Journal of Asian Earth Sciences 125 (2016) 1–21

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Full length article

Geology, ore facies and sulfur isotopes geochemistry of the Nudeh Besshi-type volcanogenic massive sulfide deposit, southwest Sabzevar basin, Iran

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ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form 24 April 2016
Accepted 26 April 2016
Available online 26 April 2016

Keywords:
Besshi-type VMS
Sulfur isotope
Late Cretaceous
Southwest Sabzevar basin
Iran

ABSTRACT

The southwest Sabzevar basin is placed in the southwestern part of a crustal domain known as the Sabzevar zone, at the north of Central Iranian microcontinent. This basin hosts abundant mineral deposits; particularly of the Mn exhalative and Cu-Zn volcanogenic massive sulfide (VMS) types. The evolution of this basin is governed by the Neo-tethys oceanic crust subduction beneath the Central Iranian microcontinent and by the resulting continental arc (Sanandaj-Sirjan) and back-arc (Sabzevar-Naien). This evolution followed two major sequences: (I) Lower Late Cretaceous Volcano-Sedimentary Sequence (LLCVSS), which is indicated by fine-grained siliciclastic sediments, gray basic coarse-grained different pyroclastic rocks and bimodal volcanism. During this stage, tuff-hosted stratiform, exhalative Mn deposits (Nudeh, Benesbourd, Ferizy and Goft), oxide Cu deposits (Garab and Ferizy) and Cu-Zn VMS (Nudeh, Chun and Lala) deposits formed. (II) Upper Late Cretaceous Sedimentary Dominated Sequence (ULCSS), including pelagic limestone, marly tuff, silty limestone and marl with minor andesitic tuff rocks. The economically most important Mn (Zakeri and Cheshmeh-sefid) deposits of Sabzevar zone occur within the marly tuff of this sequence. The Nudeh Cu–Zn volcanogenic massive sulfide (VMS) deposit is situated in the LLCVSS. The host-rock of deposits consists of alkali olivine basalt flow and tuffaceous silty sandstone. Mineralization occurs as stratiform blanket-like and tabular orebodies. Based on ore body structure, mineralogy, and ore fabric, we recognize three different ore facies in the Nudeh deposit: (1) a stringer zone, consisting of a discordant mineralization of sulfides forming a stockwork of sulfide-bearing quartz veins cutting the footwall volcano-sedimentary rocks; (2) a massive ore, consisting of massive replacement pyrite, chalcopyrite, sphalerite and Friedrichite with magnetite; (3) bedded ore, with laminated to disseminated pyrite, and chalcopyrite. Chloritization, silicification, sericitization and epidotization are the main wall-rock alterations; alteration intensity increases towards the stringer zone. The $\delta^{34}S$ composition of the sulfides ranges from −1.5‰ to +3.69‰ with a general increase of $\delta^{34}S$ ratios of massive ore facies to stockwork zone. The heavier values indicate that some of the sulfur was derived from seawater sulfate that was ultimately thermochemically reduced in deep hydrothermal reaction zones. Sulfur isotopes, along with sedimentological, textural, petrological, mineralogical, and geochemical evidences, suggest that this deposit should be classified as a Besshi-type VMS ore deposit.

1. Introduction

Volcanogenic massive sulfide (VMS) deposits are widespread and of significant economic importance, especially for Cu, Zn and Pb. The deposits occur as various types, mainly in two tectonic settings: ocean-spreading centers dominated by basaltic magmatism and magmatic arcs characterized by bimodal magmatic rocks (Franklin et al., 2005).

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http://dx.doi.org/10.1016/j.jseaes.2016.04.022
1367-9120/

Volcanogenic massive sulfide deposits are important sources of base metals in Iran, and previous mineralogical and geochemical studies have revealed five different types of sulfide deposits, following the classical nomenclature proposed by Franklin et al. (2005). The most important VMS deposits include the Bavanat Cu-Zn-Ag deposit (pelitic-mafic or Besshi-type) (Mousivand and Rastad, 2005; Mousivand et al., 2007), the Sargaz Cu-Zn deposit (bimodal-mafic or Noranda-type) (Badrzadeh et al., 2011), the Chahgaz Zn-Pb-Cu deposit (silicoclastic-felsic or Bathurst-type) (Mousivand et al., 2011), the Barika gold-rich deposit (bimodal-felsic or Kuroko-type) (Yarmohammadi, 2006), and the Sheikh Ali Cu deposit (mafic or Cyprus Type) (Rastad et al., 2002) (Fig. 1).

The Nudeh copper deposit is located 95 km to the southwest of Sabzevar city, northeastern Iran. It has been described as a VMS deposit (Maghfouri et al., 2011), exposing a 3–5 m-thick and 900 m-long mineralized orebody. The deposit contains approximately 2 Mt of ore grading 2–4% Cu, and up to 100 g/t Ag. It has been mined discontinuously from ancient times until to the present day. The Nudeh deposit is both stratabound and stratiform, and occurs within a bimodal volcano–sedimentary sequence (Fig. 2) (Maghfouri, 2012). Based on stratigraphic constraint and regional geology, the Nudeh host sequence is Lower Late Cretaceous (Maghfouri, 2012).

Previous studies of the area include general geological, petrographical and petrological aspects of the Upper Cretaceous igneous host rocks as well as of the associated Benesbord Mn mineralization (Masoudi, 2008; Vahdati Daneshmand, 1999). As a result of field and petrographic studies conducted in the 1995s and 2005s (Bani-Adam and Badakhshan, 2000), the Nudeh deposit was classified as a sedimentary-exhalative massive sulfide deposit. Maghfouri (2012) studied the Nudeh deposit, which is located in the southwestern part of the Sabzevar basin (Fig. 1), and classified it as a bimodal pelitic-mafic (or Besshi type) VMS deposit model (cf. Franklin et al., 2005). He further proposed that the formation of VMS deposits in this basin is related to the evolution of an extensional continental margin in a back-arc environment that affected the Central Iranian Microcontinent. Despite the above-mentioned genetic models for base–metal mineralization in the southwest Sabzevar basin, detailed information on the ore geology of its deposits is lacking in the international literature. The aim of this paper is to provide an integrated type of deposits, metallogenic model, at the regional scale, for the VMS Cu–Zn mineralizations in the southwest Sabzevar basin, based on an accurate revision of recent geological data, sulfur isotope composition of the Nudeh deposit and on a tectono-sedimentary interpretation of the host sequence (the Lower Late Cretaceous Volcano-Sedimentary Sequence; LLCVSS) and of the host basin. In addition, the geological factors controlling the VMS Cu-Zn metallogenesis and key questions explaining when, where and why these mineralizations formed are proposed and discussed in this study.

2. Outline of the geology of the Nudeh deposit

The Nudeh Cu deposit is located in the northeastern segment of the Sabzevar zone (SZ), between the Central Iranian Microcontinent (CIM) to the south and the Kopeh Dagh sedimentary basin to the north (Fig. 2). The basement of the SZ consists of Precambrian metamorphic rocks (Taknar Formation) covered by Paleozoic epicontinental sedimentary rocks (Fig. 2). In the SZ, the Sabzevar ophiolitic complex is the largest one in northeastern Iran extending over 150 km length and 10–30 km wide (Fig. 2). The post-ophiolitic rocks in northeast SZ consist of a thick sequence of Tertiary andesitic and dacitic lavas, tuffs, agglomerates, minor limestone, sandstone, and evaporite beds (Emami et al., 1993).

The ore deposits of the eastern segment of the SZ can be separated into three groups, showing different metal associations, spatial distributions and geodynamic settings (Fig. 2).

(1) The first group of mineralization is associated with Ordovician host rocks and characterized by the Taknar polymetal (Fe-rich) massive sulfide deposit (Malekzadeh, 2004).
(2) The Cretaceous mineralized orebodies consist of Cr ore deposits associated with serpentinized peridotites (Vatanpour et al., 2008), VMS deposits, and Mn ore deposits in volcano-sedimentary sequences (Rozbeh Kargar and Ghomian, 1997; Maghfouri, 2012).
(3) Paleogene mineralization in eastern segment of the Sabzevar zone includes porphyry deposits and Redbed-type Cu mineralizations hosted in sandy red marl.

The VMS mineralizations, as exemplified by the Nudeh deposit, the Kalateh Lala (Lala), the Fereizy, the Grab and the Chun occurrences, are exposed in the southwestern part of the Sabzevar basin (Fig. 3).

2.1. Stratigraphy of the southwest Sabzevar basin

The Sbzevar Basin is characterized by (1) the Lower Late Cretaceous Volcano-Sedimentary Sequence (LLCVSS), including fine-grained siliciclastic sediments and bimodal volcanics and pyroclastic rocks, and (2) the Upper Late Cretaceous Sedimentary Dominated Sequence (ULCSS), formed by pelagic limestone, marly tuff, silty limestone and marl (Figs. 3 and 4) (Maghfouri, 2012). To the southwest of the basin, the volcano-sedimentary sequences are deformed and form an anticline structure extending 8–14 km in width and about 100 km in length (Fig. 3). The overall strike of the structure is broadly SW-NE, parallel to the general regional trend of the Sabzevar zones (Maghfouri, 2012).

2.1.1. The Lower Late Cretaceous Volcano-Sedimentary Sequence (LLCVSS)

Representative stratigraphic columns of the southwestern part of the Sabzevar basin are shown in Fig. 4. In this basin, the LLCVSS (with an overall maximum thickness of 1320 m) unconformably overlies the Lower Cretaceous Formation (Maghfouri, 2012). It is typified by: (a) abrupt changes of facies and thickness, (b) wedge-shaped basin fill geometry, (c) bimodal volcanism, and (d) a typical rift-related sedimentary sequence. Maghfouri (2012) divided this sequence into three different units (Fig. 4).

(1) The LLCVSS starts with a basal sedimentary unit (Unit 1) that, to the S and SE of the Nudeh area, consists of shallow marine gray lithic tuff, rhyolite flow, andesitic tuff, andesite (hosting a Cu oxide mineralization in the Garab and Ferizy areas), red tuff (hosting Mn mineralization in the Nudeh, Benesbourd, Ferizy and Goft areas), trachyandesite, pillow lava and dacite porphyry (Fig. 4). This unit displays abrupt changes in thickness, reaching 630 m in the Nudeh syncline but tapers rapidly eastward, as it approaches the edge of the basin. Unit 1 includes bimodal mafic character, which comprises rhyolite, dacite, andesite and basaltic pyroclastic rocks (Fig. 4) (Maghfouri, 2012).
(2) Unit 2 includes a 390 m thick sequence of agglomerate, lapilli tuff, gabbro sill, alkali olivine basalt flow with minor tuffaceous silty sandstone (Fig. 4). The basalt flow laterally changes to tuffaceous silty sandstone, which hosts several VMS Cu-Zn orebodies (e.g., Nudeh, Chun and Lala). This ore-bearing level displays a variable thickness along the basin: 40–50 m in the Nudeh area, 20–30 m in the Chun area, and 25–35 m in the Lala area. According to Maghfouri