

INTRODUCTION OF THE DEH HOSEIN ANCIENT TIN-COPPER MINE, WESTERN IRAN: EVIDENCE FROM GEOLOGY, ARCHAEOLOGY, GEOCHEMISTRY AND LEAD ISOTOPE DATA

BATİ İRAN'DAKİ ESKİ BİR KALAY MADENİ, DEH HOSEİN'İN TANITIMI: JEOLJİ, ARKEOLOJİ, JEOKİMYA VE KURŞUN İZOTOP VERİLERİ

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ÖZET

İran'ın orta kesiminin batısında bulunan eski bakır ve kalay işletmesi Deh Hosein'in keşfinin ardından yapılan yeni araştırmalar, batı Asya uygarlıklarının yararlandıkları kalay kaynaklarının neresi olduğu sorusuna önemli yeni bir açılım kazandırmıştır.. Deh Hosein bakır-kalay madeninden elde edilen cevher örneklerinin analizi yapılmış ve bu sonuçlar, Luristan ile Mezopotamya'daki tunç buluntular ile karşılaştırılarak aralarındaki ilişki sorgulanmıştır.

¹⁴C analizleri ve arkeolojik kanıtlarla birlikte burada bulunan çok sayıda eski ocağın ve madencilik ile ilgili kalıntılarının en geç MÖ 2. binyıl başı ile MÖ 1. binyıl arasına ait olduğu ortaya çıkmıştır. Ayrıca yapılan cevher analizleri sonucunda Sn, Cu, As, Pb, Zn, ve Au'nun da yoğun olduğu görülmüştür. Daha da önemlisi cevher örneklerindeki kurşun izotop oranları dar bir yelpaze içindedir ve MÖ 2. binyıla ait Luristan, MÖ 3. binyıla ait Basra Körfezi'nin güneyi, Ege ve yine Luristan ile Mezopotamya'nın bu tarihe ait örnekleri ile uyum sağlamaktadır. Ayrıca iz analizi ve tarihlendirme sonuçlarının yanı sıra Mezopotamya'nın doğusunu kaynak olarak işaret eden yazılı metinler de, Deh Hosein'in İran, Mezopotamya ve hatta belki batı için önemli bir kalay kaynağı olduğunu düşündürmektedir.

INTRODUCTION

In spite of rather extensive archaeological and geological investigations in Western Asia during the past decades, the source of tin for the huge bronze production in the ancient Near- and Middle-East has long remained enigmatic. Recently, by discovery of an ancient tin-copper mine at Deh Hosein in West Central Iran (Momenzadeh *et al.* 2002) on the eastern rim of the Zagros Mountains; it seems that a pivotal clue for solving this old riddle has emerged. In this paper the ancient mine at Deh Hosein will be introduced and described. Lead isotope as well as compositional analyses of ores from Deh Hosein are compared with results of Early Bronze and Iron Age bronze artifacts from Luristan and Western Asia. As will be seen, much geological, analytical, chronological, and geographical evidence together with archaeological and textual records attest that the Deh Hosein mine has been a major ore supplier for bronze in prehistoric times.

The Deh Hosein ancient Sn-Cu-(Au) mine (Fig. 1), in the northeastern rim of the Luristan area and eastern part of central Zagros Mountains is located in the northern part of the Sanandaj-Sirjan tectonic unit which consists mainly of Mesozoic schist, Middle Jurassic-Early Tertiary intrusive rocks and their contact metamorphic aureoles and pegmatite. The Sanandaj-Sirjan zone (Stöcklin 1968) is a metamorphic NW-SE aligned belt. This belt ranges parallel to the Zagros Mountains and extends from Sanandaj in the northwest to Sirjan in the southeast of Iran. Magmatism in the northern part of the Sanandaj-Sirjan zone including the study area is manifested by exposure of large intrusive bodies with a northwest-southeast general trend, named as west Iranian granitoids in the Sanandaj-Sirjan zone (Valizadeh 1992), which favors the occurrence of Deh Hosein-like deposits. Regional metamorphism in the area has reached a peak of green schist facies, but further metamorphism has occurred locally, associated with granitoid emplacement.

ANCIENT WORKS AND RELICS AT DEH HOSEIN ANCIENT MINE

The recently discovered (2000) ancient mine of Deh Hosein has been named after the adjacent village of Deh Hosein which is located 7 km south-

east of the town of Astaneh. The ancient workings at Deh Hosein occur as numerous (more than 75) big ellipsoidal open depressions, along the mineralized horizons, in an area of $4.5 \times 6 \text{ km}^2$ (Figures 1 and 2a). The old workings are up to 70 by 50 by 15 meters in size which are aligned over a length of up to 500 m (Fig. 2a, and 2b). All the visible ore bearing zones on the surface are worked out by ancient miners. Small remains of the ore are visible as weak mineralized selvages of the diggings or as scattered pieces in the dumps. It is possible that underground workings extend underneath each depression and the adits are blocked by debris. Huge waste dumps are piled up at the periphery of some depressions.

Several hammer stones of two different materials, namely silicified phyllite and granite (which are common rocks in the area) and pottery shards have been found in the open cast mines (Fig. 2). Besides the diggings two rather small areas with building structures were found, possibly houses for living or workshops. Pieces of ore within the structures relate them to the mining site. Several grinding stones, hammer stones and pottery shards are visible on the surface of these sites. The larger site is a rectangular ($50 \times 30 \text{ m}^2$) structure on a hill, on the northeastern side of the mining area which overlooks all mining sites. A rather big rectangular grinding stone ($70 \times 35 \text{ cm}^2$) and several pieces of smaller ones of granitoidic material (Fig. 2f), a carved stone with an unknown sign, plenty of pottery shards (Fig. 2g) and pieces of copper ore were found on the surface of the site. The grinding stones are of two types, concave and convex with smooth surfaces. The pottery shards are variable in color and thickness and are sporadically depicted with a black material which according to preliminary inspection by archaeologists, date to the early first millennium BCE (Fig. 2g).

During a mining exploration campaign accomplished by Zaryaban Exploration Company, pieces of charcoal were found in one of the diggings in a depth about 2 m. Radiocarbon measurement of this charcoal yielded a date of $3380 \pm 55 \text{ BP}$, which on calibration results in an interval of 1775-1522 BCE at the 2-sigma confidence level (95% probability). It has to be noted that this date relates to an intermediate layer of the mine; the earliest mining activity can be even older.

No evidence for ancient smelting was found in the vicinity of the mine. The ore exploited may have been transported to the settlements and smelted outside the area. Also, no sign of medieval or modern mining has been observed in the area of ancient mining.

GEOLOGY, MINERALOGY AND GEOCHEMISTRY OF DEH HOSEIN

The mineralization of Deh Hosein is located in Jurassic meta-sedimentary rocks, which have experienced a green schist metamorphic facies and were intruded by the Astaneh complex in the north. The area has a moderate topography and is covered with many farm fields that in some cases have covered the ancient diggings (Fig. 1 and 2a).

The mineralization continues in the southern part of the Astaneh intrusion at its contact with the metamorphic country rocks. The meta-sedimentary rocks consist of alternating meta-sandstone, phyllite, schist, spotted slate and hornfels at the contact with the Astaneh intrusion. Although the mineralization is not restricted to any specific rock unit, it shows an obvious connection with intercalations of meta-sandstone present in phyllite, schist and spotted slate. The mineralization has occurred in the form of quartz, sulfide (arsenopyrite) and quartz-sulfide veins and veinlets. These fracture-controlled veins show mainly NW-SE, NE-SW and sporadically E-W trends which are up to 1.5 m wide and several 10 m long. Furthermore, the mineralization appears in the form of disseminations and impregnations, especially in the vein selvages. Quartz veins hosting the sulfide mineralization is the dominant ore-related feature of mineralization. The mineralization continues into the contact granodiorite and tourmaline-granite but it is less intense there.

On the surface the mineralization is highly altered by weathering and many sulfide minerals are thoroughly oxidized (Fig. 3a). Arsenopyrite and chalcopyrite are the dominant sulfide minerals, with lesser amounts of pyrite, pyrrhotite and cassiterite. Ore microscopy has revealed some 35 different ore minerals in the Deh Hosein occurrence, including arsenopyrite, chalcopyrite, native copper, cuprite and other supergene copper minerals, cassiterite, native bismuth and bismuth minerals, ferberite, galena, limonite, pyrite, pyrolusite, pyrrhotite, sphalerite, stannite and sulfosalts (Figure 3,

Nezafati *et al.* 2005; Nezafati 2006). Cassiterite is a rather abundant ore mineral and has been observed in both meta-sedimentary and granitic host rocks. It has been observed in quartz-sulfide (gossan) veins at Ghara Ghouii, Ahmad Jigi II, and at the east and center of the occurrence (including samples 7A, 42, 43, and 47, table 1 and Fig. 1).

Cassiterite occurs in the form of grains up to 250 μm in size and is in association with oxidized copper minerals and gossan (Fig. 3c and 3d). In addition, heavy mineral prospection in the streams of the ancient mining area by Zaryaban Exploration revealed nuggets of cassiterite.

18 ore samples from Deh Hosein were analyzed by Neutron Activation Analysis (NAA) at Actlabs, Canada (for gold and trace elements by programs Au+48 and Au+34) in order to examine the content of trace elements in the ore (Table 1). According to results, the tin in the veins ranges from 0.01 to 6.72%. The Cu, As, Pb, Zn, Au and, W amounts of veins are as much as 10%, 23.9%, 3.7%, 0.75%, 13.3 ppm and 2420 ppm. Ag, Sb and Ni show also rather considerable amounts in the ore. The highest gold concentrations are found in samples containing visible arsenopyrite, chalcopyrite, pyrite, sulfosalts and highly oxidized iron (gossan).

The high content of arsenic and copper along with tin in the ore of Deh Hosein is noteworthy, especially when we consider this fact that the co-occurrence of arsenic and tin is characteristic of Early Bronze Age metallurgy in Mesopotamia (Fleming *et al.* 2005).

The comprehensive analytical research on Luristan bronzes of different periods performed by Fleming *et al.* (2005) show high arsenic contents in the early artifacts which clearly becomes lower with time and technological improvements in the Iron Age. As a result of this fact arsenic is no longer an important alloying ingredient in the Iron Age. According to this study (Fleming *et al.* 2005), it has also been realized that there was usually no technical control on the percentage of tin in the final products (either weapons or ornaments) and the admixture has occurred randomly. This variation in Sn contents in finished artifacts may imply that they have simply used a naturally mixed source of copper and tin which could be the Deh Hosein.

Comparison of the analytical results of the ore from Deh Hosein with the results of Luristan bronzes accomplished by Rickenbach 1992, Fleming *et al.* 2005, and Nezafati 2006 implies that the Deh Hosein ore, with up to 6.72% Sn and up to 10% Cu, could well be the source of many of these artifacts. In addition to copper and tin, other elements like arsenic, iron, lead, and zinc show high contents in many samples of both sides. Gold, silver, nickel and antimony which indicate traces in the artifacts also show anomalies in the ore.

LEAD ISOTOPE ANALYSIS (LIA)

The study of lead isotope ratios has nowadays consolidated its status in archaeological sciences and greatly contributed to the provenance studies (Pernicka *et al.* 1984). Geological studies of this technique had demonstrated that a large range of potential lead isotope “fingerprints” could be expected from different types of mineralization formed at different periods in the Earth’s history (Gulson 1986; Weeks 2004). The existence of isotopically discrete ore fields from particular regions lead to the speculation that isotope ratios of archaeological objects could be related to these discrete fields, thus providing a provenance for the analyzed object (Weeks 2004). Since the isotope composition of lead is more or less constant within an ore body and is not changed at all by chemical reactions during smelting or corrosion (Hezarkhani and Pernicka 2000), it is possible to utilize the lead isotope ratios as fingerprints of individual ore deposits whose ores have been used for production of certain finished artifacts. This is true as long as the ore of two or more deposits of different lead isotope ratios were mixed for the production of artifacts. In case of admixture of ores from different sources, the lead isotope ratios would be homogenized and the results differ from each individual deposit. Therefore, the application of lead isotope ratios provides, strictly speaking, conclusive evidence only in the negative sense, i.e. a specific ore deposit can be conclusively excluded as a possible source of raw metal when its isotope fingerprints do not match the artifact under study (Hezarkhani and Pernicka 2000).

For lead deposits and ancient lead artifacts the application of LIA is straightforward, but similar reasoning applies to copper deposits, because most copper ores contain at least small concentrations of lead that pass through the smelting process and end up with the cop-

per metal. If the ancient copper or copper-based alloy does not contain more than a few percent of lead, the necessary precondition that lead in copper is an accidental contamination deriving from the copper ore and is thus an indicator for the provenance of the copper can be regarded as fulfilled. This even holds true for copper-tin alloys, because tin metal is usually very pure, even in antiquity, and its concentration in bronze rarely exceeds 15% (Hezarkhani and Pernicka 2000).

18 ore samples from Deh Hosein were examined with a multi-collector inductivity coupled plasma mass spectrometer, VG Axiom MC, for lead isotope ratios (Table 2). All 2σ (95% confidence level) errors are less than 0.05% for the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios. All experiments were performed at the Institute of Archaeometry at the TU Bergakademie Freiberg. The samples were prepared and measured following the procedure of Niederschlag *et al.* (2003).

The lead isotope data of bronze artifacts of different periods and locations published by Weeks (Southern Persian Gulf including Al Sufouh, Tell Abraq, Unar 1 and Unar 2, 1999, 2004), Begemann *et al.* (Thermi in the Aegean, 1992) as well as data from Nezafati (2nd and 1st millennium Luristan, 2006), and Begemann *et al.* (3rd millennium Luristan, Troia, Mesopotamia and, Jordan, 2008) have been used in order to compare the results and have more accurate conclusion.

By comparison of the lead isotope ratios of the ores from the ancient mine at Deh Hosein with bronze artifacts from Luristan, the southern Persian Gulf, Mesopotamia, and the Aegean (Fig. 4) the following conclusions can be drawn:

The Deh Hosein deposit shows a rather small variation of lead isotope ratios disregarding if the ratio is from copper minerals, galena, arsenopyrite, copper and tin minerals or bulk samples which contain different range of minerals.

The metal used in a number of the bronze artifacts is isotopically compatible with the Deh Hosein deposit. These include most of the 3rd millennium BCE Luristan artifacts, half of the 1st and 2nd millennium BCE Luristan objects, some southern Persian Gulf artifacts, two samples from Thermi, one artifact from Kish (Mesopotamia), and Zeiraqun (Jordan). This indicates that the Deh Hosein ancient mine could

have been a major supplier of the tin which was used in the contexts of a wide area from western Turkey to southern Persian Gulf in a rather wide period of time from the third to the first millennium BCE.

Although a sample from Kish, two samples from Tell Abraq, two samples from Unar 2, the sample from Zeiragun, and a sample from Thermi do not match exactly the samples from Deh Hosein, they plot in the same area as the Deh Hosein samples.

Interestingly, the lead isotope ratio of a tin-arsenic bangle from the site Tell Abraq reported by Weeks (1999, 2004) matches very well with the isotope ratio of the ore at Deh Hosein.

There are rather numerous outliers to the main distribution (not all shown in figure 4). These outliers which are from the sites of Tell Abraq, Unar1, Unar 2, Al Sufouh, Thermi and some 1st and 2nd millennium BCE Luristan artifacts indicate that either another source of tin has been used for them or their metal derives from a mixture of Deh Hosein ore with some copper ore with a different lead isotope ratio.

Although a positive assignment is not possible out of principle, the very small variation of lead isotope ratios in the Deh Hosein deposit and the almost identical lead isotope ratios in ores from there and in bronze samples from Luristan, Southern Persian Gulf, Western Turkey and Mesopotamia strongly suggest that the ore from Deh Hosein have already been known and exploited as early as the third millennium BCE. It is also reasonable because the Deh Hosein ancient mine is the only so far known copper-tin deposit which is located in the vicinity of ancient cultures and its lead isotope ratios matches the ones from ancient artifacts. In the other hand, if tin sources are very scarce, one or a very limited number of sources could have supplied a very large area, and such isotopic matches could be a reflection of shared provenance (Weeks 2004).

Except for the Deh Hosein ancient mine, some tin deposits have lately been discovered in different regions of western and central Asia. These include *Kestel/Göltepe* in Turkey (Yener and Özbek 1987; Yener *et al.* 1989; Yener and Goodway 1992; Willis 1990, 1992; Yener and Vandiver 1993), *Jabal Silsilah* and *Kutam* in the western Arabian Peninsula (Stacey *et al.* 1980; Du Bray 1985; Du Bray *et al.* 1988; Kamilli and Criss 1996; Overstreet *et al.* 1988), *Abu Dabbab*,

Nuweibi, *Igla*, *El Mueilha*, and *Homr Akarem* in Eastern Desert of Egypt (Wertime 1978; Muhly 1978; 1993), *Mesgaran* in Afghanistan (Shareq *et al.* 1977; Berthoud 1979; Stech and Pigott 1986), and *Kharnab* and *Mushiston* in Central Asia (Masson and Sarianidi 1972; Wertime 1973; 1978; Crawford 1974; Ruzanov 1979; Alimov *et al.* 1998; Boroffka *et al.* 2002) which could be considered as suppliers of the ancient tin needs. But based upon the recent lead isotope studies accomplished by Weeks (1999, 2004), along with archaeological evidence (Garenne-Marot 1984; Muhly 1973; Glanzman 1987; Fleming and Pigott 1987; Wertime 1978; Weeks 1999; 2004), many of these deposits including deposits of Egypt and the Arabian Peninsula as well Anatolia (Kestel) have been withdrawn as possible sources of tin for the early Bronze Age.

SUMMARY AND CONCLUSIONS

The recent discovery of the Deh Hosein tin-copper occurrence together with ancient mining along with new analytical results (including lead isotope analysis) of bronze artifacts from Iran, United Arab Emirates, and some other ancient sites, provide a pivotal clue to find an answer for the old archaeological question in terms of tin and tin-copper ore. The following evidence attest that the Deh Hosein ancient mine has been a major supplier of tin for ancient civilizations of ancient Iran and Mesopotamia and even perhaps further localities to its west:

THE MINERALOGICAL AND ANALYTICAL EVIDENCE

The simultaneous occurrence of tin and copper minerals within one mineralization, the strong correspondence of lead isotope ratios as well as good correlation between trace elements of the Deh Hosein ancient mine and the ancient artifacts including high tin, copper and arsenic contents attest to the role of this mine in supplying copper-tin ore of the ancient workshops.

THE CHRONOLOGICAL EVIDENCE

According to ¹⁴C dating and archaeological evidence, the Deh Hosein ancient mine has been in operation at least from early second millennium till first millennium BCE.

THE ANCIENT TEXTUAL RECORDS (REPEATED TEXTUAL REFERENCE)

In the ancient cuneiform texts, it has been several times mentioned that copper, bronze and tin come

from the east. Among these texts, the text from Kanesh which refers to tin coming overland through the Zagros Mountains to Mesopotamia from northwestern Iran (Muhly 1973), and the text referring to mines behind Jabal Hamrin (Ebih) (*Innana and Ebih*, Muhly 1973) may have mentioned Deh Hosein Mine.

THE GEOGRAPHICAL EVIDENCE

The recently discovered Deh Hosein ancient mine is the only known tin (-copper) bearing source in close distance to the eastward Mesopotamia and Luristan area.

THE STATISTICAL EVIDENCE

The abundance of bronze artifacts from the mid Bronze Age to the end of Iron Age in the whole Mesopotamia and western Iran attests to a rich source of ore in the vicinity of these areas, especially when it would be taken into consideration that this abundance has emerged mainly in these areas and not to adjacent areas.

THE DENOMINATION EVIDENCE

The Greek word for tin, *κασσιτερος* ((Kassiteros), can be interpreted as metal “coming from the country of the Kassites” (Ghirshman 1954), and the Kassites lived in central and west central Iran. Also the characteristic Luristan Bronze artifacts appear under the reign of the Kassites in west central Iran and Mesopotamia. Finding two canonical artifacts of Luristan Bronze on Samos and Crete islands (Muscarella 1988) may confirm the influence of Kassites (or Luristani people) and the export of their wares to ancient Greek territories in the late 8th or 7th century BCE. Although the huge amount of bronze finds in the

ancient sites of Western Asia implies that the ancient mine at Deh Hosein may not have been the only source of copper-tin ore in antiquity, the geological evidence indicates that the whole northern part of Sanandaj-Sirjan belt is favourable for the occurrence of such types of ore deposits. It is thus a major target for the prospection of ancient workings. As an example, the Nezam Abad prospect (about 12km southwest of Deh Hosein) with up to 0.87% tin and 10% copper has already revealed some ancient workings and shows similar lead isotope ratios to Deh Hosein. Although the number of ancient diggings is smaller and the content of tin lower than at Deh Hosein, it could nevertheless an indication that there may be even more tin-bearing mines in the region.

Since Deh Hosein has only recently been discovered (2000), it may well lead to more extensive surveys in the in the northern part of the Sanandaj-Sirjan zone once one knows what to look for.

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THE DEH HOSEIN ANCIENT TIN-COPPER MINE, WESTERN IRAN

Sample No.	Description	Location	As ppm	Au ppb	Ag ppm	Cu %	Pb ppm	Zn ppm	S %	Sn %	W ppm	Bi ppm	Sb ppm	Se ppm	Fe %	Ni ppm	Co ppm	Ba ppm
DHN-1A	Chalcopyrite, Bi-minerals, pyrite, Fe-oxides	N33° 45.406', E049° 18.993', Digging east of the prospect	44.7	31	19.2	6.039	2117	228	0.64	<0.02	17	1252	98.9	29	4.11	60	16	<50
DHN-1B	Chalcopyrite, galena, pyrite, Fe-oxides	N33° 45.406', E049° 18.993', Digging east of the prospect	17.1	22	59.6	0.031	37694	31	0.71	<0.02	18	3	223	<3	0.47	3	3	<50
DHN-2	Pyrolusite + Fe-oxides	39s 0341207, UTM 3738556, Cheshmek Jafar Khan	278	34	<0.3	0.204	1064	413	0.07	<0.02	<1	<2	36	4	41.2	92	46	<50
DHN-4	Fe-oxides + pyrite	39s 0341626, UTM 3737312, North of Deh Hosein village	2150	28	1.1	0.086	202	48	0.03	<0.02	1	115	33.3	<3	25.8	32	28	<50
DHN-5	Chalcopyrite, pyrite, Fe-Cu-oxides	Ancient settlement	378	47	14	3.492	52	459	0.04	<0.02	6	5	6	<3	5.16	41	29	460
DHN-7A	Pyrite, chalcopyrite, cassiterite, pyrolusite, galena, stannite	39s 0343347, UTM 3737263, Ghars Ghosuli	2450	161	49.7	3.964	2591	1245	0.66	<0.01	57	50	1530	<3	29.5	44	48	120
DHN-10A	Chalcopyrite, pyrite, arsenopyrite	39s 0342443, UTM 3737013, Ahmad Jigi I	4100	135	21.8	3.691	37	156	0.02	<0.02	<1	<2	35.4	6	3.02	20	11	<50
DHN-10B	Chalcopyrite, pyrite, delafusite	39s 0342443, UTM 3737013, Ahmad Jigi I	3350	53	26.7	5.069	98	186	0.71	<0.02	<1	<2	28.1	<3	2.51	21	7	<50
DHN-15B	Fe-oxides + pyrite, chalcopyrite	39s 0340895, UTM 3738846, Ghaidan	1600	50	1	0.249	209	662	0.01	<0.02	7	44	23.3	<3	22.5	67	35	<50
DHN-16B	Fe-oxides + pyrite	39s 0340182, UTM 3739756, Ghaidan	1380	372	26.9	0.211	9793	7544	0.23	<0.03	<1	43	65.6	15	51	249	219	<50
DHN-34	Native copper, pyrite, arsenopyrite	39s 0342443, UTM 3737013, Ahmad Jigi I	19600	206	103.3	10	54	266	2.08	<0.02	<1	73	107	<3	10.2	54	28	<50
DHN-38	Arsenopyrite, pyrite, chalcopyrite, Bi-minerals	39s 0342546, UTM 3736831, Ahmad Jigi II	214000	5359	6.5	0.722	234	20	3.78	<0.02	<1	1686	1277	66	19.4	12	28	<50
DHN-42	Chalcopyrite, pyrite, cassiterite, Fe-oxides, etc.	39s 0343347, UTM 3737263, Ghars Ghosuli	1660	109	27	2.93	279	625	0.58	0.42	32	800	137	<3	15.6	60	12	<50
DHN-43	Fe-oxides + pyrite, cassiterite, sphalerite	39s 0344246, UTM 3737047, Close to the ancient settlement	16000	1101	98.4	0.438	3930	2010	0.09	6.72	150	916	1353	<3	39.5	79	61	<50
DHN-47	Chalcopyrite, arsenopyrite, gold, cassiterite, ferberite, Fe-oxides	N33° 46.61', E049° 19.99', Granodiorite	541	845	19	4.478	541	106	1.39	<0.02	2420	1805	10.8	30	8.23	51	38	<50
DHN-60	Fe-oxides + pyrite, arsenopyrite	N33° 46.083', E049° 18.992', Northeast of the prospect	4340	314	130	N.A.	N.A.	897	N.A.	<0.01	<1	N.A.	178	29	17.8	<20	9	<50
DHN-71	Fe-oxides + pyrite, chalcopyrite	N33° 45.337', E049° 18.406', Beside the dirt road	9270	<2	<6	N.A.	N.A.	<50	N.A.	<0.01	<1	N.A.	<1	<3	33.9	<25	3	<50
DHN-93	Arsenopyrite, Bi-minerals	39s 0342443, UTM 3737013, Ahmad Jigi I	239000	13300	<5	N.A.	N.A.	<50	N.A.	<0.05	<20	N.A.	428	75	20.6	<50	913	<100

Table 1: Chemical analyses of ore samples from the Deh Hosein ancient mine, measured by NAA. Detection limits: Au (2 ppb), As (0.5 ppm), Ag (0.3 ppm), Bi (2 ppm), Sb (0.1 ppm), W (1 ppm), Sn (0.01%)

Sample No.	Location	Description	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$
DHN-1A	N33° 45.406', E049° 18.993', Digging east of the prospect	Copper ore	18.439	0.8488	2.0938
DHN-1B	N33° 45.406', E049° 18.993', Digging east of the prospect	Galena	18.415	0.8494	2.0949
DHN-7A	39s 0343347 . UTM 3737263, Ghara Ghouii	Copper ore, cassiterite, pyrite, galena	18.445	0.8484	2.0924
DHN-7B	39s 0343347 . UTM 3737263, Ghara Ghouii	Oxidized copper ore	18.446	0.8487	2.0928
DHN-10A	39s 0342443, UTM 3737013, Ahmad Jigi I	Copper ore, arsenovrite	18.437	0.8488	2.095
DHN-10B	39s 0342443, UTM 3737013, Ahmad Jigi I	Copper ore, pyrite	18.528	0.8452	2.0959
DHN-12A	Ahmad Jigi II	Chalcopyrite, pyrite	18.453	0.8482	2.0926
DHN-15B	39s 0340895 . UTM 3738846, Ghaiidan	Copper ore, pyrite	18.461	0.84838	2.0933
DHN-16B	39s 0340182 . UTM 3739756, Ghaiidan	Oxidized ore	18.429	0.84868	2.0933
DHN-34	39s 0342443 . UTM 3737013, Ahmad Jigi I	Copper ore (native copper), pyrite, arsenovrite	18.487	0.8468	2.0935
DHN-38	39s 0342546 . UTM 3736831, Ahmad Jigi II	Arsenovrite, chalcopyrite, pyrite	18.446	0.8485	2.0928
DHN-42	39s 0343347 . UTM 3737263, Ghara Ghouii	Quartz, chalcopyrite, malachite, azurite, Fe oxides	18.444	0.8484	2.0922
DHN-43	North of the deposit	Oxidized ore (chalcopyrite, pyrite, sphalerite, cassiterite)	18.422	0.849	2.0937
DHN-45	39s 0344246 . UTM 3737047, Close to the ancient settlement	Oxidized copper ore	18.547	0.8438	2.0857
DHN-47	N33° 46.61' . E049° 19.99', Granodiorite	Oxidized ore (chalcopyrite, arsenopyrite, ferberite)	18.517	0.8453	2.0901
DHN-60	N33° 46.083' . E049° 18.992', Northeast of the prospect	Pyrite, arsenopyrite, sphalerite	18.434	0.8486	2.0935
DHN-76	East of the deposit	Oxidized ore (chalcopyrite, galena, pyrite)	18.447	0.8486	2.0927
DHN-93	39s 0342443 . UTM 3737013, Ahmad Jigi I	Arsenopyrite	18.509	0.8458	2.0950

Table 2 Lead isotope ratios and sample description of the ore samples from Deh Hosein.

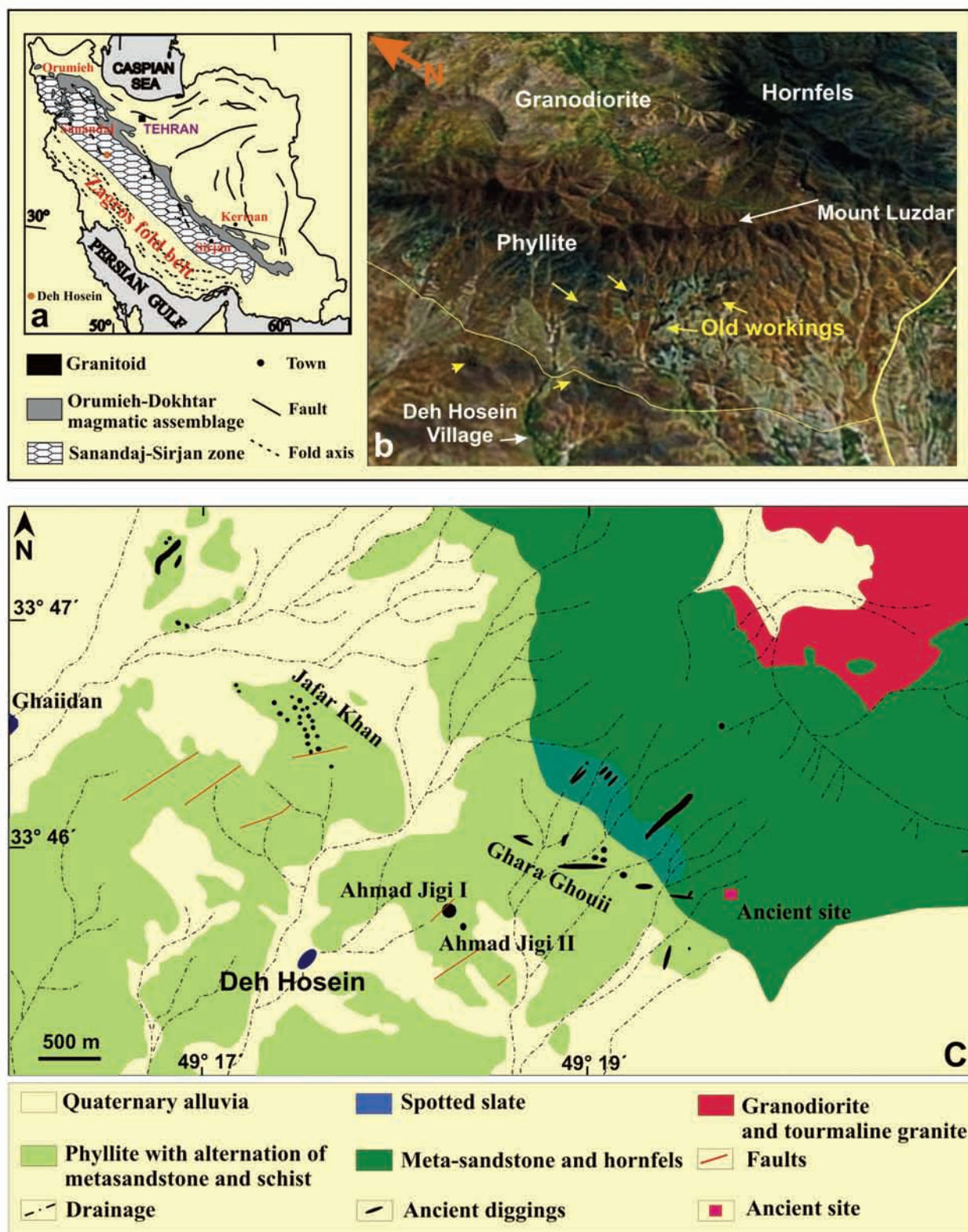


Fig. 1 a) Location of the study area in Iran, b) Satellite map of the Deh Hosein occurrence (Google Earth), c) Geology of the Deh Hosein occurrence (modified after Ojaghi et al. 2002).



Fig. 2 a) An overview of the Deh Hosein ancient mine with part of its ancient diggings, b) The Ghara Ghouii alignment of ancient diggings at Deh Hosein, c) The Ahmad Jigi ancient digging with a large mining dump, d) Hammer stone of silicified phyllite found in the Ghara Ghouii digging, e) Hammer stone of granite found in the Ghara Ghouii digging, f) Granitic grinding stones found in the greater ancient settlement, g) Pottery sherds and granitic grinding stone (top: a piece of depicted pottery sherd).

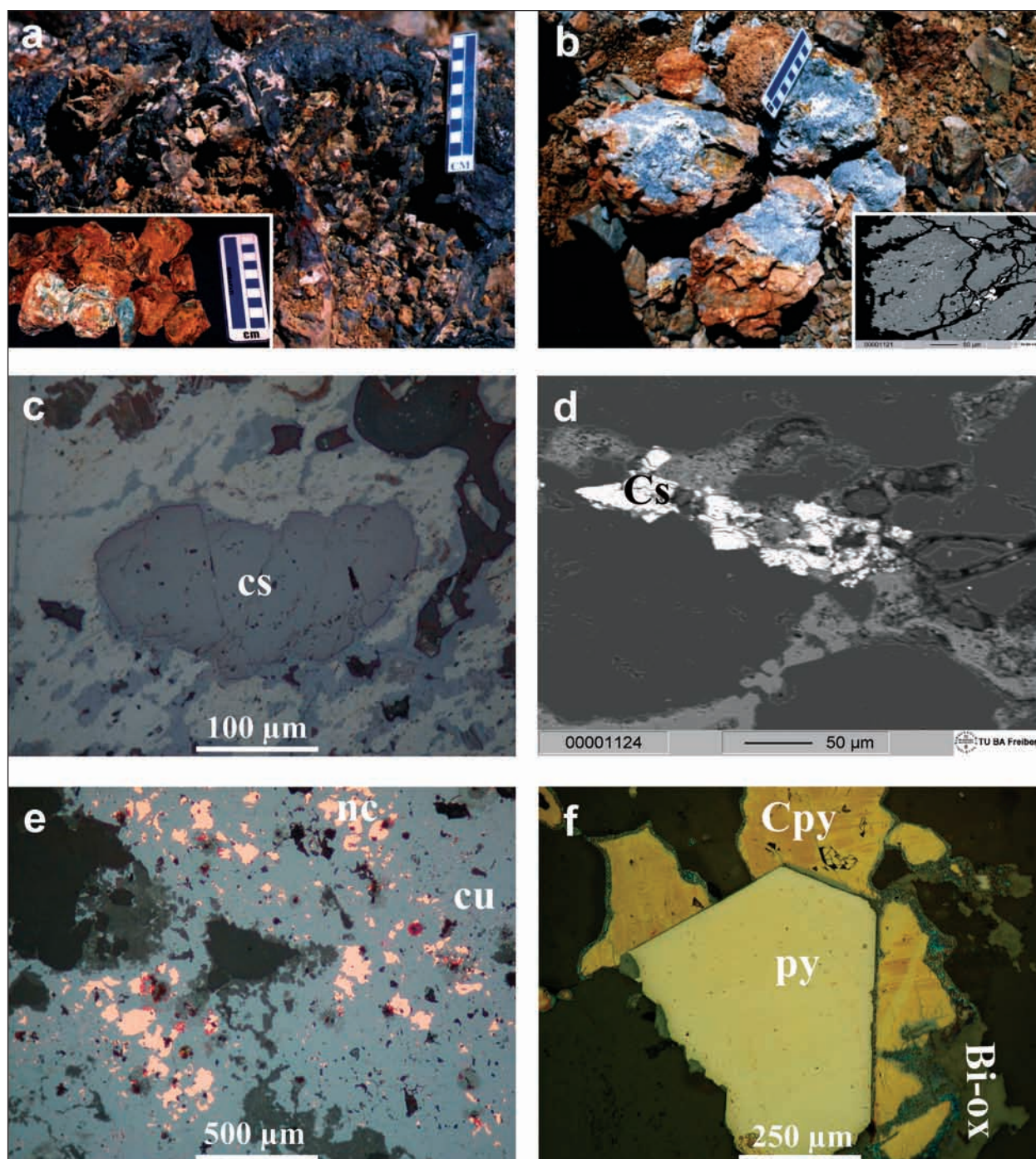


Fig. 3 a) Part of a gossan vein at the Jafar Khan locality (Bottom: Typical oxidized copper ore of the mine), b) Part of an arsenopyrite vein at Ahmad Jigi II (Bottom: Inclusions of bismuth minerals in arsenopyrite), c) Cassiterite in Fe-oxides, d) Back scattered electron micrograph of cassiterite in Fe-oxides, e) Native copper converting into cuprite and tenorite, f) An assemblage of chalcopyrite, pyrite and bismuth oxides.

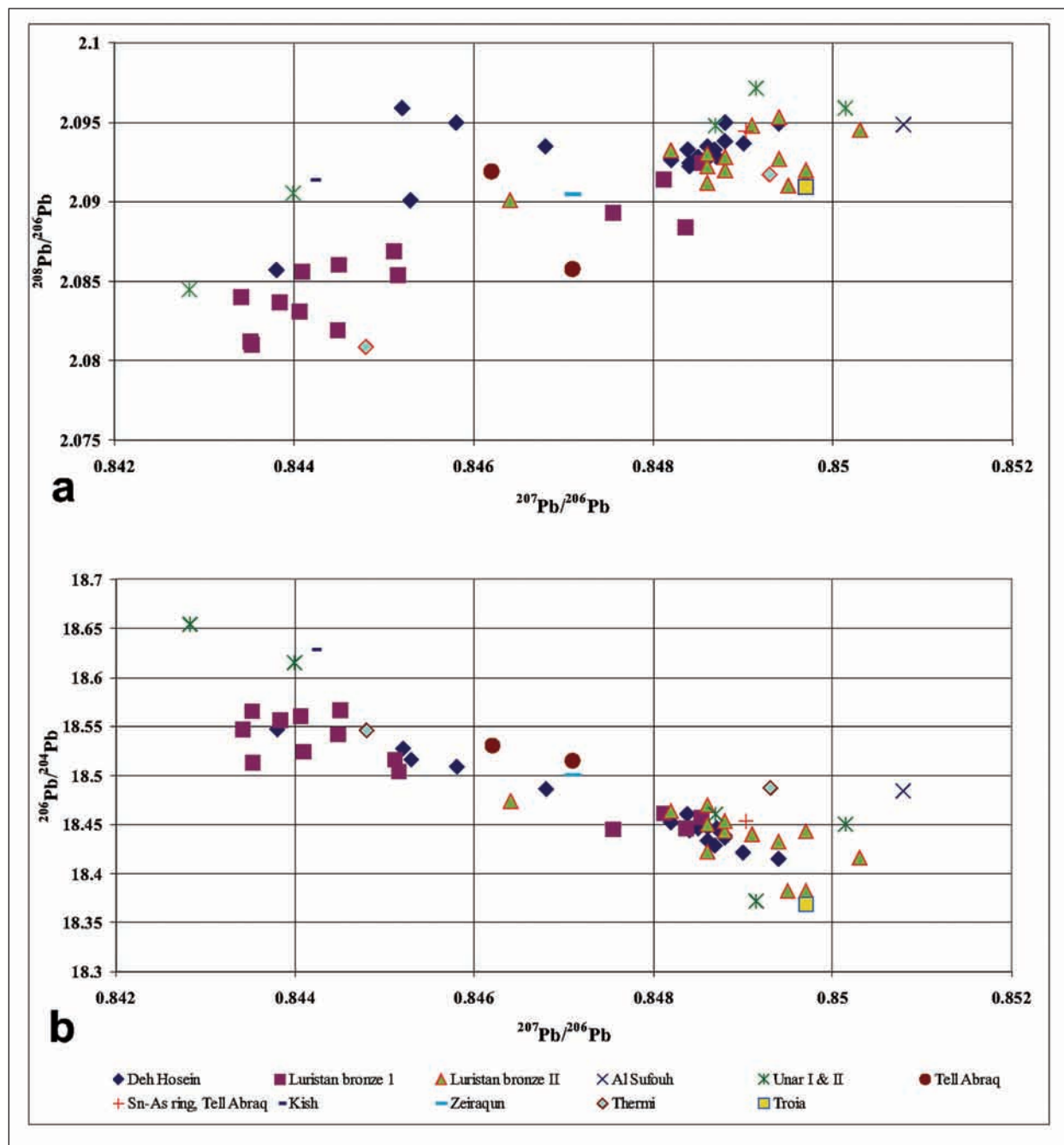


Fig. 4 Isotope plot of lead in ore samples from Deh Hosein in comparison with bronze artefacts from Luristan, UAE, Mesopotamia, and the Aegean (Fig. a and b). Luristan Bronze I refers to the 1st and 2nd millennium BCE artifacts (Nezafati 2006), while Luristan Bronze II refers to the 3rd millennium BCE samples (Begemann et al. 2008). Please note that the scale of the diagrams is greatly expanded.