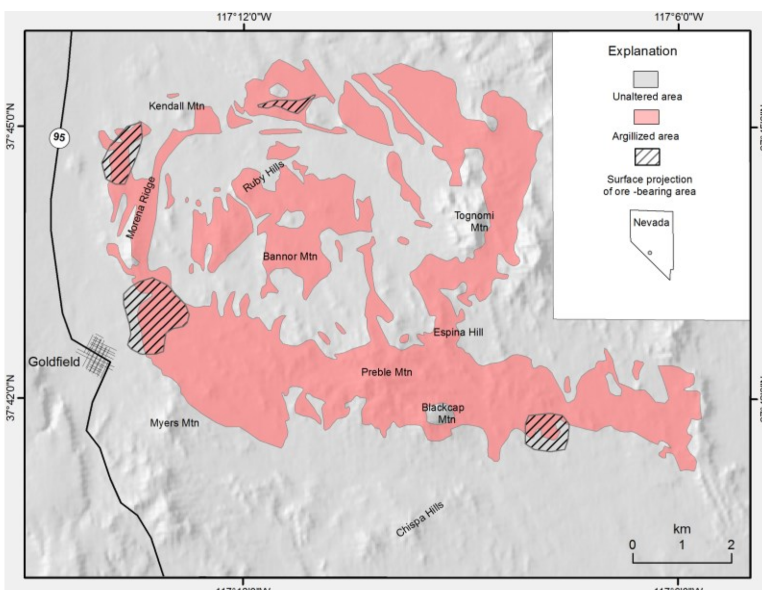

Figure 1. Map of Goldfield and vicinity showing areas of hydrothermal alteration and ore deposits (modified from Ashley, 1974).

2. Materials and methods

Goldfield gold deposit

The Goldfield epithermal gold deposits in Nevada, USA, occur within a volcanic caldera (Ashley, 1974). The volcanic rocks at Goldfield are of late Oligocene and early Miocene age. They consist of andesites, rhyolite flows and tuffs, rhyodacites, quartz latites (Ashley, 1974). The Goldfield contains a typical quartz-alunite type epithermal gold deposit. Extensive hydrothermal alteration is visible on the surface (Figure 1, 2). The gold mineralization occurs in silicified zones within the advanced argillic alteration zone at several locations along the west and north sides of an inferred ring-fracture system (Ashley, 1974). The main minerals in the Goldfield epithermal alteration assemblage that have spectral features in the visible to short wave infrared are alunite, kaolinite, illite, and iron hydroxides (e.g., Kruse, 2012).

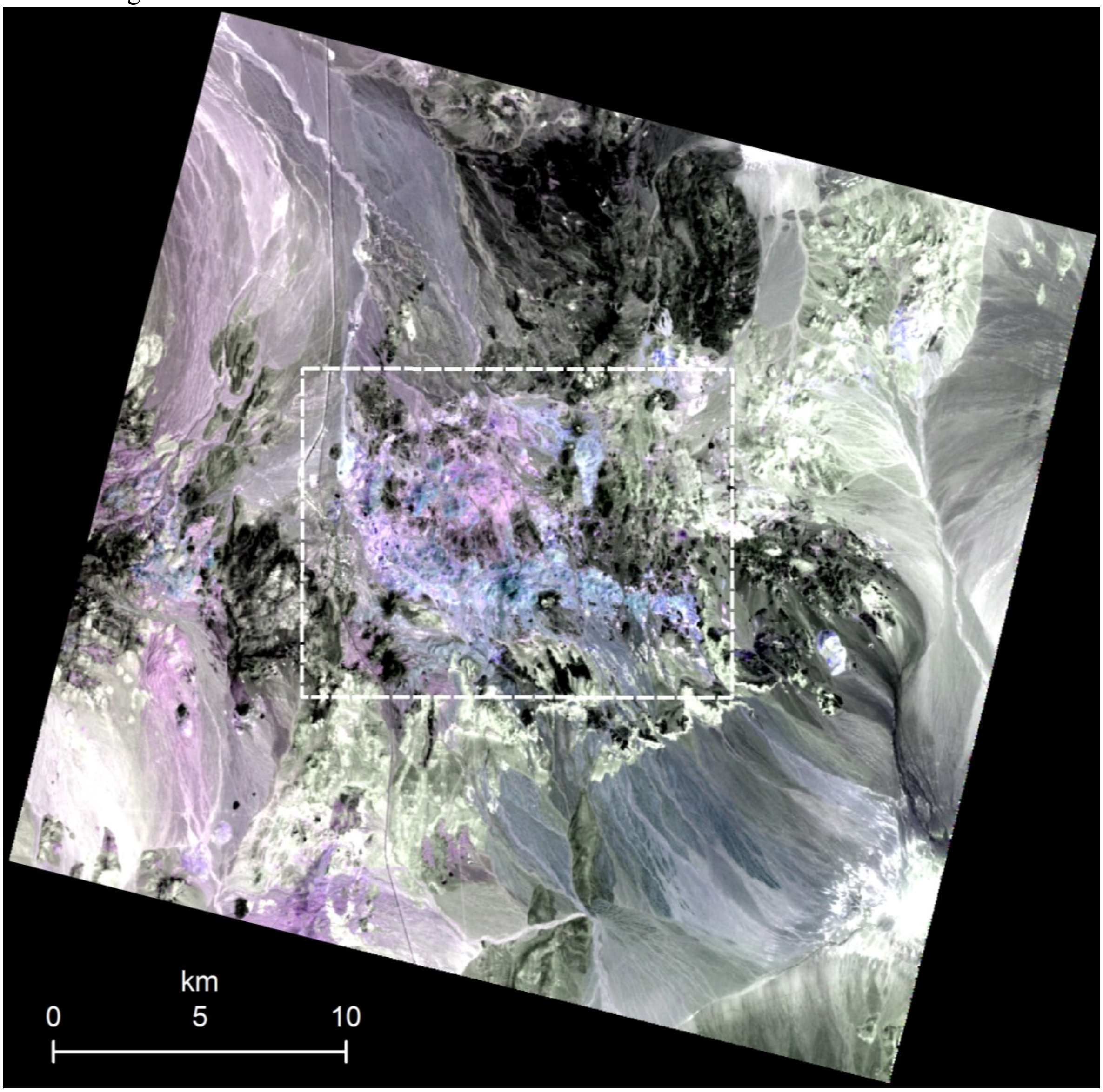

Figure 2. The PRISMA hyperspectral scene of the Goldfield, Nevada. Note the anomalous colors of the altered zones. The white dashed line shows the spatial extent of Figure 1 for reference.

Rodalquilar gold deposit

The Cabo de Gata Miocene volcanic field consists of intermediate to acidic calc-alkaline volcanic rocks (Figure 3, Rytuba et al., 1990). The Cabo de Gata volcanic is well known among exploration geologists for the presence in it of epithermal gold deposits. The most important quartz-alunite type epithermal gold deposits are located within the Rodalquilar caldera complex, an oval-shaped collapse structure (Figure 3). In the Rodalquilar caldera complex the epithermal gold deposits are associated with an extensive east-west trending zone of over twenty-five km^2 of hydrothermally altered rocks (Figure 3; Arribas et al., 1995). Alteration mineralogy of the epithermal gold deposits consists of quartz, alunite, clays, and iron hydroxides (e.g., Arribas et al., 1995; Bedini et al., 2009). Five major alteration types are exposed in the surface: silicic, advanced argillic, supergene acid sulfate alteration, intermediate argillic, and propylitic.

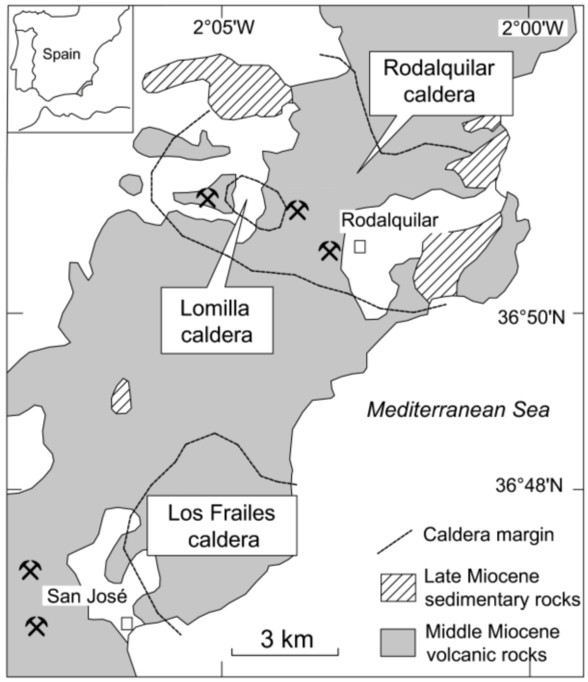

Figure 3. The Rodalquilar caldera complex in the central part of the Cabo de Gata volcanic field (modified from Arribas, 1992). The inset shows the location of the Cabo de Gata volcanic field in south-eastern Spain.

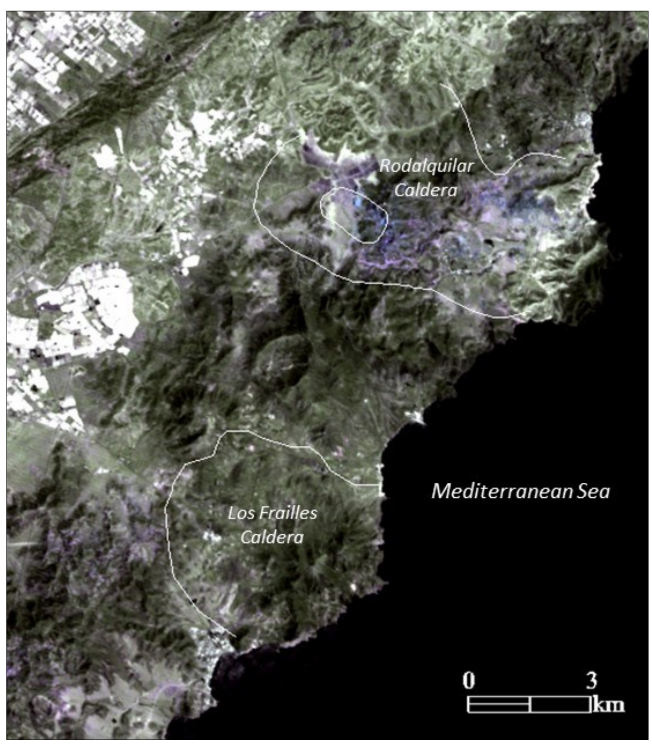

Figure 4. The Rodalquilar PRISMA image. The boundaries of the Rodalquilar caldera complex and Los Frailles caldera are plotted onto the map for reference with Figure 3.

PRISMA data analysis

The PRISMA data are made available from ASI processed to top-atmosphere radiance, ground radiance, and surface reflectance. Radiance data are useful in several environmental applications as for example the detection of methane emissions (Guanter et al., 2021). Surface reflectance data is a requirement for most of hyperspectral imaging applications. The Goldfield and Rodalquilar PRISMA images were acquired in July 2020 and June 2020 respectively.

The PRISMA hyperspectral images were processed using the Spectral Mixture Analysis (SMA) technique (Settle and Drake, 1993). The study focused on the mapping of the spatial distribution of alunite, illite and kaolinite as three important alteration minerals to outline the alteration zones of quartz-alunite gold epithermal alteration assemblages (e.g., van der Meer et al., 2012; Bedini, 2019).

3. Results and discussion

The results of the spectral mixture analysis processing of the PRISMA image for the main alteration minerals at Goldfield, Nevada are shown in Figure 5. The PRISMA data analysis has correctly mapped the alteration zone within the area of the Goldfield gold deposits (*see* Figures 1 and 5). The mapped distribution of the alteration minerals alunite, kaolinite and illite is comparable with results from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) hyperspectral airborne data (e.g., Kruse, 2012).

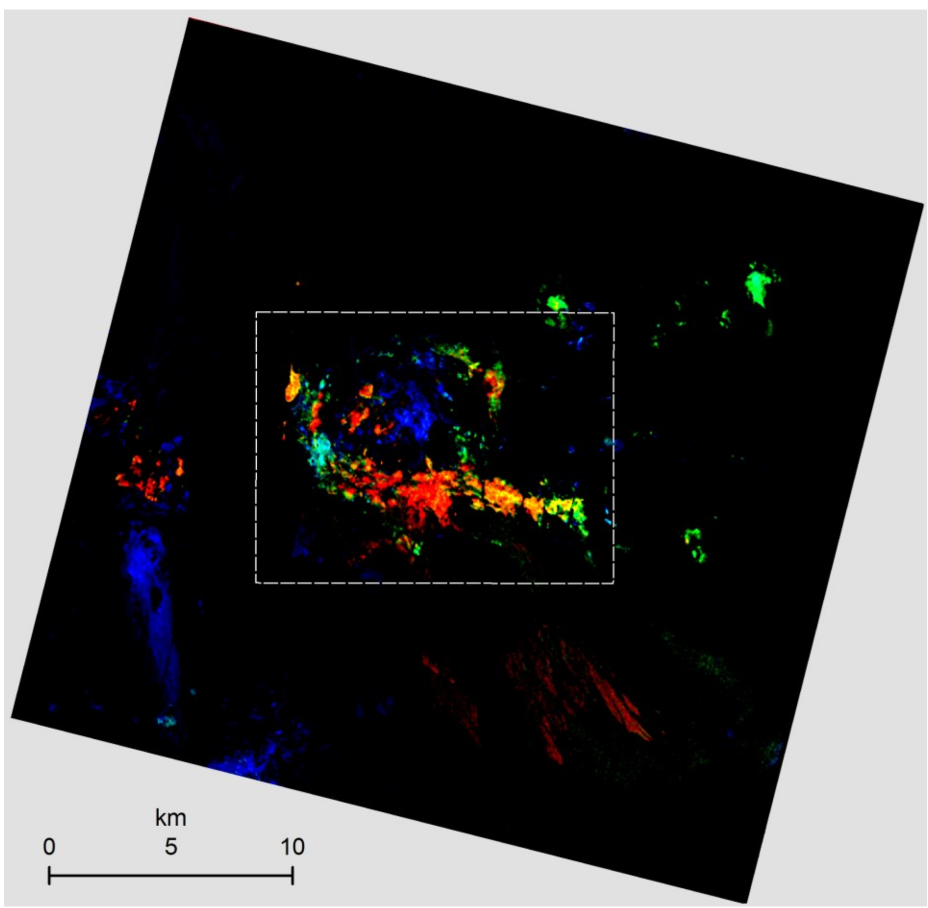

Figure 5. Color composite of the fraction abundances for alunite (red), kaolinite (green), and illite (blue) produced from the Spectral Mixture Analysis analysis of PRISMA Goldfield image. The white dashed line shows the spatial extent of Figure 1 plotted onto the image for reference.

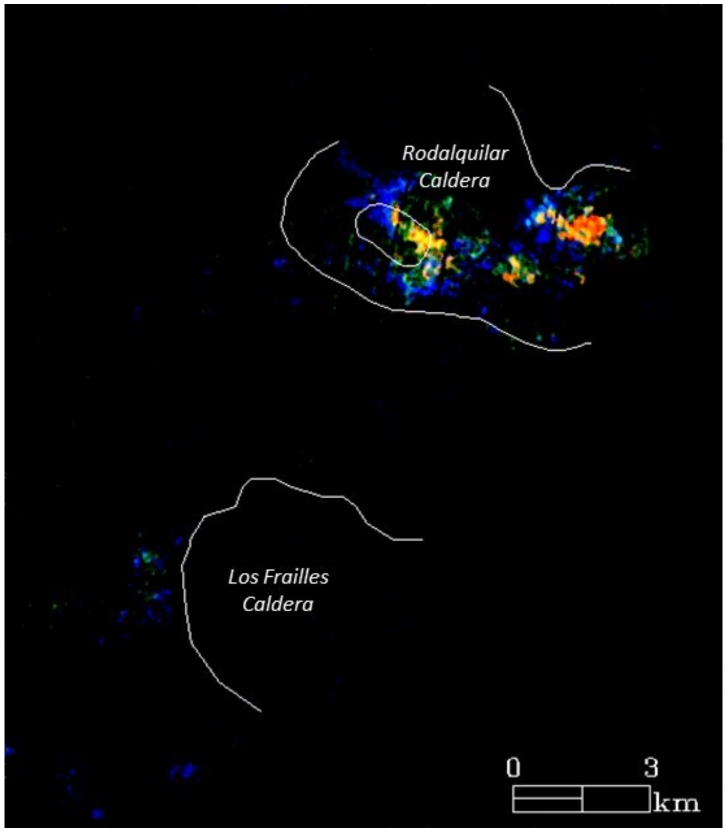

Figure 6. Color composite of the fraction abundances for alunite (red), kaolinite (green), and illite (blue) produced from the Spectral Mixture Analysis analysis of PRISMA Rodalquilar image. The white lines show the boundaries of the Rodalquilar caldera complex, Lomilla caldera and Los Frailles caldera plotted onto the image for reference with Figures 2 and 3.

The PRISMA identified an extensive zone dominated by alunite and kaolinite, which often are also mapped as alunite-kaolinite mixtures (shown in yellow color in Figure 5). The data processing has also detected an alunite-rich zone in the western part of the image, outside of the Goldfield area defined in Figure 1. This and several kaolinite-rich areas detected in other parts of the image merit further attention for gold mineralization prospection.

In Figure 6 are shown the results of the Rodalquilar PRISMA data analysis. Within the Rodalquilar caldera complex the PRISMA has identified alunite and kaolinite-rich hydrothermally altered rocks that correspond with the location of gold deposits within the Lomilla caldera (*see* Figures 3, 6, 7a), and with an extensive alteration zone but without known gold mineralization in the eastern side of the Rodalquilar caldera complex (*see also* Bedini, 2019; Arribas et al., 1995). Figure 7b shows alunite–rich altered rocks within the alteration zone in the eastern side of the Rodalquilar caldera complex. Zones of kaolinite and illite alteration are also detected west of the Los Frailles caldera. These areas correspond to alteration associated with base metal mineralization. To be mentioned that the moderate 30 m spatial resolution of the PRISMA satellite hyperspectral data may hinder the accurate detection and mapping of relatively small alteration zones. In addition, at the Rodalquilar caldera complex the moderate spatial resolution of the hyperspectral data has produced more alunite-kaolinite mixtures (the yellow color in Figure 6), than analysis of high spatial resolution multispectral or hyperspectral imagery (e.g., Bedini et al., 2009; Bedini, 2019). The areas dominated by the spectral response of alunite and kaolinite correspond to advanced and intermediate argillic alteration zones (e.g., Arribas et al., 1995).

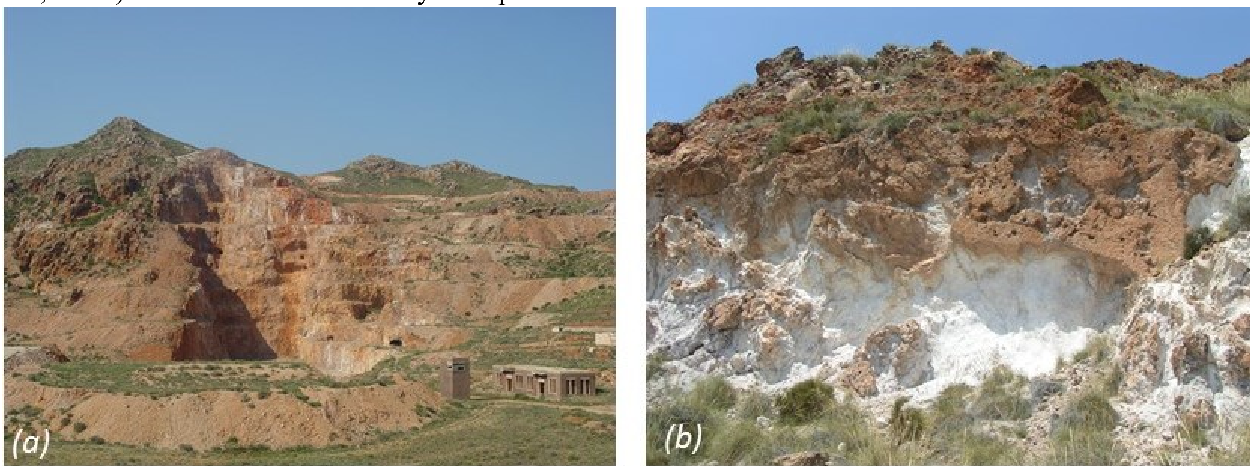

Figure 7. (a) Altered rocks at the Lomilla caldera that occurs within the Rodalquilar caldera complex. Gold has been mined out at this location. (b) Alunite-rich zones in the eastern part of the Rodalquilar caldera complex.

Quartz-rich zones within such alteration assemblages are often important for localizing gold mineralization, as it is associated with the most acidic fluids (e.g., Arribas et al., 1995). Without spectral bands in the thermal infrared the PRISMA cannot detect quartz. The quartz-rich zones in the surface can be detected by analyzing coincident ASTER thermal infrared imagery that have a spatial resolution of 90 m (e.g., Bedini, 2019). However, thermal infrared imagery with a higher spatial resolution (of at least 30 m) would be very useful in geological remote sensing studies of epithermal gold deposits.

4. Conclusions

This study analyzed PRISMA satellite hyperspectral imagery of Goldfield, Nevada and Rodalquilar, southeastern Spain where typical quartz-alunite epithermal gold deposits occur. The analysis of the PRISMA data mapped important alteration minerals (alunite, kaolinite, illite) in the mineral alteration assemblages of these gold deposits. At the area of Goldfield in Nevada the PRISMA correctly identified the spatial distribution of the alteration minerals within the area included in an alteration map compiled by Ashley (1974). In addition, a zone with abundant alunite and prospective for gold mineralization is detected west of Goldfield. The large and extensive hydrothermal alteration zones at Goldfield and its vicinity allow the PRISMA hyperspectral data to produce results comparable with results from airborne hyperspectral data for the mapping of important alteration minerals. At Rodalquilar the PRISMA correctly identified the altered areas within the Rodalquilar caldera complex. At the Lomilla caldera the mapped alunite and kaolinite alteration zone corresponds with the location of the main Rodalquilar epithermal gold deposits. In other parts of the Rodalquilar caldera complex, the extensive km-scale alteration is not associated with known epithermal gold deposits (e.g. Arribas et al., 1995; Bedini et al., 2009). The zones dominated from the spectral response of illite at Rodalquilar correspond to outer parts of the intermediate argillic alteration and to the propylitic alteration. Rock alteration detected by the spectral response of kaolinite and illite is mapped west of the non-mineralized Los Frailles caldera. The moderate spatial resolution of the PRISMA data may hinder a more detailed mapping of altered rocks in these areas west of the Los Frailles caldera.

The PRISMA data are useful for the characterization of alteration assemblages associated with quartz-alunite epithermal gold deposits. The

PRISMA hyperspectral satellite of the Italian Space Agency represents a major technological achievement opening new opportunities for the application of hyperspectral remote sensing or "imaging spectrometry" to a wide range of disciplines.

Acknowledgment

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