# Developing Wind and Mineral Exploration Models using GIS for Project Development in Argentina.

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**Abstract:** Kenex in partnership with Emprendimientos Energéticos y Desarrollos S.A (EEDSA) have recently completed a number of strategic business development projects in Argentina to develop wind energy and mineral resources. A partnership was developed with EEDSA in 2010 to explore for and develop wind energy opportunities in Argentina using Kenex's recently developed wind prospecting techniques. These techniques have been successfully used to map wind farm locations in New Zealand and rank each site according to its economic potential. After a year of data collection and modelling, which has successfully mapped potential wind farm sites in a number of provinces in Argentina, the partnership decided to expand into mineral exploration. Spatial Data Modelling techniques were used to map potential mineral exploration opportunities for gold, copper, base-metals, tin, tungsten and uranium at a regional scale in Argentina and Chile. Regional scale prospectivity models were developed for Argentina and Chile to identify prospective areas for a variety of metals and mineralisation styles. Fuzzy logic techniques were used to develop the wind prospectivity maps and Weights of Evidence modelling techniques were used to develop the mineral potential maps in Argentina and Chile.

The models have successfully identified areas that are prospective for wind energy and gold, copper and silver and have also identified areas where new mineralised systems could be discovered with further exploration and development. Economic and risk factors will be included and target areas can then be sorted and mapped according to positive and negative exploration risk. A similar analysis will be carried out for the wind targets. This will lead to the development of an Argentina wide database of prioritised metal and wind energy targets for exploration and development. The prioritised targets will then be combined with social and logistical factors to highlight projects for acquisition. The regional targeting work for both wind energy and mineral resources has now been completed and the partnership is in the process of developing a number of business opportunities that have been identified by this work where more detailed local scale targeting work will be completed.

**Resumen:** Kenex, en asociación con Emprendimientos Energéticos y Desarrollos S.A. acaba de completar varios proyectos de desarrollo empresarial estratégico en Argentina para trabajar con energía eólica y recursos minerales. Se estableció una alianza con EEDSA en 2010 para realizar prospecciones y crear oportunidades de energía eólica en Argentina, empleando las nuevas técnicas de prospección eólica de Kenex. Éstas técnicas han sido utilizadas exitosamente para mapear sitios de parques eólicos en Nueva Zelanda y asignar valores a cada sitio según su potencial económico. Después de un año de recopilación y modelado de datos, que exitosamente ha permitido mapear los sitios potenciales para parques eólicos en varias provincias de Argentina, la alianza ha decidido expandirse a la exploración minera. Técnicas de modelado de datos espaciales fueron empleadas para mapear las oportunidades potenciales de exploración minera de oro, cobre, estaño, tungsteno y uranio, a escala regional en Argentina y Chile. Modelos de prospectividad a escala regional fueron desarrollados para Argentina y Chile para identificar áreas prospectivas de diversos metales y estilos de mineralización. Técnicas de lógica difusa (Fuzzy logic techniques) fueron utilizadas para elaborarlos mapas de prospectividad eólica y técnicas de ponderación de modelado de evidencia (Weights of Evidence modelling techniques) para la confección de mapas de potencial minero en Argentina y Chile.

Los modelos han logrado exitosamente identificar zonas prospectivas, tanto para energía eólica, como para oro, cobre y plata. También así, se han identificado áreas donde nuevos sistemas mineralizados podrían ser descubiertos con futuras exploraciones y desarrollos. Factores económicos y de riesgo serán considerados y posteriormente áreas objetivas podrán ser clasificadas y mapeadas según los riesgos de exploración positivos y negativos. Un análisis parecido será llevado a cabo para los objetivos eólicos. Esto dará lugar al desarrollo de una base de datos argentina de metales y de energía eólica priorizados para la exploración y el desarrollo. Los objetivos priorizados serán posteriormente combinados con factores sociales y logísticos para destacar proyectos para adquisición. El trabajo de identificar objetivos a escala regional ya ha sido finalizado, tanto para energía eólica como para recursos mineros. La alianza está en el proceso de elaborar varias oportunidades empresariales que han sido identificadas por este trabajo. Para los propósitos de estas oportunidades, más trabajos de identificación de objetivos a escala local serán realizados.

# 1. Introduction

Kenex in partnership with Emprendimientos Energéticos y Desarrollos S.A. (EEDSA) have recently completed a number of strategic business development projects in Argentina to develop wind energy and mineral resources. EEDSA are Buenos Aeries based wind industry professionals who have been involved in the renewable energy market in Latin America since the formative years of the sector. EEDSA has participated in numerous projects through the provision of advice and sector investment. Their experience comes from involvement in projects and developments in Chile, Argentina, Uruguay, Mexico, Brazil, Costa Rica & the Caribbean. A partnership was developed with EEDSA in 2010 to explore for, and develop, wind energy opportunities in Argentina, using Kenex's recently developed wind prospecting techniques. These techniques were developed by Kenex in New Zealand to explore for wind energy resources at regional and local scales by using new satellite derived meteorological and terrain data in combination with spatial data modelling techniques. These techniques have been successfully used to map wind farm locations in New Zealand and rank each site according to its economic potential.

After a year of data collection and modelling, which has successfully mapped potential wind farm sites in a number of provinces in Argentina, the partnership decided to expand into mineral exploration. Spatial Data Modelling techniques were used to map the potential mineral exploration opportunities for gold, copper, base-metals, tin, tungsten and uranium at a regional scale in Argentina and Chile. Regional scale prospectivity models were developed for Argentina and Chile to identify prospective areas for a variety of metals and mineralisation styles. Fuzzy logic techniques were used to develop the wind prospectivity maps and Weights of Evidence modelling techniques were used to develop the mineral potential maps in Argentina and Chile. The models have successfully identified areas of known mineralisation as prospective and have also identified areas where new mineralised systems could be discovered with further exploration and development.

The regional targeting work for both wind energy and mineral resources has now been completed and the partnership is in the process of developing a number of business opportunities that have been identified by this work where more detailed local scale targeting work will be completed. This presentation describes the data, techniques and processes used in both mineral and wind energy spatial data modelling and highlight the potential for the development of new wind and mineral opportunities in Argentina and Chile.

# 2. Wind Energy Project Development in Argentina

Renewable Energy generation in Argentina, like elsewhere in the world is steadily on the increase due to the opening up of the electricity sector by the central government. Significant production from hydroelectricity already exists, but although wind and solar energy industries are in their infancy they are considered to have an increasing influence in any energy production mix in the future. Wind energy projects have been developed in Argentina but are only small local scale projects. There is a significant opportunity for increased wind energy development in the near future because of this.

Argentina is highly prospective for wind energy, with nearly 70 % of its land area covered by winds with an annual average speed, measured at 50 metres above ground level, exceeding 6 metres/second (m/s). In Central and Southern Argentina wind speeds can reach averages up to 9 m/s and up to 12 m/s, consequently regions such as Patagonia, south of Buenos Aires and interior provinces such as Cordoba are considered to have significant potential for wind power generation. Despite the country's natural wind potential only 30MW of wind generation has been installed to date (mainly between the late 1990's and early 2000's). This is despite Argentina experiencing recurring natural gas shortages over the past eight years, so it is surprising that with the wind potential that further developments have not occurred as yet.

Barriers to the development of wind power are mainly due to government intervention in the energy market to protect consumers from hikes in energy prices. Because of this, the market has not been allowed to use the marginal cost of generation to set the wholesale price and customer bills have been subsidised by the state. With a significant differential between the spot price and the marginal costs there has been little incentive for an investor to participate in the renewable sector as the ability to recoup investment and operating cost is too great. However, this may be starting to change as subsidies are becoming too costly, compromising government spending in other areas. This could be positive for the wind energy generation industry in the future. Like New Zealand, there is also significant potential for wind as a complementary power with hydro generation in Argentina. A significant proportion of hydro generation capacity with storage capabilities is located in the region of Comahu, one of the areas with a likely high potential for wind generation. Economic benefits could be gained by using wind power to save water in the summer months that can then be used in the winter months when natural gas is in short supply and minimise the need for expensive thermal power generation with diesel. Other benefits of wind power include a diversification of energy sources, less dependency on fossil fuels and greater stabilisation of energy prices, which in the long run would benefit the economy as a whole. Wind energy also helps to create new high-quality jobs and promotes the development of more rural

regional economies through the construction of wind farms outside of urban areas.

The regulatory framework for renewable energy in Argentina has set a target of 8% renewable energy generation by 2016. A Feed in Tariff with a bonus tariff to wind generators that will be provided by a Renewable Energy Trust Fund, is to be created specifically for meeting the 2016 target. Consequently, there is momentum in the industry with new projects underway including: Vientos de Patagonia I in Chubut Province, expansion of the Arauco wind farm in La Rioja Province. These remain at a small scale and there is no integrated national assessment of the potential for wind energy production or its location. This has created an opportunity for Kenex and EEDSA to use our prospecting techniques for wind energy to look for, and start development of, what could be a number of new valuable projects.

## 3. Mineral Exploration Project Development in Argentina

Mineral exploration discovery rates for all metals in the last fifty years have been falling due to increased exploration maturity and reduced real commodity prices for all metals (Blain, 2000). This has been compounded by mergers and acquisitions reducing the number of experienced mineral exploration companies and consequent loss of experienced geologists from the industry. In addition many major mining companies have reduced in-house mineral exploration, preferring to depend on acquisitions and brown-fields exploration to replace and grow their resources. Consequently, few significant new mineral resource discoveries have been made in the last decade, while demand for metals continues to increase. Current mines are rapidly being depleted and there is continued pressure for new discoveries to replace resources. There is a need, because of this, for exploration and mining companies to use cutting edge technologies to help develop new projects in under explored regions.

While working on wind prospecting in Argentina it became clear that compared other parts of the world Argentina has been relatively underexplored and, in many cases, the new computer based exploration techniques available to modern exploration companies have not been used. Argentina is particularly well placed for the development of new mineral exploration projects as the country is located along the eastern margin of the Andean Cordillera, which is host to many of the world's largest metal deposits. The tectonic setting of Argentina allows for the development of a large number of mineral system styles that host a range of important metals, including copper, silver, gold, tin and tungsten (Figure 1).

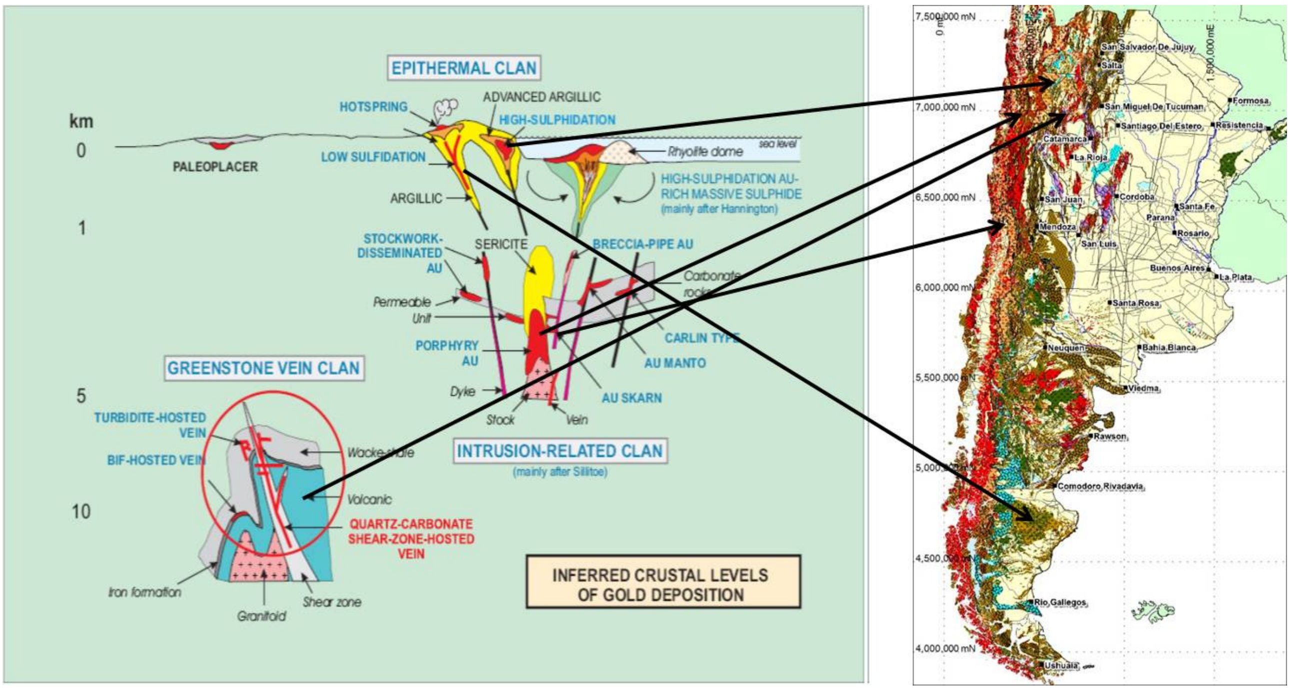


Figure 1. Important mineral systems in Argentina and Chile used to constrain the spatial data modelling project.

Argentina historically has a long connection with mining and was named for its silver mineralisation and is famed for its world class mineral deposits including porphyry copper-molybdenum-gold (Bajo de la Alumbrera), high sulphidation epithermal gold-silver (Veladero, Pascua-Lama), low sulphidation epithermal gold-silver (Cerro Vanguardia, Esquel) and volcanism related lead-silver (Navidad). Argentina has significant deposits of uranium and numerous smaller deposits containing a variety of metals. Interest in mining in Argentina goes back to the 1500's with the arrival of the conquistadors and was critical in the settlement and exploration of the country. In 1516 Juan Dias de Solis reached the delta of the river Parana and named it Rio de la Plata (the silver river). However, it wasn't until the

1930s (Aguillar; Pb-Zn-Ag deposit in Jujuy) and late 1970's (Farallon Negro; Au-Ag mine in Catamarca) that many of these discoveries were turned into producing mines. Bajo de Alumbrera was the first of the modern era discoveries which, took until 1997 before it began producing ore, largely due to the logistics of transporting ore from the high Andes. The 1990's signalled a turning point in the history of mining in Argentina with key legislation being put in place to liberalise the mining sector. These include the Mining Investment Law of 1993 and the Federal Mining Covenant also of 1993. A number of new discoveries can be attributed to the new legislation and in 2000, Argentina and Chile entered into the Treaty of Mining Integration, which allowed for exploitation of shared mines, easy border crossing and a framework for tax coordination along the 4,500km of the Andean frontier. All of these recent initiatives have changed the industry perception to Argentina now being a very attractive jurisdiction for mineral exploration investment.

Very few modern exploration techniques have been employed in Argentina due to the late entry of mineral explorers; consequently the most prospective regions are still relatively immature exploration targets. For example, most new discoveries are deposits outcropping at surface and have been discovered by prospecting (stream panning, soil geochemistry, geological mapping of float and veining patterns). More recently geophysical techniques have been used. In particular, aeromagnetic surveys have been flown over some areas looking for characteristic bulls eye anomaly patterns associated with magnetite bearing alteration haloes around some porphyry deposits (e.g., Arizaro-Lindero & Bajo de Alumbrera). Because of the immature nature of the terrane exploration activity in Argentina remains high and is increasing, with many projects either in feasibility or development. The mineral potential of the country is considered to be significant, with an array of mineralisation styles and highly prospective geological terrains (Figure 1). From Kenex mineral occurrence database (Figure 2), searches of the literature and web searches, it appears that the dominant mineral system styles in Argentina are as follows (with many variations on the theme of epithermal, mesothermal, hypothermal, hydrothermal – related breccias, disseminations, stockworks and veining):

- Porphyry
- Skarn
- Granite related
- IOCG
- High sulphidation epithermal Au-Ag
- Low sulphidation epithermal Au-Ag & Pb-Ag
- Intermediate sulphidation epithermal Ag-Au

Like wind energy the recent availability of new regional geological, geochemical and geophysical datasets has created an opportunity for Kenex and EEDSA to use our prospecting techniques for mineral exploration and project development.

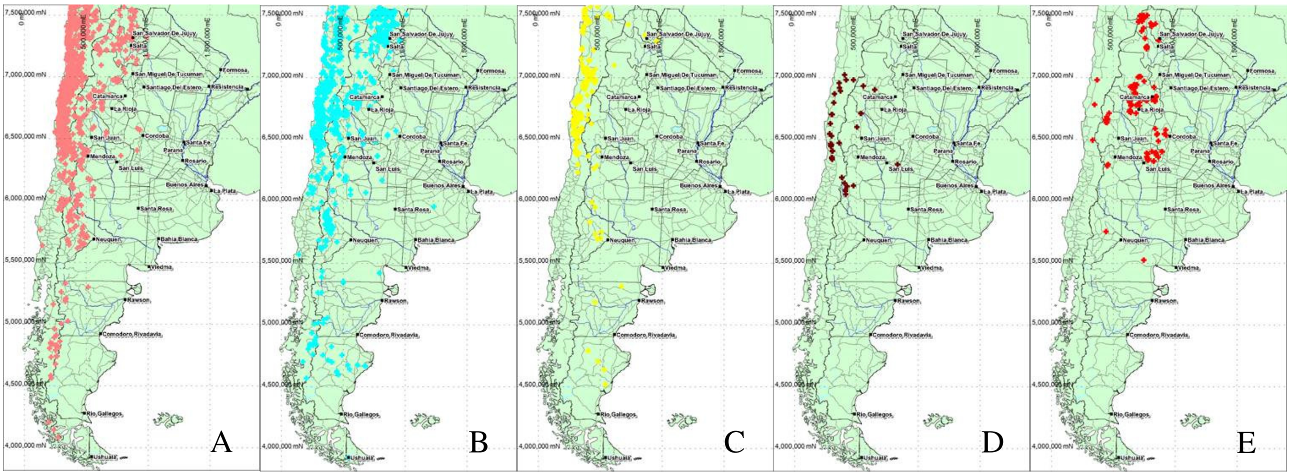


Figure 2. Location of main mineral systems used to constrain the spatial data modelling. A. Porphyry copper gold, B. Low Sulphidation Epithermal gold silver, C. High Sulphidation Epithermal gold, D. Skarn gold basemetal and E. granite related gold tin tungsten.

## 4. Data Availability

The approach used by Kenex and EEDSA is to take advantage of the wealth of digital data that is available and the powerful capability of spatial modelling software to combine multiple layers, resulting in predictive maps that identify the best sites for wind and mineral development and their likely size and extent. It is also critical that all the factors involved in the processes being modelled are understood and replicated in the model for spatial data modelling techniques to be effective. A variety of predictive maps need to be created that replicate the system being modelled. This means the final map not only integrates all the digital data available but also the knowledge of the process being modelled. Consequently, data coverage and the processes involved in wind energy generation and metal genesis are critical components of any spatial data modelling project. EEDSA wind engineers provided an understanding of the important processes involved in determining economic wind power generation for the wind modelling and the genetic processes involved in the mineral systems modelled in Argentina were determined from current university and industry research.

A review of the possible mineral systems present in Argentina confirm that a number of the mineralisation styles to be modelled extend into Chile and that to best understand the mineral potential of Argentina, data from Chile and Argentina should be combined to allow the various mineral systems to be modelled over their full extent (Figure 2). Consequently, the required digital data were acquired for both countries. Argentina and Chile have good modern digital data coverage at a national and province scale for the main geological, topographic and meteorological data sets required for spatial data modelling of mineral systems and wind energy. Work to date has utilised existing datasets, as well as updating those datasets when necessary, to generate revised geological and structural interpretations.

Meteorological and topographic data for wind modelling was compiled at a national scale and more detailed data at a province scale. Wind speed data was obtained for Argentina from 3Tier at 5 km resolution and 15km resolution wind direction data (Figure 3). A digital terrain model for Chile and Argentina was developed from the SRTM 90m global data set that is freely available (Figure 7B). Other data come from internal Kenex databases, SEGEMAR and ESRI world data (roads, waters, built-up areas, protected areas; Figure 4). The transmission data were provided by EEDSA (Figure 4).

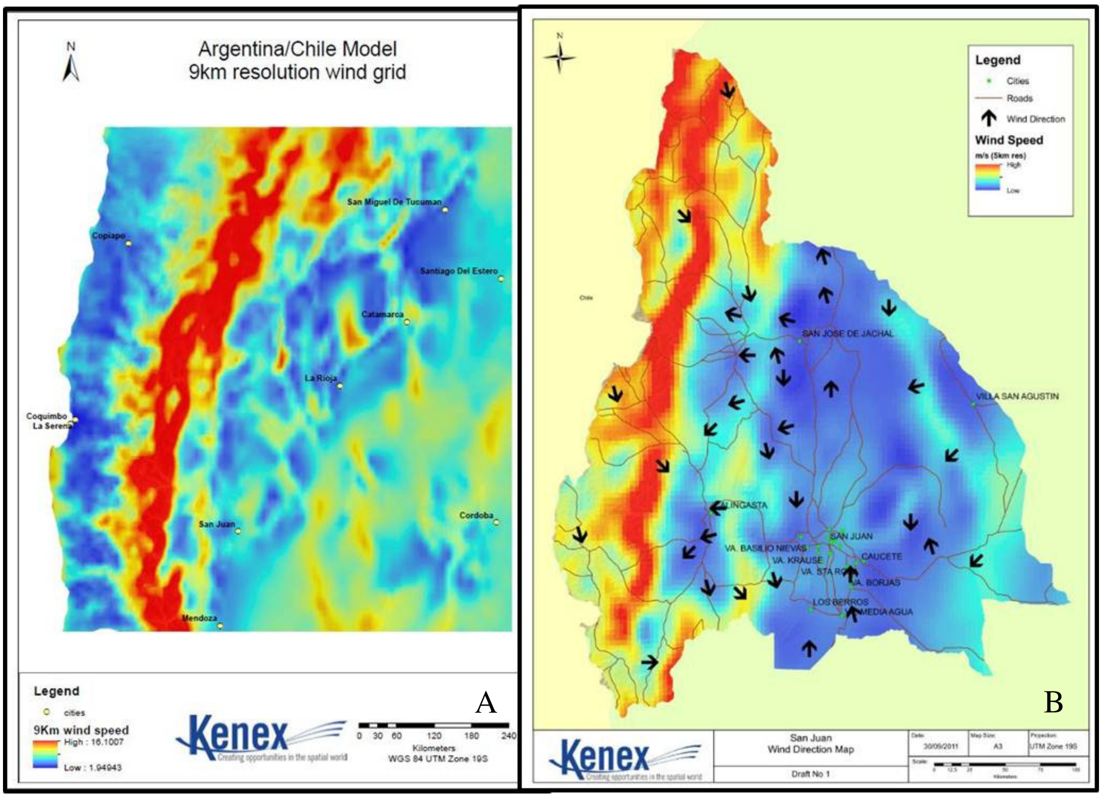


Figure 3. Wind data compiled for modelling over Argentina and Chile. A. Wind speed. B. Wind direction.

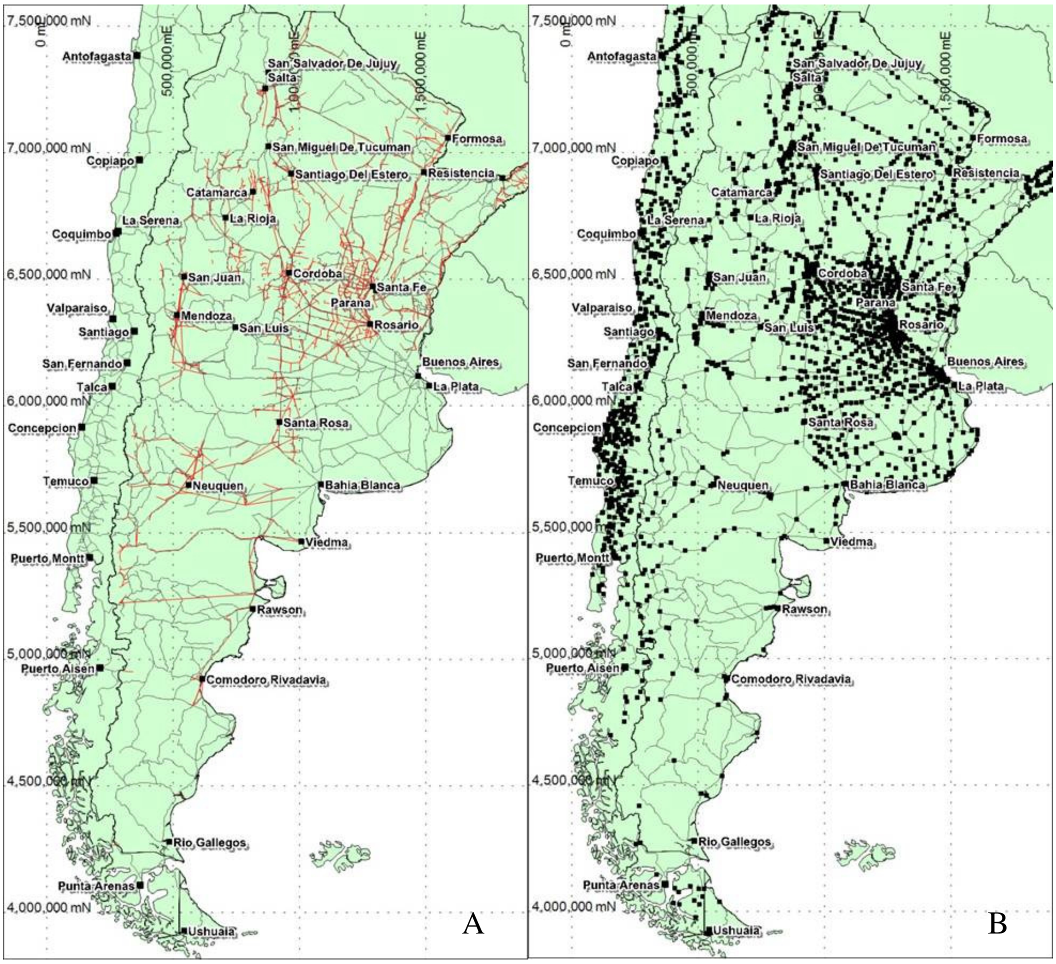


Figure 4. Infrastructure data compiled for modelling over Argentina and Chile. A. Electrical grid. B. Population.

Many of the maps in mineral targeting project GIS have been derived from databases maintained by Argentina's national geological survey SEGEMAR, from South America Gold Ltd, the USGS, Orr and Associates and Kenex's internal global databases. Mineral occurrence data points were derived from a number of sources and the locations of all mineral occurrence data points were reviewed and adjusted according to recently published 1:1,000,000 SEGEMAR metallogenic paper and digital maps and where required checked on Google Earth (Figure 2). The mineral occurrence database was also revised using available scientific literature and company reports. The revised database contains 2,680 porphyry (42%), 1,227 low sulphidation epithermal (19%), 366 high sulphidation epithermal (6%), 12 orogenic (0.1%), 8 IOCG (0.1%), 70 skarn (1%) and 145 granite related (2%). Resource and reserve data was updated from sources including Infomine.com and company websites.

Geology data were compiled for both Argentina and Chile from 1:1,000,000 and 1:500,000 digital geology edited and seamlessly merged by Kenex (Figure 5). As a result of the different map scales and different surveys for each province and countries, many inconsistencies in geology attributing and polygons occur along the map sheet boundaries. These were corrected and updated by Kenex geologists developing a consistent geological map along the Argentina and Chile cordillera. Minor revision of geological map attributes, including updating age dates with new dates published in scientific literature. Nation-wide precious, multi-element and base metal geochemistry datasets were acquired in paper and Excel format from SEGEMAR and the USGS. The geochemical datasets tend to be clustered, and do not cover the entire national study area, but provide enough coverage for modelling when combined with the mineral occurrence data (Figure 6). A downloadable, global-scale free-air gravity dataset at 1 minute resolution was acquired from the Scripps Institute of Oceanography based at the University of California, San Diego (Figure 7A). The gravity data were clipped to Argentina and Chile country boundaries and re-projected to match the geological datasets. The resolution of the gravity data allows for the interpretation of large regional-scale structures and the regional geological structural maps were revised using this gravity dataset. The DTM developed for the wind modelling was also used to interpret and modify the regional structural mapping (Figure 7B).

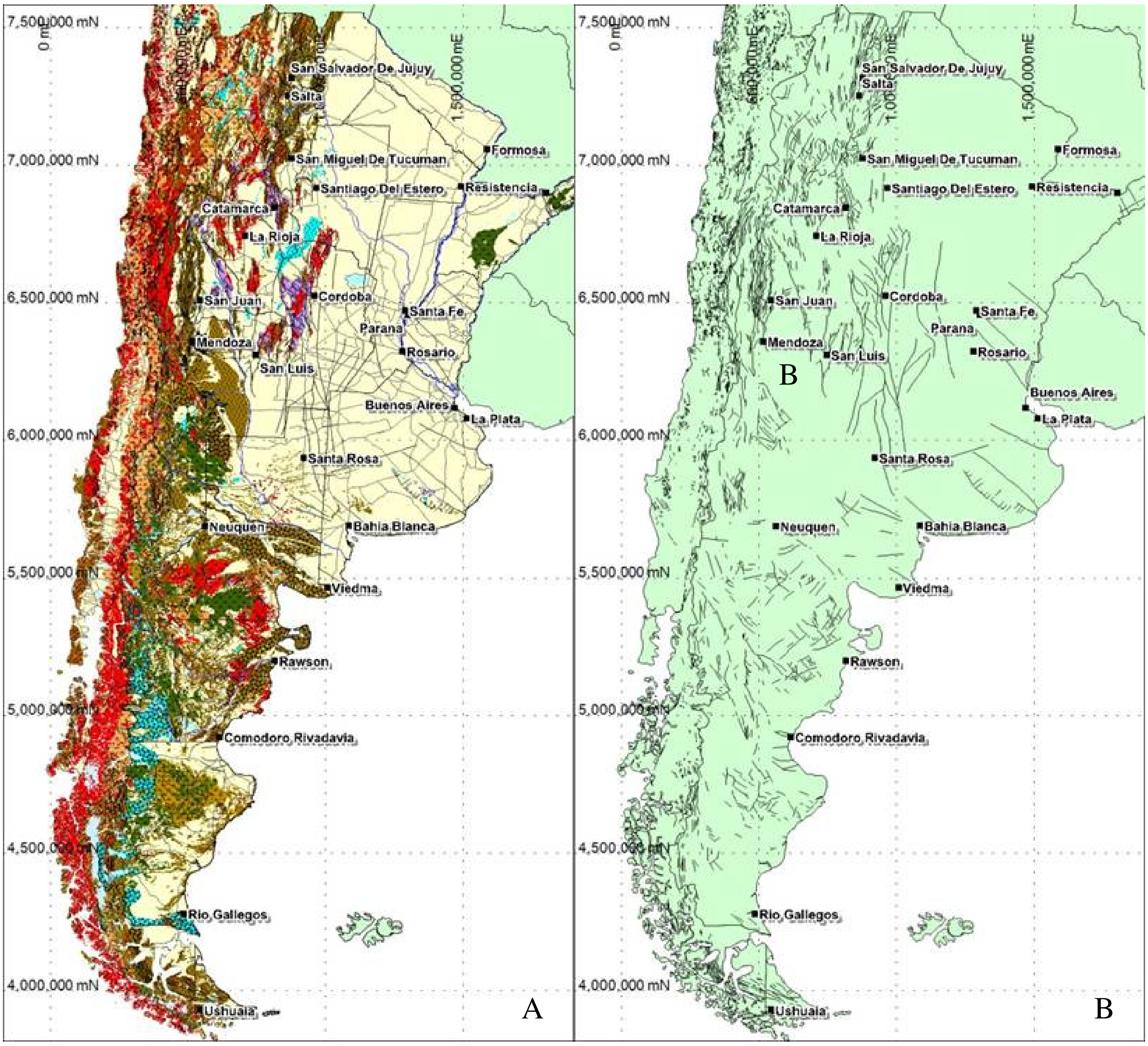


Figure 5. Geological data compiled for modelling over Argentina and Chile. A. Geology. B. Fault data.

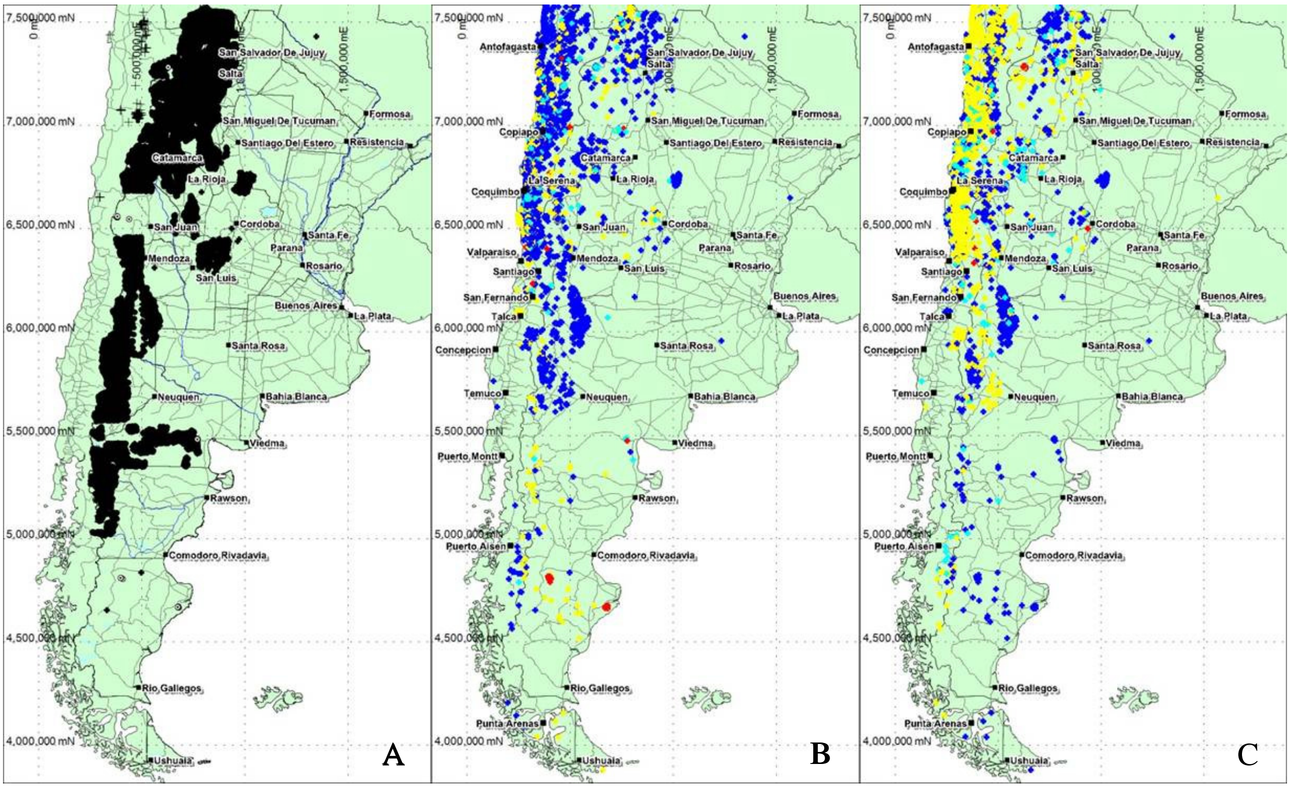


Figure 6. Geochemical data compiled for modelling over Argentina and Chile. A. Complete database coverage. B. Rock sample coverage for gold. C. Rock sample coverage for copper.

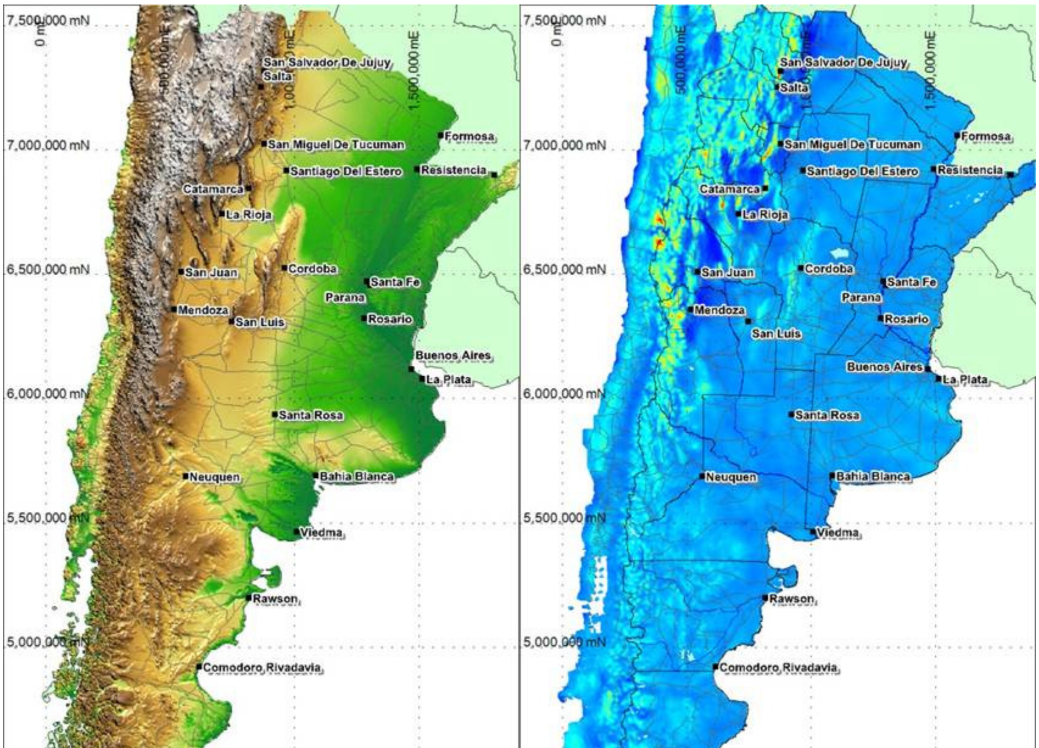


Figure 7. Raster data compiled for modelling over Argentina and Chile. A. DTM. B. Gravity.

## 5. Wind Energy Prospecting

With global energy trends moving steadily towards sustainable solutions, developers require more efficient ways to effectively target potential economic wind farm sites. Wind prospecting using traditional methods tends to be subjective, based on limited data and often requires time-consuming preliminary field research in order to locate a suitable site. This means, in many cases, wind farm development is based on land access, government subsidies and funding rather than the economic potential of the project area. Research in New Zealand during the past three years by Kenex has led to the development of GIS-based spatial wind prospecting models that combines satellite models of wind speed and direction, advanced terrain analysis, land use and transmission grid parameters to identify economically viable locations for a new wind farm before field assessment is undertaken, reducing significantly the economic risk and the overall development time frame of a project (see http://kenex.co.nz).

Expert knowledge from wind farm engineers (Aurecon in New Zealand and EEDSA in Argentina) has been used to create a series of binary or multiclass predictive maps in the wind prospecting GIS that represent the most important parameters that affect the economic potential for the production of wind energy. The parameters used are organised in three groups:

- Technical feasibility variables: wind speed and terrain (slope, aspect, terrain complexity and surrounding terrain)
- Site acceptability variables: proximity to roads, distance from built-up areas, population density, elevation, distance from waterways, and land use.
- Transmission grid variables: proximity to grid lines and power stations, grid lines voltage, density of grid lines and power stations.

For preliminary modelling a 100 m by 100 m resolution grid is generated over the area of interest. The resolution of the grid is chosen as being appropriate for national and province scale modelling, balancing sufficiently high resolution for wind and terrain analysis against the practicalities of data management and computer processing. The maps developed from these parameters are then spatially and statistically analysed and combined as an output probability map showing the most favourable sites for wind farm development. A list of targets based on the resulting probabilities is then created and the targets can be ranked in order of priority for follow-up investigations, with those areas with the highest probabilities given the highest priority ranking. These techniques have been successfully used in New Zealand to assess new sites for wind farm development and to evaluate planned turbine locations for current projects (see http://kenex.co.nz).

Spatial data modelling for wind prospecting in Argentina has been undertaken using a two stage process. Stage One utilises low-resolution mesoscale modelling (3 km or 9 km) to define areas likely to have sufficient wind resources for detailed prospecting combined with simplified terrain and suitability analysis to eliminate areas that can't be developed such as national parks, ecologically sensitive areas and areas of overly complex terrain. The Stage One models are developed at an appropriate resolution so that models can cover large regions such as entire counties or provinces. Stage Two then uses 3 or 1 km mesoscale modelling of wind and detailed terrain analysis to identify wind farm targets within the Stage One target areas. Depending on the extent of area to be modelled, it may be appropriate to run a simplified model at lower resolution such as 9 km as a first step to identify areas of interest for Stage One prospecting.

The fuzzy logic technique developed by Bonham-Carter of the Canadian Geological Survey is used to develop both the Stage One and Stage Two models. The models were created using the Spatial Data Modeller extension (ArcSDM) developed for ESRI's ArcView GIS software. Fuzzy logic is a popular and easily understood method for combining datasets using subjective judgment (e.g. Bonham-Carter, 1994). This method relies on expert opinion to derive weights that rank the relative importance of the variable for the map combination. Each dataset to be used is weighted using a fuzzy membership function (0-1), which expresses the degree of importance of the various map layers as predictors of the feature under consideration. Themes may be combined by a variety of fuzzy combination operators (fuzzy AND, fuzzy OR, fuzzy GAMMA, etc.) according to a scheme that may be represented with an inference network. The output from the spatial modelling is a map showing feature favourability, combining the effects of the input predictive maps. For the Stage One prospecting, twelve predictive maps were created with the data available to represent as many of the identified spatial factors affecting wind farm locations as possible. The map classes are assigned fuzzy membership functions based on expert opinion as to the importance of the predictive map. These membership functions are weights with the general effects. The predictive maps are then combined using fuzzy AND and fuzzy GAMMA operators to produce a final map of probabilities that can be used to prioritise sites for wind farm development. To check that the chosen weights for each predictive map are working the model results can be compared with existing wind farms. This can also be done statistically using area frequency calculations to determine how well the model predicts the turbine locations. Also, the highly suitable areas above a defined cut-off can be interrogated to assess whether all of the input parameters at that location are in fact highly desirable. Although the weights are modified and many models are run to test different combinations, the results do not differ significantly indicating there is limited sensitivity in the weights when they are changed by small amounts. It is important to note that the relative weightings of classes within a

predictive map and between layers are more important than the absolute values used.

The aim of the project has been to gain a comprehensive understanding of the wind farm potential in each province in Argentina and then create a portfolio of target sites that have the most potential for wind farm development. Kenex with help from EEDSA has used a range of data layers in the initial models including 5km resolution wind speed data, detailed terrain data, infrastructure data (transmission grid, substations, roads, built-up areas), environmental data (waterways, national or ecological parks), and population data. This approach is effective in eliminating areas that have limited development potential. These results are then further filtered by the other suitability parameters such as distance to grid (transmission lines/substations) and environmental indicators. Any cell in the model can be interrogated to understand the combination of scores for each parameter that lead to its overall ranking. Following Stage Two prospecting, pre-feasibility assessment of a site can be rapidly completed using the information generated in the prospecting study. The terrain analysis and other suitability modelling provides a good indication of the total potential capacity of a site and turbine layouts can be quickly developed by placing turbines within areas of suitable terrain and attractive wind speeds. Preliminary energy yield prediction can then be completed using virtual mast data extracted from the 1 km resolution mesoscale modelling to initiate high-resolution modelling with products such as WindPro/WAsP.

One kilometre, three kilometre and nine kilometre national scale models have been completed as part of the Stage One targeting. These models were used to target more detailed Stage Two models at a province scale. The Stage One province scale wind modelling has been completed over ten provinces, including: Buenos Aires, Santa Cruz, Neuquen, San Juan, Chubut, San Luis, Mendoza, Cordoba, Rio Negro and La Pampa. The results of the province scale modelling are currently being reviewed and target areas being developed with the local knowledge of EEDSA's wind engineers. One project is now far enough advanced for preliminary feasibility studies and economic modelling to be considered and discussions with the provincial government have commenced.

## 6. Mineral Prospectivity Modelling

Ore deposit models are at the core of most exploration target ranking schemes and include a complete array of process factors of ore-formation, products of the mineralisation process, characteristics of the regional and local geology and structure, inferences about the tectonic setting and grade and tonnage data. However, the weakness of these models is that they tend to focus on the differences between deposit types rather than emphasise similarities that can be used as predictive variables when targeting. It has been recognised more recently that mineral deposits are the focal points of much larger systems of energy and mass flux, similar to those described for petroleum systems (Wyborn et al., 1994; Kreuzer et al., 2008; Hronsky and Groves, 2008). The mineral systems approach is essentially an adaptation of the petroleum systems approach. Even though mineral systems are generally thought of as being more diverse and complex than petroleum systems, the critical parameters of ore deposit formation can be reduced to those geological factors that control the generation and preservation of mineral deposits, the processes that are involved in mobilising ore components from a source, transporting and accumulating them in more concentrated form and then preserving them throughout subsequent geological history. Ore deposit formation is precluded where a particular mineral system lacks one or more of these essential components. Being process-based, the application of the mineral systems approach is neither restricted to a particular geological setting nor limited to a specific ore deposit type; indeed, the flexibility of this approach allows for multiple ore deposit styles to be realised within a single mineral system, thereby acknowledging the inherent natural variability among ore bodies. Applied to mineral exploration, the mineral systems approach requires identification at various scales of the critical ore-forming processes and ingredients that can be mapped that characterise a particular mineral system. These diagnostic features can then be used as guides in area selection and exploration targeting using spatial data modelling.

A variety of tools and techniques are now available that when used with computer based geographic information systems (GIS) allow mineral prospectivity and economic risk analysis to be carried out, including assessing uncertainty (e.g., Henley, 1997; Partington and Sale, 2004; Kreuzer et al., 2008; Hronsky and Groves, 2008). The oil industry has been using similar techniques successfully for a number of years. More recently, the mineral exploration industry has taken this approach further and with the help of spatial data modelling in GIS it is now possible to measure the probability of exploration success in relation to project economics in an objective way, using techniques such as Fuzzy Logic, Weights of Evidence and Neural Networks. Spatial data modelling is a rapidly developing predictive technique that is increasingly being used in geology (e.g. Bonham-Carter 1994; Bonham-Carter et al. 1988; Agterberg et al. 1993; Raines, 1999; Partington 2000; Partington et al., 2002; Tangestani and Moore, 2003), other spatially based sciences such as Archaeology (Mensing et al., 2000) and by government organisations such as New Zealand Petroleum and Minerals; the New Zealand Ministry of Economic Development (Partington et al., 2001; Partington et al., 2002), United States Geological Survey (Boleneus et al., 2001; Mihalasky, 2001) and the Canadian Geological Survey (Bonham-Carter et al., 1988) for resource assessment. There are a growing number of mineral exploration companies who now believe that by using such modern statistical techniques and state of the art ore deposit models it is possible to

add the greatest value to mineral assets and increase the probability of discovery of new mineral resources (Bonham-Carter et al. 1988; Partington et al., 2001; Partington and Sale, 2004; Partington and Mustard, 2005; Archibald and Holden, 2009; Partington 2010).

The exploration strategy being followed in Argentina for minerals is to use the mineral systems concept to constrain weights of evidence modelling to identify prospective regions for metal deposits at a regional scale. These national scale targets are then followed up with more detailed data collection from historic sources and in the field to develop more detailed prospect scale prospectivity target maps. Weights of Evidence modelling requires the creation of a variety of predictive maps for a particular mineral system style, based on the relevant mineral system model. These predictive maps are then statistically analysed using training data to test their predictive capacity, which allows the calculation of a spatial correlation value or weight (e.g., Bonham-Carter, 1994; Partington and Sale, 2004). In this case, the training data were drawn from the mineral occurrence database using the locations for hard rock mineralisation. The predictive maps are then combined using the weights to calculate the probability of undiscovered mineral resources over a regular grid (e.g., Bonham-Carter 1994).

The particular mineral systems of interest and permissive geology are not constrained by national or international borders; consequently both Chile and Argentina were included in the study area (Figure 1 and Figure 2). A review of the mineral occurrence database was carried out to identify the mineral systems that were to be used to guide the spatial data modelling. The most important mineral systems with an appropriate number of training data for modelling were determined to be:

- Porphyry copper, gold, molybdenum
- Low sulphidation epithermal gold silver
- High sulphidation epithermal gold silver
- Skarn iron, copper and gold
- Granite related gold, tin, tungsten, base metal and uranium.

The mineral system concept (e.g., Wyborn et al., 1994) was then used to develop relevant predictive maps for use in Weights of Evidence modelling. Predictive maps for possible sources of metals for the five mineral system styles come from the spatial relationship of the various intrusive complexes in the region and co-magmatic volcanic rocks. These lithologies have been mapped throughout the study area and have a range of ages of formation. The spatial relationship of these intrusives to the various training data has been used to create predictive maps for sources of heat and metals. The fluids and metals within a mineral system have to be able to migrate in a focussed way to a site of deposition for economic quantities of metals to be present. The main fluid pathways that are important in this case are provided by syn-intrusive and syn-volcanic faults and mapped alteration. The gravity data and national scale DTM are particularly useful datasets for interpreting the location of structures that may have acted as fluid pathways for mineralising fluids. Metals in the mineral systems are deposited when metal rich hydrothermal fluids become oversaturated in metal compared to the fluids carrying capacity. This may be due to variations in pressure or temperature and is due to chemical reactions between the fluids carrying the metals and host rocks. Consequently, the main regional controls (trap) on mineralisation are structural and chemical relative to erosion level. This can be mapped from geological information, including geochemistry, veining, structure, alteration, host rock geochemistry and host rock competency. The efficiency of the processes controlling the deposition of the metals of interest in a mineral system is critical to the grade and continuity of economic mineralisation in any ore deposit. Many of the controls on metal grade are also directly and indirectly related to the lithological and structural traps present as well as fluid chemistry and physics. The best evidence for the efficiency of metal distribution comes from geochemical anomalism for gold, copper, molybdenum, silver, tin, tungsten, lead and zinc in stream sediment, soil, rock and drill samples. There is also evidence that some of the mineral system styles are associated with magnetite and pyrrhotite alteration and should consequently be associated with magnetic anomalies. If present these would be a direct measure of the scale of mineralisation.

A Weights of Evidence model was created for each of the five mineral system styles, using predictive maps that represent all stages of the mineral system model. The predictive maps for the models were chosen as having the best regional coverage, a significant spatial association with the mineral system model being considered and where possible not to duplicate predictive map patterns. The predictive maps were added after the map values for each cell were weighted by their W+ and W- spatial correlation values. The model was developed using Arc-SDM software through Spatial Analyst in ArcGIS 9.2 (Sawatzky et al., 2008). The modelling produced up to five grids that calculate the posterior probability (an estimate of geological potential) and various measures of uncertainty and a grid response map containing the intersection of all of the input themes in a single integer theme called a unique conditions grid. Each row of the attribute table contains a unique row of input map values. The variances of the weights and variance due to missing data are summed to give the total variance of the posterior probability in these maps.

Various measures to test the conditional independence assumption were made, confirming that conditional dependence is an issue in all of the models. Most geological datasets and geochemical data sets have some form of interrelationship that may lead to an over emphasis of prospective areas. Consequently, the posterior probabilities in the models should be thought of as relative rankings rather than actual probabilities of finding an ore body. The predictive capability of each model was also tested statistically by creating efficiency curves of the post probability map grid from the modelling with the training data and all mineral occurrences in the study area; some of which were not used in the initial modelling.

The Weights of Evidence modelling has successfully modelled, at an international scale, the probability of the five mineral system styles of mineralisation in Argentina and Chile for each grid cell in the study area. All the prospectivity maps highlight the importance of geology, geochemistry and alteration maps as predictors of mineralisation, with alteration, geology and structure particularly important. Some of the areas that are geochemically anomalous also have geophysical signatures and alteration that would be expected with the style of mineralisation. The Weights of Evidence models also map accurately those areas that have similar predictive geological variables to known mines. All cells with post probability values above the prior probability have at least one or more of the predictive variables present and therefore have an increased probability of hosting a mineral deposit. The final stage of the modelling will now involve reclassifying the model grid to define high priority exploration targets for the various mineral systems modelled. This will be done by using the prior probability as a lower cut-off and the post probability values calculated for the economic mines in the region as an upper threshold.

Spatial data modelling techniques, where individual predictor themes of geology geochemistry and geophysical data are combined into a single predictive map, are particularly useful when targeting mineralisation in Argentina. Geological data have proved to be fundamental predictors of mineral occurrences in all predictive maps and the model developed to date. An understanding of the structure and temporal development of the geology of an area is critical, especially at a prospect scale. The benefits of carrying out this type of analysis include effective data compilation, QC of digital data, understanding of critical geological factors to be used in follow-up exploration, ranking of prospects, prioritising exploration, exploration budgeting and management, understanding of risk and cost reduction. The Weights of Evidence technique is particularly useful for mineral exploration, as it is possible to derive the data and weights that contribute to any area with high probabilities from the predictive map theme. This allows the exploration manager to identify those geological, geochemical or geophysical data themes that are the best predictors of mineralisation. More importantly it allows the identification of missing data in areas of lower probabilities that if collected could increase the prospectivity of the area. The Weight of Evidence technique needs to be combined with economic factors to allow a complete understanding of exploration risk to be measured. This allows targets with differing geology, amounts of metal and economic factors to be compared and prioritised. The work in Argentina and Chile confirms the potential for new discoveries in the region, which at higher metal prices make attractive exploration targets.

## 7. The Next Steps

The mineral system analysis of the mineral occurrence database identified an additional two mineral system styles of mineralisation that are less common in the region but could be economically valuable if found. Because there are less mineral occurrences these mineral systems are more difficult to model using weights of evidence techniques. Consequently, Fuzzy Logic techniques are more appropriate for assessing geological potential. Future work will therefore include two Fuzzy Logic prospectivity models for Orogenic Gold and Iron Oxide Copper Gold mineralisation.

The modelling carried out in Argentina for wind and minerals provides a measure of the geological and wind potential, but does not take into account financial cost and return on any investment; consequently the economic risk of development is unknown. It is possible to calculate the economic risk by combining the geological and wind probability values with the cost and reward from development (e.g., Kreuzer et al., 2007, Partington, 2010). This can be done for each target defined by the prospectivity modelling or other targeting methodology to develop a district wide exploration risk profile for each target. The probability of geological success has been calculated by the Weights of Evidence modelling, the probability of discovering chosen tonnes and grade can be calculated from grade tonnage curves and cost and revenue data can be derived from historic information updated for current costs and metal prices. The exploration risk can be calculated by multiplying the cost of exploration and development by the probability of failure and subtracting this from the NPV value of the project times the probability of success (Kreuzer et al., 2007). This allows the identification of the highly prospective targets that have the best returns in an exploration portfolio.

A database of exploration targets is being developed for Argentina that lists the geological predictive variables and geological potential for each targets. A list of economic parameters will also be developed for each target, including potential target tonnes and grade ranges, metal prices, operating costs based on distance to local treatment facilities and whether a deposit is likely to be an open cut or underground operation, production rate, exploration costs based on logistics and likely capital costs. These will then be combined with the geological probability values to estimate mine life, margin, NPV and the exploration risk for each target. The economic risk analysis assumes minimum, likely and maximum input variables which when simulated allow the calculation of the uncertainty of the outcome, which in this case is estimated NPV and exploration risk. The economic and geological data can then be simulated using Monte Carlo techniques to calculate the chance of a positive NPV and positive exploration risk for each target. The target areas can then be sorted and mapped according to positive and negative exploration risk. A similar analysis will be carried out for the wind targets. This will lead to the development of an Argentina wide database of prioritised metal and wind energy targets for exploration and development. The prioritised targets will then be combined with social and logistical factors to highlight projects for acquisition.

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