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# Origin and formational history of some Pb-Zn deposits from Alborz and Central Iran: Pb isotope constraints

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Several Pb-Zn deposits and occurrences within Iran are hosted by Mesozoic–Tertiary-aged sedimentary and igneous rocks. This study reports new Pb isotope analyses for galena from 14 Pb-Zn deposits in the Alborz and Central Iran structural zones. In general, Pb isotope ratios are extremely variable with data plotting between the upper crustal and orogenic curves in a plumbotectonic diagram. The latter may be attributed to Pb inputs from crustal and mantle end-members. Most of the galena samples are characterized by high $^{207}Pb/^{204}Pb$ ratios, suggesting significant input of Pb from old continental crust or pelagic sediment. Pb isotope data also indicate that some of the deposits, which are hosted by sedimentary rocks in Central Iran and Alborz, have similar Pb isotopic compositions and hence suggest similar source regions. Most of the galenas yield Pb model 'ages' that vary between ~140 and ~250 Ma, indicating that mineralization resulted from the extraction of ore-bearing fluids from Upper Triassic–Lower Jurassic sequences. The similarity in Pb isotope ratios for the Pb-Zn deposits located within these zones suggests analogous crustal evolution histories. Our preferred interpretation is that Pb-Zn mineralization within the sedimentary and igneous rocks of the Central Iran and Alborz tectonic regions occurred following a Late Cretaceous–Tertiary accretionary stage of crustal thickening in Iran.

**Keywords:** Pb isotopes; Pb-Zn deposits; Central Iran; Alborz; galena

## Introduction

The Iranian Plate, a major segment of the Cimmerian micro-continent, had detached from northeastern Gondwana by the end of Permian and collided with the Turan Plate (part of Eurasia) towards the end of the Triassic (Şengör 1990; Stampfli *et al.* 1991; Saidi *et al.* 1997; Mirnejad *et al.* 2013). From the Early Jurassic to Senonian, the young Neo-Tethyan oceanic basin was reduced in extent by its subduction under the Iranian continental plate and the final closure of the Neo-Tethys, marked by the collision between the Iranian and Arabian plates, took place during the Neogene (Berberian *et al.* 1982; Shahabpour 2005; Ahmadi Khalaji *et al.* 2007).

The Iranian plateau is divided into several zones from SW to NE (Figure 1): Zagros fold-thrust belt (ZFTB), Sanandaj–Sirjan metamorphic zone (SSMZ), Urumieh–Dokhtar volcanic belt (UDVB), Central Iran zone (CIZ), Alborz zone (AZ), Kopeh Dagh zone (KDZ), and Eastern Iran zone (EIZ) (Falcon 1967; Stöcklin 1968; Dewey *et al.* 1973; Stöcklin and Nabavi 1973; Jackson and McKenzie 1984; Şengör 1984; Byrne *et al.* 1992; McCall 2002; Blanc *et al.* 2003; Alavi 2004; Walker and Jackson 2004). A number of Pb-Zn deposits have been reported from these structural zones, although the largest reserves occur in the CIZ and AZ.

Pb isotope studies of ore deposits or metallogenic provinces have aided in estimating the initial Pb isotopic composition of the metallogenic source and in determining the ages of deposits or prospects (e.g. Gulson 1986). Particularly, galena (PbS) is the most suitable mineral for analysis of Pb isotope ratios of Pb-Zn deposits because it contains abundant Pb but no U content, and thus its isotopic composition has remained unchanged since the time of its formation. In recent years, new studies on the Pb isotopic compositions of Pb-Zn deposits from Iran have been conducted, including those of Anguran (Gilg *et al.* 2006), Emarat (Ehya *et al.* 2010), Chahgaz (Mousivand *et al.* 2011), and Shahmirzad (Bazargani-Guilani *et al.* 2011). Lancelot *et al.* (1997) reported Pb isotope ratios of galena from five Iranian Pb-Zn deposits and Mirnejad *et al.* (2011) reported Pb isotopic compositions of 18 Zn–Pb deposits and occurrences within SSMZ and UDVB, as well as a sole deposit in ZFTB. The results of duplicate analyses by these authors on galena samples point to the homogeneity of Pb isotope ratios. Although the CIZ and AZ are important metallogenic provinces with reference to the number of Pb-Zn mineral deposits in Iran (Ghazanfari 1993), petrogenetic and geochronological information for these ore deposits is scarce. This study presents new Pb isotopic compositions for 14 Pb-Zn deposits within the

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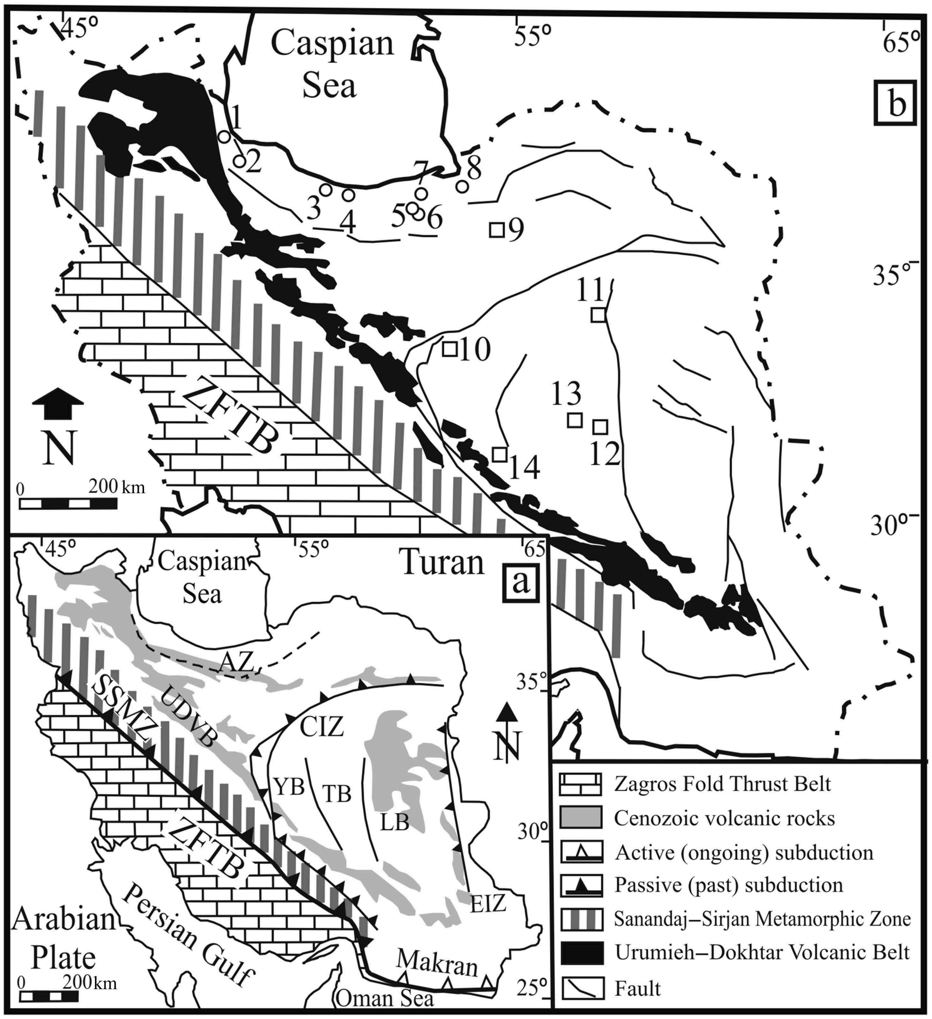


Figure 1. (a) Location of different structural segments of Iran. (b) Sample location. Sample abbreviations and numbers corresponding to the deposits are listed in Table 1.

Abbreviations: GKF, Great Kavir Fault; SSMZ, Sanandaj–Sirjan Metamorphic Zone; UDVB, Urumieh–Dokhtar Volcanic Belt; CIZ, Central Iran Zone; YB, Yazd Block; TB, Tabas Block; LB, Lut Block; AZ, Alborz Zone; ZFTB, Zagros Fold–Thrust Belt; EIZ, East Iran Zone.

tectonic zones of AZ and CIZ, with the purpose of discussing the possible source of these metals in relation to the tectonic history of the region.

## Geological setting and mineralization

The AZ tectonic region in northern Iran (Figure 1) was affected by several successive tectonic events, from the Late Triassic Eo-Cimmerian orogeny to a Late Cretaceous–Tertiary compressional event (Allen *et al.* 2003; Golonka 2004; Guest *et al.* 2006; Horton *et al.* 2008; Zanchi *et al.* 2009). The tectonic style of the AZ is dominated by thrust faults, giving rise to displacement of the structural elements and the formation of duplex systems, such as composite antiformal stacks (Vernant *et al.* 2004). From the Precambrian to Palaeozoic, AZ was part of Gondwana, but the AZ then separated due to rifting associated with the formation of the Palaeo-Tethys (Berberian and King 1981; Şengör *et al.* 1988; Stampfli *et al.* 1991; Shafaii Moghadam and Stern 2014). With gradual cessation of compressional magmatic activities, a continental shelf developed on the broken continental crust around Permian to Late Triassic times. Between the Late Triassic and Middle Jurassic, this shelf closed and resulted in the consumption of Palaeo-Tethys oceanic assemblage, faulting, thrusting, uplift, metamorphism, and the formation of a foreland basin (Assereto 1966; Stampfli 1978). The sedimentation of new continental/epicontinental shelf sediments on areas that had been deformed and metamorphosed during the Cimmerian orogeny started in the Middle Jurassic–Upper Cretaceous, and these sediments deposited in an unstable tectonic environment during their formation (Alavi 1996). The Palaeocene and Eocene stratigraphy is characterized by an irregular distribution of andesitic and basaltic volcanic rocks, indicating the proximity to an active volcanic margin (Berberian 1983; Saidi 1995; Brunet *et al.* 2003). The folded and thrusted Palaeozoic to Mesozoic sedimentary sequences in the AZ, which include middle Permian limestone (Routeh formation), Lower–Middle Triassic dolomite and limestone (Elika formation), Jurassic limestone (Dalichay and Lar formations), and Cretaceous limestone and dolomite, host a variety of Pb-Zn deposits. Previous studies suggest that most of the Pb-Zn deposits in the AZ are Mississippi Valley-type (MVT) occurrences, although some are vein and skarn types which are related to Tertiary magmatic activity (Bazargani-Guilani 1982; Nekouvaght Tak *et al.* 2009). A second group of AZ-related Pb-Zn deposits are strata-bound occurrences hosted by Cenozoic volcanic and pyroclastic rocks, which occur both proximal and distal to intrusive rocks (Bazargani-Guilani *et al.* 2011).

The CIZ tectonic region is the most complicated and largest geological unit in Iran, and is an area of continuous continental deformation in response to the ongoing convergence between the Arabian (Gondwanan) and Turan (Eurasian) plates. The series of tectonic events that shaped the early evolution of the CIZ are best designated as Peri-Gondwanan or Proto-Tethyan. At least two further episodes of orogenic activity, one in the Early Triassic and another in the Late Tertiary, impacted the CIZ prior to its final incorporation into the Alpine–Himalayan Belt (Stöcklin 1974). The CIZ was a stable platform during the Palaeozoic, but Late Triassic movements resulted in the formation of horsts and grabens (Zanchi *et al.* 2009). The structural trends were created during the Mesozoic when the contiguous platform of the CIZ was divided into small segments (e.g. Stöcklin 1968; Ramezani and Tucker 2003). The CIZ consists, from east to west, of three major crustal domains (Figure 1): the Lut Block, Tabas Block, and Yazd Block (e.g. Alavi 1991). These blocks are separated by a series of intersecting regional-scale faults (Berberian 1981). The CIZ hosts many Pb-Zn deposits that often occur in Palaeozoic–Tertiary carbonate rocks, in particular Cretaceous carbonates. A large number of deposits hosted within pyroclastic rocks are also located within the Torud–Chah Shirin belt in the northern part of the CIZ. On the basis of regional and tectonic considerations, Alavi (1991, 1996) suggested that the Torud–Chah Shirin range and volcanic rocks in the adjacent areas are related to Eocene magmatism in the CIZ, and not to the volcanic rocks of the AZ. The igneous rocks within this area contain magmatic arc signatures, similar to the geochemical features proposed by Pearce and Peate (1995).

## Sampling and analytical techniques

Fifteen fresh galena samples representative of Pb-Zn deposits and occurrences from the CIZ and AZ regions were collected on several field trips. Table 1 lists their descriptions and Figure 1b shows the sample locations. Galena separates were carefully hand-picked to avoid inclusions from surrounding minerals. Between two and three milligrammes of sample were dissolved using ultrapure (double-distilled) HCl. Pb isotope compositions were analysed using a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) instrument (Nu Instruments Ltd, Wrexham, UK) within the Radiogenic Isotope Facility at the University of Alberta. Sample aliquots were subsequently mixed and diluted with ~1.5 ml of a 2% $HNO_3$ solution spiked with NIST SRM 997 Thallium standard (2.5 ppb), and aspirated (~100 μl $min^{-1}$) into the ICP source using an ARIDUS micro-concentric nebulizer (Nu Instruments Ltd). The analytical protocol for Pb isotope measurement outlined below follows the procedure described in Simonetti *et al.* (2004).

Simultaneous measurement of all Pb and Tl isotopes and $^{202}$Hg ion signal was achieved using seven Faraday collectors. The $^{205}$Tl/ $^{203}$Tl ratio was measured to correct for instrumental mass bias (exponential law; $^{205}$Tl/$^{203}$Tl = 2.3871). The average measured $^{205}$Tl/$^{203}$Tl ratio for all Pb isotope analyses reported here is relatively constant at 2.4253 ± 0.0016 (2σ standard deviation), which corresponds to an average 'beta' mass fractionation factor of −1.60. Upon sample introduction, data acquisition consisted of two half-mass unit baseline measurements prior to each integration block, and three blocks of 20 scans (10 sintegration each) for isotope ratio analysis. $^{204}$Hg interference (on $^{204}$Pb) was monitored and corrected using $^{202}$Hg. The fraction of $^{204}$Hg relative to the $^{204}$Pb ion signal was essentially negligible and varied between 0 and 0.027%, with most analyses containing <0.01% $^{204}$Hg (of the total 204 mass ion signal). At the beginning of the analytical session, a 25 ppb solution of NIST SRM 981 Pb standard, which was also spiked with NIST SRM 997 Tl standard (1.25 ppb), was analysed. External reproducibility of the protocol was evaluated via repeated measurement ($n$ = 3) of NIST SRM 981 standard solution and yielded the following mean values and associated (2σ) standard deviations: $^{206}$Pb/$^{204}$Pb = 16.936 ± 0.006, $^{207}$Pb/$^{204}$Pb = 15.489 ± 0.004, $^{208}$Pb/$^{204}$Pb = 36.690 ± 0.009, $^{207}$Pb/$^{206}$Pb = 0.915 ± 0.00012, and $^{208}$Pb/$^{206}$Pb = 2.166 ± 0.0003.

## Results

Table 2 lists the Pb isotope ratios of galena samples from selected Pb-Zn deposits within the AZ and CIZ. $^{206}$Pb/$^{204}$Pb, $^{207}$Pb/$^{204}$Pb, and $^{208}$Pb/$^{204}$Pb are variable and define the following ranges, respectively: 18.404–19.081, 15.586–15.722, and 38.5–39.113. In Figure 2, all samples (excluding a galena from Qullehkaftaran) plot above the model curve for average crustal Pb isotope evolution (Stacey and Kramers 1975), and do not show

Table 1. Summary of the studied ore deposits showing their names, geologic relationships, and major ore types. Sample numbers correspond to those in Figures 1–3. AZ, Alborz zone; CIZ, Central Iran zone.

| Sample no. | Deposit name | Location | Geologic relationship and host rock | Ore and gangue type | Ore type | Tonnage and grade |
|---|---|---|---|---|---|---|
| AZ | | | | | | |
| 1 | Balakuh | 48º48′05″ E 37º10′26″ N | Vein, small lenses and disseminated in altered zones in carbonate rocks | Galena and cerussite (ore), calcite (gangue) | MVT? | Pb 0.5%. |
| 2 | Marjanabad | 49º29′30″ E 36º47′12″ N | Fault and fracture infilling of Permian carbonate and carbonated siltstone of Shemshak Formation | Galena, sphalerite, smithsonite, hemimorphite, and cerussite (ore), quartz, and calcite(gangue) | MVT? | 28,464 t: Zn 8.15%, Pb 0.88% |
| 3 | Duna | 51º21′13″ E 36º20′25″ N | Fracture open-space infilling of Middle Permian limestone and dolomite | Galena (ore) barite and quartz (gangue) | Synsedimentary exhalative (Bazargani-Guilani 1982); epithermal to mezotermal vein (Samani Rad 1999) | 6.5 Mt: Pb 5%, Zn 1%, Ag 200–500 g/t |
| 4 | Nemar | 52º03′47″ E 36º05′26″ N | Disseminated and fracture infilling at the contact of Jurassic carbonates with trachyte rocks | Galena and sphalerite (ore), calcite, quartz, and some calc. silicate minerals (gangue) | Skarn (Azizi 2005; Azizi *et al.* 2006, Sayyah 1998) | 200,000 t: Pb 7%, Zn 10% |
| 5 | Erambozorg* | 53º16′52″ E 36º50′46″ N | Strata-bound, disseminated faults and fractures and breccia infilling of Cretaceous carbonates | Galena (ore), calcite, and barite (gangue) | MVT (Rabiei 2008) | Abandoned Pb mine |
| 6 | Asaran* | 53º16′52″ E 35º50′46″ N | Strata-bound, disseminated fault and fracture infilling of Cretaceous carbonates | Galena and sphalerite (ore), calcite and barite (gangue) | MVT (Rabiei 2008) | Abandoned Pb-Zn mine |
| 7 | Pachimiana | 53º16′21″ E 36º04′32″ N | Massive, karstic, solution space, fault and fracture filling in Lower–Middle Triassic carbonate units | Galena (ore), fluorite, barite, and calcite (Gangue) | MVT (Davoudi 1997); (Gorjizadeh 1995) | 338,000 t; Pb 7%, |
| 8 | Ahvano* | 54º10′54″ E 36º13′07″ N | Strata-bound, brecciated and fracture infilling within Middle–Upper Jurassic carbonates | Galena and sphalerite (ore), calcite (gangue) | MVT? Fathi and Mosaddegh 2012) | Abandoned Pb-Zn mine |
| CIZ | | | | | | |
| 9 | Qullehkaftaran | 54º54′17″ E 35º30′45″ N | Vein and veinlet in altered and fractured zones in Eocene granodiorite | Galena, sphalerite (ore), quartz, and barite (gangue) | Polymetal vein (Emamjome *et al.* 2009) | 850,000 tonnes: Pb 5%, Zn 1.3% |
| 10 | Nakhlak | 53º50′10″ E 33º34′30″ N | Infilling fault and fracture open space, massive, brecciated minerals and cements of breccia in Cretaceous carbonate | Galena (ore), barite, calcite, dolomite, and quartz (gangue) | MVT (Jazi and Shahabpour 2010) | 850,000 tonnes, t @ 7% Pb. |
| 11 | Chahsorb* | 56º39′02″ N 34º03′15″ E | Strata-bound, vein, karst and open-space infilling within Jurassic limestone and dolomitic limestone | Galena (ore), calcite, quartz, and barite (gangue) | MVT (Pourabdollahi 2009) | Abandoned Pb mine |
| 12 | Kamarmehdi | 56º30′14″ E 32º02′06″ N | Fault and brecciated zone infilling of Triassic carbonates | Galena (ore), fluorite, calcite, dolomite, and quartz (gangue) | Epithermal (Sadeghibojd 1995) | 124,000 tonnes: Pb 5% |
| 13 | Geijerkuh | 56º58′25″ E 31º53′28″ N | Fault and fracture infilling within Permian–Triassic(?) carbonate | Sphalerite, galena (in deep parts of deposit), and oxide and carbonate minerals of Zn-Pb in upper part of deposit (ore), barite, calcite, and quartz (gangue) | MVT? | 6000 tonnes: Zn 18.38% Zn, Pb very low. |
| 14 | Mehdiabad | 50º01′30″ E 31º29′03″ N | Infilling open space of faults and fractures, massive, brecciated minerals and cements of breccia in lower Cretaceous carbonate | Sphalerite, galena, and other Zn-Pb carbonates and oxide minerals (ore), barite, and calcite (gangue) | Eastern part of deposit is similar to MVT and the central and western parts are similar to Irish type (Ghasemi 2007). MVT (Hitzman *et al.* 2003; Reichert 2007) | 218 Mt: Pb 2.3%, Zn 7.2%, Ag 51 g/t Ag. |

Note: *No information on tonnage and grade is available for this deposit.

Table 2. Pb isotope compositions of ore deposits in the Alborz zone (AZ) and Central Iran zone (CIZ).

| Deposit name | $^{206}Pb/^{204}Pb$ | $^{207}Pb/^{204}Pb$ | $^{208}Pb/^{204}Pb$ | μ ($^{238}U/^{204}Pb$) | Model age (Ma) |
|---|---|---|---|---|---|
| AZ | | | | | |
| Balakuh | 18.505 ± 0.005 | 15.618 ± 0.005 | 38.593 ± 0.014 | 9.7 | 127 ± 7 |
| Marjanabad | 18.992 ± 0.004 | 15.689 ± 0.004 | 39.113 ± 0.012 | 9.9 | −86 ± 5 |
| Duna | 18.681 ± 0.004 | 15.644 ± 0.004 | 38.748 ± 0.013 | 9.9 | 50 ± 6 |
| Nemar | 18.770 ± 0.004 | 15.635 ± 0.004 | 39.007 ± 0.012 | 9.7 | −38 ± 6 |
| Erambozorg | 18.505 ± 0.007 | 15.629 ± 0.006 | 38.583 ± 0.018 | 9.8 | 151 ± 7 |
| Asaran | 18.535 ± 0.006 | 15.661 ± 0.006 | 38.671 ± 0.017 | 9.9 | 195 ± 7 |
| Pachimiana | 18.598 ± 0.003 | 15.655 ± 0.003 | 38.632 ± 0.008 | 9.9 | 135 ± 4 |
| Ahvano | 18.404 ± 0.002 | 15.639 ± 0.003 | 38.538 ± 0.008 | 9.9 | 247 ± 3 |
| CIZ | | | | | |
| Qullehkaftaran | 18.461 ± 0.004 | 15.586 ± 0.004 | 38.500 ± 0.011 | 9.69 | 92 ± 6 |
| Nakhlak | 18.511 ± 0.005 | 15.637 ± 0.005 | 38.642 ± 0.013 | 9.89 | 163 ± 3 |
| Nakhlak | 18.516 ± 0.002 | 15.638 ± 0.002 | 38.641 ± 0.006 | 9.8 | 162 ± 3 |
| Chahsorb | 18.427 ± 0.004 | 15.647 ± 0.004 | 38.575 ± 0.012 | 9.9 | 246 ± 5 |
| Kamarmehdi | 19.081 ± 0.003 | 15.722 ± 0.003 | 38.910 ± 0.009 | 10.1 | −82 ± 4 |
| Geijerkuh | 18.514 ± 0.003 | 15.704 ± 0.004 | 38.696 ± 0.013 | 10.1 | 297 ± 12 |
| Mehdiabad | 18.499 ± 0.003 | 15.658 ± 0.003 | 38.634 ± 0.010 | 9.9 | 215 ± 4 |

Note: Uncertainties are reported as two sigma standard deviations.

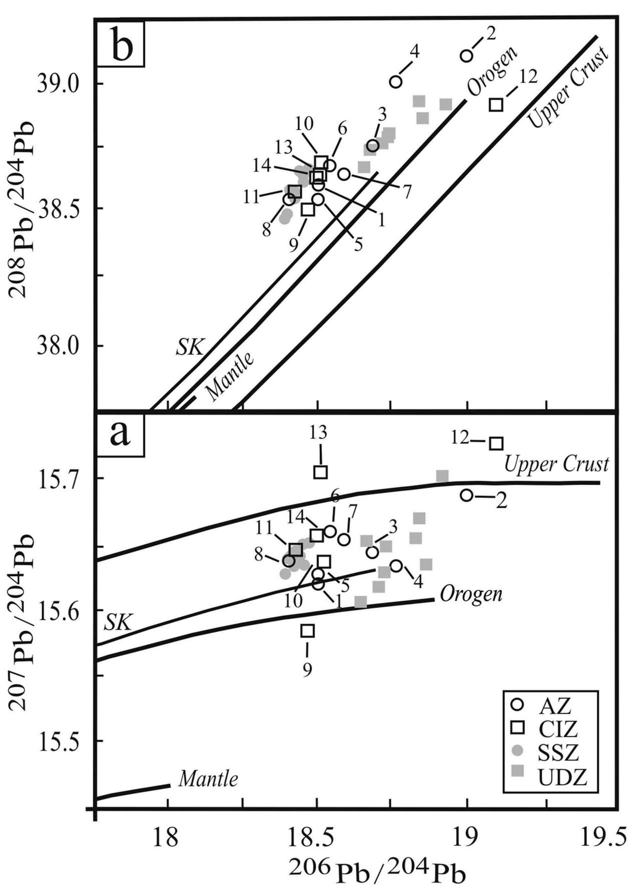


Figure 2. Pb isotope ratios of galena samples from Alborz (AZ) and Central Iran zone (CIZ) on a 'plumbotectonic' diagram (Zartman and Doe 1981) and Stacey and Kramers (SK) curve (1975). Data from the Urumieh–Dokhtar zone (UDZ) and Sanandaj–Sirjan zone (SSZ) are after Mirnejad *et al.* (2011). Sample abbreviations are given in Table 1.

any grouping or trend. Moreover, the Pb isotope data plot between the 'Orogen' and 'Upper crust' growth curves of Zartman and Doe (1981; Figure 2). The μ and model age values were calculated using the two-stage model of Stacey and Kramers (1975):

$$\mu = \left(\left({}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb}\right) - 11.152\right)/\left(e^{\lambda_1 T} - e^{\lambda_1 t}\right) \qquad (1)$$

$$\left(\left({}^{207}\mathrm{Pb}/{}^{204}\mathrm{Pb}\right) - 12.998\right)/\left(\left({}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb}\right) - 11.152\right) = (1/137.88)\left(\left(e^{\lambda_2 T} - e^{\lambda_2 t}\right)/\left(e^{\lambda_1 T} - e^{\lambda_1 t}\right)\right), \qquad (2)$$

$$T = 3.7\ \mathrm{Ga},\ t = \text{model age},$$

$$\lambda_1 = 1.55125*10^{-10}\mathrm{y}^{-1}\left({}^{238}\mathrm{U}{\rightarrow}{}^{206}\mathrm{Pb}\right),$$

$$\lambda_2 = 9.8485*10^{-10}\mathrm{y}^{-1}\left({}^{235}\mathrm{U}{\rightarrow}{}^{207}\mathrm{Pb}\right),$$

$$\mu = \left({}^{238}\mathrm{U}/{}^{204}\mathrm{Pb}\right).$$

Although the studied galena samples occur in Palaeozoic, Mesozoic, and Cenozoic host rocks, their calculated model ages are either Mesozoic or Cenozoic and some yield 'anomalous' (negative) ages (Table 2).

## Discussion

With the exception of three samples (i.e. Geijerkuh, Kamarmehdi, and Marjanabad), all galena separates hosted by sedimentary rocks plot between the orogen and upper crustal growth curves in the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plumbotectonic diagram (Figure 2a). Thus, it may be deduced that the Pb isotope compositions of the Pb-Zn deposits investigated here resulted from several sources during orogenic events. However, the high $^{207}Pb/^{204}Pb$ ratios (15.629–15.661) for deposits hosted within sedimentary rocks (Mehdiabad, Nakhlak, Chahsorb, Ahvano, Asaran, Erambozorg, and Pachimiana) may be attributed to a greater contribution from old crust or pelagic sediments. The large variation in Pb isotope ratios for galenas from the CIZ and AZ also reflects the heterogeneity of basement rocks in these zones. In the $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram (Figure 2b), most samples plot above the upper crust, mantle, and orogen average values, indicating a major contribution of Th-derived lead.

Figure 3 compares the Pb isotope ratios for selected Pb-Zn deposits from the AZ and CIZ to those from the SSMZ and UDVB regions. Pb isotope ratios for the Chahsorb Pb-Zn deposit in the CIZ are similar to those of the Ahvano deposit in the AZ, and to those of the Pb-Zn deposits in the SSMZ. The most important characteristic of the Chahsorb, Ahvano, and Pb-Zn deposits of SSMZ is the vast distribution of thick (several thousand metres) Upper Triassic–Lower Jurassic sediments (Shemshak Formation located under the host rocks) in these areas, and the influence of tectonic activities (e.g. crustal thickening and orogenic events) in mineralization. Previous studies in these regions considered the Shemshak Formation as a probable source of metals, and suggested that mineralization occurred following the extraction of ore-bearing fluids from Shemshak shales during crustal thickening and orogenic phases (Ghasemi Todshkchoii 1995; Aliabadi 2000; Pourabdollahi 2009). The similarity of Pb isotope ratios for the Chahsorb, Ahvano, and Pb-Zn deposits of SSMZ corroborates the interpretations from previous studies in that these deposits had similar metal sources. According to Vaasjoki (1986) and Gulson (1986), the homogeneity of Pb isotope compositions from carbonate-hosted deposits seems to depend on the proximity of the ores to deep sedimentary basins, and the combined effects of sedimentation, diagenesis, and prolonged brine circulation can contribute to isotope homogeneity. We also believe that the Chahsorb and Ahvano Pb-Zn deposits inherited their Pb isotopic signatures from Shemshak sediments, and that the isotope homogeneity reflects the combined effects of sedimentation, diagenesis, and prolonged circulation of fluids during crustal thickening and orogenic activities due to the closure of the Neo-Tethys and the collision between the Iranian and Arabian plates during the Neogene. Thus, it would seem that host sedimentary sequences and their associated formation fluids were important sources of metals for some deposits.

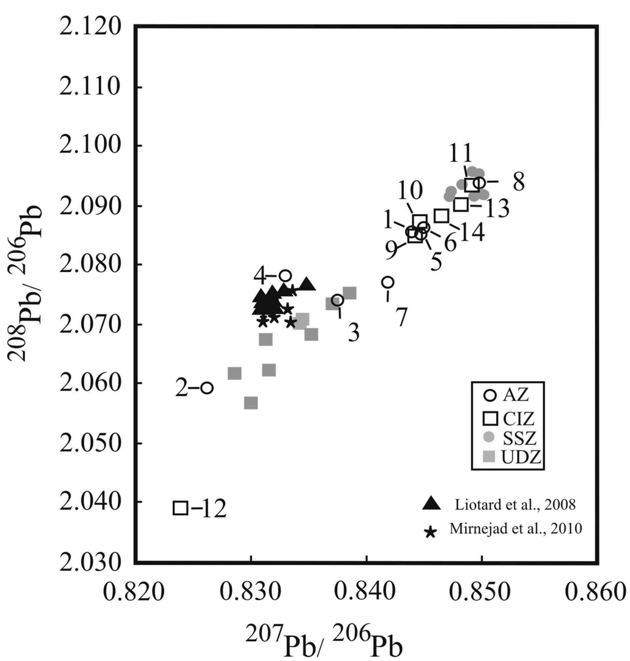


Figure 3. Plot of Pb isotope ratios in this study and previously published data on other Pb-Zn deposits in Iran (filled squares: Urumieh–Dokhtar zone; filled circles: Sanandaj–Sirjan zone; Mirnejad *et al.* 2011) on $^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$ diagram. Pb isotope data from Damavand lavas (Liotard *et al.* 2008; Mirnejad *et al.* 2010) are presented for comparison. Sample abbreviations are given in Table 1.

In contrast to the sedimentary-hosted deposits, galena samples hosted by igneous rocks are characterized by lower μ ($^{238}U/^{204}Pb$) ratios (9.69–9.7) (Table 2), and this may be attributed to lesser contributions from upper crustal sources. Among deposits with igneous host rocks (i.e. Nemar and Qullehkaftaran), the Qullehkaftaran deposit from the CIZ has the lowest $^{207}Pb/^{204}Pb$ ratio and μ value (Table 2), and the Pb isotope data plot below the orogen curve (Figure 2). These features reflect a higher contribution of mantle-derived and/or lower crust material in the Pb ore-forming fluids. The relationships between mineralization, subvolcanic intrusive bodies which are currently undated, and the unradiogenic nature of the Pb isotope data (Figures 2 and 3) indicate that a significant amount of Pb was derived from the mantle/lower crust region via Neo-Tethys subduction. Of interest, Pb isotope ratios for the Nemar skarn deposit (Table 2) located north of Damavand Mountain in the AZ are near those for trachyandesite lavas in Damavand (Liotard *et al.* 2008; Mirnejad *et al.* 2010). This feature indicates a link between the source of metals for the Nemar deposit and Cenozoic magmatic activities in the AZ. In addition, field observations and previous geochemical studies confirm that ore-forming fluids for the Nemar deposit were of magmatic origin (Azizi 2005).

Based on the Pb isotope data shown in Figure 3, it is clear that the ore-forming fluids are of magmatic origin for some deposits hosted by both sedimentary and igneous rocks within the AZ. Pb isotope ratios for the Nemar and Duna deposits plot in the vicinity for those from the UDVB deposits (Figure 3), and therefore the source of Pb can be related to the Cenozoic magmatic activity of the AZ that was coeval with that of the UDVB (Hassanzadeh *et al.* 2002). Previous mineralogical, geochemical, and geological studies on the Pb-Zn deposits from Duna (Samani Rad 1999) and Nemar (Azizi 2005) also suggested that the source of mineralizing fluids was magmatic.

In contrast to the Pb isotope ratios for Pb-Zn deposits within the SSMZ and UDVB regions, those from the CIZ and AZ plot in similar fields (Figure 3). This can be attributed to similarities in crustal evolution for the AZ and CIZ regions during the Late Cretaceous–Palaeocene, as opposed to the SSMZ and UDVB, which formed dominantly during the Mesozoic and Tertiary, respectively. The AZ is considered a marginally folded terrane of the CIZ, with no distinct geological boundary between the two regions (Stöcklin 1968; Aghanabati 2004). In addition, the beginning of main compressional deformation in the AZ, as well as strong folding, magmatism, and uplift in CIZ, occurred in the Late Cretaceous–Palaeocene (Şengör 1990). These contemporaneous events in both the AZ and CIZ played an important role in Pb-Zn mineralization, along with their similar crustal evolution stages. The peak of Alpine orogenic activities in the early Tertiary was evidently coeval with high-grade metamorphism and anatexis of portions of the Iranian crust (and its cover rocks), in addition to the widespread near-surface magma emplacement within shallow and subvolcanic parts of the crust (Ramezani and Tucker 2003; Rahmati Ilkhchi 2009). These episodes may be key agents in remobilization of Pb from older sources and the occurrence of mineralization in the CIZ and AZ regions. This is consistent with Dixon and Pereira (1974) in that, during Cretaceous times, extensive submarine volcanism and collisional tectonics between the Arabian and Iranian plates resulted in the formation of important ore deposits.

## Conclusions

The Pb isotopic compositions for galena separates from Pb-Zn deposits from the AZ and CIZ indicate that Pb was derived from sources with high, time-integrated U/Pb and Th/Pb ratios. For many of the deposits investigated here, the Pb isotope data plot between the 'upper crust' and 'orogen' growth curves (Zartman and Doe 1981), which suggests that Pb was derived from mixed continental crust–mantle source(s). In most cases, calculated model ages point to the Mesozoic to Cenozoic, which are older than those of the host rocks. Therefore, it is possible that Pb derivation from the source(s) in both the AZ and CIZ is related to orogenic activities that occurred during the Mesozoic to Cenozoic. Tectonic events and crustal thickening after the Cretaceous played an important role in remobilization of Pb from older sources and the occurrence of Pb-Zn mineralization in the host rocks. The similar Pb isotope ratios for galena from both the CIZ and AZ can be attributed to their similar tectonic and crustal evolution histories.

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