Age, tectonic setting, lithogeochemistry and hydrothermal alteration of volcanogenic massive sulfide mineralization in the Chahgaz region, South Sanandaj-Sirjan zone of Iran

Introduction

Iran hosts several volcanogenic massive sulfide (VMS) deposit types that occur within different tectonic assemblages formed during discrete time periods (Mousivand et al. 2008a). The most prospective area for VMS exploration in Iran is the Sanandaj-Sirjan zone (SSZ) (Fig. 1), particularly the southern part of this zone.

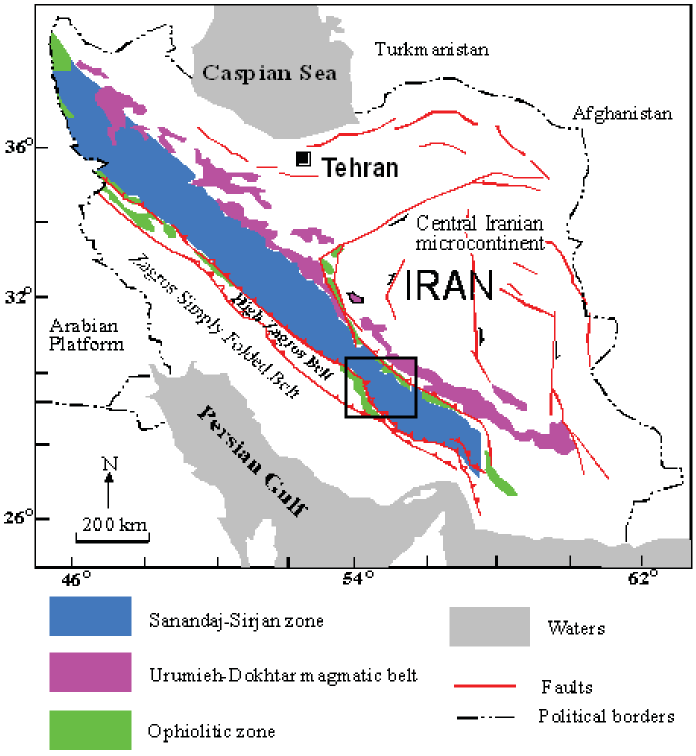

Figure 1. Tectonic element distribution map of the Zagros Orogen (Alavi 1994); black outline shows location of the Bavanat-Chahgaz region within southern SSZ shown in Figure 2.

The Chahgaz region of the SSZ (Fig. 2) is of the most important regions in the south SSZ for VMS exploration and hosts several deposits and occurrences, including the economically important Chahgaz Zn-Pb-Cu deposit (Fig. 2) which was first recognized as a VMS-type deposit by Mousivand et al. (2008b).

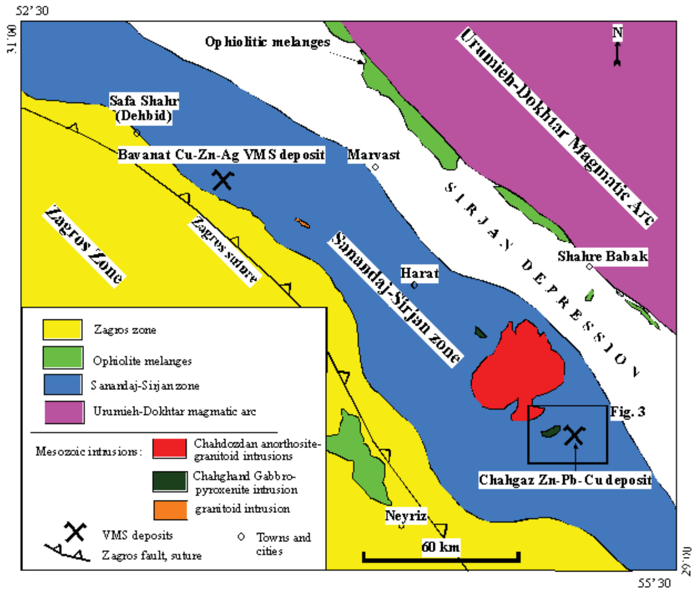

Figure 2. Simplified geological map of the Bavanat-Chahgaz region, based on the Eqlid, Anar and Neyriz 1:250000 scale maps (e.g. Houshmandzadeh & Soheili 1990; Soheili 1981; Sabzehei et al. 1993), showing the location of the Bavanat Cu-Zn-Ag and Chahgaz Zn-Pb-Cu VMS deposits within the SSZ. Black box shows location of the area shown in Figure 3.

Iran has an arid to semi-arid climate with much rock outcrop exposure. For this reason, surficial and lithogeochemical techniques are effective and commonly used in mineral exploration. Host rocks to the Chahgaz deposits are dominantly fresh to weakly weathered, and close to the deposits the rocks have been intensely hydrothermally altered.

Mining in Iran dates back to at least 5000 years B.C., and most mineral deposits in the country show indications of ancient mining (e.g. Momenzadeh 2004). The Chahgaz deposit, one of the largest VMS deposit in the country, was (re) discovered by tracing evidence of ancient mining activities, and modern mining at this deposit commenced in 2007.

Detailed geological and geochemical studies on the Chahgaz deposit were recently completed by Mousivand (2010). Host rock and mineralized samples were analyzed for major, trace and rare earth element contents by inductively coupled-plasma mass spectrometry and inductively coupled-plasma atomic emission spectrometry (ICP-MS/AES) methods at Acme Analytical Laboratories Ltd. (Vancouver, Canada). These data were used to determine rock type, petrotectonic setting, chemostratigraphy, hydrothermal alteration style

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and intensity, and sulfide metal zonation. Herein, we provide a brief synopsis of our research on VMS mineralization in the Chahgaz region, including its age, tectonic setting, metal zonation and wallrock alteration.

Tectonic setting

The Tethyan orogen was caused by the collision of Eurasia with Gondwanaland (Sengör & Natal'in 1996). The Zagros orogenic belt is part of the Tethyan orogen (e.g. Berberian & King 1981; Sengör 1991; Alavi 1994), and consists of four parallel tectonic assemblages from southwest to northeast: (1) the Zagros simply folded belt, (2) High Zagros belt; (3) the Sanandaj-Sirjan zone, and (4) the Urumieh-Dokhtar magmatic assemblage (Alavi 1994) (Fig. 1). The SSZ is 150-250 km wide and extends from the extreme northwest of Iran to the southeast for a strike distance of over a 1500 km (Fig. 1). The SSZ consists of regionally metamorphosed and deformed Mesozoic volcano-sedimentary rocks that are spatially associated with abundant deformed and undeformed Mesozoic plutons. Berberian (1983) considered the SSZ to be a paired Mesozoic magmatic-arc and Tertiary fore-arc.

VMS mineralization in the Chahgaz area

The Chahgaz region, situated in the southern part of the SSZ, encompasses an area 100 km by 50 km (Fig. 2). The Chahgaz Zn-Pb-Cu VMS deposit is located 60 km south of the city of Shahre-Babak and 174 km south east of the Bavanat Cu-Zn-Ag Besshi- or pelitic mafic-type VMS deposit, the only other economically significant VMS deposit in the area (Mousivand 2003; Mousivand et al. 2007; Mousivand et al. 2008b; Mousivand 2010; Fig. 2). The Chahgaz deposit occurs within a Middle Jurassic metamorphosed and highly deformed bimodal volcano-sedimentary sequence (Mousivand et al. 2010) (Figs. 3 and 4). The immediate host rocks to the deposit consist of rhyodacitic volcaniclastics and carbonaceous to tuffaceous shales (Fig. 4).

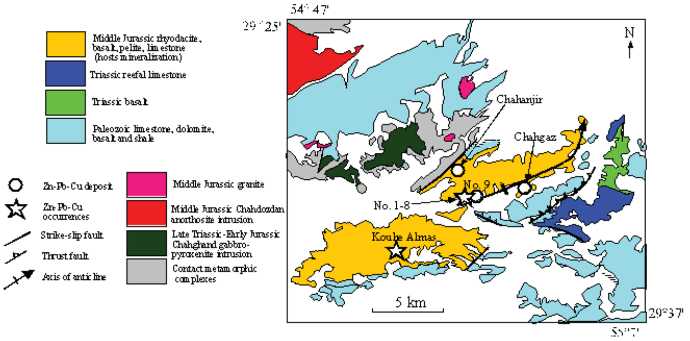

Figure 3. Geological map of the Chahgaz area (based on the geological map of Neyriz; modified from Sabzehei et al. 1993), showing the locations of the Chahgaz deposit and occurrences in the Chahgaz volcano-sedimentary complex.

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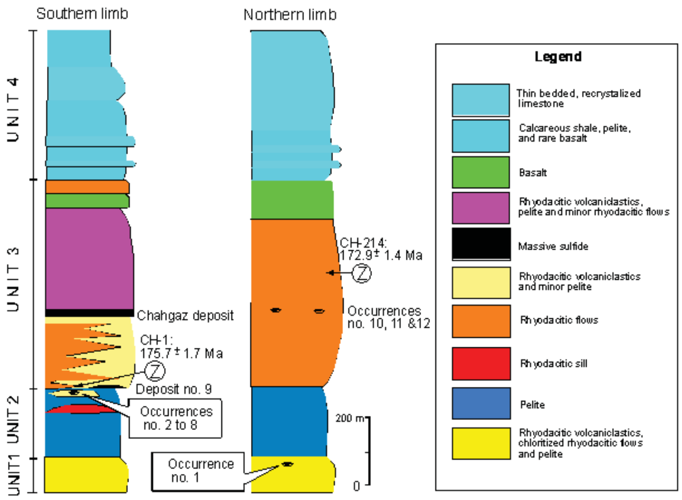

Figure 4. Schematic stratigraphic sections for the northern and southern limbs of the Chahgaz anticline. Z= U-Pb zircon sample locality.

The Chahgaz, Chahanjir and Number 9 deposits, and numerous other occurrences (Kouhe Almas, Occurrences 1 through 8) are characterized by stratabound and stratiform massive sulfide mineralization (Figs. 3 and 4), predominantly in the southern limb (Fig. 4) of the Chahgaz anticline. The Chahgaz ore horizon is 10-30 m thick and and has a strike length of over 1 km. The deposit contains approximately 6 Mt grading 15 wt.% Zn, 10 wt.% Pb, 1 wt.% Cu, up to 100 g/t Ag and up to 0.58 g/t Au (Mousivand 2010) and was delineated by induced polarization and resistivity ground geophysical surveys and surficial and lithogeochemical chip sampling surveys.

Mineralization at Chahgaz is comprised predominantly of stratiform, tabular and lenticular massive sulfide lenses that occur at a single stratigraphic horizon; each of these lenses is underlain by a vein network comprising a discrete feeder zone. Within the sulfide lenses, mineralization styles include massive, semi-massive, banded and laminated; in the feeder zones, the mineralization is disseminated and also occurs in veins. Mineralogy of the sulfide lenses is predominated by pyrite, sphalerite, galena, chalcopyrite, arsenopyrite, tetrahedrite, with minor bornite, pyrhotite, marcasite, and secondary covellite, malachite, cerussite, smithsonite, hematite and goethite. Massive sulfides consist dominantly of sphalerite and/or pyrite, whereas banded mineralization is comprised primarily of sphalerite-galena-, pyrite-, and minor chalcopyrite-rich bands. Gangue minerals are dominated by sericite, chlorite, quartz, calcite and minor barite. Semiconformable and disconformable pipe-like bodies of hydrothermally altered wall rock occur stratigraphically below the massive sulfides and these are sericite-rich, with minor chlorite-rich and silicified zones. Magnetite- and pyrite-rich hydrothermal sediments (exhalites) occur laterally away from the deposit lenses along the same mineralized stratigraphic horizon.

The orebodies and hydrothermally altered and unaltered host rock strata have all been deformed and show evidence of cataclasis and extension; banded and laminated mineralization has been boudinaged, crenulated and folded (Mousivand 2010). Two major regional metamorphic events and three main phases of deformation have been recognized in the area (e.g. Orang 2010). These Late Mesozoic to Cenozoic Barrovian-type metamorphic events occurred at upper amphibolite and greenschist facies, respectively. The two deformational events (D1, D2) have imparted two fabrics (S1, S2) (accompanied by local shearing) foliations in the rock sequences, respectively. A final (D3) shearing and mylonitic event overprinted the earlier foliations, imparting an S3 fabric. Finally, during the Cenozoic, extensional events fractured the rocks (Orang 2010).

Mineralogic and metal zoning

From the stratigraphic base to the stratigraphic top of the massive sulfide lenses, the mineral assemblages, listed in order of decreasing abundance, are: pyrite-chalcopyrite-arsenopyrite-pyrrhotite; pyrite-chalcopyrite-sphalerite-pyrite-tetrahedrite-arsenopyrite; sphalerite-galena-pyrite-chalcopyrite-tetrahedrite; and pyrite-chalcopyrite-sphalerite-galena. Chalcopyrite is generally more abundant in and near the stratigraphic base of the lenses, whereas sphalerite and/or galena are more abundant toward the stratigraphic top of the lenses. This is reflected by a decrease in Cu contents and an increase in Zn and Pb contents from the base to the top of the lenses. However, this metal zoning is not universally present as chalcopyrite is abundant in some banded ores.

Hydrothermal Alteration

Hydrothermal wallrock alteration in the rhyodacitic flows and volcaniclastic rocks and pelites occurs as: 1) semiconformable zones stratigraphically below and within the ore horizons and 2) disconformable or pipe-like zones stratigraphically beneath the orebodies. Alteration minerals include sericite, chlorite, phengite, quartz, pyrite, calcite, dolomite, ankerite, and the clay minerals halloysite, illite, montmorillonite and paragonite.

Based on petrographic studies, x-ray diffraction (XRD) analysis, and short-wavelength infrared spectrometry using a Portable Infra-red Mineral Analyzer (PIMA) (e.g., Herrmann et al. 2001), several wallrock alteration zones are recognized in the Chahgaz deposit. The composition of alteration minerals was determined by a Cameca SX 100 electron probe micro-analyzer (EPMA) at the University of Tasmania. Samples were collected at regular intervals from five cross sections perpendicular to the ore horizon. The following zonation is recognized in the alteration pipes, immediately below the orebodies and progressing peripherally outward from the distal edge of the massive sulfide lenses: 1) quartz-chlorite-sericite-phengite-pyrite; 2) chlorite-phengite-albite; 3) phengite-sericite-chlorite.

The proximal alteration is not extensive, but the chlorite-phengite-albite alteration typically occurs peripheral to the core of the feeder zone and also occurs up to 50 m stratigraphically above the ore horizon (in the hanging wall). The most widespread alteration style at Chahgaz is the distal

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(weakest) phengite-sericite-chlorite alteration zone that extends up to 200 m stratigraphically below and through the ore horizon, and more than 2 km along strike from mineralization. Chlorite compositions progress from Fe-Mg chlorites (16 wt% Fe) at the outermost margins of the alteration zones, to a more Fe-rich (21 wt% Fe) chlorite in the most intense core of the alteration pipe. Sericite is Ba-rich along the ore horizon and within the core of the alteration system. At the Number 9 deposit there is a carbonate-quartz-sericite-pyrite alteration zone developed in the stringer zone. This zone contains quartz-carbonate veins-veinlets and disseminated quartz, pyrite and sericite in a groundmass of Fe-Mg-rich carbonates. Carbonate minerals are predominantly dolomite and minor calcite.

Petrochemistry of volcanic rocks

Major, trace, and rare earth element analyses were conducted on representative least altered samples of the Chahgaz footwall and hanging wall felsic volcanic flows. Furthermore, because the volcanic and volcaniclastic rocks in the vicinity of the Chahgaz deposit are strongly altered, we have relied primarily on the immobile major element TiO2, the high field strength elements (HFSE) Zr, Nb and Y, and the rare earth elements (REE) to characterize the primary compositions. We have not used most of the major elements or low field strength elements (LFSE), which substitute for Na, K, and Ca, due to their potential mobility during hydrothermal alteration and metamorphism.

The host felsic volcanic flows plot in the rhyolite and dacite fields of the SiO2 versus Zr/TiO2 plot of Winchester and Floyd (1977). Furthermore, the volcanic rocks show dominantly subalkaline, rhyolitic compositions on this discriminant diagram (Fig. 5a), display calc-alkaline affinities on an Y versus Zr diagram of Barrett and MacLean (1999) (Fig. 5b), and indicate volcanic arc (I-type) character on the Nb versus Y plot of Pearce et al. (1984) (Fig. 5c). Chondrite-normalized (Sun & McDonough 1989) rare earth element (REE) profiles of the footwall and hanging wall rhyodacites from the Chahgaz host sequence are shown in figure 5d. REE patterns for the rhyodacites are steep, with only a small negative Eu anomaly (Fig. 5d), which suggests that little plagioclase fractionation took place (e.g. Cullers & Graf 1984). The primitive mantle-normalized patterns of the rhyodacites (Fig. 5e) show LREE enrichment and negative Nb, Eu, and Ti anomalies on a primitive mantle-normalized spider diagram of Sun and McDonough (1989); such Nb and Ti anomalies are characteristic of arc or subduction zone-influenced rocks (Murphy 2007). The rhyodacites have slightly concave upper continental crust-normalized (McLennan 2001) patterns, with variably developed Eu anomalies (Fig. 5f), likely indicating derivation from (or extensive interaction with) upper crust (e.g. Wood and Williams-Jones 1994).

U-Pb zircon geochronology

Age dating was conducted using a laser-ablation quadrupole ICP-MS at the University of Tasmania. Analyses were conducted using both laser and solution modes of the

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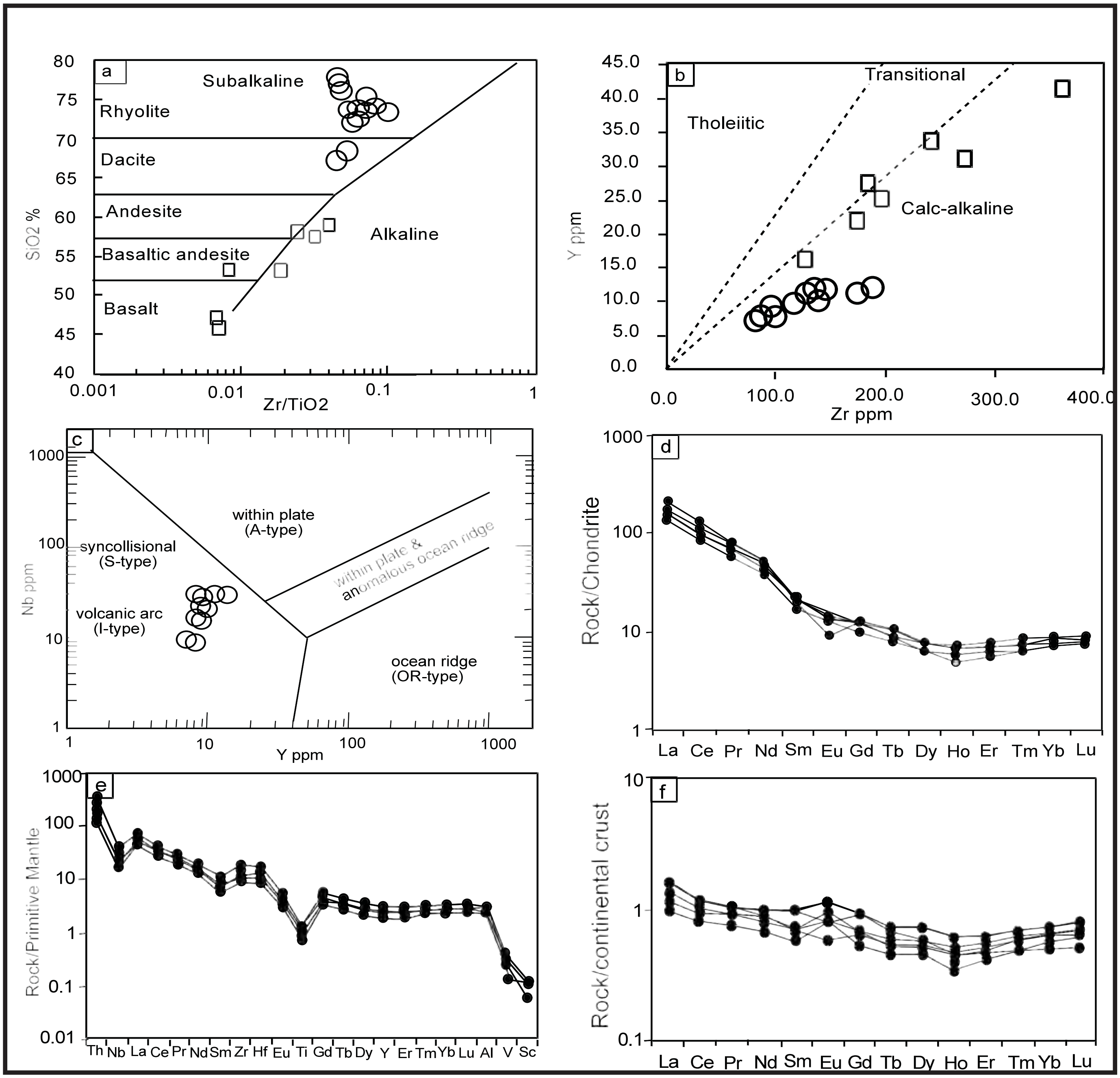

Figure 5. (a) SiO2 versus Zr/TiO2 diagram of Winchester and Floyd (1977), indicating rhyolitic composition for the rhyodacite samples (circles), and basaltic to andesitic composition for basalts (rectangles); (b) bivariate plot of Y versus Zr (after Barrett & MacLean 1999) showing dominantly calc-alkaline magmatic affinity for the footwall and hanging wall rhyodacite rocks of the Chahgaz deposit; (c) Nb versus Y plot (after Pearce et al. 1984) illustrating the volcanic arc-type (I-type) nature of the samples; (d) chondrite-normalized (Sun & McDonough 1989) REE plot of the footwall and hanging wall rhyodacites showing steep patterns, with only a small negative Eu anomaly for the rhyodacite samples; (e) Primitive mantle-normalized multi-element plots for the footwall and hanging wall rhyodacites (primitive mantle values from Sun & McDonough 1989) showing characteristic calc-alkaline patterns; and (f) upper continental crust-normalized REE plots for the footwall and hanging wall rhyodacite rocks (upper crust values from McLennan, 2001); the flat patterns relative to upper crust (f) indicate derivation from (or extensive interaction with) upper crust.

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instrument; for further details of the method, see Meffre et al. (2008). Three samples for geochronology were taken from both surface outcrops and underground workings of the Chahgaz deposit. Samples are from the stratigraphic footwall and hanging wall rhyodacitic flows from the southern and northern limbs (Fig. 4), respectively, as well as the host rhyodacitic volcaniclastic rocks. The sample from the footwall of the Chahgaz deposit is a feldspar porphyry flow which is at the same stratigraphic horizon as stratiform mineralization of the Number 9 deposit (Fig. 4). The sample 100 meters stratigraphically above the Chahgaz deposit ore horizon (Fig. 4) from the hanging is also from a feldspar porphyry flow.

The U-Pb dating of stratigraphic footwall and hanging wall rhyodacitic flows from the southern and northern limbs yield concordant ages of 175.7±1.7 Ma and 172.9±1.4 Ma, respectively. The age of the youngest zircon from the volcaniclastic host rock is 177.0±1.8 Ma, and the mean age of all zircons in the volcaniclastic host rocks is 184.45±0.91 Ma which indicates that the ore horizon is about 8.75 million years younger than the footwall. The ages of the stratigraphic footwall and hanging wall rhyodacitic flows show that VMS mineralization at the Chahgaz deposit formed between 175.7±1.7 and 172.9±1.4 Ma. However, the other deposits and occurrences formed at 175.7±1.7 Ma (deposit no. 9) and earlier (Number 1 through Number 8 occurrences; Fig. 4).

Collectively, the data give a Middle Jurassic age (mean age of the footwall and hanging wall samples = 174.0±1.2 Ma) (Fig. 6) for the mineralization at the Chahgaz deposit, based on the age of the enclosing rhyodacitic flows.

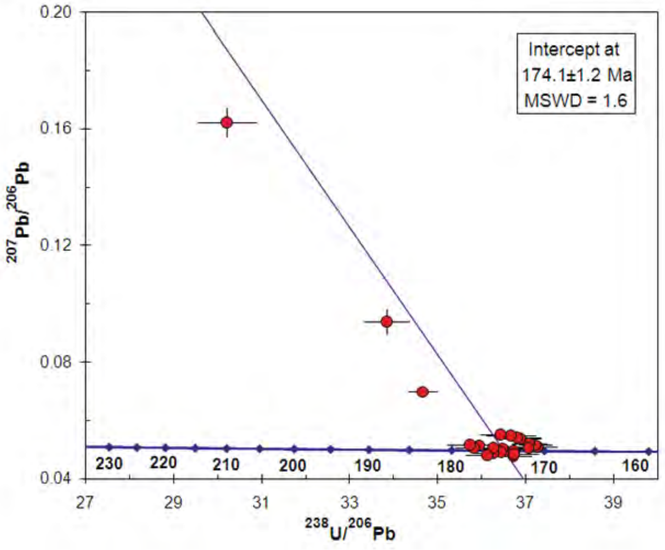

Figure 6. U-Pb zircon concordia plot for zircons from the footwall rhyodacite samples from the NW and SE limbs of the Chahgaz anticline. Data point error crosses are 1 sigma.

Discussion

VMS mineralization in the southern SSZ is hosted by volcanic and sedimentary rocks, and both mineralization and host rocks are of Middle Jurassic age. The Chahgaz deposit and several occurrences occur along three discrete stratigraphic horizons in a sequence of predominantly felsic flows and volcaniclastic rocks intercalated with pelites.

The Chahgaz rhyodacitic flows show enrichments in both HFSE and REE, which is a common feature of felsic volcanic rocks associated with VMS deposits (e.g. Lesher et al. 1986; Lentz 1998; Piercey et al. 2001; Dusel-Bacon et al. 2004). The rhyodacite volcanic flows show calc-alkaline affinities and subduction and arc-related features. These characteristics are similar to those for the Late Triassic-Early Jurassic Chahghand gabbro-pyroxenite and the Middle Jurassic Chahdozdan anorthosite intrusions in the area (Fig. 3; e.g., Jamshidi 2003; Shahabpour 2005; Sheikholeslami et al. 2008).

The Chahghand intrusion (e.g. Otrodi 2006; Otrodi et al. 2006) shows transitional to calc-alkaline and within-plate geochemical characteristics. However, an intracontinental rift setting for the intrusion has been suggested by Otrodi et al. (2006). Sheikholeslami et al. (2008) suggested that emplacement of the Chahdozdan and Chahghand intrusions occurred within extensional basins due to oblique subduction at 167 and 159 Ma, respectively. Fazlnia et al. (2007, 2009) proposed that the opening and expansion of the Neotethys Ocean occurred in the Middle Jurassic (173.0 ±1.6 Ma) at the time of emplacement of the Chahdozdan anorthosite intrusion, and based on age of the trondhjemites, suggested that the onset of its subduction beneath the southern part of the SSZ took place in the Volgian, Late Jurassic (147.4±0.76 Ma). However, the calc-alkaline nature of the Chahdozdan and Chahghand intrusions (e.g., Sheikholeslami et al., 2003) cannot be attributed to the opening of the Neo-Tethyan ocean, as suggested by Fazlnia et al. (2009), but rather may be related to the same subduction event as the Chahgaz volcanic rocks.

Based on the geological relationships and geochemical features, we suggest that both the Chahgaz volcanic rocks and the Mesozoic intrusions were emplaced during a discrete subduction arc-magmatism phase. The age and geochemical characteristics of the Chahgaz host volcanic rocks suggest that they are related to the subduction of Neo-Tethys oceanic crust beneath the Central Iranian microcontinent in the Mesozoic (e.g. Ghasemi & Talbot 2006; Omrani et al. 2008). Our data show that arc-related calc-alkaline bimodal volcanism in the Chahgaz area occurred at 174.0±1.2 Ma, approximately contemporaneous with emplacement of the Chahdozdan anorthosite intrusion, in an arc pull-apart basin. We suggest that the bimodal volcanism at Chahgaz area occurred in a rifted continental margin arc basin and was accompanied by VMS mineralization.

Conclusions

The Chahgaz region of the Sanandaj-Sirjan zone in southern Iran is highly prospective for VMS deposits. This region hosts the Chahgaz Zn-Pb-Cu VMS deposit which occurs within a metamorphosed sequence of bimodal volcanic and sedimentary rocks. This deposit is hosted by rhyodacitic volcaniclastic rocks and is underlain and overlain by rhyodacitic flows, volcaniclastics and pelites. The rhyodacitic flows are calc-alkaline, and show REE and trace element

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features characteristic of arc magmatism. Zircons extracted from stratigraphic footwall and hanging wall rhyodacitic flows of the Chahgaz deposit yield concordant U-Pb ages of 175.7±1.7 and 172.9±1.4, respectively, and a mean age of 174±1.2 Ma. This time period is interpreted to represent the age of mineralization of the Chahgaz deposit. This time period in the Middle Jurassic is suggested to be a time of significant VMS deposit formation within rifted or extensional basins formed during Neo-Tethyan oblique subduction-related arc volcano-plutonism in the SSZ. The VMS mineralization exhibits pronounced metal zoning and hydrothermal alteration.

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