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Prospectivity for epithermal gold–silver deposits in the Deseado Massif, Argentina

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ABSTRACT

Previous prospectivity modelling for epithermal Au–Ag deposits in the Deseado Massif, southern Argentina, provided regional-scale prospectivity maps that were of limited help in guiding exploration activities within districts or smaller areas, because of their low level of detail. Because several districts in the Deseado Massif still need to be explored, prospectivity maps produced with higher detail would be more helpful for exploration in this region. We mapped prospectivity for low- and intermediate-sulfidation epithermal deposits (LISEDs) in the Deseado Massif at both regional and district scales, producing two different prospectivity models, one at regional scale and the other at district-scale. The models were obtained from two datasets of geological evidence layers by the weights-of-evidence (WofE) method. We used more deposits than in previous studies, and we applied the leave-one-out cross validation (LOOCV) method, which allowed using all deposits for training and validating the models. To ensure statistical robustness, the regional and district-scale models were selected amongst six combinations of geological evidence layers based on results from conditional independence tests.
The regional-scale model (1000 m spatial resolution), was generated with readily available data, including a lithological layer with limited detail and accuracy, a clay alteration layer derived from a Landsat 5/7 band ratio, and a map of proximity to regional-scale structures. The district-scale model (100 m spatial resolution) was generated from evidence layers that were more detailed, accurate and diverse than the regional-scale layers. They were also more cumbersome to process and combine to cover large areas. The evidence layers included clay alteration and silica abundance derived from ASTER data, and a map of lineament densities. The use of these evidence layers was restricted to areas of favourable lithologies, which were derived from a geological map of higher detail and accuracy than the one used for the regional-scale prospectivity mapping.
The two prospectivity models were compared and their suitability for prediction of the prospectivity in the district-scale area was determined. During the modelling process, the spatial association of the different types of evidence and the mineral deposits were calculated. Based on these results the relative importance of the different evidence layers could be determined. It could be inferred which type of geological evidence could potentially improve the modelling results by additional investigation and better representation.
We conclude that prospectivity mapping for LISEDs at regional and district-scales were successfully carried out by using WofE and LOOCV methods. Our regional-scale prospectivity model was better than previous prospectivity models of the Deseado Massif. Our district-scale prospectivity model showed to be more effective, reliable and useful than the regional-scale model for mapping at district level. This resulted from the use of higher resolution evidential layers, higher detail and accuracy of the geological maps, and the application of ASTER data instead of Landsat ETM+ data. District-scale prospectivity mapping could be further improved by: a) a more accurate determination of the age of mineralization relative to that of lithological units in the districts; b) more accurate and detailed mapping of the favourable units than what is currently available; c) a better understanding of the relationships between LISEDs and the geological evidence used in this research, in particular the relationship with hydrothermal clay alteration, and the method of detection of the clay minerals; and d) inclusion of other data layers, such as geochemistry and geophysics, that have not been used in this study.

1. Introduction

The Deseado Massif in southern Argentina has been explored for epithermal Au–Ag deposits because of its favourable geological setting

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for this type of deposits (Schalamuk et al., 1997, 2002). The exploration activities resulted in the discovery of several new epithermal deposits, of which five have undergone mining, namely Cerro Vanguardia (Zubia et al., 1999), Manantial Espejo (Echeveste, 2010), Mina Marta (Páez et al., 2011), San José (Dietrich et al., 2012), and Lomada de Leiva (Sandefur, 2007). Other deposits are in advanced stages of exploration, such as Cerro Negro (Shatwell et al., 2011), Cerro Moro (Coupland, 2009), La Josefina (Andrada de Palomera et al., 2012; Schalamuk et al., 1999), El Dorado-Monserrat (Echavarría, 2004; Echavarría et al., 2005), and Bajo Pobre (Schalamuk et al., 1997; Zubia and Genini, 2003).

Identification of exploration targets by mineral prospecting often includes reviews of available information, interpretation of remote sensing data, geological mapping, and geochemical and geophysical surveys (Marjoribanks, 2010; Moon et al., 2006); and more recently, GIS-based mapping of mineral prospectivity (e.g., Behnia, 2007; Boleneus et al., 2001; Carranza and Sadeghi, 2010; Ford and Hart, 2013; González-Álvarez et al., 2010; Nykänen and Ojala, 2007; Porwal et al., 2010; Raines, 1999). GIS-based methods convey objectivity and reproducibility, making them useful for assigning priorities to exploration targets, helping with the assessment of different types of geological evidence, and justifying the need of additional investigation.

There are different GIS-based methods for mapping mineral prospectivity, these include logistic regression (Harris and Pan, 1999), the use of evidential belief functions (Carranza and Hale, 2003), fuzzy logic (Carranza and Hale, 2001; Porwal et al., 2003), neural network techniques (Singer and Kouda, 1999), weights-of-evidence modelling (Bonham-Carter et al., 1989), and Bayesian network classifiers (Porwal et al., 2006). Weights-of-evidence (WofE) technique is transparent and easy to interpret compared to alternative methods, such as neural networks, neuro-fuzzy, and Bayesian network classifiers (Agterberg, 2011; Agterberg and Cheng, 2002; Bonham-Carter et al., 1989; Ford and Hart, 2013; Porwal et al., 2010). Logistic regression is computationally intensive and its regression coefficients are hard to interpret (Deng, 2009), and although weighted logistic regression produces unbiased probabilities, its coefficients generally have relatively large variances (Agterberg, 2011). Fuzzy logic allows the use of multiclass variables but, up to a certain degree, it depends on reliable and correct exploration models. WofE is considered to provide conservative estimates and is suitable for areas that are only partially studied (de Quadros et al., 2006). In addition, WofE allows using zero weights for unknown or missing data, avoiding the exclusion of some layers of evidence, as in logistic regressions (Agterberg, 2011; Bonham-Carter et al., 1989; Deng, 2009).

A limitation of WofE is the requirement for conditional independence (CI) between layers of evidence. If this requirement is violated, then bias of estimated probabilities will result (Agterberg, 2011). In general, the bias leads to overestimation of probabilities. The degradation of performance increases with the number of predictor variables (Singer and Kouda, 1999). Therefore, the assumption of conditional independence should be tested when applying WofE modelling (Bonham-Carter et al., 1989).

In the Deseado Massif, regional-scale GIS-based favourability mapping of low-sulfidation epithermal deposits was tested by Carranza and Andrada de Palomera (2005) by using *evidential belief functions* and a limited number of training deposits. Their resultant regional-scale prospectivity maps provided limited help in guiding exploration within districts or smaller areas, partially because of their low level of detail. Prospectivity maps produced with higher detail and adequate effectiveness will be more helpful in guiding the exploration in those areas, and prospectivity mapping in the Deseado Massif could be improved by acquiring the most relevant types of geological evidence for the epithermal deposits being sought and representing them by the most suitable layers of evidence.

This study has three main objectives: (a) to map prospectivity of low- and intermediate-sulfidation epithermal deposits (LISEDs) in the Deseado Massif by training models with most deposits currently known in the region; (b) to test whether more detailed and diverse geological evidence can improve prospectivity mapping, particularly at district-scale; and (c) to determine the types of evidence that should be investigated further to improve prospectivity mapping in the Deseado Massif, mainly at district or larger scales. To reach these objectives, the GIS-based WofE method, and the leave-one-out cross validation method (LOOCV) were applied to two datasets with different levels of detail. The results of mapping with each dataset were compared, and the contributions of different types of evidence to the models' predictions were assessed to determine the types of evidence that need further investigation to improve prospectivity.

2. Geology and epithermal mineralization of the Deseado Massif

2.1. Stratigraphy of the Deseado Massif

The oldest rocks in the Deseado Massif (Fig. 1) belong to the La Modesta Formation of Upper Precambrian to Lower Paleozoic age (Schalamuk et al., 2002). These include schists, phyllites, slates, quartzites, gneisses, and amphibolites, which are intruded by granitic and tonalitic rocks with ductile to ductile–fragile deformation (Giacosa et al., 2002; Ramos, 2002a). The formation is unconformably overlain by continental sediments of the La Golondrina, La Juanita, and El Tranquilo Formations. The Permian La Golondrina and La Juanita Formations include quartz-feldspathic sandstones, siltstones, lithic sandstones, and conglomerates. These are present only in the eastern part of the Deseado Massif (Fig. 1). The El Tranquilo Formation of Middle or Upper Triassic age (De Giusto et al., 1980) consists of alternating fine- to coarse-grained quartz sandstones, shales, fine-grained conglomerates (Sanders, 2000), and intercalations of syn-sedimentary volcanic materials.

During the Lower Jurassic, after the deposition of the El Tranquilo Formation, I-type granitic rocks of the La Leona Formation were intruded in the NE of the region (Márquez et al., 2002; Varela et al., 1991). These rocks are calc-alkaline granodiorites, granites, adamellites, tonalites and diorites (Godeas, 1985). During the remainder of the Jurassic, abundant pyroclastic materials corresponding to the Roca Blanca, Bajo Pobre, Chon Aike, and La Matilde Formations were deposited. These formations filled NNW-trending grabens produced by the generalized extension that broke-up Gondwanaland.

The Roca Blanca Formation of Lower Jurassic (Liassic) age comprises a sub-aerial sequence of tuffs, sandstones, mudstones and volcanoclastic–sedimentary rocks. It has a maximum thickness of 900 m (Panza, 1982) and was deposited in active rift basins (Sanders, 2000).

The Bajo Pobre Formation of middle Jurassic age is composed of predominant porphyritic to aphanitic olivine basalts, subordinate porphyritic andesites and basaltic agglomerates, and minor mafic tuffs, conglomerates and sandstones (Sanders, 2000). Its thickness varies from 150 to 200 m in most outcrops, but locally reaches up to 600 m (Panza, 1994a). Related to the magmatic episode that produced the Bajo Pobre Formation, hypabyssal porphyritic andesites of the Cerro Leon Formation intruded the El Tranquilo, Bajo Pobre and Roca Blanca Formations (Panza, 1982). These are likely intrusive equivalents of the Bajo Pobre Formation (de Barrio et al., 1999; Jovic et al., 2011), and are covered unconformably by the Bahía Laura Group.

During the Middle to Upper Jurassic, rocks of the Bahía Laura Group (Feruglio, 1949; Lesta and Ferello, 1972) formed a pyroclastic volcanic–sedimentary complex of predominantly rhyolitic and partly dacitic composition. The volcanism that produced the Bahía Laura Group probably lasted for about 50 Ma (Schalamuk et al., 1999); having radiometric ages of 177–125 Ma. However, the age of the Bahía Laura Group in relation to the Bajo Pobre Formation is controversial, and radiometric ages of these two units, obtained in different sectors of the Deseado Massif, show some overlap. The Bahía Laura Group is composed of the Chon Aike and La Matilde Formations.