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The use of location–allocation techniques for exploration targeting of high place-value industrial minerals: A market-based prospectivity study of the Spanish gypsum resources

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ABSTRACT

Prospectivity mapping is used to define favorable areas for mineral exploration. The location–allocation modeling can help in ranking exploration zones for high-volume low-price industrial minerals. This type of minerals are said to have a high place-value, meaning that they derive much of their value from the fact that extraction points are located close to the demand points. With this aim, a GIS-based location–allocation model of the gypsum resources in Spain is presented in this paper. Results point to the recognition of the most interesting areas that should be investigated and places where new gypsum facilities could be located. Moreover, the model allows evaluation of the relative economic interest of the new areas as compared with the existing ones.

Based on this modeling, the geological regions with the greatest potential to place new facilities are located in the northwestern (Cantabrian zone) and north-eastern (easternmost Catalonia) parts of the Iberian Peninsula, with potential market share values higher than 5.25%. Most of the economically interesting gypsum bearing units in these regions are of Mesozoic age, although Neogene deposits of the central part of Catalonia are not ruled out. In addition, the prospectivity analysis map leads to establish an area where the excess of gypsum factories results in a drastic decrease of the market share value within this region (<1.84 %).

The maps obtained with this prospectivity analysis help in the area selection and the target identification phases of a mineral exploration. The model could easily be used for other similar high place-value industrial minerals and rocks.

1. Introduction

In this study we implement location–allocation mathematical methods on public available geologic, demographic, environmental and industrial datasets to delineate prospective gypsum zones in Spain. At the beginning of any mineral exploration activity the selection of an area is a key step (Lord et al., 2001). Rio Tinto Exploration plc (2011) structures exploration in five consecutive phases: (1) Area Selection (where to explore); (2) Target Identification (determine whether a deposit may exist); (3) Target Testing (assessing the nature of mineralization); (4) Resource Delineation (determining deposit size, grade and metallurgy) and (5) Resource Evaluation (judging whether a deposit will be economical). Prospectivity studies are a powerful tool used in the Area Selection and Target Identification phases of the exploration.

Mineral prospectivity is a predictive tool that can minimize the technical and financial risks associated with the decision making in the mineral industry (Porwal and Kreuzer, 2010). It is commonly used for exploration targeting at regional to camp scale. Prospectivity mapping, as decision-support tool, permits to prioritize exploration targets based on the modeled prospectivity of the areas containing such target zones. Geographical information systems (GIS) provide the framework to apply spatial data analysis techniques (weights of evidence, logistic regression, fuzzy logic, location–allocation, etc.) for prospectivity mapping by integrating exploration parameters such as geology, geochemistry, geophysics, land use, etc.

High-bulk low-price industrial minerals and rocks derive much of their values from extraction points being located close to the demand points, and therefore they are said to have a high place-value (Bates, 1960). For this type of industrial minerals, the quarry location determines the success or failure of the activity because of the high impact of the transport cost in the final price. Industrial minerals were grouped by Barker and McLemore (2004) depending on the transport effects on delivered costs. Gypsum, together with common clay, crushed stone, limestone and dolomites, sand and gravel, form the group named “Very High Transport Cost Importance”. These industrial minerals are only mined at points where the interaction of transport distance, geology and markets are best integrated.

Gypsum is one of the most employed industrial mineral/rock. It was the eighth largest mineral commodity produced in the world in

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2010 and 2011, after aggregates, cement, iron ore, lime, salt, bauxite and phosphate rocks. World production of gypsum for these years was estimated at 147 and 148 million tons respectively (Salazar and McNutt, 2012). This rock is mainly used by the construction industry, for wallboard and plaster products manufacture, cement production, and, in a lower proportion, in agriculture, pharmacy and chemicals (Salazar and McNutt, 2012).

In Spain, gypsum is one of the most abundant outcropping rocks. The total area of the gypsum-bearing unit outcrops of Spain is 21,077 km^2, representing 4.2% of the total country surface (Escavy et al., 2012). The National Plan of Gypsum Exploration made by the Spanish Geological Survey (IGME) estimated gypsum possible resources in Spain to be above 60,000 million tons (Regueiro and Calvo, 1997). The Spanish mine production of ~7 million tons in 2010 (Minetur, 2012b) made this country the leading European gypsum producer, ranking fifth in the world, after China, Iran, United States and Thailand. About 2.7 million tons of the mined gypsum were exported in 2010, mostly to the United Kingdom (18.1%), Venezuela (13.7%), Nigeria (12.2%) and the United States (7.4%). The remaining exported rock (48.6%) was sent to 42 other countries (Mineco, 2012).

Several authors have analyzed prospectivity for different ores such as gold (Fallon et al., 2010; Joly et al., 2012), uranium (Kreuzer et al., 2010), nickel (González-Álvarez et al., 2010; Markwitz et al., 2010; Porwal et al., 2010), Pb–Zn (Feltrin, 2008), copper (Abedi and Norouzi, 2012), etc. The analyses are mostly made by weights-of-evidence (Agterberg et al., 1990; Bonham-Carter, 1994), and weighted logistic regression methods (Agterberg, 1989; Agterberg et al., 1990, 1993).

In the case of high-bulk, low unit-value industrial minerals, Robinson et al. (2004) and Robinson and Larkins (2007) made a prospectivity analysis for crushed-stone aggregate quarry development in North and South Carolina (USA) using these methods. They had as predictive variables the bedrock map units having appropriate quality for aggregates, the proximity to principal highways and railroad lines, and the population density. Their results showed that the lithology was the variable with more influence in the results, followed by the transportation and population density. The implementation of GIS assessing the relative magnitude of geographic and geologic factors to constrain the location of a quarry (in this case, limestone for cement production) permitted Kendall et al. (2008) to establish the rock quality, the land sterilization and the overburden thickness as the main constraining factors. No prioritization of areas to exploit was presented in any of these works.

These prospectivity studies covering high place-value industrial rocks take into account the distance to the closest road or railroad, but not the total distance to final markets. In the same manner, they do not take into account the location of other facilities acting as competitors. The success of a high place-value operation is dependent on the number and location of competitor facilities and the distance of each of them to markets. The prospectivity exploration criteria seem to depend on the unit value of the target: high unit-value ores use geology as the main exploration criteria, while low unit-value ores prospectivity studies take also into account geographical factors. We consider that market factors should, as well, be included in prospectivity analyses for high place-value minerals and rocks (Fig. 1), and the present work incorporates this new factor into a prospectivity analysis of the Spanish gypsum resources.

Location–allocation modeling estimates the optimal location of facilities, based on potential market capture of each location by the analyses of parameters such as location and demand of the customers, transport costs, etc. The location–allocation model may be directly exploited by the field exploration crew or incorporated as an additional decision variable in a conventional prospectivity analysis, together with other geological and demographical parameters.

So far, location–allocation techniques have not been applied for industrial mineral prospectivity, and no previous research papers have been found in the literature. Malczewski (2006) searched and reviewed the scientific literature dealing with GIS-based multicriteria analysis (GIS-MCDA) until 2004. This author found that only 9 out of a total of 319 papers (2.8%) dealt with geology research, and none of these 9 papers was a location–allocation study.

2. Location–allocation analysis

In a competitive facility location model, in order to maximize market share, facilities attempt to serve as many customers as possible. Therefore, the main objective of any industrial site location–allocation analysis is to select a certain number of optimum locations to place facilities, and then allocate customers to each of them (Sule, 2001). There are three types of location analysis: (1) Continuous location theory, where the facility can be placed anywhere; (2) Discrete models, where the facility is placed at some discrete location; and (3) Network analysis, where the facility is positioned within a network. The former option is the most suitable for the industrial minerals sector whose products are transported through various networks such as road, railway, rivers, etc.

Location–allocation modeling was first proposed in the seventeenth century, when it was treated as a basic Euclidean spatial median problem (Farahami and Hekmatfar, 2009). Johan Heinrich von Thünen (1783–1850) looked for a strategy of facility location based on cost minimization dependent on distance and transport cost (Lambert, 1998). The location theory started formally in 1909, when Alfred Weber considered where to locate a single warehouse, lowering transport cost by minimizing distance to customers. The facility location problem with concurrent was first proposed by Hotelling (1929), who studied market capture by locating servers, and suggested that customers patronize the closest facility (*the beach ice-cream vendor problem*).

With the arrival of computers in the mid-1960s more realistic models and algorithms were produced (Hakimi, 1964; Revelle and Laporte, 1996). Huff (1964, 1966) suggested that customers divide their patronage among the competing facilities according to a gravity-based formula: the probability that a customer selects a certain facility is proportional to its attractiveness and inversely proportional to a power of the distance to that facility. The gravity model defines, for each customer, a probability distribution of patronage for all the facilities in the area. Once this probability distribution is known, the market share of each facility can be evaluated by a summation over all the customers in the area. Drezner (1982) solved the single facility location problem in the plane, whereas Hakimi (1983, 1986, 1990) formulated these problems on a network.

Current location strategies are of three different types, depending on the relative location of a facility to the demand points: (1) Market positioned, where the facility is located near the final customer; (2) Production positioned, where the facility is located close to the supply sources; and (3) Intermediately positioned, where the facility is located in an intermediate point between clients and supply sources (Lambert, 1998). Where raw materials lose much of their weight during the manufacturing process, factories are often placed as near to the raw material sources as practicable (Sule, 2001). The paradigm of this is the limestone used for cement manufacture, that, when calcined, loses 44% of its weight as CO_2. Placing cement factories far from the limestone quarry results in paying for the CO_2 transport to the plant. In the case of gypsum, weight lose can reach up to 20%, depending on the initial humidity of the rock and the degree of dehydration reached. This is why the plaster factories are usually placed close to the gypsum quarries.

Our research develops a methodology based on potential market capture, useful to select areas for detailed exploration of high place-value industrial minerals. The main parameters used in our facility location–allocation analysis are: available gypsum resources, location of current plaster factories and their associated gypsum quarries,