JOURNAL OF MAPS, 2016
VOL. 12, NO. S1, 172–177
http://dx.doi.org/10.1080/17445647.2016.1187676
Taylor & Francis
Taylor & Francis Group

SCIENCE

Geology of the Manantial Espejo epithermal district, Deseado Massif, Patagonia Argentina

Horacio Echeveste, Luciano López and Mercedes Carlini

Facultad de Ciencias Naturales y Museo, Instituto de Recursos Minerales, Universidad Nacional de La Plata, Buenos Aires, Argentina

ABSTRACT
The silver–gold epithermal mining district, Manantial Espejo, is located southwest of the Deseado Massif, Patagonia. The district is set into Jurassic volcaniclastic rocks of the Bahía Laura Group. A geological map of the district, at a scale of 1:50,000 drawn over a base map prepared from the fusion of satellite imagery and aerial photographs, is included. A suite of andesitic to rhyolitic eruptive units was identified, with prevailing high-grade rhyolitic ignimbrites. Travertine levels show the beginning of a hot-spring system in the region. Quartz veins, with typical crustiform–colloform banded structures, fill WNW, sub-vertical, normal faults, originating from extensional tectonics. The silicification of travertines, tuffs and breccia is the most common hydrothermal alteration.

ARTICLE HISTORY
Received 28 December 2015
Revised 29 April 2016
Accepted 5 May 2016

KEYWORDS
Geology; silver–gold; mining; hot-spring; epithermal; volcanism; Patagonia

1. Introduction

In the early 1980s, quartz veins with Au and Ag anomalies hosted in the Jurassic volcanic rocks of the Chon Aike Formation were discovered in the central region of the Deseado Massif, Santa Cruz province, Argentina (Genini, 1990; Schalamuk, de Barrio, Zubia, Genini, & Echeveste, 1999). Prospecting was undertaken in the region by governmental agencies such as Servicio Geológico Minero Argentino (SEGEMAR) and Fomento Minero de la Provincia de Santa Cruz (FOMICRUZ), together with private mining companies, intending to detect new mineralized areas.

This public and private exploration identified new targets with mining potential (Fernández et al., 2008 and references cited there), while academic research (Echavarría, Schalamuk, & Etcheverry, 2005; Echeveste, 2005a; Guido, 2002; Jovic, 2010; López, 2006; Moreira, 2005; Mykietiuk, 2006; Páez, 2012; Permuy Vidal, 2014; Ruiz, 2012; Wallier, 2009) provided data on the mineralization type – epithermal low to intermediate sulfidation – as well as its spatial and genetic association with the Jurassic volcanism.

The available geological map of the of the Manantial Espejo district region was published by Panza, Marín and Zubia (1998) on quadrangle 4969-I Gobernador Gregores, Santa Cruz province, at a scale of 1:250,000. This geological map was insufficient to understand the evolution of the volcanism and the associated metalliferous anomalies. The Jurassic volcanic rocks were mapped in three formations – Bajo Pobre, Chon Aike, and La Matilde – gathered in the Bahía Laura Group. However, each of these formations was formed by a suite of numerous eruption units (in the sense of Fisher & Schmincke, 1984), for which knowledge of their differentiation, lateral and vertical variations, and depositional history became essential to model the generating volcanic process.

Mapping of the prospects at a district scale (1:50,000–1:10,000) allowed the identification and mapping of the lithologic variations within the Bahía Laura Group and the definition of the volcanic evolution in the area. This contribution presents the Main map of the Manantial espejo prospect, located close to the southwestern margin of the Deseado Massif, at a scale of 1:50,000 (Echeveste, 2005a) (Figure 1). The map was prepared as part of the research project 'Metallogenic Research for Precious Metals (gold and silver) in the eastern and northwestern areas of the Macizo del Deseado, Provincia de Santa Cruz' conducted by the Institute for Mineral Resources (National University of La Plata), in early 2000.

The physiographic features in the 560 km^2 survey area are made of smooth hillocks and a meager and poorly integrated drainage basin. The area extends between latitudes 48°40′35″(S) and 48°51′25″(S), and from longitudes 69°41′(W) to 69°19′(W), with elevation between 300 and 500 m above sea level.

Studies on the petrology, mineralogy, fluid inclusions, and stable isotopes of the area allowed classification of the Manantial Espejo mineralization as a low to intermediate sulfidation, epithermal deposits (Echeveste, 2005a, 2005b; Schalamuk, Echeveste, Etcheverry, & Ametrano, 1998; Schalamuk, Ríos,

CONTACT Luciano López lopezluciano@hotmail.com

Supplemental data for this article can be accessed 10.1080/17445647.2016.1187676

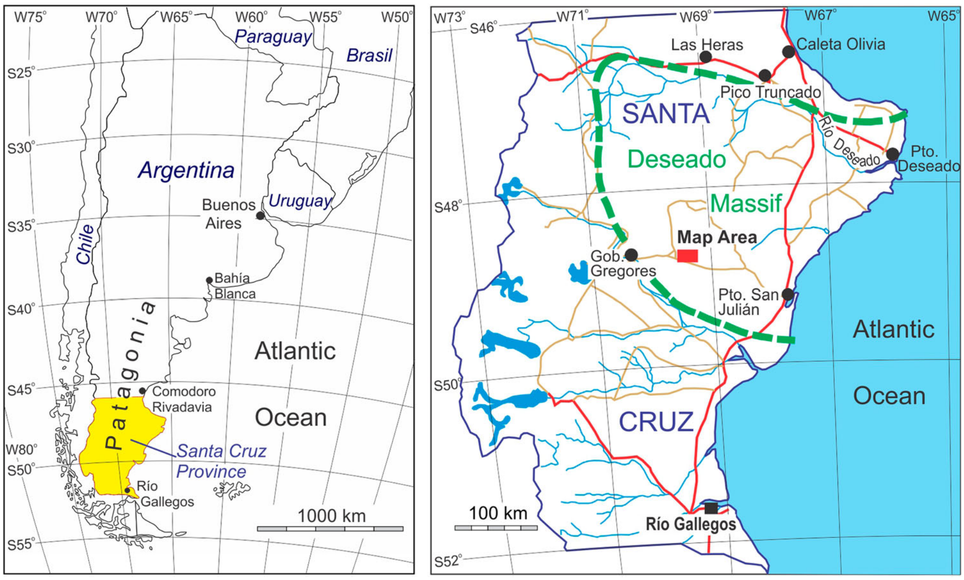

Figure 1. Location maps of the study area.

Fuzikawa, & Pimenta, 1995). The age of the hydrothermal alteration associated with the veins was estimated at 159 My (Moreira et al., 2009). In 2014, Manantial Espejo produced 3.7 million ounces of silver. The mineral proven reserves at Manantial Espejo in 2014 were 2.4 million tons with 123 g/t Ag and 1.82 g/t Au.

2. Methods

The methodology employed in the geologic mapping was based on photo interpretation of stereoscopic photograms and Landsat Enhanced Thematic Mapper Plus (ETM+) images geo-referenced using ground control points. The Campo Inchauspe Datum and Gauss Kruger coordinate system were employed. The image fusion and geometric correction was performed using ER Mapper. With the aim of identifying different lithologic units and define hydrothermal alteration zones, potentially associated with mineralized areas, TITUS software was used to identify areas of similar spectral response corresponding to different geological units. Most of the tested treatments were based on the selection of entities defined previously in the field as proxies (Schalamuk, de Barrio et al., 1999, Schalamuk, Echeveste, Etcheverry, & Ametrano, 1999). The scarce vegetation cover and lack of a soil helped to distinguish most of the outcropping geological units in the area. For detailed examination of the images, and the identification of other geological units, several band combinations were tested; RGB 741 was amongst those shown to have better contrast.

The study of grayscale bands allowed differentiation of andesitic lava outcrops of the Bajo Pobre Formation, which records a higher absorption over all of the bands. The analysis of the near infrared band (TM4) allowed the definition of outcrops of amphibole and biotite-rich ignimbrite, an assemblage of dikes (later classified as rhyolitic), tuff and tuffaceous sandstone, and most of the outcrops of the post-Jurassic sedimentary deposits. After the digital analysis, a fusion was performed of the Landsat ETM+ RGB 741 image with a panchromatic SPOT image, using ER Mapper software. This process, known as pan sharpening, decreases the size of the 30 × 30 m pixel to 10 × 10 m, thus increasing the spatial resolution of the image. For some areas, a fusion of the Landsat ETM+ image with 1:60,000 aerial photographs allowed for a resolution of 5 × 5 m. The final image with a UTM grid overlay was plotted at a scale of 1:40,000 into several A4 size sheets, with a 10% overlap, was used as a base map for the regional field mapping. During the field survey photo interpretation of stereoscopic pairs, interpretation of the satellite imagery and the positioning of geological observations (using a GPS receiver) was undertaken.

Errors in the positioning of the GPS geo-referenced observations were assumed to be negligible as errors at the selected scale (1:40,000) would be less than 0.5 mm on the map.

The final regional geological map was produced using Esri ArcMap. The contacts between the different eruptive and sedimentary units, faults, joints, mineralized structures, and lineaments were mapped.

To show altimetry, contours from 1:100,000 topographic maps were digitized. Final map production was undertaken using CorelDRAW.

3. Results

A total of 20 rock units were identified and mapped, of which 14 are eruptive and correspond to the Bahía Laura Group. They are mostly ignimbrites, defined by their field attributes (occurrence, texture, and color on the satellite images) and petrography. A small granitic basement outcrop was identified, and five sedimentary units of diverse age, from Jurassic to recent. Even though the temporal relationship between the Jurassic eruptive units could not always be defined, the complete volcano-sedimentary sequence for the study area is shown in Figure 2.

3.1. Pre-Jurassic units

The pre-Jurassic basement, formed by quartz-biotitic schists, was identified in the form of accessory lithic fragments in ME-2 Rhyolitic Ignimbrite (Figure 3(a)), and in a small outcrop of granite (Figure 3(b)), of granular texture, with K-feldspar shaped in elongated strips, displaying a neat cleavage, white colored plagioclase in tabular specimens, and smoky quartz.

3.2. Volcanic, volcaniclastic, and volcanogenic sedimentary Jurassic units

The oldest Jurassic unit is ME-1 Andesitic Lava (Figure 3(c)), in which eight high-grade ignimbrite units were identified, one of dacitic composition (ME-1 Dacitic Ignimbrite), the rest are rhyolitic with interspersed tuff and tuffaceous sandstone. Also interspersed among the volcanic units, thermogenic travertine (Figure 3(d)) deposits were encountered which are associated with a hot-spring environment (Echeveste, 2005b) and are a precursor to the main gold and silver mineralization event. The volcano-sedimentary sequence is cut by small rhyolitic domes and co-genetic dikes striking NNW with coherent facies and autoclastic facies (Figure 3(e)). The interaction of these ascending acid

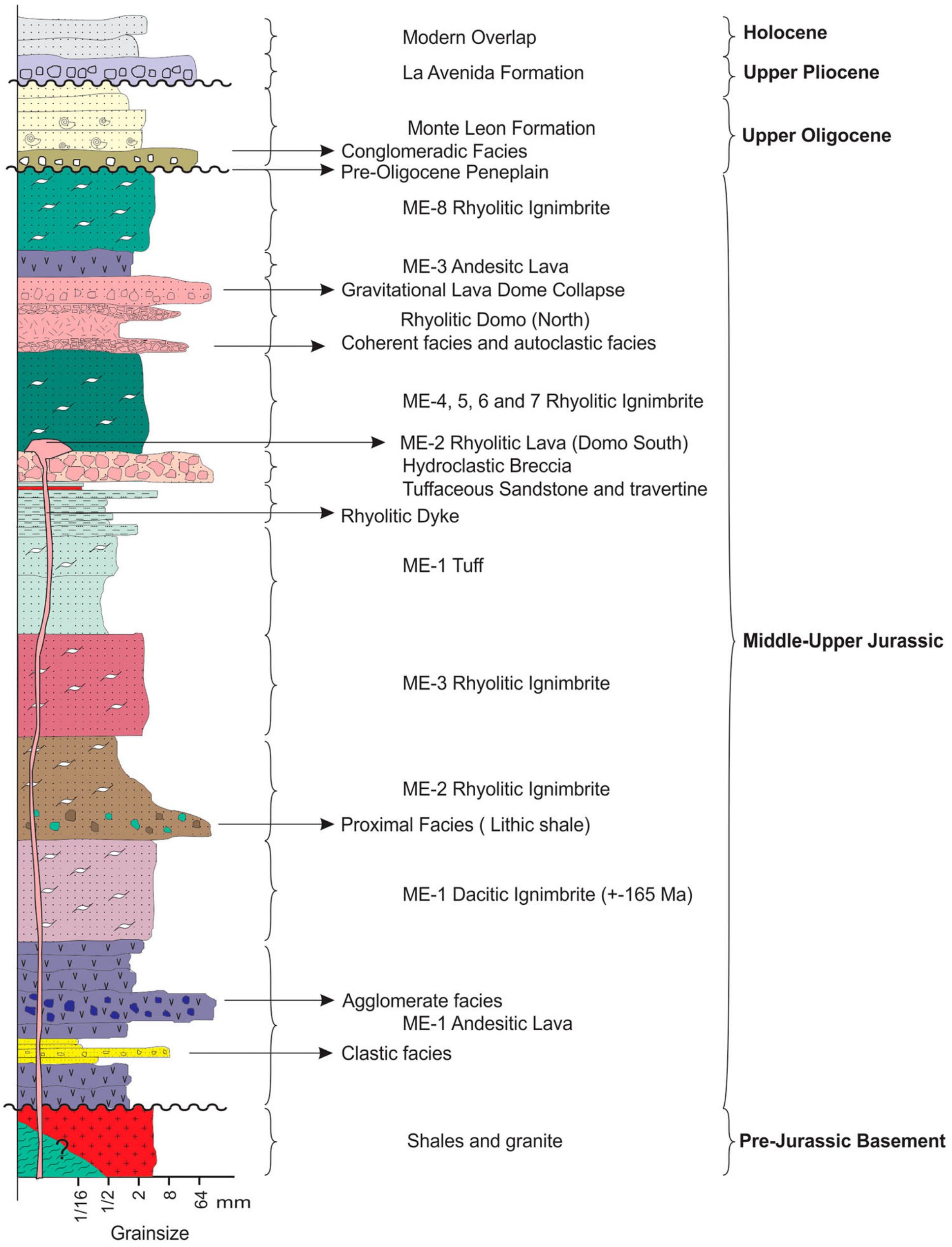

Figure 2. Simplified volcano-sedimentary sequence for the Manantial Espejo area (modified from Echeveste, 2005b). ME refers to Manantial Espejo project name

magmas with groundwater or sediments resulted in a hydroclastic breccia (sensu Hanson, 1991) formed of lava fragments from the host rocks of the ascending magmas, and from surface deposits (Figure 3(f)). Along discontinuous outcrops, the breccia covers an area of approximately 1800 ha. The following deposits comprise at least five ignimbrite units, ME-4, 5 (Figure 3(g)), 6, 7, and 8 Rhyolitic Ignimbrites, whose temporal relationships are not clear because of the lack of stratigraphic contacts. The ignimbrites are mostly of high grade

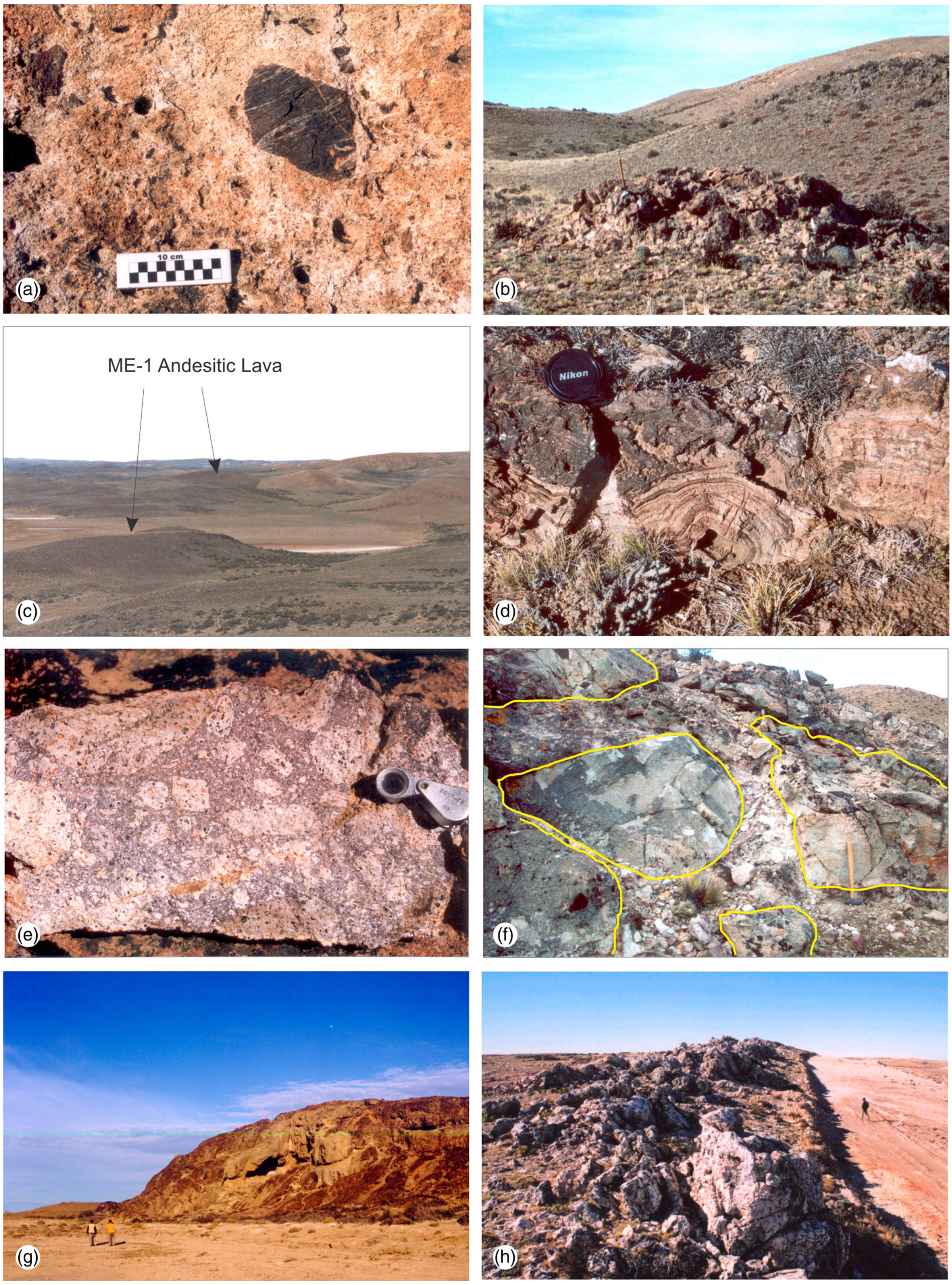

Figure 3. (a) Sub-angular fragment of biotitic-quartz schist in proximal facies of ME-2 Rhyolitic Ignimbrite. (b) Granite basement outcrop. (c) ME-1 Andesitic Lava flow making a topographic low in the western area of the district. (d) Banded travertine displaying stromatolitic growth. (e) Autobrecciated lava with variable sized fragments in a re-crystallized glass matrix and phenocrysts. (f) Clast-propped phreatomagmatic breccia with large sub-angular lava blocks in proximal zone (clasts outlined in photograph). (g) Panoramic view of an ME-5 Rhyolitic Ignimbrite outcrop, forming a flow more than 20 m thick with large erosion caves. (h) Panoramic view from west of the central area of Vein María. The thickness, over 5 m in this area, can be appreciated in the foreground. To the right, atop the structure, a level portion of the ground is seen, where short exploration holes were drilled.

(sensu Walker, 1983). Dating by the U-Pb-SHRIMP method of one zircon sample from ME-1 Dacitic Ignimbrite yielded an age of 156 My (Moreira et al., 2009).

3.3. Mineralization

Quartz veins and stockworks, bearing gold and silver minerals, lodge into faults and joints of prevailing WNW strike, dipping near the vertical, and add up to some 13,600 m of mineralized structures, covering a WNW–ESE elongated area of about 50 km^2. Because its dimensions and reserves, the most important is Vein María (Figure 3(h)), some 1000 m long and up to 22 m thick, displaying a crustiform–colloform banded structure with evidence of platy calcite replacement. Following in importance are the Karina-Union, Concepción, and Marta veins.

3.4. Post-Jurassic units

After the Jurassic volcanic event, the region underwent an incipient planation, very smoothly sloping southeast. This surface is covered by a thin, poorly sorted, conglomeratic deposit, and by grainstones and calcareous sandstones of the Late Oligocene Monte León Formation (Bertels, 1970). Covering the former, and a large part of the southern portion of the mapped area, appears the fluvial sandy gravel sheet of the Late Pliocene La Avenida Formation (Marín, 1982). Recent sedimentary deposits are limited and confined to the fill of the valleys of ephemeral streams discharging in the abundant endorheic depressions, and to the silty deposits filling the abundant permanent and temporary ponds in the region.

4. Structure

The structural analysis of the district (Echeveste, 2010) established the existence of at least two systems of fragile extensional deformation. These systems were active prior to 159 My (Callovian), and are associated with the rhyolitic volcanism and epithermal activity in the region. The older system follows the main NNW–SSE stress, producing two fracture systems, one at about 25° and the other around 140°. These fractures were occupied by rhyolitic dikes and allowed the circulation of bicarbonate aqueous fluids associated with the presence of a hot-spring type system causing surface calcite veins and travertine deposits. A second deformation system caused a simple shear system with a $\sigma 1 \sim$ N 35° W, similar to a Riedel shear conjugate system, with extension fractures of 120°–150° azimuth originating normal faults dipping NNE and SSW. These faults, through a combined normal and dextral movement, produced dilational jogs, echelon joints, and sigmoidal tension gashes, mostly forming the new hydrothermal fluid circulation channels, and the lodgment of the veins in the district.

5. Conclusions

The observation, description, and interpretation of the mapped units allow the reconstruction of the historical evolution of the region, especially the Jurassic volcanic units associated with the silver–gold bearing veins. Also, the existence of an igneous-metamorphic basement on which the Jurassic volcanic sequence lies was identified. The occurrence of an extensional tectonic regime in mid-Jurassic times favored the onset of the rhyolitic–andesitic volcanic event, beginning with the ascent and effusion of andesitic lava.

The continuity of the extensional process let the more acid magma rise, dacitic initially and rhyolitic afterwards, as different ignimbrite flows and tuffs. Together with the NNE and NNW striking calcite veins, travertine chemical deposits, made of thin, laminar, carbonate, and amorphous silica rhythmites, are the first evidence of hydrothermal activity of the 'hot-spring' type.

After the deposition of ME-5 and ME-6 ignimbrites, the extensional tectonic regime allowed the rise of fluids generating the silver–gold mineralized quartz veins, mainly from WNW–ESE-oriented fractures. Likewise, besides generating the hydrothermal alteration of the host rock, on some occasions, these solutions form jasperoids when replacing chemical and biogenic carbonate levels, volcanic cinders of tuffaceous levels, and breccias.

Software

ER Mapper was used for the fusion of images and geometric correction. The spectral analysis of the geologic units was performed using TITUS (under Windows). The geological map of the Manantial Espejo District was produced using Esri ArcMap 10. Final map artwork was completed in CorelDraw Graphics Suite X6.

Acknowledgements

This work was carried out within the framework of the BID 802/OC AR PID 32/98 Project: 'Investigación metalogenética por metales preciosos (oro y plata) en los sectores oriental y noroccidental del Macizo del Deseado. Provincia de Santa Cruz', Agencia Nacional de Promoción Científica y Tecnológica de la República Argentina.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Luciano López http://orcid.org/0000-0003-4072-3273

References

Bertels, A. (1970). Sobre el "Piso Patagoniano" y la representación de la época del Oligoceno en Patagonia austral (República Argentina). *Revista de la Asociación Geológica Argentina*, *25*, 495–501.

Echavarría, L. E., Schalamuk, I. B., & Etcheverry, R. O. (2005). Geologic and tectonic setting of deseado massif epithermal deposits, Argentina, based on El Dorado-Monserrat. *Journal of South American Earth Sciences*, *19*, 415–432. doi:10.1016/j.jsames.2005.06.005

Echeveste, H. (2005a). *Metalogénesis del distrito argento-aurífero Manantial Espejo, Macizo del Deseado. Provincia de Santa Cruz* (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

Echeveste, H. (2005b). Travertinos y jasperoides de Manantial Espejo, un ambiente hot spring jurasico. Macizo del Deseado, provincia de Santa Cruz, Argentina. *Latin American Journal of Sedimentology and Basin Analysis*, *12*, 23–39. Retrieved from http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S1851-49792005000100004&lng=es&nrm=iso

Echeveste, H. (2010). Control estructural de la mineralización epitermal del distrito Manantial Espejo, Santa Cruz, Argentina. *Revista de la Asociación Geológica Argentina*, *66*, 325–334. Retrieved from http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S0004-48222010000200004&lng=es&nrm=iso

Fernández, R. R., Blesa, A., Moreira, P., Echeveste, H., Mykietiuk, K., Andrada de Palomera, P., & Tessone, M. (2008). Los depósitos de oro y plata vinculados al magmatismo jurásico de la Patagonia: revisión y perspectivas para la exploración. *Revista de la Asociación Geológica Argentina*, *63*, 665–681. Retrieved from http://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S0004-48222008000400015&lng=es&nrm=iso

Fisher, R. V., & Schmincke, H. U. (1984). *Pyroclastic rocks*. 472 p. 339 Abb. Heidelberg: Springer Verlag Berlin.

Genini, A. D. (1990). Cerro Vanguardia. Provincia de Santa Cruz. Nuevo prospecto auroargentífero. *3° Congreso Argentino de Geología Económica*, *3*, 97–110. Olavarría.

Guido, D. M. (2002). *Geología y metalogenesis del sector oriental del Macizo del Deseado, provincia de Santa Cruz*. (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

Hanson, R. E. (1991). Quenching and hydroclastic disruption of andesitic to rhyolitic intrusions in an submarine island-arc sequence, northern Sierra Nevada, California. *Geological Society of America Bulletin*, *103*, 804–816. doi:10.1130/0016-7606(1991)103<0804:QAHDOA>2.3.CO;2

Jovic, S. (2010). *Geología y Metalogénesis de las mineralizaciones polimetálicas del área El Tranquilo (Cerro León), sector central del Macizo del Deseado, provincia de Santa Cruz* (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

López, R. G. (2006). *Estudio Geológico-Metalogenético del área oriental al curso medio del Río Pinturas, sector noroeste del Macizo del Deseado, provincia de Santa Cruz, Argentina* (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

Marín, G. (1982). *Descripción geológica de la Hoja 55c Gobernador Gregores, provincia de Santa Cruz*. Informe preliminar. Servicio Geológico Nacional. Unpublished.

Moreira, P. (2005). *Geología y Metalogénesis del Distrito La Josefina, Macizo del Deseado, Provincia de Santa Cruz* (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

Moreira, P., Echeveste, H., Fernández, R., Hartmann, L., Santos, J., & Schalamuk, I. (2009). Depositional age of Jurassic epithermal gold-silver ore in the Deseado Massif, Patagonia, Argentina, based on Manantial Espejo and La Josefina prospects. *Neues Jahrbuch für Geologie und Paläontologie – Abhandlungen*, *253*, 25–40. doi:10.1127/0077-7749/2009/0253-0025

Mykietiuk, K. (2006). *Volcanismo y alteración hidrotermal en el prospecto de metales preciosos del área de la estancia La Esperanza, Macizo del Deseado, Santa Cruz*. (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

Páez, G. N. (2012). *Génesis del yacimiento de metales preciosos Mina Martha, sector sudoccidental del Macizo del Deseado, provincia de Santa Cruz* (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

Panza, J. L., Marín, G., & Zubia, M. (1998). Hoja geológica 4969-I, Gobernador Gregores, provincia de Santa Cruz. *Servicio Geológico Minero Argentino. Boletín*, *239*, 1–87.

Permuy Vidal, C. (2014). *Caracterización detallada de la mineralización en veta Eureka, y su comparación con otras mineralizaciones del Distrito Cerro Negro, Macizo del Deseado, Santa Cruz, Argentina* (Unpublished PhD thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata.

Ruiz, R. (2012). *Geología y mineralizaciones del sector sudoccidental del Macizo del Deseado, provincia de Santa Cruz, Argentina* (Unpublished Ph.D. Thesis). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata.

Schalamuk, I., de Barrio, R., Zubia, M., Genini, A., & Echeveste, H. (1999). Provincia Auroargentífera del Deseado, Santa Cruz. En: Recursos minerales de la República Argentina. In E. Zappettini (Ed.), *Instituto de geología y recursos minerales SEGEMAR, anales* (vol. 35, pp. 1177–1188). Buenos Aires: Servicio Geológico Minero Argentino. Instituto de Geología y Recursos Minerales.

Schalamuk, I., Echeveste, H. Etcheverry, R., & Ametrano, S. (1999). Prospecto Manantial Espejo, Santa Cruz. En: Recursos Minerales de la República Argentina. In E. Zappettini (Ed.), *Instituto de geología y recursos minerales SEGEMAR, anales* (vol. 35, pp. 1211–1217). Buenos Aires: Servicio Geológico Minero Argentino. Instituto de Geología y Recursos Minerales.

Schalamuk, I., Ríos, F., Fuzikawa, K., & Pimenta, M. (1995). Fluid inclusions studies in epithermal auriferous-quartz deposits of Macizo del Deseado, Santa Cruz, Argentina. Abstract XIII ECROFI. *Boletín de la Sociedad Española de Mineralogía*, *18*, 220–221.

Schalamuk, I. B., Echeveste, H., Etcheverry, R., & Ametrano, S. (1998). Metalogénesis del yacimiento de oro-plata "Manantial Espejo", Macizo del Deseado, provincia de Santa Cruz. *Anales de la Academia Nacional de Ciencias Exactas Físicas y Naturales, Buenos Aires*, *50*, 217–236.

Walker, G. P. L. (1983). Ignimbrite types and ignimbrite problems. *Journal of Volcanology and Geothermal Research*, *17*, 65–88. doi:10.1016/0377-0273(83)90062-8

Wallier, S. (2009). *The geology and evolution of the Manantial Espejo epithermal silver (gold) deposit, Deseado Massif, Argentina* (Unpublished PhD thesis). University of British Columbia, Vancouver, Canada.