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Exploration feature selection applied to hybrid data integration modeling: Targeting copper-gold potential in central Iran

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ABSTRACT

A Sugeno-type fuzzy inference system is implemented in the framework of an adaptive neural network to map Cu–Au prospectivity of the Urumieh–Dokhtar magmatic arc (UDMA) in central Iran. We use the hybrid "Adaptive Neuro Fuzzy Inference System" (ANFIS; Jang, 1993) algorithm to optimize the fuzzy membership values of input predictor maps and the parameters of the output consequent functions using the spatial distribution of known mineral deposits. Generic genetic models of porphyry copper–gold and iron oxide copper–gold (IOCG) deposits are used in conjunction with deposit models of the Dalli porphyry copper–gold deposit, Aftabru IOCG prospect and other less important Cu–Au deposits within the study area to identify recognition criteria for exploration targeting of Cu–Au deposits. The recognition criteria are represented in the form of GIS predictor layers (spatial proxies) by processing available exploration data sets, which include geology, stream sediment geochemistry, airborne magnetics and multi-spectral remote sensing data. An ANFIS is trained using 30% of the 61 known Cu–Au deposits, prospects and occurrences in the area. In a parallel analysis, an exclusively expert-knowledge-driven fuzzy model was implemented using the same input predictor maps. Although the neuro-fuzzy analysis maps the high potential areas slightly better than the fuzzy model, the well-known mineralized areas and several unknown potential areas are mapped by both models. In the fuzzy analysis, the moderate and high favorable areas cover about 16% of the study area, which predict 77% of the known copper–gold occurrences. By comparison, in the neuro-fuzzy approach the moderate and high favorable areas cover about 17% of the study area, which predict 82% of the copper–gold occurrences.

1. Introduction

Geologically and economically meaningful exploration targeting requires (a) a clear understanding of ore-forming processes and relevant recognition criteria at the scale of prospectivity modeling, (b) good-quality exploration data sets with consistent coverage over the study area, (c) preprocessing of exploration data sets to extract appropriate spatial proxies (or predictor patterns) for the recognition criteria, and lastly (d) selection of appropriate models for weighing the spatial proxies and integrating them. However, most published literature on prospectivity modeling focuses only on the last aspect — mathematical models. A variety of data integration models and their applications are described in the literature. Some of these models rely on expert knowledge for weighing spatial proxies while others use some measure of spatial association of known deposits with the spatial proxies; accordingly they have been broadly classified into knowledge-driven and data-driven. Fuzzy logic (e.g., An et al., 1991; Bonham-Carter, 1994; Carranza and Hale, 2001a; Lusty et al., 2012; Yousefi and Carranza, 2015; Yousefi et al., 2013), fuzzy-AHP (Abedi et al., 2013), interval valued fuzzy sets topsis (Jafari Rad and Busch, 2011), Boolean logic (e.g., Bonham-Carter, 1994), index overlay (e.g., Bonham-Carter, 1994) and Dempster–Shafer belief theory (An et al., 1994a,b; Moon, 1990) are examples of knowledge-driven models used in mineral prospectivity. The most widely used data-driven models are weights of evidence (Asadi and Hale, 2000; Bonham-Carter et al., 1989; Ford and Hart, 2013), logistic regression (Carranza and Hale, 2001b; Mejía-Herrera et al., 2014), neural networks (Abedi and Norouzi, 2012; Porwal et al., 2004), evidential belief functions (Carranza, 2008, 2014; Carranza and Hale, 2003), Bayesian network classifiers (Porwal et al., 2006) and support vector machine (Abedi et al., 2012; Yu et al., 2012; Zuo and Carranza, 2011). Porwal et al. (2004) implemented a fuzzy inference system in the framework of neural network using the

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ANFIS algorithm developed by Jang (1993). This model used expert-knowledge for weighing the spatial proxies, but the weights were fine-tuned using a neural network that was trained on known mineral occurrences. Theoretically, this approach leads to an optimum utilization of both expert-knowledge and deposit distribution pattern.

The present study applies the ANFIS algorithm to copper–gold prospectivity modeling in the poorly explored Urumieh–Dokhtar magmatic arc (UDMA) in central Iran. The ANFIS results are compared with the results of pure knowledge-driven fuzzy modeling in order to verify if hybrid modeling does indeed lead to improved results. The model inputs (spatial proxies) are derived from regional geological, geochemical, magnetic, and Aster satellite imagery data sets on the basis of recognition criteria of porphyry copper–gold, IOCG, hydrothermal Cu–Au vein and skarn mineralizations.

2. Study area

The study area is a sparsely vegetated, semi-arid, mountainous region that covers some 13,600 km^2 of the central part of the UDMA in central Iran (Fig. 1). The UDMA is the most important volcanic arc of Iran that extends about 2000 km in a NW–SE direction in the central part of the Tethyan metallogenic belt. This arc hosts world class porphyry copper deposits such as Sar-Cheshmeh, Songun, Meiduk, Kahang, Darezar, Darreh-Zerreshk and Dalli (Ayati et al., 2013; Hezarkhani, 2006; Hezarkhani and Williams-Jones, 1998; Shafiei et al., 2009). Most of these deposits are either located in the southeast or northwest of the UDMA belt. The central UDMA is a frontier region with high mineral potential (Afshooni et al., 2013; Ayati et al., 2013; Azadi et al., 2014) for which an innovative regional exploration approach is required. Dalli porphyry Cu–Au deposit and Aftabru IOCG prospect are the two prominent copper and gold mineral systems in the central UDMA (Ayati, 2009; Ayati et al., 2013; Soltani and Asadi, 2013).

3. Geodynamic and metallogenic setting of UDMA

The Zagros orogenic belt of Iran is part of the central Tethyan region, located between the Arabian and Eurasian plates. The Tethyan metallogenic belt extends across central and southeast Europe, Turkey, Iran, Pakistan, through the Himalayan region and southeast Asia. A number of large deposits have been discovered in the central Tethyan belt, which passes through Turkey, Iran and Pakistan, even though the belt is relatively poorly explored and is difficult to access. Some of the world class deposits in the belt include Sar-Cheshmeh porphyry Cu deposit (1.2 Gt @ 0.7% Cu), Sungun porphyry Cu deposit (500 Mt at 0.75% Cu), Sari Gunay epithermal Au deposit (58 Mt @ 1.8 g/t Au), Zarshuran Carlin-type Au deposit (11 Mt @ 5.4 g/t Au), Dalli porphyry Cu–Au deposit (17 Mt @ 0.53% Cu and 0.65 g/t Au) and Chahezard epithermal Au deposit (5 Mt @ 2.5 g/t Au and) in Iran; Reko Diq porphyry Cu–Au deposit (2.2 Gt @ 0.53% Cu and 0.3 g/t Au) and Sandyk porphyry Cu deposit (412 Mt @ 0.4% Cu) in Pakistan; and Copler epithermal Au deposit (95.4 Mt @ 1.4 g/t Au) and Kisladag epithermal Au deposit (153 Mt @ 1.12 g/t Au) in Turkey. These deposits

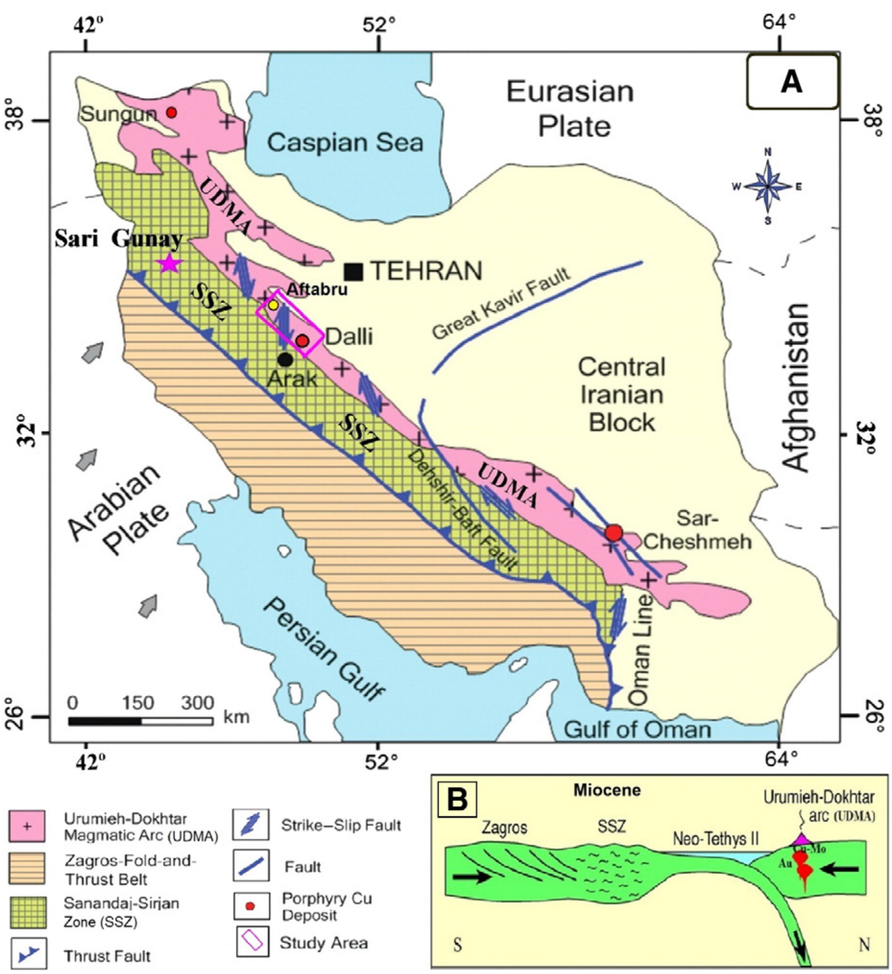

Fig. 1. (A) Map showing the study area in UDMA and other major geological subdivisions of the Zagros orogenic belt of Iran (modified from Zarasvandi et al., 2005). (B) Subduction of Neo-Tethys ocean to the north beneath central Iran, giving rise to the formation of UDMA and porphyry mineralization (modified after Glennie, 2000).