Predictive mapping for copper–gold magmatic-hydrothermal systems in NW Argentina: Use of a regional-scale GIS, application of an expert-guided data-driven approach, and comparison with results from a continental-scale GIS

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Abstract

Geographic Information Systems (GISs) are very useful tools for managing, checking, and organizing spatial information—from many sources and of many types—in thematic layers. Processing of these data enables exploration-oriented GISs to produce potential and predictive maps for a given commodity, which constitute documents of real use in decision-making. Integration of all information in a single reference system enables a better understanding of the parameters controlling a region’s metallogeny, in terms of both time and space. But what scale should be used for developing a mineral exploration GIS? Should preference be given to systems with high spatial resolutions (scale <1:500,000), or to more general systems with scales of around 1:1,500,000 or 1:2,000,000? Will the gain be worthwhile relative to the additional work generated by compilation at a higher scale? In order to make greater use of previous predictive studies performed on gold-rich epithermal and porphyry systems at the scale of the entire Andes, an expert-guided data-driven approach is now applied to a regional-scale GIS of NW Argentina, between the Puna and the Sierras Pampeanas, where known deposits like Bajo de la Alumbrera, Agua Rica, and others, account for a metal potential of over 10 Mt Cu and 750 t Au. In developing this new predictive map, three criteria that were likely to be connected to the mineralizing event were selected and quantified: (i) lithostratigraphy, because of its role as a favourable environment for the development of mineralization, based on its physico-chemical properties; (ii) lithostratigraphic contacts, based on the rheological properties of the formations in contact; and (iii) the orientation of structural discontinuities, which channel source magmas and encourage the circulation of hydrothermal fluids. Assigning a score enables classification of the favourabilities calculated for each of the criteria considered. This approach is employed here to check and standardize the statistical results obtained by methods such as Weight of Evidence Modelling or an algebraic approach. For each criterion, four classes were distinguished: very favourable: score=3; favourable: score=2; slightly favourable: score=1; and unfavourable: score=0. The predictive map is obtained by adding the scores for the three favourable criteria defined above.

The regional-scale work identified 20 anomalous envelopes with cumulative scores greater than 5. They correspond to mining areas that are active (e.g., Bajo de la Alumbrera), under development (e.g., Agua Rica), or abandoned (e.g., La Mejicana), or to new
areas (e.g., the Vicuña Pampa Volcanic Complex). Structural analysis of the region, integrating the orientation of the favourable envelopes, suggests that the mineralizing fluids were emplaced under extensional conditions, sub-parallel to the principal directions of shortening: (i) WNW–ESE, found along the southern edge of the Puna; and (ii) E–W, seen in the Sierra de Famatina. It appears that a regional-scale information system is a tool that is well suited to the definition of areas for mineral prospecting, and to the study and confirmation of metallogeneic units usable for mineral exploration.

Comparison with work conducted on the basis of a 1:2,000,000 geological compilation shows that the principal mining districts can indeed be found at continental scale. On the other hand, the lack of detail inherent at a scale of 1:2,000,000 may lead to inaccuracies, in particular fictitious favourabilities assigned to formations that are genetically unrelated to the mineralization, but that contain, for example, small Tertiary intrusive bodies that cannot be recorded at this scale. This comparison therefore shows that the use of a continental-scale GIS is effective, and well suited to the definition of prospective areas at a strategic level.

Keywords: GIS; Multi-criteria processing; Metallogeny; Gold; Andean tectonics

1. Introduction

Geographic Information Systems (GIS) are very useful tools for managing spatial information. Coming as it does from sources of many kinds, such information is often heterogeneous in nature, quality, distribution, and density. However, once it has been checked and organized into thematic layers, an exploration-oriented GIS can produce predictive maps for a given commodity, and can be of great value in decision-making (e.g., Bonham-Carter et al., 1989; Bonham-Carter, 1994; Burrough and McDonnell, 1998; Billa et al., 2004). A GIS can also be a tool for research: once all the information is under a single reference system, the user can better explore the interactions between the various parameters that control the mineralization, and better define the laws governing the distribution of mineral concentrations in space and time (e.g., Cassard et al., 2003, 2004).

What is the best scale for developing a GIS for mineral exploration? Should one aim for good spatial resolution, at a detailed scale (>1:500,000) over a limited area (say, thousands of km²); or should one take a more general view, at 1:1,500,000 or 1:2,000,000, covering a much larger area but including well-studied sites and zones of poorer information? Recent studies of multi-representational geographic bases, at multiple resolutions, have shown that the problems of changing scale are not trivial and are still far from being solved (Parent et al., 2000; Spaccapietra et al., 2000). To build a GIS, the user can choose between (1) the semi-continental approach, based on geodynamic criteria, an accuracy of the order of ±2 km for geological contacts, deposits and prospects, and the plotting of calculations on pixels 10 km by 10 km square; or (2) the regional approach, which involves an accuracy much better than 1 km, detailed geology, detailed structural analyses, geophysical or geochemical surveys of limited areas (if available), and plotting on pixels 0.5 km by 0.5 km square.

In this paper, we describe a regional approach to studying the Famatina and Farallón Negro gold districts of NW Argentina with a two-fold objective:

1. In terms of methodology, we wished to investigate the predictive capacity of a regional GIS, as compared with that of a continental GIS. Using a similar methodology at continental scale, Billa et al. (2004) successfully identified the main Andean gold districts between Ecuador and Chile. At regional scale, would the resulting gain be worth the additional work of compilation? Although we might expect greater accuracy, when working on a smaller area, there will be fewer deposits for which information is reliable;

2. In terms of metallogeny, we wished to investigate the magmatic and structural controls on mineralization in a supra-subduction environment (Nelson, 1996). The continental approach had already yielded a strong positive correlation between (1) Neogene epithermal and porphyry gold deposits in the Central Andes and (2) gently dipping segments of the Benioff zone (Cassard et al., 2001; Billa et al., 2002). Would the regional approach yield a correlation with volcanic centres and with the major structural lineaments that are present in NW Argentina (Rossello et al., 1996b,c; Rossello, 2000)?

2. Geodynamic, geological, and metallogenetic setting of NW Argentina

2.1. Geodynamic setting of the Central Andes

From W to E, the main structural units of the Central Andes are the Cordillera Principal, the Pre-Cordillera,
the Puna, the Sub-Andean ranges, and the Sierras Pampeanas (Fig. 1). From north to south, the mountain belt becomes narrower (Jordan et al., 1983) and lower, in steps (Allmendinger et al., 1997).

Currently, the Nazca plate subducts beneath the South American plate in a nearly E–W direction and at a rate of 7.8 cm/year. From the Oligocene to the Early Miocene, convergence was more nearly NE–SW and much faster (on the order of 15 cm/year; Pardo-Casas and Molnar, 1987; Somoza, 1998). Currently, the dip of the subducting slab is on the order of 30°, to the N of latitude 27°S, becoming progressively more gentle to the S (Cahill and Isacks, 1992). Also from north to south, the continental lithosphere becomes thinner (Whitman et al., 1996) and the amount of horizontal shortening decreases (Isacks, 1988). Although there is now a gap in volcanic activity (Fig. 1) between latitudes 27°S and 33°S (Kay et al., 1999), magmatic activity has been intense here during the last 10 Ma (Fig. 2). During the Neogene, the Nazca plate may have flattened, causing a widening of the magmatic arc towards the east (Kay et al., 1999; Kay and Mpodozis, 2002). Along a few transverse lineaments (Salfity, 1985; Boudesseul et al.,

![Geodynamic setting illustrating main topographic features and subduction zone geometries of the Andes between 21°S and 34°S. Contours (in km) are for depth to Benioff zone (Cahill and Isacks, 1992), including Chilean flat slab (Jordan et al., 1983; Kay et al., 1999). Large arrow indicates direction of convergence between Nazca and South America (Pardo-Casas and Molnar, 1987; Somoza, 1998). In the study area (rectangle), main Miocene–Pliocene mining districts and major structural lineaments are indicated (Tucumán Transfer Zone—TTZ; de Urreiztieta, 1996; de Urreiztieta et al., 1996, and Desaguadero-Valle Fértil Lineament—DVFL; Rossello et al., 1996b).](image-url)
1999), magmatic centres are developed more than 400 km from the trench. In Argentina, these include the Cerro Galán, Vicuña Pampa, and Farallón Negro volcanic complexes. The major porphyry deposits are also along these lineaments and close to the volcanic complexes (Fig. 2).
Fig. 3. Geological map of study area. Main map (a) shows lithology, structures, and ore deposits at regional scale. Enlargements focus on Farallón Negro Volcanic Complex (b) and Sierra de Famatina (c). For lithostratigraphic units, see Appendix A. Volcanic complexes are Vicuña Pampa (1) and Farallón Negro (2). Other localities are Alumbrera del Cerro Negro (ACoNo), Agua Rica (AR), Agua Tapada (AT), Bajo de la Alumbrera (BA), Bajo las Juntas (BJu), Bajo San Lucas (BSn), Capillitas (Ca), Cerro Atajo (CoAt), Cerro Azul (CoAz), Cerro Negro (CoNo), Cerro Peinado (CoPe), Cueros de Purulla (CPu), Cumichango (Cu), El Moradito (EMo), El Oro (EOr), El Pararrayo (EPa), El Tigre (ETi), Farallón Negro-Alto de la Blenda (FaNo-AB), Filo Colorado (FoCo), Guacuray (Gu), King Tud (KT), La Cuesta (LCu), La Descubridora (LDc), La Mejicana (LMe), Las Termas (LTc), Los Bayitos (LBa), Mal Paso (MP), Mogote Rio Blanco (MRBco), Montey (Mo), Offir (Off), Puerto Piedra (PPdra), Sotran (So), Vernacua (Ver) and Vicuña Pampa (ViPa). The map projection for all layers is Transverse Mercator, Datum WGS 84, centred on meridian 68°W.
2.2. Geological and structural setting of NW Argentina

2.2.1. Geological setting

Crystalline basement crops out in the Sierras Pampeanas. It consists of metamorphic rocks (e.g., schists, gneisses, orthogneisses, and migmatites) and granites of Precambrian to late Palaeozoic age (Fig. 3 a). According to Ramos (1999), these rocks result from tectonic accretion of microcontinents at the western margin of Gondwana, during the Famatinan orogeny (465 to 385 Ma) and the Gondwanan orogeny (290 to 250 Ma).

During the Mesozoic, back-arc extension prevailed in southwestern Gondwana (Ramos, 1999), its effects reaching as far west as what is now the Atlantic margin (Rossello and Mozetic, 1999). However, in NW Argentina outcrops of Mesozoic rocks are rare and of limited extent (Fig. 3a). Examples are Triassic sandstones and shales, on the southwestern side of the Sierra de Famatina, and Cretaceous basalts within continental sandstones, near Belén on the southern side of the Campo del Arenal (Rossello and Mozetic, 1999).

During the Neogene, Andean compression resulted in a series of alternating basement blocks and basins, as in the Rocky Mountains of the western USA (Jordan and Allmendinger, 1986). Erosion of the mountains produced detritus, which progressively filled the developing basins. On the western edge of the study area, in the Bolsón de Jagüe, the resulting detrital sequence is up to 15 km thick; and in the north, on the edge of the Puna plateau, the El Bolsón basin contains up to 5 km of interbedded sediment and volcanic rocks. Tertiary volcanic rocks crop out only in the northern part of the study area (Fig. 3a). Ignimbrites and andesitic and dacitic lava flows are all that remain of former stratovolcanoes at Vicuña Pampa (Rossello, 1980) and Farallón Negro (Fig. 3a and b). Into these rocks and into the Palaeozoic basement, dacitic to monzonitic magmas intruded, forming stocks. Magmatic activity reached a climax during the Late Miocene and Early Pliocene (Sasso and Clark, 1998). Its products are numerous along the Vicuña Pampa–Filo Colorado lineament, which trends NW–SE (Figs. 2 and 3b), parallel to other tectonic lineaments (Salfity, 1985; Boudesseul et al., 1999) and to magnetic lineaments (Chernicoff et al., 2002). To the south, although volcanic rocks are scarce or absent, there are hypovolcanic intrusions of Pliocene age (Losada-Calderón et al., 1994) in Early Cainozoic sedimentary sequences (for example, at Mogote Río Blanco) and in Palaeozoic basement (for example, in the Sierra de Famatina, Fig. 3c).

2.2.2. Structural setting

In the Sierras Pampeanas and Puna, thick-skinned faults involve the crystalline basement (Jordan et al., 1983; Kley et al., 1999); whereas in the Sub-Andes, between latitudes 15°S and 27°S, thin-skinned thrusts have formed within the cover rocks of the main foreland basin (Allmendinger et al., 1997).

Marking a transition between the southern Puna and northern Sierras Pampeanas is the Tucumán lineament (Mon, 1976) or Tucumán Transfer Zone (TTZ, Fig. 1; de Urreiztieta, 1996; de Urreiztieta et al., 1996). This NE–SW zone, about 100 km wide, was formed under right-lateral transpression. To the SW, the NNW–SSE Desaguadero–Valle Fértil Lineament (DVFL; Rossello et al., 1996b,c) formed under left-lateral transpression. At the restraining intersection of these two transpressional structures is the Umango–Maz uplift, which trends N–S (Sierra de Maz, Fig. 3a; Rossello et al., 1996b). Parallel to it are other ranges, bounded by deep-seated reverse faults. These have opposing vergences in the Sierra de Famatina and an easterly vergence in the Sierra de Velasco. Summits become progressively lower towards the east, suggesting that the amount of thrusting diminishes in this direction (Fig. 1; Rossello et al., 1996b).
Although the region as a whole is seismically active, earthquakes are most numerous at the edge of the Puna. From their focal mechanisms, the greatest stress is horizontal and perpendicular to the edge of the plateau (Assumpção and Araujo, 1993; Fig. 4a). Along the southern edge of the Puna, Neogene and currently active faults form two families (de Urreiztieta, 1996; de Urreiztieta et al., 1996; Fig. 4b). To account for the first family, the greatest stress trends N080°E, sub-parallel to the direction of convergence between the Nazca and South American plates. To account for the second family, the greatest stress trends N140°E, sub-perpendicular to the southern edge of the Puna. Probably, the first family results mainly from an intra-plate stress field, whereas the second family results mainly from gravity spreading of the plateau (Assumpção and Araujo, 1993) and right-lateral transpression along the Tucumán Transfer Zone (de Urreiztieta, 1996; Rossello et al., 1996a; Marques and Cobbold, 2002). In general, the principal directions of stress and of shortening must have varied in space and time, depending on the relative magnitudes of these components.

Many of the Neogene faults formed by reactivation of older structures. Notable examples are Mesozoic normal faults, trending NE–SW to NW–SE (Rossello...
2.3. Metallogenetic setting

In the area studied (Fig. 3), 34 occurrences (deposits or showings) contain gold, either as the main mineral or as a by-product (Table 1). Of these occurrences, 22 are of Cenozoic age, 3 of Mesozoic age, 3 of Palaeozoic age, and 6 of unconstrained age. Moreover, 64% of the ore deposits that contain gold are of porphyry type (10 occurrences) or related to shallow intrusions (12 occurrences). The main gold-bearing occurrences in the foreland of the Cordillera Principal formed during the Late Cenozoic, as the volcanomagmatic arc widened towards the east (Sasso and Clark, 1998).

Near latitude 27°S on the TTZ, Farallón Negro is Argentina’s biggest gold district (Figs. 1 and 3a and b). Production is under way at Bajo de la Alumbrera [767 Mt of reserves at 0.51% Cu and 0.64 g/t Au (Angera, 1999)] and Farallón Negro [1.5 Mt with grades of ~6 g/t Au and 99 g/t Ag (BRGM, 2001)]. Other occurrences are under evaluation, e.g., Agua Rica [1,457 Mt of measured and indicated reserves at 0.2% Cu cutoff grading 0.44% Cu, 0.03% Mo, 0.19 g/t Au, and 3 g/t Ag (electronic communication, Northern Orion website)]. Neogene mineralization in this district is associated with porphyry intrusions (e.g., Bajo de la Alumbrera) or andesites.

In the Sierra de Famatina (Fig. 1; Fig. 2b), between the TTZ and the DVFL, are the mining districts of La Mejicana [300 Mt at 0.06% Mo, 0.37% Cu, and 0.9 g/t Ag (Mayón, 1999)] and El Oro [200,000 t at 5.8 g/t Au and 0.37% Cu (Brodtkorb and Schalamuk, 1999)]. Gold mineralization concentrates around porphyry intrusions of dacitic to andesitic composition in a basement of metamorphic rocks and Palaeozoic granitoids (e.g., La Mejicana). In contrast to Farallón Negro, Tertiary volcanic rocks are rare or absent. An alteration zone, more than 20 km wide, is visible on satellite images of La Mejicana (NASA, S-19-25, 2000).

From geochronological data (40Ar/39Ar, K/Ar, or Apatite Fission Track), we infer that gold mineralization occurred after a magmatic phase and in the early stages of a compressional tectonic phase (Table 2). Kay et al. (1999) deduced a similar timing for Cu–Au porphyry-type deposits in Chile.

In the northern part of the area studied, at the Bajo de la Alumbrera, Farallón Negro, and Agua Rica deposits, the mineralization is of Middle Miocene to Early Pliocene age (Sasso and Clark, 1998), whereas to the south, at La Mejicana, it is of Pliocene age (Losada-Calderón et al., 1994).

3. Construction of a regional-scale gold deposit model: methodology

3.1. Available data and format

In our study at 1:500,000, we constructed a deposit model from vector data of point type (“deposits” layer), line type (“tectonic structures” layer and “lithostratigraphic contacts” layer), and polygon type (“lithostratigraphy” layer).

The “deposits” layer was extracted from GIS Andes (Cassard, 1999a; Cassard, 1999b; BRGM, 2001), at a scale of 1:2,000,000. Because of the change in scale, it was necessary to improve the georeferencing of the deposits, and to update the database, adding prospects not shown at 1:2,000,000. The attributes used were location, age of mineralization, deposit type, and ore paragenesis. Information on metal content was not used, because it was considered too fragmentary. A total of 34 prospects and deposits hosting gold (as a main mineral or by-product) were used to calculate favourability.

Information for the “lithostratigraphy” layer came from maps at 1:500,000 for the provinces of Tucumán (González et al., 1994), Catamarca (Martínez et al., 1995), and La Rioja (Guerrero et al., 1993), and at 1:200,000 for the areas of Bajo de la Alumbrera (González Bonorino, 1947) and Famatina (Turner, 1971). For easy comparison with previous work, the groupings and geological codes assigned to the polygons (see Appendix A) are those used by Billa et al. (2004) for GIS Andes, and not the ones from the original geological maps.

From the “lithostratigraphy” layer, we generated a “lithostratigraphic contacts” layer. Each family of contacts is identified by a code for the two lithologies in contact. This layer is intended to show the importance of lithological interfaces, which may produce barrier effects or alternatively drain effects, encouraging the trapping of mineralization.

For the “tectonic structures” layer, we extracted faults from 1:500,000 maps of Catamarca (Martínez et al., 1995) and La Rioja (Guerrero et al., 1993), and from 1:200,000 maps of NW Argentina (González Bonorino, 1947; Turner, 1971). Additional data came from our field studies and from Landsat images.

1 All the codes are available for consultation at the following address: http://gisandes.brgm.fr/gis_geol_legend.htm.
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<th>Deposit type</th>
<th>Gold production (Mt)</th>
<th>Cu (%)</th>
<th>Au (g/t)</th>
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<td>Mal Paso</td>
<td>Pzp</td>
<td>Unspecified</td>
<td>Syn-, late orogenic veins</td>
<td>Main commodity</td>
<td></td>
<td></td>
<td></td>
<td>Mayón, 1999</td>
</tr>
<tr>
<td>Puerto Piedra Sotran</td>
<td>Pzp</td>
<td>Mesozoic (?)</td>
<td>Unspecified Syn-, late orogenic veins</td>
<td>Main commodity</td>
<td></td>
<td></td>
<td></td>
<td>Garcia and Rossello, 1984; BRGM, 2001</td>
</tr>
<tr>
<td>Vernancua</td>
<td>Pzm</td>
<td>Unspecified</td>
<td>Veins in shallow-depth intrusion</td>
<td>Main commodity</td>
<td></td>
<td></td>
<td></td>
<td>BRGM, 2001</td>
</tr>
<tr>
<td>Vicuña Pampa</td>
<td>Tp</td>
<td>Cainozoic</td>
<td>Unspecified Unspecified</td>
<td>Unspecified</td>
<td></td>
<td></td>
<td></td>
<td>Rossello, 2000</td>
</tr>
</tbody>
</table>

For lithostratigraphic units, see Appendix A. Deposits may be of Low Sulphidation (LS) or High Sulphidation (HS).
The attribute that we adopted for calculating favourability is fault trend (in class intervals of $10^8$). Fault-slip data do not make good attributes, because the information is fragmentary and unevenly distributed.

### 3.2. Data preparation

The processing phase requires transforming the polygons on the “lithostratigraphy” vector layer into a grid of pixels, to be used as a counting surface. Since all the data are at a scale of 1:500,000 (the scale of the geological compilation and the plotting of deposit and prospect locations), the pixel size is $500 \times 500$ m (1 mm$^2$ on the 1:500,000 map). The small pixel size limits the placement errors, which may otherwise occur during the transfer of calculated information with reference to fixed points when the counting pixels are large in size.

The data were processed with ArcView Spatial Analyst ESRI® software and two plug-in extensions for multi-criteria approaches, SynArc BRGM® (Braux, 1996) and Arc-SDM (Kemp et al., 2001). The information was captured at a scale of 1:500,000. The projection for all layers was Transverse Mercator, Datum WGS-84, centred on 68°W.

### 3.3. Processing

The processing procedure was in three stages: (i) identification of criteria that are relevant and can be used in the calculations, (ii) quantification of the selected criteria, and (iii) compilation and production of the metallogenic map, predictive for deposit spatial distribution.

#### 3.3.1. Stage 1: identification of criteria

The three main parameters, which carry sufficient information at this scale, provide uniform coverage, and may correspond to metallotects that control the distribution of mineralization (Table 1), are (1) lithostratigraphy of the country rock, (2) faults, and (3) lithostratigraphic contacts. Major regional structures were not considered in the calculation phase, because they are too poorly defined in extent (especially in width).

#### 3.3.1.1. Lithostratigraphy of the country rock

Some mineralization is genetically related to one type of host rock. This is particularly true for porphyry deposits (e.g., Bajo de la Alumbrera, Agua Rica) and their associated epithermal manifestations. However, one of the problems encountered is the size of these mineral-bearing intrusions: their outcrop size or related alter-

<table>
<thead>
<tr>
<th>Period</th>
<th>Dating method</th>
<th>Geological event</th>
<th>Locality</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sierra de Famatina</td>
<td>AFT</td>
<td>Uplift and cooling by exhumation</td>
<td>Sierra de Famatina</td>
<td>Coughlin et al., 1998</td>
</tr>
<tr>
<td>From 4.50 to 4.19 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Alteration and high sulphidation vein system</td>
<td>Famatina District</td>
<td>Losada-Calderón et al., 1994</td>
</tr>
<tr>
<td>From 4.84 ± 0.41 to 4.19 ± 0.27 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Uplift and cooling by exhumation</td>
<td>Famatina District</td>
<td>Losada-Calderón et al., 1994</td>
</tr>
<tr>
<td>From 4.84 ± 0.41 to 4.19 ± 0.27 Ma</td>
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<td>Magmatic activity</td>
<td>Sierras de Farallon, Altiplano</td>
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</tr>
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<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 6.38 ± 0.37 to 4.24 ± 0.11 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>2.7 ± 0.8 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>5.35 ± 0.14 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Uplift and cooling by exhumation</td>
<td>Sierras de Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 5.35 ± 0.14 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>6.10 ± 0.04 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Uplift and cooling by exhumation</td>
<td>Sierras de Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>6.10 ± 0.04 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
</tbody>
</table>

### Table 2

Chronology of magmatic, tectonic, and mineralizing events in NW Argentina

<table>
<thead>
<tr>
<th>Period</th>
<th>Dating method</th>
<th>Geological event</th>
<th>Locality</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sierra de Famatina</td>
<td>AFT</td>
<td>Uplift and cooling by exhumation</td>
<td>Sierra de Famatina</td>
<td>Coughlin et al., 1998</td>
</tr>
<tr>
<td>From 4.50 to 4.19 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Alteration and high sulphidation vein system</td>
<td>Famatina District</td>
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</tr>
<tr>
<td>From 4.84 ± 0.41 to 4.19 ± 0.27 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
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<td>Famatina District</td>
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</tr>
<tr>
<td>From 4.84 ± 0.41 to 4.19 ± 0.27 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
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<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 4.84 ± 0.41 to 4.19 ± 0.27 Ma</td>
<td>K/Ar</td>
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<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
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<tr>
<td>From 6.38 ± 0.37 to 4.24 ± 0.11 Ma</td>
<td>K/Ar</td>
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</tr>
<tr>
<td>2.7 ± 0.8 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>5.35 ± 0.14 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Uplift and cooling by exhumation</td>
<td>Sierras de Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 5.35 ± 0.14 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>6.10 ± 0.04 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Uplift and cooling by exhumation</td>
<td>Sierras de Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>6.10 ± 0.04 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 7.6 to 6.0 Ma</td>
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<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>8.56 ± 0.48 Ma</td>
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<td>Uplift and cooling by exhumation</td>
<td>Sierras de Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 8.56 ± 0.48 Ma</td>
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<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
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<td>Sierras de Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>8.41 ± 0.08 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
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<tr>
<td>From 12.56 ± 0.36 to 8.59 ± 0.10 Ma</td>
<td>$^{40}\text{Ar}^{39}\text{Ar}$</td>
<td>Uplift and cooling by exhumation</td>
<td>Sierras de Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
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<td>Magmatic activity</td>
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<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 25.0 ± 1.0 to 14.0 ± 0.5 Ma</td>
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<td>Sasso and Clark, 1998</td>
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<tr>
<td>25.0 ± 1.0 Ma</td>
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<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>From 38.0 ± 3.0 to 29.0 ± 3.0 Ma</td>
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<td>Uplift and cooling by exhumation</td>
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<td>Sasso and Clark, 1998</td>
</tr>
<tr>
<td>38.0 ± 3.0 Ma</td>
<td>K/Ar</td>
<td>Magmatic activity</td>
<td>Farallon, Altiplano</td>
<td>Sasso and Clark, 1998</td>
</tr>
</tbody>
</table>

AFT: Apatite Fission-Track (AFT).
ation halo may be extremely small (e.g., less than 1 km² at Bajo de la Alumbrera; J. Angera, personal communication), making their plotting progressively more difficult as the scale of the geological compilation decreases. Thus for intrusions that are small or that do not crop out, the favourability might be assigned to a country rock polygon whose lithostratigraphy has no direct connection with the mineralization. Such a lithostratigraphy—with no genetic link to the mineralization—may nevertheless, as a country rock, be favourable to the development of mineralization, because of its physico-chemical properties (rheology, porosity, composition, etc.) (Table 3).

3.3.1.2. Faults. In metallogeny, the presence of structural discontinuities is generally considered to be a major criterion for the presence of deposits. Faults facilitate the passage of source magmas and the circulation of hydrothermal fluids (e.g., Wyborn et al., 1994; Sillitoe, 1997; Oyarzún, 2000; Hanuš et al., 2000) (Table 4).

3.3.1.3. Contacts between lithostratigraphies of different types. The proximity of some lithostratigraphic contacts is empirically considered to be favourable for the presence of mineralization. Rheological contrasts may favour fracturing and the formation of openings, followed by the channeling and trapping of mineralized fluids (Castaing et al., 1993; Sillitoe, 1997) (Table 5).

3.3.1.4. Regional geological structures (magmatic, volcanic, or structural axes). Mineralization is frequently associated with major tectonic or magmatic corridors. The superposition (or intersection) of several metallo-tects generally enhances favourability (Routhier, 1980). Such structures are shown on the predictive map, but were not used in the calculation phase for the reasons mentioned above.

The next stage consists of assessing—essentially by statistical and probabilistic methods—the representation of these criteria in the vicinity of the deposits studied, and thereby their potential contribution to the genesis of mineral concentrations.

3.3.2. Stage 2: quantification of criteria

This stage consists of assigning a numerical value to each of the criteria previously selected, aiming to avoid over- or under-valuing certain relationships, and then mapping them over the entire area studied. Several

<table>
<thead>
<tr>
<th>Lithostratigraphic units</th>
<th>Area (km²)</th>
<th>Area (%)</th>
<th>Number of deposits in this unit</th>
<th>% of Deposits</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>Contrast ($W^+ - W^-$)</th>
<th>Score</th>
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<td>Q</td>
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<td>50.61</td>
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<td>–</td>
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<tr>
<td>Qe</td>
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<td>–</td>
<td>–</td>
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<tr>
<td>Qv</td>
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<td>0</td>
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<td>–</td>
<td>–</td>
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<tr>
<td>QTv</td>
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<td>–</td>
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<tr>
<td>Ts</td>
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<td>–</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Tvs</td>
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<td>–</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Tv</td>
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<td>1.24</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0</td>
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<tr>
<td>Tvb</td>
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<td>9</td>
<td>1.26</td>
<td>–0.07</td>
<td>1.33</td>
<td>2</td>
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<tr>
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<td>35</td>
<td>6.04</td>
<td>–0.43</td>
<td>6.48</td>
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<tr>
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<tr>
<td>Kp</td>
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<td>Trs</td>
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<td>Pz s</td>
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<td>1.09</td>
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<td>–</td>
<td>–</td>
<td>0</td>
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<tr>
<td>Pz v s</td>
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<td>3</td>
<td>0.04</td>
<td>0.00</td>
<td>0.04</td>
<td>1</td>
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<td>0.41</td>
<td>–0.06</td>
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<tr>
<td>Pz m</td>
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<td>4.12</td>
<td>1</td>
<td>3</td>
<td>–0.34</td>
<td>0.01</td>
<td>–0.35</td>
<td>0</td>
</tr>
<tr>
<td>Pz p z s</td>
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<td>0.14</td>
<td>0</td>
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<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Pe Pz p</td>
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<td>4.23</td>
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<td>–</td>
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<tr>
<td>Pe Pz m</td>
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<td>8</td>
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<td>0.93</td>
<td>–0.17</td>
<td>1.11</td>
<td>2</td>
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<tr>
<td>Sebkha</td>
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<td>0</td>
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<td>–</td>
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<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>95,572.994</td>
<td>100.00</td>
<td>34</td>
<td>100</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0</td>
</tr>
</tbody>
</table>

Scores are 0 (unfavourable), 1 (slightly favourable), 2 (favourable), and 3 (very favourable). For method of calculation, see Table 6.
methods are available for doing this (see reviews in Knox-Robinson and Groves, 1997; Lips et al., 2002; Billa et al., 2004).

- The Boolean method. For a given criterion, each of the elements on the map is either favourable or unfavourable for the presence of a deposit.

- The “knowledge-driven” approach. This is based on the knowledge and experience of the geologist, and seeks to find an association of favourable criteria in a study area. It employs methods such as fuzzy logic or the Dempster-Shafer belief functions, and is based on models of existing or conceptual deposits.

- The “data-driven” approach. This is based on the quantification of relationships between the criteria and the known deposits. Statistical methods use techniques such as regression, weights of evidence (WofE; Bonham-Carter, 1994), neural networks (cf. Brown et al., 2000; Bougrain et al., 2003) and data mining (cf. Salleb and Vrain, 2000; Salleb, 2003). The algebraic methods (Knox-Robinson and Groves, 1997) attempt to determine a deposit or occurrence density or a contained metal density per unit of area (or of length), thereby getting around certain limitations of WofE when applied to geological maps, so as to avoid the requirement of conditional independence and allow deposit size to be incorporated into the assessment.

- The hybrid “expert-guided data-driven” approach. This combines two of the above approaches, so as to take advantage of their respective benefits. During the preliminary phases of WofE, performed on lithostratigraphy, it was found that the presence of Tertiary intrusions is a very strong determining criterion. It masks all the other criteria likely to signal mineralization. However, it is highly probable that certain favourable Tertiary intrusions or hydrothermal alteration zones are not incorporated at a scale of 1:500,000, or have not been identified. So in order to take into account more subtle distribution criteria that are nevertheless likely to point towards new mineralized areas, an assessment and scoring operation was performed, based on calculated favourabilities (WofE and densities) for the various evidential themes (in the specialized language of GIS, an evidential theme is a map or area layer, in either vector or raster format, used for prediction of point objects, such as mineral occurrences): very favourable = 3; favourable = 2; slightly favourable = 1; and unfavourable = 0. These favourability scores were then added on a compilation (“predictive”) map, where the values range from 0 (unfavourable) to a maximum value equal to the sum of the favourable scores.

### 3.3.2.1. Quantification of lithostratigraphy criterion.

The method selected for quantifying the lithostratigraphy criterion is the WofE, which is a probability-based approach (Bonham-Carter, 1994) that uses Bayes’ rule.
to combine evidence with an assumption of conditional independence. Where sufficient data are available, it can be applied to estimate the relative importance of evidence by statistical means.

Calculating it on a geological map, covering several geological formations, is similar to using a multi-class evidential theme. At the end of the calculation, three numerical values are selected to characterize each geological formation (see Bonham-Carter, 1994; Kemp et al., 2001 for details of these calculations). The positive and negative weights (written $W^+$ and $W^-$) provide a measure of the spatial association between the training points (in this case the mineral deposits) and the evidential theme (Eqs. (1) and (2)). A weight is calculated for each class of the evidential theme:

$$W^+(B) = \ln \left( \frac{P(B|D)}{P(D)} \right)$$

$$W^-(B) = \ln \left( \frac{P(B|\bar{D})}{P(\bar{D})} \right).$$

In this equation: $D$ is the number of unit cells containing a prospect or deposit (training point); $B$ is the number of unit cells containing a given formation $b$;

<table>
<thead>
<tr>
<th>Lithostratigraphic contacts</th>
<th>Cumulative length, Length$_i$ (km)</th>
<th>$Lr_i = \frac{\text{Length}<em>i}{\text{Length}</em>{\text{tot}}}$ (%)</th>
<th>$n_i$</th>
<th>$Pr_i = \frac{n_i}{N_{\text{tot}}}$ (%)</th>
<th>Fav$_i$</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tp–Tp</td>
<td>1.028</td>
<td>0.01</td>
<td>1.33</td>
<td>1.65</td>
<td>5.29</td>
<td>3</td>
</tr>
<tr>
<td>Pzs–Tp</td>
<td>1.961</td>
<td>0.02</td>
<td>0.89</td>
<td>1.10</td>
<td>4.24</td>
<td>3</td>
</tr>
<tr>
<td>Pzp–Tp</td>
<td>36.489</td>
<td>0.30</td>
<td>9.01</td>
<td>11.15</td>
<td>3.63</td>
<td>2</td>
</tr>
<tr>
<td>PePzs–Tp</td>
<td>4.265</td>
<td>0.03</td>
<td>1.00</td>
<td>1.24</td>
<td>3.58</td>
<td>2</td>
</tr>
<tr>
<td>PePzm–Tp</td>
<td>70.321</td>
<td>0.57</td>
<td>12.54</td>
<td>15.52</td>
<td>3.30</td>
<td>2</td>
</tr>
<tr>
<td>PePzs–Pzs</td>
<td>9.133</td>
<td>0.07</td>
<td>1.54</td>
<td>1.90</td>
<td>3.25</td>
<td>2</td>
</tr>
<tr>
<td>Tp–Ts</td>
<td>7.780</td>
<td>0.06</td>
<td>1.00</td>
<td>1.24</td>
<td>2.98</td>
<td>2</td>
</tr>
<tr>
<td>Q–Tp</td>
<td>11.091</td>
<td>0.09</td>
<td>0.94</td>
<td>1.16</td>
<td>2.56</td>
<td>0$^a$</td>
</tr>
<tr>
<td>Tp–Tv</td>
<td>111.546</td>
<td>0.90</td>
<td>8.81</td>
<td>10.90</td>
<td>2.49</td>
<td>2</td>
</tr>
<tr>
<td>PePzs–Tv</td>
<td>32.087</td>
<td>0.26</td>
<td>2.04</td>
<td>2.53</td>
<td>2.27</td>
<td>2</td>
</tr>
<tr>
<td>Kp–Pzs</td>
<td>15.723</td>
<td>0.13</td>
<td>1.00</td>
<td>1.24</td>
<td>2.27</td>
<td>2</td>
</tr>
<tr>
<td>Kp–Pzp</td>
<td>3.967</td>
<td>0.03</td>
<td>0.16</td>
<td>0.20</td>
<td>1.85</td>
<td>1</td>
</tr>
<tr>
<td>PePzm–Pzp</td>
<td>407.979</td>
<td>3.30</td>
<td>11.29</td>
<td>13.97</td>
<td>1.44</td>
<td>1</td>
</tr>
<tr>
<td>Pzp–Tv</td>
<td>180.177</td>
<td>1.46</td>
<td>4.06</td>
<td>5.03</td>
<td>1.24</td>
<td>1</td>
</tr>
<tr>
<td>PePzs–Pzp</td>
<td>63.894</td>
<td>0.52</td>
<td>1.31</td>
<td>1.62</td>
<td>1.14</td>
<td>1</td>
</tr>
<tr>
<td>Pzs</td>
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<td>0.69</td>
<td>0.85</td>
<td>1.05</td>
<td>1</td>
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<tr>
<td>Pzs–Tv</td>
<td>103.310</td>
<td>0.84</td>
<td>1.88</td>
<td>2.33</td>
<td>1.02</td>
<td>1</td>
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<tr>
<td>Pzs–Ts</td>
<td>115.714</td>
<td>0.94</td>
<td>1.77</td>
<td>2.19</td>
<td>0.85</td>
<td>1</td>
</tr>
<tr>
<td>Ts–Ts</td>
<td>74.989</td>
<td>0.61</td>
<td>1.00</td>
<td>1.24</td>
<td>0.71</td>
<td>1</td>
</tr>
<tr>
<td>PePzm–Pzs</td>
<td>115.026</td>
<td>0.93</td>
<td>1.19</td>
<td>1.48</td>
<td>0.46</td>
<td>1</td>
</tr>
<tr>
<td>Pzp–Pzp</td>
<td>93.138</td>
<td>0.75</td>
<td>0.96</td>
<td>1.18</td>
<td>0.45</td>
<td>1</td>
</tr>
<tr>
<td>PePzm–Pzvs</td>
<td>101.286</td>
<td>0.82</td>
<td>0.79</td>
<td>0.98</td>
<td>0.18</td>
<td>1</td>
</tr>
<tr>
<td>Pzm–Tv</td>
<td>162.296</td>
<td>1.31</td>
<td>1.00</td>
<td>1.24</td>
<td>–0.06</td>
<td>0</td>
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<tr>
<td>Pzp–Pzs</td>
<td>850.882</td>
<td>6.89</td>
<td>4.74</td>
<td>5.86</td>
<td>–0.16</td>
<td>0</td>
</tr>
<tr>
<td>Q–Tv</td>
<td>503.180</td>
<td>4.08</td>
<td>1.23</td>
<td>1.52</td>
<td>–0.99</td>
<td>0</td>
</tr>
<tr>
<td>Pzm–Pzp</td>
<td>434.433</td>
<td>3.52</td>
<td>1.00</td>
<td>1.24</td>
<td>–1.05</td>
<td>0</td>
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<tr>
<td>Pzs–Pzvs</td>
<td>483.850</td>
<td>3.92</td>
<td>1.00</td>
<td>1.24</td>
<td>–1.15</td>
<td>0</td>
</tr>
<tr>
<td>Pzs–Q</td>
<td>1393.472</td>
<td>11.29</td>
<td>1.85</td>
<td>2.28</td>
<td>–1.60</td>
<td>0</td>
</tr>
<tr>
<td>Pzp–Ts</td>
<td>397.496</td>
<td>3.22</td>
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<td>0.55</td>
<td>–1.77</td>
<td>0</td>
</tr>
<tr>
<td>Pzs–Pzs</td>
<td>118.862</td>
<td>0.96</td>
<td>0.13</td>
<td>0.16</td>
<td>–1.81</td>
<td>0</td>
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<tr>
<td>PePzm–Q</td>
<td>1430.717</td>
<td>11.59</td>
<td>1.39</td>
<td>1.72</td>
<td>–1.91</td>
<td>0</td>
</tr>
<tr>
<td>Pzp–Q</td>
<td>2013.994</td>
<td>16.31</td>
<td>1.74</td>
<td>2.15</td>
<td>–2.03</td>
<td>0</td>
</tr>
<tr>
<td>Ts–Tv</td>
<td>196.545</td>
<td>1.59</td>
<td>0.13</td>
<td>0.16</td>
<td>–2.29</td>
<td>0</td>
</tr>
<tr>
<td>Q–Ts</td>
<td>2095.159</td>
<td>16.97</td>
<td>0.78</td>
<td>0.97</td>
<td>–2.86</td>
<td>0</td>
</tr>
<tr>
<td>Pzm–Q</td>
<td>666.926</td>
<td>5.40</td>
<td>0.19</td>
<td>0.24</td>
<td>–3.12</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>12,345.357</td>
<td>100.00</td>
<td>80.81</td>
<td>100.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scores are 0 (unfavourable), 1 (slightly favourable), 2 (favourable), and 3 (very favourable). For method of calculation, see Table 6.

$^a$ See explanation in the text.
$P(B \mid D)$ is the probability of occurrence of formation $b$, given the condition of being on a deposit; $P(B \mid \bar{D})$ is the probability of occurrence of formation $b$, given the condition of not being on a deposit; $P(\bar{B} \mid D)$ is the probability of non-occurrence of formation $b$, given the condition of being on a deposit; $P(\bar{B} \mid \bar{D})$ is the probability of non-occurrence of formation $b$, given the condition of not being on a deposit.

The absolute value of a weight indicates whether a criterion is slightly significant ($0<W<0.5$), significant ($0.5<W<1$), very significant ($1<W<2$), or discriminant ($W>2$). The contrast, $C$, which is the difference between the weights ($C=W^+-W^-$), is an overall measure of spatial association between the training points and the evidential theme, combining the effects of the two weights.

The spatial analysis is performed on the “deposits” and “geology” layers, using the Arc-SDM (Spatial Data Modeller) extension, developed for ArcView 3.x/ Spatial Analyst ESRI® (Table 3).

3.3.2.2. Quantification of fault criterion and lithostratigraphic contact criterion. We used the algebraic method (Knox-Robinson and Groves, 1997) to quantify fault criteria and lithostratigraphic contact criteria. The objective is to determine a weighted density for the deposits (or quantity of metal) per unit of area (for lithostratigraphic formations), or per unit of length (for faults or lithostratigraphic contacts). The method is similar to that used for $W^+$ in the WofE: identified relationships are quantified as in the weight of evidence technique, except that instead of calculating a probabilistic measure of prospectivity for areas of low and high prospectivity, a measure of deposit density is used (Knox-Robinson and Groves, 1997).

The favourability of faults and lithostratigraphic contacts was calculated by using the line favourability tool in the SynArc® software developed by BRGM (Braux, 1996). It is based on deposits (or occurrences), to which the same value 1 is assigned to indicate the presence of mineralization, whatever their size (the data regarding metal content being too fragmentary for use; see above). This tool allows a value based on a “points” layer (deposits) to be assigned to a linear object (faults or lithostratigraphic contacts). Placing a value on the line consists of looking for deposits located inside a band parallel to the line (Fig. 5). This band is defined by a minimum distance ($d_{\min}$) and a maximum distance ($d_{\max}$). A linear weighting is then performed: a value equal to 1 is given to any point located between the line and the minimum distance [100%]; a (linearly) decreasing value between 0 and 1 is given to any point lying between the minimum distance [100%] and the maximum distance [0%].

The minimum distance used in this study is 1 km, whereas the maximum distance is 3 km, in accordance with the distances actually observed between deposits and faults (Fig. 6): ~50% of the deposits are at less than 1 km from a fault (maximum influence of the fault on the distribution of prospects), ~40% between 1 and 3 km (decreasing influence of the fault on the distribution of prospects), and 10% are beyond 3 km (no influence). Although the connection is less clearly defined for lithostratigraphic contacts, for the sake of uniformity the same distance parameters were used. Notice that the same deposit, for example one located near an intersection, may be included in several categories of faults or lithostratigraphic contacts.

Values were assigned to the “faults” criterion according to strike (using 10° class intervals, i.e., 0° to 10°, 10° to 20°, . . . 170° to 180°). The weight ($n_i$) of fault category $i$, calculated from the line favourability, is equal to the sum of the weights of each of the faults belonging to this category. The calculated favourability, written $Fav_i$, is the relative index weight quotient ($Pr_i$=weight of each fault category, $n_i$, over the total weight of all the categories, $N_{tot}$), weighted by the relative length ($Lr_i$=length of family $i$, or Length, over the total length of all the faults in the area studied, $Length_{tot}$), (Eqs. (3), (4), (5), and Table 6).

$$Pr_i = \frac{n_i}{N_{tot}}$$

$$Lr_i = \frac{Length_i}{Length_{tot}}$$

$$Fav_i = \ln \left( \frac{Pr_i}{Lr_i} \right)$$
The same procedure was applied for the "lithostratigraphic contacts" criterion. Each family of contacts is first identified by the two formations placed in contact. The weight \( n_i \) of a contact category \( i \) (e.g., Tp–Ts, Tp–Tp, etc.), calculated from the favourability of the line, is equal to the sum of the weights of each of the contacts belonging to this category. The calculated favourability, written \( \text{Fav}_i \), is calculated in the same way as above.

For these two criteria, the ratio is greater than 1 for the most favourable families (\( \text{Fav}_i \) positive, in log value), and less than 1 for the least favourable families (\( \text{Fav}_i \) negative, in log value); see Eq. (5).

The results of the quantification of the fault and lithostratigraphic contacts criteria are shown in Tables 4 and 5, respectively.

### 3.3.2.3. Geological structures criterion

At regional scale, two kinds of geological structures have been described in this part of NW Argentina: (i) the Tucumán and Desaguadero-Valle Fértil transfer zones (Fig. 1), and (ii) the Vicuña Pampa–Filo Colorado volcanic axis (Fig. 2). The precise nature of the transfer zones is debatable (Mon, 1976; de Urreiztieta, 1996; de Urreiztieta et al., 1996; Rossello, 2000). Toward their edges, the intensity of deformation decreases. Their quantification is therefore still subject to discussion. Nevertheless, their probable area of influence has been plotted on the compilation map.

### 3.3.3. Stage 3: development of the predictive map

The predictive map is a synthesis of the spatial association rules established and quantified during the preceding stages. Its objective is to produce a picture of the metallogenic potential of the area studied, in order to reach a better understanding of the factors that control the distribution of mineralization, and to trigger eventual exploration work in new areas. For the latter reason it is also called a prospectivity map (Knox-Robinson and Groves, 1997). In practice, this predictive map was obtained by adding up the various favourability scores for the three criteria defined during the preceding stages. In theory, it should enable the "rediscovery" of a high percentage of the known ore deposits, thus representing a kind of quality control for the method. However, its main interest is, of course, the
targeting of new areas for mineral exploration, i.e., areas with high favourability but without any known ore deposits or occurrences.

4. Predictive map: results and discussion

4.1. Results for favourability criteria

Lithostratigraphy Criterion (Table 3 and Fig. 7). The values of $W^+$ being fairly close to those of the contrast, $C$, these were the values finally selected. The area evaluated covers nearly 100,000 km$^2$. Of it, 50% are Quaternary sediments, 30% are basement, and the rest is essentially composed of Mesozoic rocks (~10%) and Tertiary sediments or volcanic rocks (~10%). The results obtained by using WofE show major differences between formations: the probability of having a deposit in the Tp formation is six times greater than in the Tvb formation. Intrusions of Tertiary age (Tp) are therefore clearly the most favourable formation. They carry 50% of the gold-bearing deposits, although they represent only 0.10% of the total area. The other favourable lithologies are Tertiary volcanic rocks (Tvb), Palaeozoic sedimentary formations (Pzs), Proterozoic–Palaeozoic metamorphic rocks (Pzpm), and to a lesser degree Palaeozoic plutonic rocks (Pzp) and volcano-sedimentary deposits (Pzvs). The favourability of these basement formations is due to deposits that, at 1:500,000 scale, are still assigned to these polygons (e.g., Montey, Offir, El Oro), whereas the ore deposits are actually in or around Tertiary intrusions that do not crop out or are too small in size to be mapped at this scale. The other formations are unfavourable, or given as indeterminate by the method.

Faults Criterion (Table 4 and Fig. 8a, b). The favourability calculations, performed on fault trend, show four main groups. The most favourable (Fav$_i$>1), are transverse structures, trending N060°–N070°E, N080°–N090°E, N100°–N110°E, and N120°–N130°E. Faults trending N070°–N080°E, N090°–N100°E, and N140°–N150°E appear slightly less favourable (1>Fav$_i$>0.6). These seven families seem to play a preponderant role in the distribution of gold, confirming previous studies at Andean scale (Hanuş et al., 2000), field observations at regional scale, and observations at the local scale at Bajo de la Alumbrera (Angera, 1999; Proffett, 2003), Agua Tapada (Alderete, 1999a), Agua Rica (Roco and Koukharsky, 1999), and La Mejicana (Mayón, 1999).

Faults trending NE–SW appear only slightly favourable (0.6>Fav$_i$>0) despite their significance in terms of regional structure (de Urreiztieta, 1996).

Lithostratigraphic Contacts Criterion (Table 5 and Fig. 9). Four families of contacts can be distinguished. Two families of contacts are considered to be very favourable (Fav$_i$>4), nine are favourable (4>Fav$_i$>2), 2), and eleven are slightly favourable (2>Fav$_i$>0). The
other 13 appear unfavourable. Most of the favourable contacts are between Tertiary intrusions and other formations with favourable lithologies (e.g., Tvb, Pzs, PePzm, and Pzp), or to a lesser extent with formations having unfavourable lithologies (e.g., PePzs and Ts). The cumulative length of contacts whose calculated
favourability is greater than 2 (favourable to very favourable) is not great (~2.5% of the total length of lithostratigraphic contacts), so that the criterion is relatively selective and enables attention to be focussed on the areas that carry deposits.

4.2. Comments on the method

Four categories of score were identified for each of the criteria: very favourable = 3, favourable = 2, slightly favourable = 1, and unfavourable = 0 (Figs. 7, 8 and 9). This notation enables the same range of scores to be applied to all the criteria. The various criteria have therefore not been prioritized or weighted during processing.

Information on lithostratigraphy is used twice, once for country rock formations and once for contacts. Are these criteria independent (or redundant)? The lithostratigraphy of the country rock formations refers to chemical and petrochemical properties, whereas the contact between lithologies of different kinds involves the mechanical (physical) behaviour and rheological properties of the rocks. Though independence between these criteria may not be absolute, they nevertheless draw on separate properties.

The processing may sometimes create artefacts. It is essential to have an expert check these results, to confirm that they do not contradict field observations. For most of the criteria, the results seem to be correct, except for the Q-Tp category of the “lithostratigraphic contacts” criterion. For that category, the score was reduced to 0 (Table 5, category hatched in Fig. 9), in spite of its strong calculated favourability (Fav = 2.98), as these appears to represent a redundant artificial expression of the recent cover over the favourable Tp formation.

4.3. Comments on the predictive map

Superposition of the various criteria results in a predictivity map plotted on a scale that goes from 0 to 8, and not 9 as is theoretically possible (Fig. 10). The favourable groupings are relatively closely confined for values greater than 5; this score is one point above the mean, and resulting from the superposition of at least two favourable criteria.

The map shows 20 anomalous envelopes (1 to 20, Fig. 10). Some of these contain known deposits, whereas others do not. Some overlap with mining areas that are active (Bajo de la Alumbrera, Farallón Negro-Alto de la Blenda [envelope 1]), under development (Agua Rica [envelope 3]), or being explored and identified as prospects (Bajo San Lucas [envelope 2], Filo Colorado [envelope 3], Vicuña Pampa [envelope 5], and Cerro Azul [envelope 7]). On the other hand, others cover abandoned areas, suggesting that it would be useful to re-examine the data or do a more detailed study (Cerro Peinado [envelope 8], Mogote Rio Blanco [envelope 12], El Pararrayo [envelope 13], and La Mejicana [envelope 14]). Finally, some envelopes are in completely new areas (for example, 4, 6 to 11, and 15 to 20). The cutoff score value (favourability score ≥ 5) seems to be realistic: favourable areas are not too large, and their distribution is consistent with the structure of the area studied (70% of the known ore deposits are within the envelopes defined as favourable). Due to the above-mentioned exclusion of the favourable score for the Q-Tp lithostratigraphic contact, no favourable envelopes are taken across the Quaternary. This does not exclude the existence of hidden occurrences under the Quaternary cover, but is beyond the scope and limits of our approach.

At the southern edge of the Puna, favourable envelopes are about 30 km apart and they trend NW–SE (~N140°E) [envelopes 4 to 8; and, to a lesser extent, 1 and 2]. They mostly lie along the Vicuña Pampa–Filo Colorado volcanic axis, but seem to be somewhat offset in the SE. The work of Rossello (2000) suggests a genetic relationship between plutonic activity and mineralization around Vicuña Pampa (north of envelope 5) and Farallón Negro (envelope 1). To the south, near the Sierra de Famatina, two other anomalies [13 and 14] also trend NW–SE. At La Mejicana (Fig. 3a), the plutons hosting the mineralization were emplaced in structures trending NW–SE. They were later cut by post-mineralization fractures, trending N–S (Mayón, 1999).

Structures trending NE–SW enhance the favourability of certain areas, such as those south of Vicuña Pampa (envelope 5) and Farallón Negro (envelopes 1 and 2), as well as certain isolated areas in the Sierra de Velasco (envelope 16) and the Sierra de Ambato (envelope 19).

In the Sierra de Velasco, envelopes 16 to 18 are due to superposition of lithostratigraphy and fault criteria. However, these areas must be viewed with caution, because the tectonic structures here were interpreted from Landsat images (NASA, S-19-25, 2000). Envelopes 15 (south of the Sierra de Famatina) and 19 and 20 (in the Sierra de Ambato) appear more interesting, because favourability is due to the three main types of criteria, deduced from geological maps.

On the map, the position of the Tucumán Transfer Zone (Fig. 10) strengthens the interest of otherwise isolated areas (envelopes 9, 10, and 11). Likewise, the
Vicuña Pampa–Filo Colorado volcanic axis, considered to be favourable, gives added value to envelopes 1 to 8 and suggests that right-lateral displacement on the TTZ, during the Neogene, has offset the mineralized belt by about 40 km. Independently, restoration of fault heaves on a map, yields (i) horizontal displacements of at least 20 km along the TTZ, and (ii) clockwise rotations of fault blocks about vertical axes (de Urreiztieta, 1996; Gapais et al., 2000). Palaeomagnetic studies have yielded rotations of as much as 29° (Aubry et al., 1996).
According to Chernicoff et al. (2002), faults trending NE–SW cut older faults trending WNW–ESE in the vicinity of Farallón Negro.

5. Comparison of results from the continental- and regional-scale models

5.1. Methodological aspects: effects of a change in scale

Billa et al. (2004) did a multi-criteria study of Andean mineralization at continental scale (1:2,000,000). This was based on 113 gold orebodies and deposits of epithermal and porphyry type of Neogene age. To compare the results obtained at continental scale with those obtained at regional scale (1:500,000), we have plotted contours from the previous study (favourability score ≥ 4, i.e. 95% of the metal content) on the favourability map produced during the current study (Fig. 10).

On the 1:2,000,000 predictive map, the main districts (Farallón Negro, Agua Rica, and Famatina) were identified but mislocated by about 5 to 10 km (areas A, B, M, and O). New areas, such as Vicuña Pampa and its extension to the SE, were also identified (areas E and F) but mislocated. Because the mislocations were almost systematically to the SW, we believe that they mainly resulted from misinterpretation of projection systems on the original maps that were used for geological compilation. However, a lack of precision is not surprising, in view of the scale selected for the continental study and the corresponding pixel size (10 × 10 km).

At 1:2,000,000 (GIS Andes) some information becomes degraded, particularly when geological formations are of small surface area (for example, Tertiary porphyry stocks, which host the mineralization). During statistical processing, the deposit is assigned to a country rock polygon, which may thereby acquire an exaggerated favourability. This bias becomes smaller or non-existent at 1:500,000, because most of the Tertiary intrusions could then be mapped in detail and the deposits were georeferenced with greater accuracy. This explains why a certain number of areas that were favourable at the continental scale were not confirmed at the regional scale (e.g., areas C, D, I, J, K, L, N, and P). Although the basement formations still retain some favourability, it is less significant.

New anomalous areas were delimited at 1:500,000, particularly envelopes 9, 10, and 11 (along the Tucumán Transfer Zone), 15 (south of Sierra de Famatina), 16 to 18 (Sierra de Velasco), and 19 and 20 (Sierra de Ambato). These studies also led to new ideas about the spatial distribution of mineralized areas, for example, favourable envelopes develop along fault corridors trending E–W or NW–SE (Fig. 10), and lie on a volcano-magmatic axis.

The regional-scale work has allowed us (1) to easily recognize the mineralized areas, (2) to identify new targets or to re-identify occurrences that had not been included in the data calculation, and (3) given the accuracy (precision) of the information, to define better certain metallotects, such as the preferred directions of emplacement of mineralization. The processing procedure seems well suited to identifying areas of interest at regional scale (over areas of 100 to 300 km²). On the other hand, the continental-scale work, although it is less detailed and more general in nature, is still efficient for identifying targets of larger size (on the order of 300 to 1000 km²). It identified the main deposits and targets such as Vicuña Pampa, which has been confirmed independently by field studies (Roselló, 1980, in press). However, the lack of detail, which is inherent to mapping at 1:2,000,000, results in favourabilities that may be fictitious and may dominate parts of the predictive map. The tool, therefore, remains best suited to defining areas of interest at the strategic level.

5.2. Metallogenetic aspects: effects of the jump in scale and of structural knowledge of the region

At regional scale, more details can be included. Good examples are structural data (de Urreiztieta, 1996; de Urreiztieta et al., 1996; Fig. 4b). The metallotects described in the preceding paragraphs seem to be controlled by the orientations of certain structural features. Moreover, a compilation of the chronology of mineralizing events during the Neogene (see Table 2) shows that the emplacement of the mineral occurrences is (i) later than a magmatic phase; and (ii) earlier than or synchronous with a phase of compressional tectonics. In NW Argentina, two different situations for the emplacement of mineralization can be distinguished, one typical of the northern part (Vicuña Pampa and Farallón Negro), the other of the southern part (Sierra de Famatina).

In the north, the Tucumán Transfer Zone appears to offset the Vicuña Pampa–Filo Colorado magmatic axis (Fig. 11a). In the known ore deposits, mineralized veins and Neogene andesitic dykes trend mainly N125°E to N150°E (Proffett, 2003). This is particularly true for the Farallón Negro–Alto de la Blenda mine (Fig. 11b), where the veins reach maximal thickness when they have such trends (Alderete, 1999c). Around Bajo de la
Alumbrera mine, Rossello et al. (1996a) attributed the elliptical shape and spatial arrangement of outcrops to Neogene deformation within the TTZ. Transverse faults, striking ~N145°E, appear to have controlled Miocene–Pliocene sub-volcanic intrusions and they in turn are associated with the main mineral deposits (Rossello, 2000). The transverse faults have left-lateral components and are conjugate to the right-lateral faults of the TTZ. The mineralization is in dilational zones, which are close in orientation to the inferred greatest principal stress (compression), as might be expected for hydraulic fracturing (Fig. 11a). The principal stress

Fig. 11. Control of inferred principal stress on emplacement of mineralization in NW Argentina. Right-lateral Tucumán transpressional zone (TTZ) and left-lateral Desaguadero-Valle Fértil transpressional zone (DVFL) are conjugate structures (after Rossello et al., 1996b). A regional consequence of the TTZ is the offset of the Vicuña Pampa–Filo Colorado magmatic axis (VP–FC) by about 40 km. Inset maps show andesitic dykes and veins in Farallón Negro Volcanic Complex (b; after Proffett, 2003), and mineralized veins at La Mejicana mine, Sierra de Famatina (c; after Brodtkorb and Schalamuk, 1999). Broad arrows indicate principal stresses, $\sigma_1$ (black), $\sigma_2$ (grey) and $\sigma_3$ (white).
direction would appear to be controlled, partly by the
topographic effect of the Puna and partly be right-lateral
transpression in the TTZ (Fig. 4a and b).
In the south, the mineralization at La Mejicana mine
is in veins striking N070°E to N080°E (Fig. 11c; Brodtkorb
and Schalamuk, 1999). It was controlled by Plio-
cene intrusive bodies channelled by NW–SE structures
(Mayón, 1999). This strike (~N080°E) is superimposed
on that of the E–W to WSW–ENE axes of shortening
obtained from a kinematic study of the faults (de Ureiz-
ticata et al., 1996), and is in agreement with the direction
of convergence between the Nazca and South American
Plates (Fig. 1; Pardo-Casas and Molnar, 1987; Somoza,
1998). The Sierra de Famatina (SF) trends N–S, be-
tween two major transpressional tectonic structures,
the TTZ and the DVFL. The latter is bounded on the
east and west by high-angle reverse faults. The uplift of
this range as a “pop-up” structure implies crustal thick-
ening (Ramos et al., 2002). It may also have occurred
under constriction (Rossello et al., 1996b), so that the
principal stresses \( \sigma_1 \) and \( \sigma_2 \) were sub-horizontal and had
similar values \( \sigma_1 \geq \sigma_2 > \sigma_3 \). This state of stress would
be propitious to the development of a laccolith at depth,
itself surface expression being the large hydrothermal
alteration halo seen at La Mejicana. If the reverse faults
that bound the Sierra de Velasco (SV) on the east
reached an equivalent depth under the Sierra de Famatina,
the source magma might have escaped towards the
east. This could explain the favourable areas (anomalies
16 to 18, Fig. 10) that appeared during multi-criteria
processing (see above). The hypothesis, whereby min-
eralization and hydrothermal activity are due to a lac-
colith, warrants more detailed study in the Sierras
Pampeanas and a comparison with similar systems else-
where, e.g., Baia Mare in Romania (Crahmalicu and
Crahmalicu, 1997; Bailly et al., 1997).

To both north and south, the mineralization is along
a network of veins and veinlets, which appear to have
formed in orientations sub-parallel to the principal
stress \( \sigma_1 \) and perpendicular to the minimum stress \( \sigma_3 \),
as obtained experimentally for hydraulic fractures
(Hubbert and Willis, 1957).

6. Conclusions

A multi-criteria predictive study for gold in NW
Argentina, conducted at 1:500,000, has recognized min-
ing areas that are active (e.g., Bajo de la Alumbrera),
under development (e.g. Agua Rica), or abandoned
(e.g., La Mejicana), and has identified new targets
(e.g., Vicuña Pampa). The predictive map was compiled
from data acquired in the field, and data available in the
literature (e.g., geological maps) or included in the GIS
Andes database (BRGM, 2001). Production of a predic-
tive map requires a homogeneous population of depos-
ts, likely to have been controlled by an identical set of
factors: the same commodity, the same metallogenic
period, and the same ore-forming processes. The change
of scale (from continental to regional) obviously leads
to greater precision. However, the reduction in area is
accompanied by a corresponding decrease in the number
of available ore deposits for the calculation and learning
phases, and their descriptions are no more detailed. A
population that contains relatively few deposits, and
whose associated data are not always homogeneous,
makes interpretation difficult. The validity of the results
must be confirmed by an expert in the field: hence the
use of an “expert-guided data-driven” approach. More-
over, this reduction in scale invalidates the use of some
of the information layers. This is especially true of
géo-dynamics-related criteria (depth and dip of the sub-
ducted plate) and of the “regional structures” criterion.
At regional scale, the depth and dip of the subducted
plate do not vary significantly, and “regional structures”,
as a criterion, is too vague and poorly constrained. On
the other hand, at this scale a more precise knowledge of
the structural context has led to better understanding of
the principles governing the distribution of deposits.

According to structural and kinematic analyses, the
direction of shortening was (1) E–W in the Sierra de
Famatina, as a result of plate convergence and (2) NW–
SE in the Farallón Negro district, due to the combined
effects of topography and right-lateral faulting in the
TTZ at the southern edge of the Puna. The orientations
of the veins in the deposits coincide with these two
directions. In situations of this kind, the mineralization
is emplaced in dilational fractures, sub-perpendicular to
the least principal stress.

The continental-scale GIS is particularly suited for
use at the strategic scale of country, craton, or orogen.
The suggested upper limit of use of GISs for mineral
potential mapping, placed at 1:500,000 scale by Knox-
Robinson and Groves (1997), may therefore be extend-
ed to 1:2,000,000 (Lips et al., 2002). As we have seen,
the effectiveness of these systems will then greatly
depend on the quality of their application and on de-
tailed checking of the data. Ignoring the projection
system of any map used in a compilation (a frequent
occurrence) may lead to significant errors, which may
not be easy to detect. On the other hand, a regional-
scale GIS, which by its nature draws on much more
detailed data, will enable a better understanding of the
roles of the various metallotects, and the identification
of more varied targets. A system of this type, therefore,
is particularly suited to tactical exploration, over limited areas.

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Appendix A. Lithostratigraphic units and their abbreviations

Q=Undifferentiated Quaternary; Qe=Quaternary salar evaporite deposits; Qv=Undifferentiated Quaternary arc volcanic rocks; Ts=Undifferentiated Tertiary marine and continental deposits; Tv=Undifferentiated Tertiary volcanic rocks; Tp=Undifferentiated Tertiary plutonic rocks; Tvs=Undifferentiated Tertiary volcano-sedimentary deposits; Tvbs=Tertiary basaltic volcanic rocks; Ks=Undifferentiated Cretaceous marine and continental deposits; Kp=Undifferentiated Cretaceous plutonic rocks; Trs=Undifferentiated Triassic marine and continental deposits; Pz-Mz=Undifferentiated Palaeozoic–Mesozoic rocks; Pz=Undifferentiated Palaeozoic marine and continental deposits; Pzvs=Palaeozoic volcano-sedimentary deposits; Pzv=Undifferentiated Palaeozoic volcanites; Pzp=Undifferentiated Palaeozoic plutonic rocks; Pzm=Undifferentiated Palaeozoic metamorphic rocks; PePzs=Undifferentiated Proterozoic and Palaeozoic metamorphic rocks; PePzp=Undifferentiated Proterozoic and Palaeozoic metamorphic rocks.

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