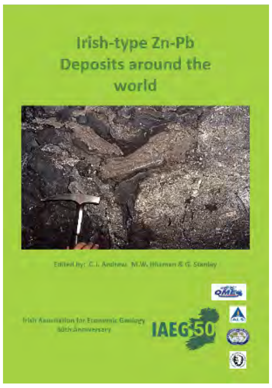
Irish-type Zn-Pb Deposits around the world

An introduction to Irish-type Zn-Pb deposits in early Cretaceous carbonate rocks of Iran

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An introduction to Irish-type Zn-Pb deposits in early Cretaceous carbonate rocks of Iran

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Abstract: Early Cretaceous carbonates are the most common host rocks for Irish-type deposits in Iran. They are largely concentrated in the Malayer-Esfahan metallogenic belt (MEMB) in southwestern Iran, and Yazd-Anarak metallogenic belt in Central Iran. They include some world-class ore deposits such as Mehdiabad, Irankuh, and Ahangaran. These stratabound deposits are hosted mostly in carbonates with minor siltstones and volcanic components, that formed in extensional and passive margin environments that are related to the Nain-Baft back-arc basin. The deposits are stratabound and comprise wedge-shaped to tabular sulphide-barite orebodies and occur in several different stratigraphic horizons. Dolomitization and silicification are the main wall-rock alteration styles. Replacement textures are common, and orebodies represent complex textures of sulphides and barite, such as brecciated, colloform, zebra, minor laminated, and banded replacement. Barite is an important gangue mineral in the MEMB and YAMB deposits, partly replaced by coarse-grained galena, sphalerite, and chalcopyrite. Sulphides from these Irish-type deposits have a wide spread of light $\delta^{34}S$ values (with the majority falling between -25 to +5‰) with mostly bacterial sulphate reduction (BSR) origin. Fluid inclusion studies show that homogenization temperatures of ore minerals are typically 120 to about 280°C (majority 225-275°C), and salinities range from 2 to 24 wt.% NaCl eq, with the majority falling between 8 and 22 wt% NaCl eq. Using the criteria outlined in this study, early Cretaceous extensional sedimentary basins (e.g., Nain-Baft) are highlighted as target areas for exploration of world-class Irish-type ore deposits and correspond well with the periods of expulsions of Cretaceous $CaCl_2$-rich brines.

Keywords: Iran, metallogeny of Zn-Pb deposits, massive sulphide, sub-seafloor replacement Zn-Pb, sideritic Fe-Mn-Pb-Zn deposits, barite replacement

Introduction

More than 350 sediment-hosted Zn–Pb±Ag±Ba deposits have been reported in Iran (Rajabi *et al*., 2012a, 2013, 2019a; Rajabi, 2022). These include shale-hosted massive sulphide (e.g., Koushk, Chahmir, Zarigan, Hosseinabad, Ab-Bagh I), Irish-type (e.g., Kuhkolangeh, Mehdiabad, Irankuh, Ahangaran, Farahabad, Mansourabad, Robat) and Mississippi Valley-Type (e.g., Nakhlak, Khanjar-Reshm, Talkhab, Gowmar, Zenoghan, Ab-bid) deposits (Fig. 1a; Boveiri *et al.,* 2017; Mahmoodi *et al.*, 2018, 2021; Niroomand *et al*., 2019; Peernajmodin *et al.*, 2019; Movahednia *et al*., 2020; Rajabi *et al*., 2012b, 2015a, 2015b, 2020, 2022) that occur in a wide variety of siliciclastic and carbonate rocks from the early Cambrian to the Tertiary. Cretaceous carbonates are the most common host rocks for the Irish-type deposits of Iran, which are largely concentrated in the Malayer-Esfahan metallogenic belt (MEMB) in southwestern Iran, and in the Yazd-Anarak metallogenic belt (YAMB) in Central Iran (Figs. 1a and 2; Rajabi *et al.*, 2012a, 2013). These metallogenic belts cover approximately 30,000 square kilometres and comprise the major portions of the outcrops of the early Cretaceous carbonate rocks in Iran.

The origin of the Cretaceous Zn-Pb (±Ag±Ba) deposits in Iran has been the subject of lively and prolonged discussion since their discovery, and despite a number of studies (e.g., Momenzadeh, 1976; Rastad, 1981; Ghazban *et al.*, 1994; Ehya *et al.*, 2010; Rajabi *et al.*, 2012a; Yarmohammadi *et al*., 2016; Boveiri *et al.*, 2017, 2018; Karimpour & Sadeghi, 2018; Karimpour *et al.*, 2017; Rajabi *et al*., 2019a; Rajabi, 2022), there is still considerable uncertainty regarding their genesis. Based on geologic studies, Momenzadeh (1976) suggested a syngenetic and sedimentary exhalative (SedEx) model for the origin of these deposits. Rastad (1981) and Boveiri *et al.* (2017; 2018) based on ore facies analysis studies on the Irankuh mining district, suggested a syn-sedimentary to very early diagenetic

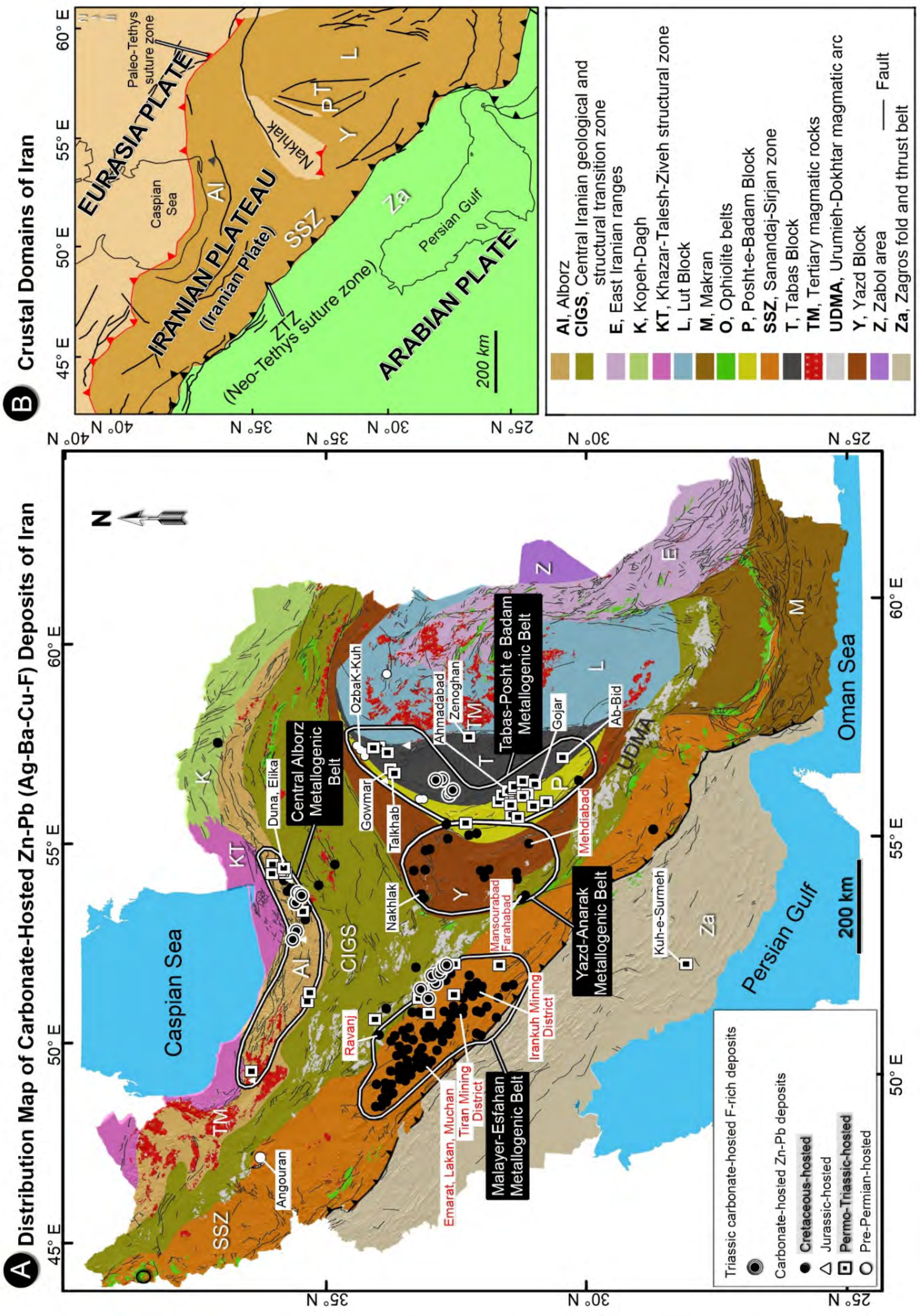
A Distribution Map of Carbonate-Hosted Zn-Pb (Ag-Ba-Cu-F) Deposits of Iran
B Crustal Domains of Iran
N
Caspian Sea
Persian Gulf
Oman Sea
200 km
45° E
50° E
55° E
60° E
25° N
30° N
35° N
40° N
SSZ
TM
AI
CIGS
KT
K
Y
T
P
L
E
Z
M
Za
UDMA
Angouran
Duna, Elika
Central Alborz Metallogenic Belt
Ravanj
Emarat, Lakan, Muchan
Tiran Mining District
Malayer-Esfahan Metallogenic Belt
Irankuh Mining District
Mansourabad Farahabad
Nakhlak
Yazd-Anarak Metallogenic Belt
Mehdiabad
Talkhab
Gowmar
OzbaK-Kuh
Ahmadabad
Zenoghan
Tabas-Posht e Badam Metallogenic Belt
Gojar
Ab-Bid
Kuh-e-Surmeh
Triassic carbonate-hosted F-rich deposits
Carbonate-hosted Zn-Pb deposits
Cretaceous-hosted
Jurassic-hosted
Permo-Triassic-hosted
Pre-Permian-hosted
EURASIA PLATE
Paleo-Tethys suture zone
IRANIAN PLATEAU (Iranian Plate)
ZTZ (Neo-Tethys suture zone)
ARABIAN PLATE
Caspian Sea
Nakhlak
Persian Gulf
AI, Alborz
CIGS, Central Iranian geological and structural transition zone
E, East Iranian ranges
K, Kopeh-Dagh
KT, Khazar-Talesh-Ziveh structural zone
L, Lut Block
M, Makran
O, Ophiolite belts
P, Posht-e-Badam Block
SSZ, Sanandaj-Sirjan zone
T, Tabas Block
TM, Tertiary magmatic rocks
UDMA, Urumieh-Dokhtar magmatic arc
Y, Yazd Block
Z, Zabol area
Za, Zagros fold and thrust belt
Fault

Figure 1: *(Opposite page)* ***A)*** *Simplified tectonic map of Iran (Aghanabati, 1998) and distribution map of carbonate-hosted (MVT and Irish-type) Zn-Pb and F-rich deposits according to the age of host rocks in the Central Alborz, Tabas-Posht e Badam, Malayer-Esfahan, and Yazd-Anarak metallogenic belts (Rajabi et al., 2012a; 2019a; 2022). Major Irish-type deposits are indicated with red font.* ***B)*** *Simplified terrane map of the western Tethysides, and crustal domains of Iran (Rajabi et al., 2019a).*

origin. However, some authors (Ghazban *et al*., 1994; Ehya *et al*., 2010; Hosseini-Dinani & Aftabi, 2016; Karimpour & Sadeghi, 2018) proposed an orogen-related Mississippi Valley-type (MVT) model and attributed their formation to the consequence of the Zagros Orogeny (collision of the Arabian plate with the Iranian plateau). Rajabi *et al.* (2012a) relied on tectono-sedimentary and textural evidence to describe the metallogeny and origin of the Cretaceous-hosted Zn-Pb (±Ag±Ba) deposits and proposed that most of these deposits formed as a result of SedEx-like (Irish-type) ore-forming processes, related to the early Cretaceous back-arc basins which formed southwest of the Central Iranian Microcontinent (Nain-Baft basin). Recent geological and geochemical studies in these belts (Yarmohammadi *et al*., 2016; Boveiri *et al.*, 2015; Mahmoodi, 2018; Peernajmodin, 2018; Peernajmodin *et al*., 2018; Niroomand *et al*., 2019; Maghfouri *et al*., 2019) provided evidence of unusual Zn-Pb (±Ag±Ba) mineralizing processes, by sub-seafloor replacement in an extensional environment, akin to those of the sediment-hosted Irish-type deposits.

However, several mineralization models have been proposed for many of the individual deposits in the Malayer-Esfahan (”MEMB”) and Yazd-Anarak (“YAMB”) metallogenic belts although there are many fundamental geological and geochemical similarities among these deposits. Rajabi *et al.* (2019a) and Rajabi (2022) recognized tectonic and stratigraphical positions of different ore deposit types within these belts and classified them as Irish-type ore deposits. This paper reviews these characteristics, highlighting the importance of the stratigraphic and tectonic setting of the deposits to give a new insight into the Irish-type mineralization in Iran.

Tectonic framework of Iran

The metallogeny of the early Cretaceous carbonate-hosted Zn-Pb (±Ag±Ba) deposits is mainly the result of the tectonic evolution of the Neo-Tethys Ocean in Iran (Rajabi *et al*., 2012a). The Central Iranian Microcontinent (including the YAMB inthe west) and the Sanandaj-Sirjan zone (including the MEMB at the centre), and along with the Alborz Mountains,

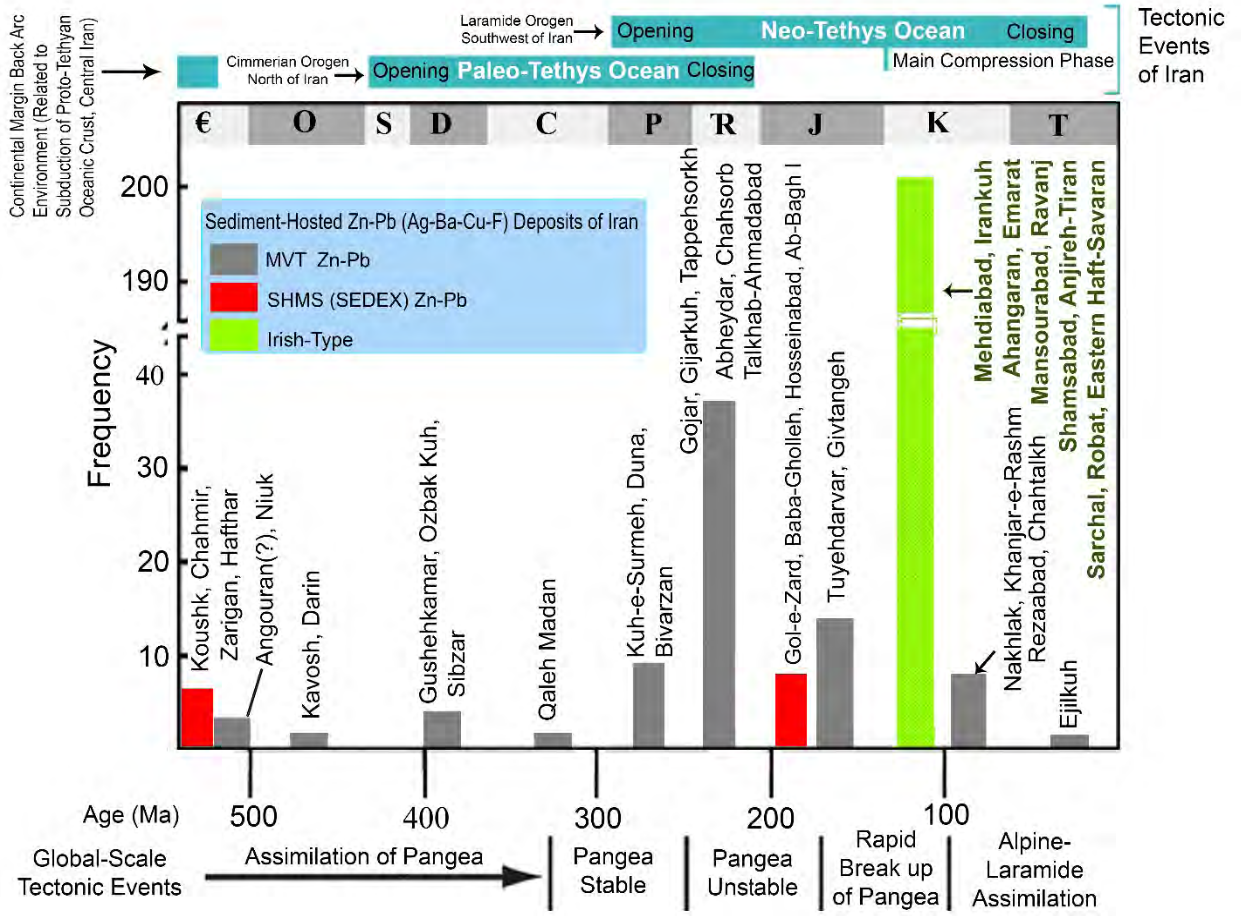

Figure 2*: Schematic age (host rocks) distribution of sediment-hosted Zn–Pb deposits in Iran plotted against tectonic evolution of Iran and global-scale tectonic events (modified after Rajabi et al., 2012a, 2013).*

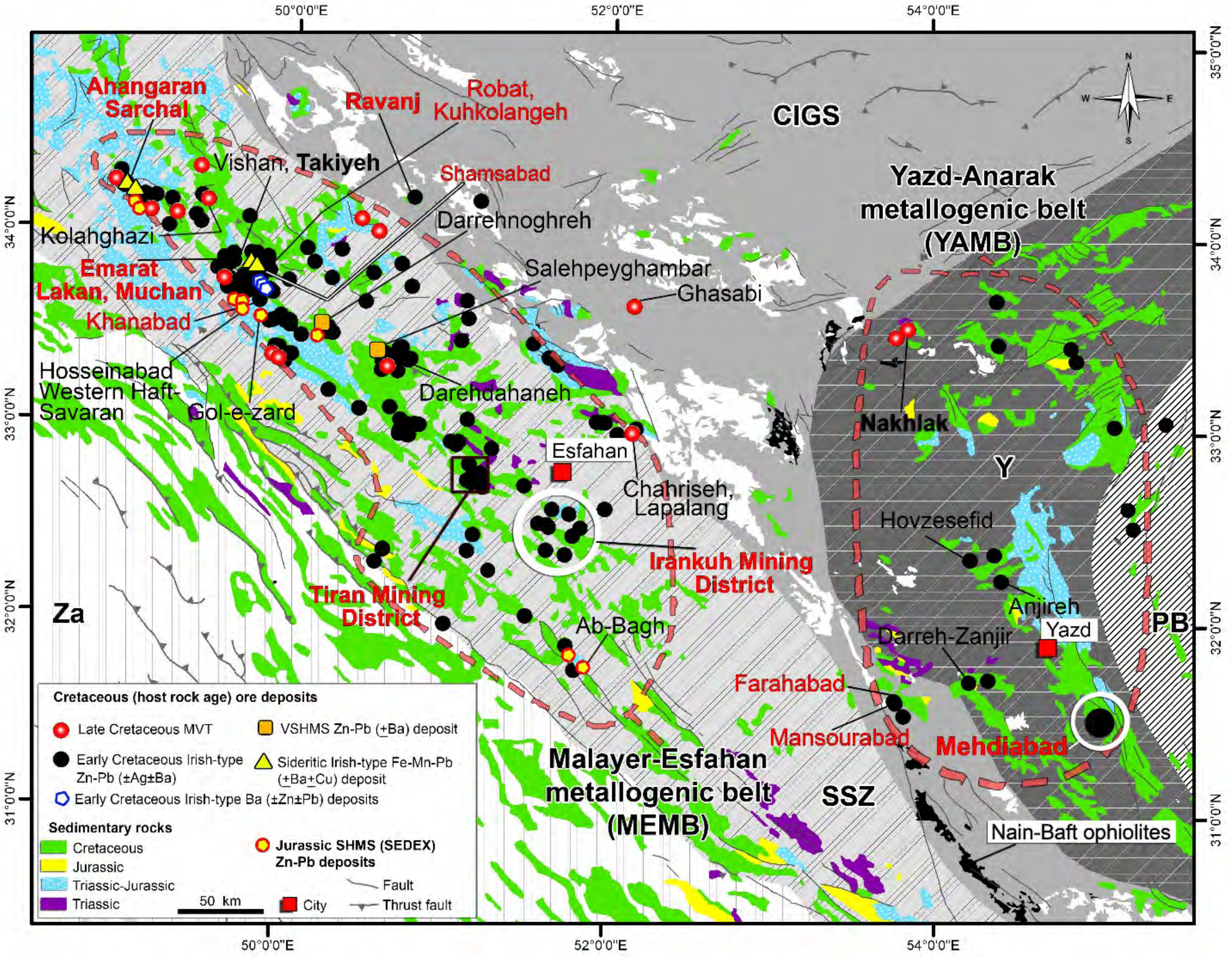

Figure 3: *Distribution map of Irish-type, SHMS (SedEx) and VSHMS deposits in the Malayer-Esfahan and Yazd-Anarak metallogenic belts of Iran (after Rajabi et al., 2012a). These deposits occur on both sides of the Nain-Baft back-arc basin, characterized by ophiolites.*

form the Iranian plateau, comprising a critical structural plateau (the domain in the Middle Eastern Tethysides (Fig. 1b). The Iranian Cimmerian terranes of Iran, Fig. 1b) is located along the Tethyan sutures between Eurasia (Variscan domain) and the Arabian plate and records the closure of the Paleo-Tethys in Mesozoic and the Neo-Tethys in the Cenozoic.

The MEMB is situated in the central part of the Sanandaj-Sirjan Zone, and the northeastern edge of the Zagros Range (Fig. 1b). A striking feature of the Sanandaj-Sirjan Zone is the immense volume of Paleozoic and Mesozoic magmatic and metamorphic rocks. The NW-trending Zagros Orogen, approximately 1500km by 100–150km, is a part of the extensive Alpine-Himalayan orogenic belt. It resulted from the collision of the Arabian margin of Gondwana with the Iranian plateau during the Middle-Late Eocene to Oligocene or early Miocene (Ghasemi & Talbot, 2005; Allen & Armstrong, 2008; Horton *et al.*, 2008). The large-scale Zagros thrust zone (Fig. 1b), located between the Sanandaj–Sirjan Zone and Zagros fold-and-thrust belt, is generally considered to represent the suture between the Arabian plate and the Iranian plateau (Golonka, 2004; Agard *et al*., 2005). Recent observations from ophiolites (Fig. 3) and igneous rocks show that the sutures between the Sanandaj-Sirjan Zone and Central Iranian Microcontinent are complex structures related to a closing back-arc basin (Bagheri & Stampfli, 2008) known as the Malayer-Esfahan (or Nain-Baft) super basin. The Malayer-Easfahan and Yazd-Anarak basins were formed around this super-basin in the early Cretaceous.

The Malayer-Esfahan Metallogenic belt

The Malayer-Esfahan metallogenic belt ("MEMB") in southwestern Iran (Fig. 3) contains a very large accumulation of different sediment-hosted Zn-Pb-Ba (±Ag-±Cu), Fe-Mn-Pb-Zn (±Ag ±Ba±Cu) and barite mineralizations, including some world-class deposits. Currently, at least 12 major mines/mining districts are active in this belt: Irankuh (20 Mt at 2.5% Pb and 11.0% Zn, remaining ore), Emarat (10 Mt at 2.2% Pb and 6.0% Zn), Ahangaran (40Mt Fe ore, 6Mt sulphide ore at 6% Pb and 0.5% Zn, 200 g/t Ag), Shamsabad (Proven and probable ore reserves are estimated at 48.7 and 300Mt, respectively; 40% Fe and 3% Mn; 1Mt Pb+Zn), Sarchal (30Mt Fe ore, 1 Mt sulphide ore), Robat (5Mt ore at 3% Zn+Pb), Eastern Haft-Savaran (2Mt at 3% Zn and 2% Pb), Saki, Ghezeldar, Arreh-Gijeh, Tiran, Khanabad and Takiyeh (Fig. 3; Rajabi, 2022); additionally, there are numerous prospects under exploration (e.g., Kuhkolangeh, Lakan, Muchan). The MEMB is a broad, northwest-southeast trending, 500 km-long, folded and thrust belt that spans the length of the Sanandaj-Sirjan Zone (Momen

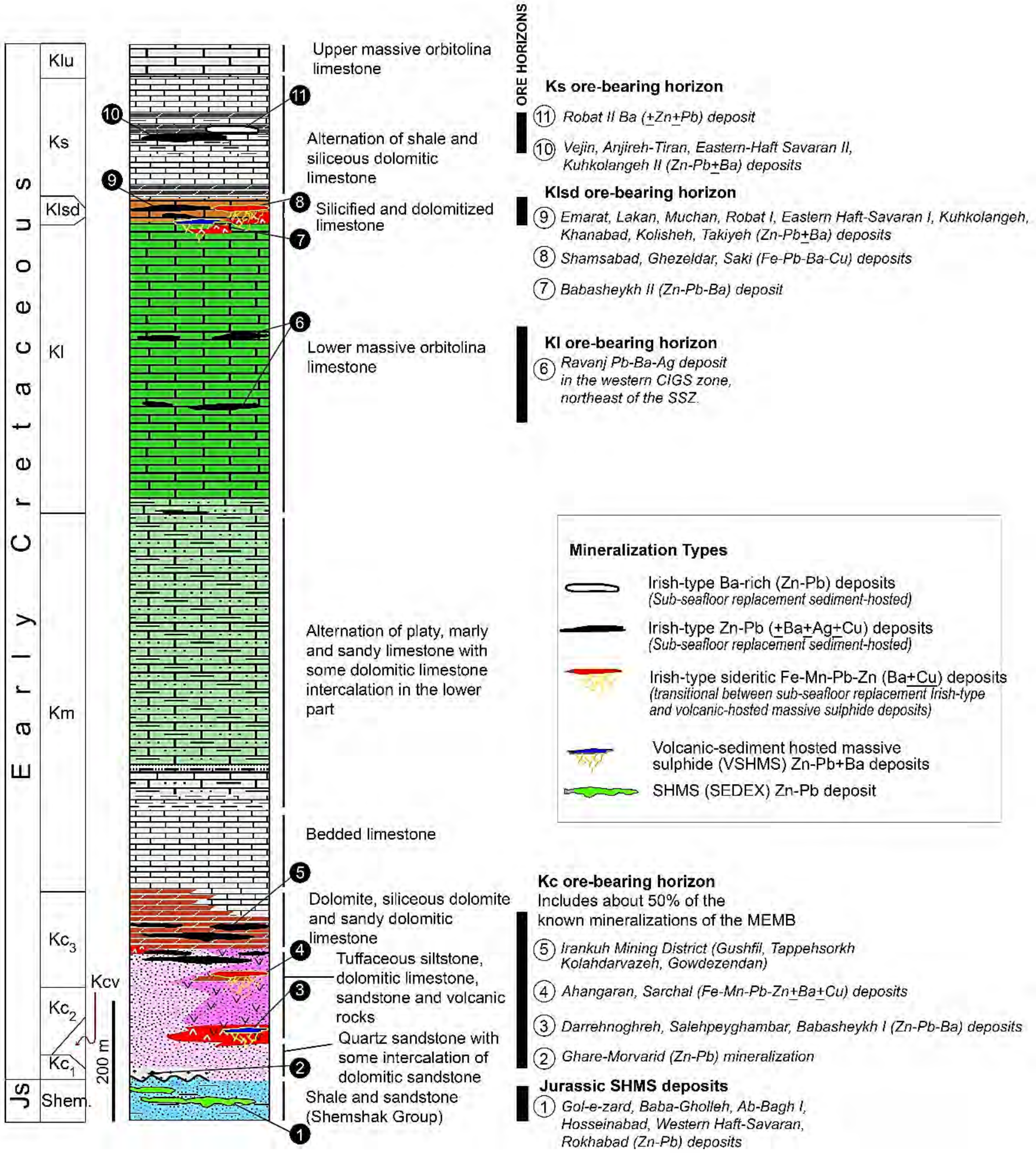

***Figure 4:** Generalized schematic stratigraphic column of the early Cretaceous sequence of the MEMB and western CIGS transition zone, with the main ore-bearing strata (modified after Momenzadeh (1976) and Rajabi et al. (2012a; 2019a)).*

zadeh, 1976). The most common host rocks of the deposits in this belt are Jurassic shales and sandstones, early Cretaceous carbonates, and sometimes siltstones and volcanic rocks (Fig. 4), although some deposits have late Cretaceous carbonate host rocks (Rajabi *et al.*, 2012a; Fig. 3).

Most deposits of the MEMB are hosted within the early Cretaceous (Barremian to Albian) sequences developed during extensional events of the Malayer-Esfahan (Nain-Baft) back-arc super basin (Rajabi *et al.*, 2012; 2019a). The MEMB contains folded shallow marine carbonates of early Cretaceous age, unconformably overlying late Triassic and/or late Jurassic shales, and sandstones (Fig. 4). In some places (e.g., Ahangaran, Sarchal, and Ab-Bagh areas) this boundary is conformable between the late Jurassic and early Cretaceous sedimentary rocks.

Transgressive sediments of the early Cretaceous sequence start with the deposition of 20 to 150m of terrestrial conglomerates and sandstones which overlie Jurassic clastic sedimentary (Barremian, “Km” unit). The “Kc” detrital sedimentary rocks laterally change to interbedded siltstones and volcanic and volcaniclastic rocks (“Kcv” unit), especially in the Ahangaran, Sarchal, Darrehnoghreh, and Salehpeyghambar areas, in the

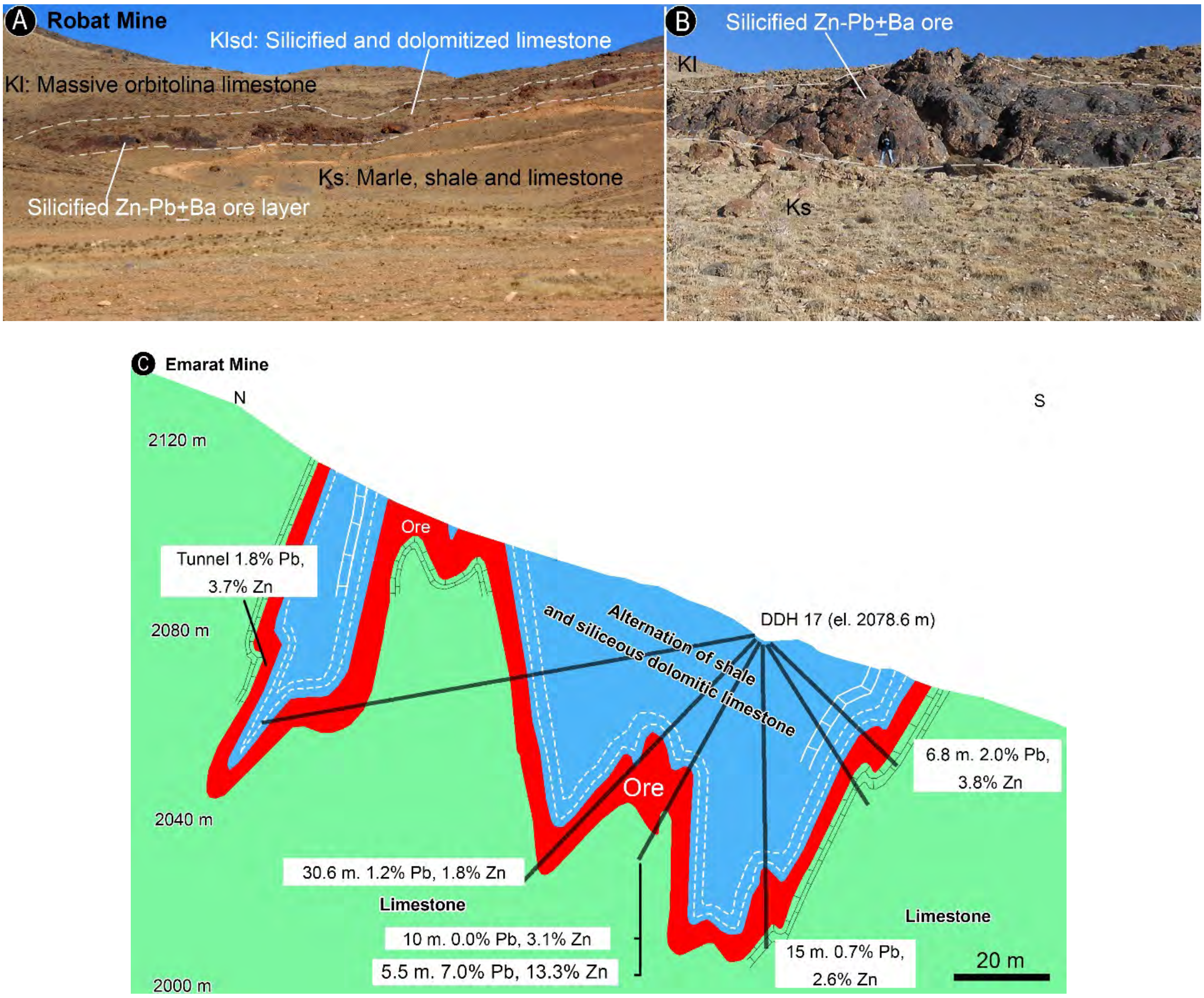

Figure 5: *A), B) Sheet-like stratabound Zn-Pb (±Ba) mineralization in the silicified and dolomitized limestone (Klsd), best developed concordantly under the marls of the "Ks" unit, Robat deposit. C) Geological cross-section no. 1000/1 from the Emarat deposit showing the small-scale folding of the orebody and its tabular shape (modified after Ehya et al., 2010).*

northwestern and eastern parts of the MEMB. The "Km" unit is overlain by 400m of thick-bedded limestones with preserved fossils, mainly orbitolina and rudists (Barremian-Abtian, "Kl" unit), representing a shallow marine carbonate platform environment. The "Kl" limestones are overlain by Albian marl, shales, and thin-bedded limestones of the "Ks" unit. This succession continues with a 100m thick medium to thick-bedded massive orbitolina limestone ("Klu" unit).

The Irish-type mineralization in the MEMB

Although sulphide mineralization is dominant in the MEMB, supergene non-sulphide ores are also common (e.g., Irankuh mining district). Based on the lithologies of the ore-bearing strata (Rajabi, 2022; Rajabi & Mahmoodi, 2023), mineralization is restricted to five main stratigraphic positions (Fig. 4):

(1) the Jurassic ("Js") ore-bearing horizon that includes shale-hosted massive sulphide (SHMS or SedEx) deposits at the top of the late Jurassic shales and sandstones (e.g., Kachuieh, Kolahbid, Gol-e-Zard, Baba-Gholleh, and Rokhabad deposits) are most concentrated in the southern (such as Ab-Bagh deposit) and the northwestern part (e.g., Gol-e-Zard, Hosseinabad and western Haft-Savaran deposits) of the MEMB (Rajabi *et al*., 2019a; Movahednia *et al*., 2020; Mahmoodi *et al*., 2018, 2021).

(2) The "Kc" horizon at the base of the Cretaceous sequence hosts Irish-type Zn-Pb (±Ag±Ba) deposits, such as Irankuh in dolomitic limestone, along with siltstone in the southeastern part of the belt. This horizon in the center and northwestern part of the metallogenic belt hosts sideritic Fe-Mn-Pb-Zn (±Ag ±Ba±Cu) and barite deposits in dolomitic limestone, siltstone, sandstone and tuffaceous siltstones (e.g., Ahangaran and Sarchal deposits) that were labelled as Irish-type deposits by Rajabi *et al*. (2019a) and Maanijou *et al*. (2020), and some zinc-lead ± barite mineralizations in volcanic, pyroclastics and sedimentary rocks that are known as volcanic-sediment hosted massive sulphide (VSHMS; such as Darehnoghreh and Salehpeyghambar).

3) The "Klsd" horizon in the upper part of the Kl unit includes

intense silicified and dolomitic limestone, which hosts Irish-type Zn-Pb (±Ag±Ba) deposits (e.g., Robat I, Lakan, Khanabad, Emarat, Muchan, and Eastern Haft-Savaran) and some sideritic Fe-Mn-Pb-Zn (±Ba±Cu) deposits (e.g., Shamsabad, Saki and Ghezeldar).

4) the "Ks" ore-bearing horizon, with alternating shales and siliceous dolomitic limestones, lies above the "Klsd" and below the "Klu" unit, and hosts zinc-lead deposits such as Anjireh-Tiran, Robat II, and Kuhkolange II deposits.

In addition, the stratabound Ravanj mineralization is the only known deposit in the "Kl" unit of the belt.

According to the geology, mineralogy, and commodities of the major early Cretaceous MEMB deposits, these mineralizations can be divided into two categories – Irish-type and Sideritic Irish-type.

Irish-type Zn-Pb (±Ag±Ba) deposits

The Irish-type Zn-Pb (±Ag±Ba) deposits (e.g., Irankuh, Tiran, Robat, Emarat, Eastern Haft- Savaran, Kuhkolangeh, Arreh-Gijeh, Muchan) occur throughout the early Cretaceous sequence and are widespread in the MEMB. These deposits are hosted in silicified-dolomitized limestone with minor siltstones or shales. In some cases, they are hosted by tuffaceous rocks or associated with minor submarine volcanic rocks (Fig. 4). These deposits occur in several different stratigraphic horizons/positions (Fig. 4), that emphasizes the host strata (the host basin) are the significant ore controlling factors in the formation of these deposits. Except for a few examples (not all) in the Tiran and Irankuh regions, most deposits are unrelated to post-ore thrust/reverse faults.

The early Cretaceous Zn-Pb (±Ba±Ag) deposits in the MEMB are stratabound, and most of them occur concordantly (Fig. 5) at the contact between the early Cretaceous massive orbitolina limestone and the upper shale and marl units (e.g., Emarat, Robat, Kuhkolangeh, Lakan and Muchan), which show tabular shapes. However, they are stratabound, since their shapes are concordant with the host layers and experienced the same folding deformation due to the post-ore compressional tectonism. This indicates that orebodies formed before the compression and are not related to the thrust fault systems which are later.

The sulphide orebodies comprise sphalerite and galena with minor chalcopyrite, pyrite and tetrahedrite. Ore sulphides comprise complex textures including replacement, colloform, banded replacement, brecciated and minor laminated or framboidal pyrites. Barite is an important gangue mineral, replaced by coarse-grained galena and sphalerite (e.g., Irankuh and Tiran mining districts, Robat and Kuhkolngeh deposits) and some of the barite ores are economic (e.g., Robat II deposit). However, dolomitization is common in these deposits, but silicification is the major hydrothermal alteration at the Emarat (Ehya *et al.*, 2010), Lakan, Robat, Kuhkolangeh (Peernajmodin *et al.*, 2018; Niroomand *et al.*, 2019), Khanabad and Eastern Haft-Savaran deposits (Mahmoodi, 2018; Rajabi *et al.*, 2019a). Fe-rich dolomite is also a frequently observed alteration in these deposits (Boveiri *et al.*, 2018; Mahmoodi *et al.*, 2019).

Detailed mineralogical and textural studies on the Zn-Pb (± Ba ± Ag) deposits generally indicate two (or three in some deposits) main paragenetic types of sulphides that are common in most of these deposits (e.g., Irankuh and Tiran mining districts, Robat, Eastern Haft-Savaran, Lakan, and Khanabad deposits): (1) deposition of volumetrically minor, early, fine-grained, disseminated (to laminated in some of them, Fig. 6) sulphides and euhedral barite in unconsolidated sediments (Rajabi *et al.*, 2012a; Boveiri *et al.*, 2017; Mahmoodi *et al.*, 2019), which in most deposits are associated with a large content of framboidal pyrite (Yarmohammadi *et al.*, 2016; Boveiri *et al.*, 2017; Mahmoodi *et al.*, 2019; Peernajmodin *et al.*, 2018; Rajabi & Mahmoodi, 2023). These sulphides and barite are followed by (2) the main coarse-grained sulphide mineralization and extensive replacement of barite, carbonates, and early sulphide laminae/bands by sphalerite, pyrite and galena, and hydrothermal minerals such as quartz and Fe-bearing dolomite within the host siltstone and/or limestone units (Fig. 7). (3) The last type of sulphide mineralization is observed in some deposits (e.g., Irankuh and Tiran mining districts; Yarmohammadi, 2015; Boveiri *et al.*, 2017) and includes coarse-grained sphalerite and galena with minor pyrite concentrated in some reverse fault zones due to the later orogenic movements. In these faults, both sulphide minerals and the host rocks show signs of intense deformation.

Detailed tectonic studies and measurement of kinematic indicators in Tiran and Irankuh mining districts and also in Kouhkolangeh, Shamsabad, and Ab-Bagh II deposits suggest that the formation of these deposits are related to syn-sedimentary normal faults of the early Cretaceous (Yarmohammadi *et al.*, 2016; Boveiri *et al.*, 2017; Peernajmodin, 2018; Movahednia *et al.*, 2020), some of which were subsequently reactivated as reverse faults after the late Cretaceous tectonic event (Nakini, 2013; Boveiri, 2016). Yarmohammadi (2015) reported some igneous components, sedimentary breccias, and debris flows adjacent to the normal fault at the Vejin-Paein deposit (Fig. 8). Debris flows and sedimentary breccias abruptly increase in thickness toward the normal faults. Interfingering of debris flows with fine-grained sediments, along with abrupt lateral changes in facies and thickness, indicate the proximity of syn-sedimentary faults (Deb & Goodfellow, 2004).

Sideritic Irish-type Fe-Mn-Pb-Zn (±Ag±Ba±Cu) Deposits

The northwestern part of the MEMB hosts several unusual base metal deposits, characterized by extensive iron ore along with copper, lead, zinc, and barite mineralization. The five major Fe-Mn-Pb-Zn (±Ag±Cu±Ba) deposits of the MEMB are generally classified as Irish-type deposits and include Ahangaran, Shamsabad, Sarchal, Ghezeldar, and Saki deposits (Figs. 3 and 9). These ore deposits are hosted in early Cretaceous sandstone, tuffaceous siltstone, dolomitized and silicified limestone and sandstone, and they are associated with minor volcanic rocks (Fig. 10; Akbari, 2017; Akbari *et al.*, 2020; Peernajmodin, 2018; Rajabi *et al.*, 2019a; Maanijou *et al.*, 2020; Han *et al.*, 2020; Ehya & Marbouti, 2021). In these deposits, Fe-bearing carbonates (siderite and ankerite) are the most important hydrothermal minerals that are associated with barite, chalcopyrite, pyrite, galena, pyrolusite, todorokite,

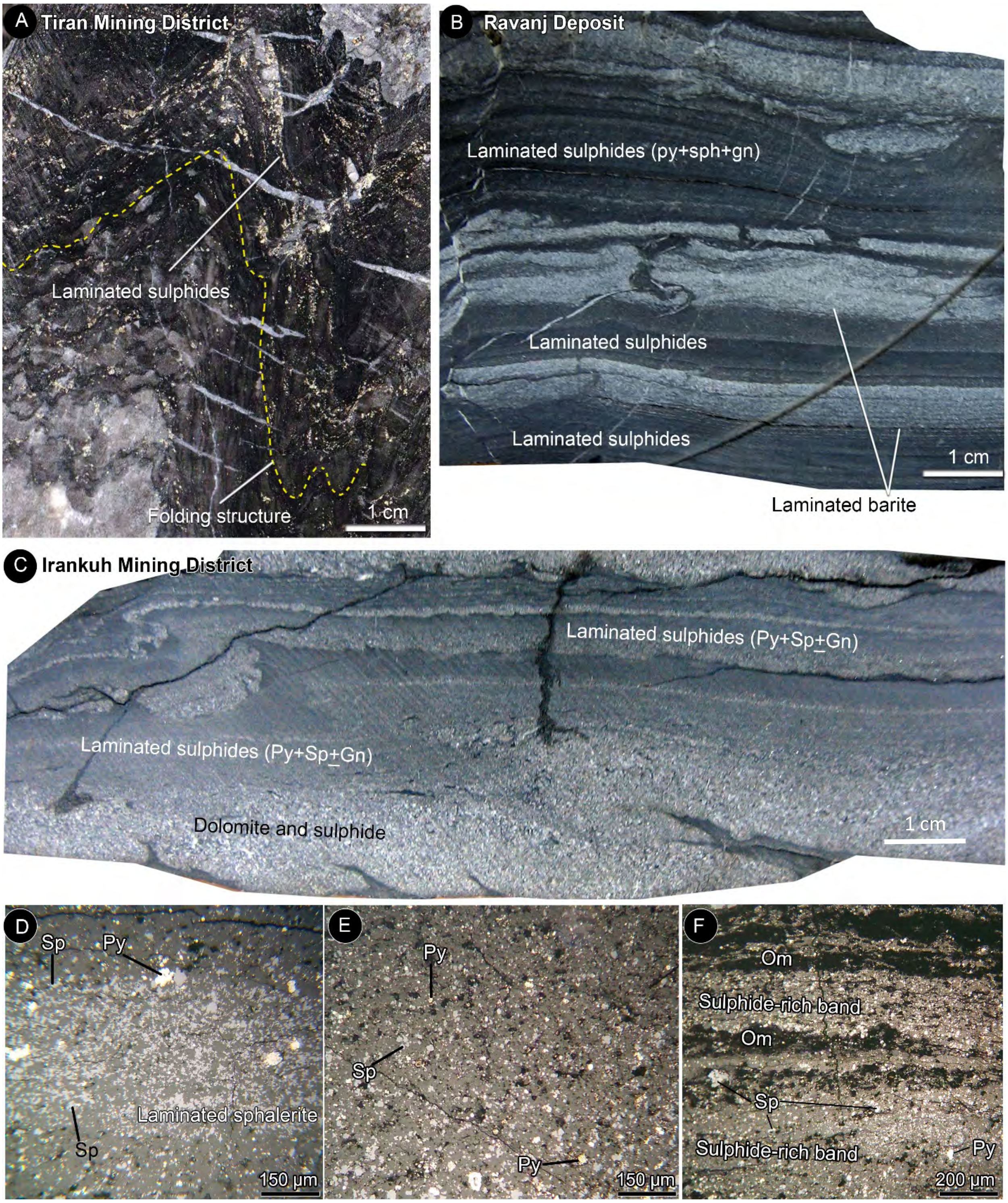

Figure 6: *A) Folded laminated sulphides, Tiran mining district. B) Laminated barite, pyrite, galena, and sphalerite (Py + Gn + Sph) in organic matter-bearing limestone, Ravanj deposit. C) Laminated framboidal pyrite, fine-grained sphalerite, galena (light grey), and algal-laminated dolomite (dark grey). Folded dolomitic ore-bearing layers show typical convolute bedding texture. D), E) and F) Microscopic photographs (reflected light) of fine-grained laminated (D and F) and disseminated sulphides in sulphide-rich bands (E), hosted in silty limestone, Gushfil deposit, Irankuh mining district. Sp: sphalerite, Py: pyrite, Om: organic matter, Gn: galena.*

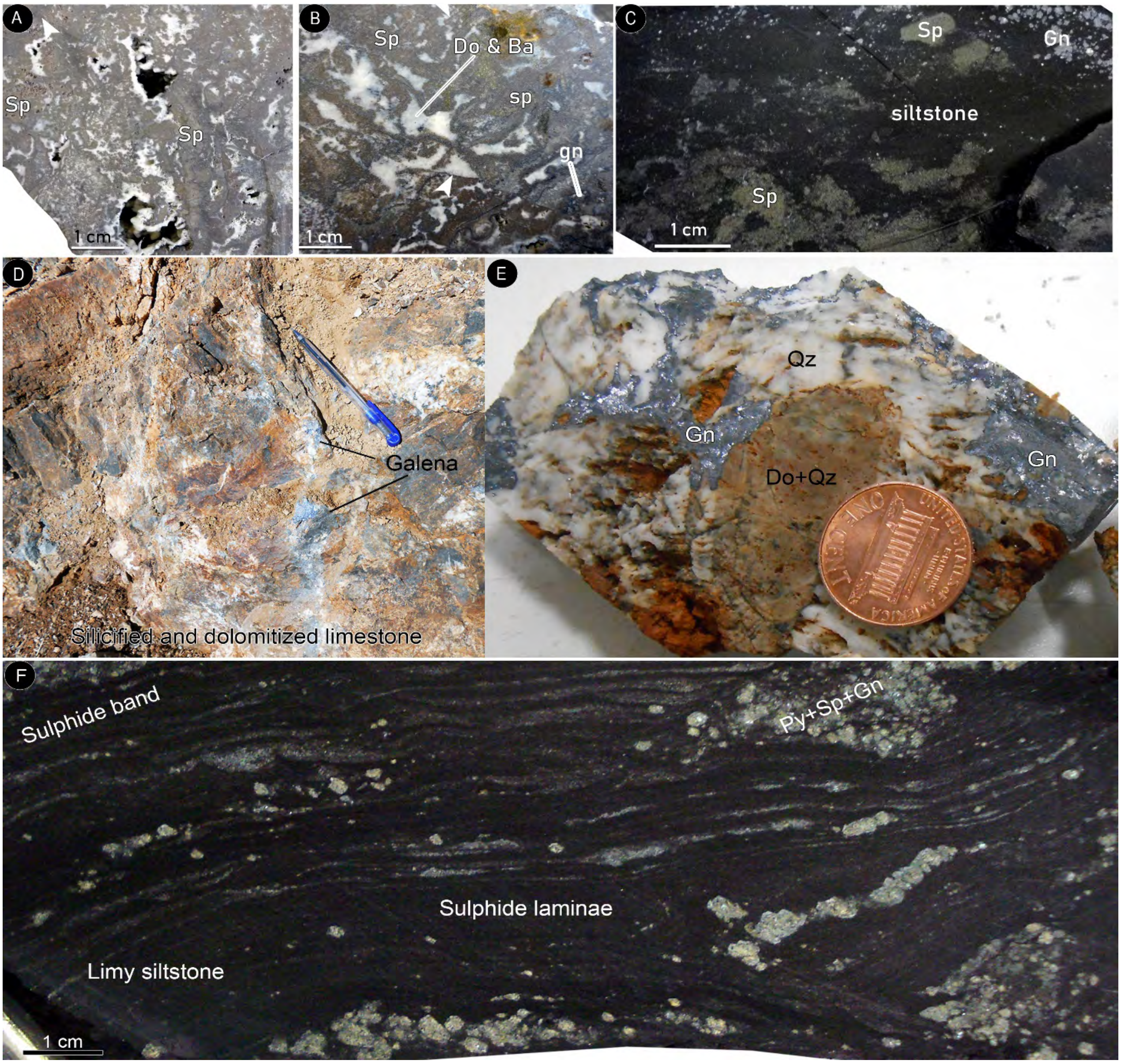

Figure 7: *A), B) and C) Hand specimen samples of coarse-grained sulphide mineralization in the Irankuh mining district. D) and E) Outcrop (D) and hand specimen (E) photographs of the coarse-grained galena mineralization in the brecciated and silicified limestone, Robat deposit. F) Hand specimen photographs of banded replacement ore in black limey siltstone, Tiran mining district. Sp: sphalerite, Gn: galena, Py: pyrite, Do: dolomite, Qz: quartz, Ba: barite.*

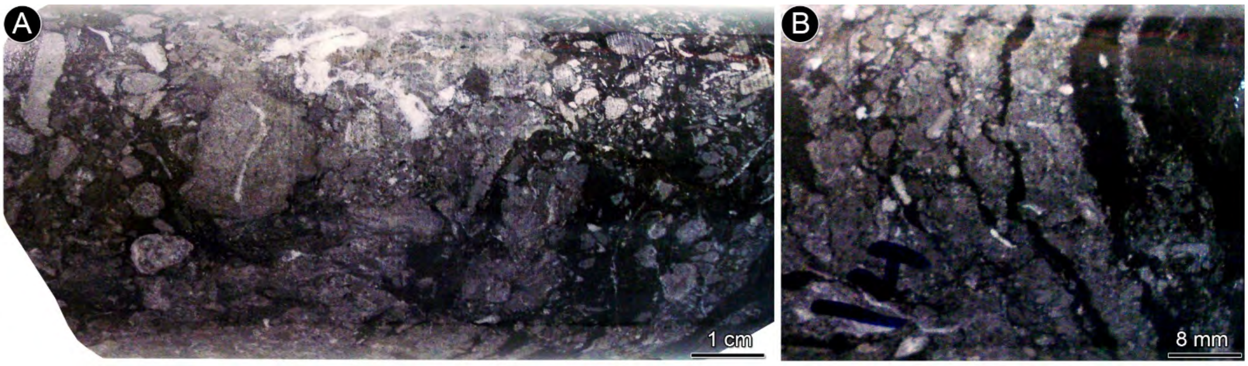

Figure 8: *Hand specimen photograph of debris flows occur interfingered with mineralized host rocks, Tiran mining district.*

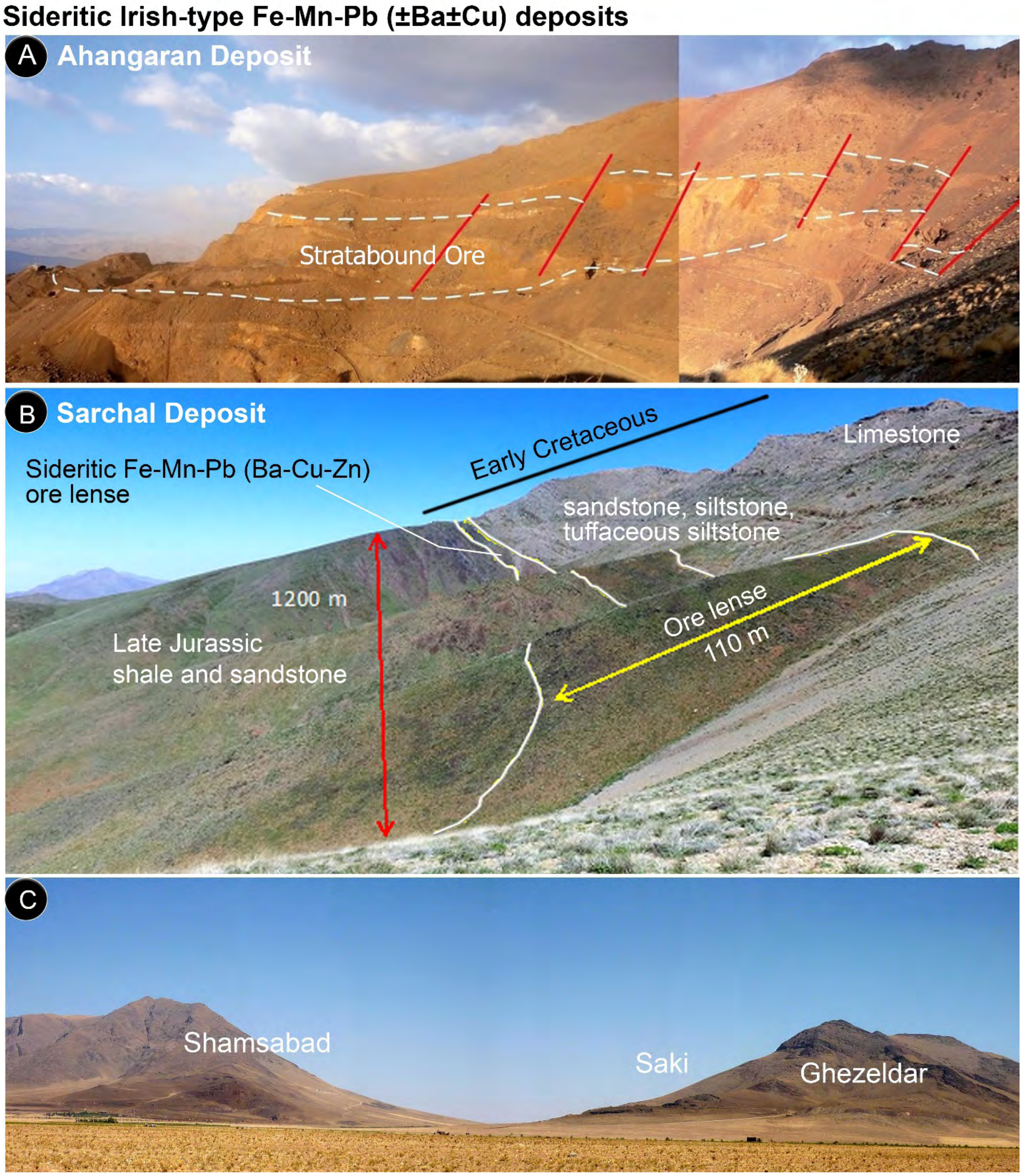

Figure 9: *Outcrop views of sideritic Irish-type Fe-Mn-Pb-Zn (±Ag±Ba±Cu) deposits in the early Cretaceous tuffaceous siltstones and dolomitized and silicified limestone, Malayer-Esfahan metallogenic belt.*

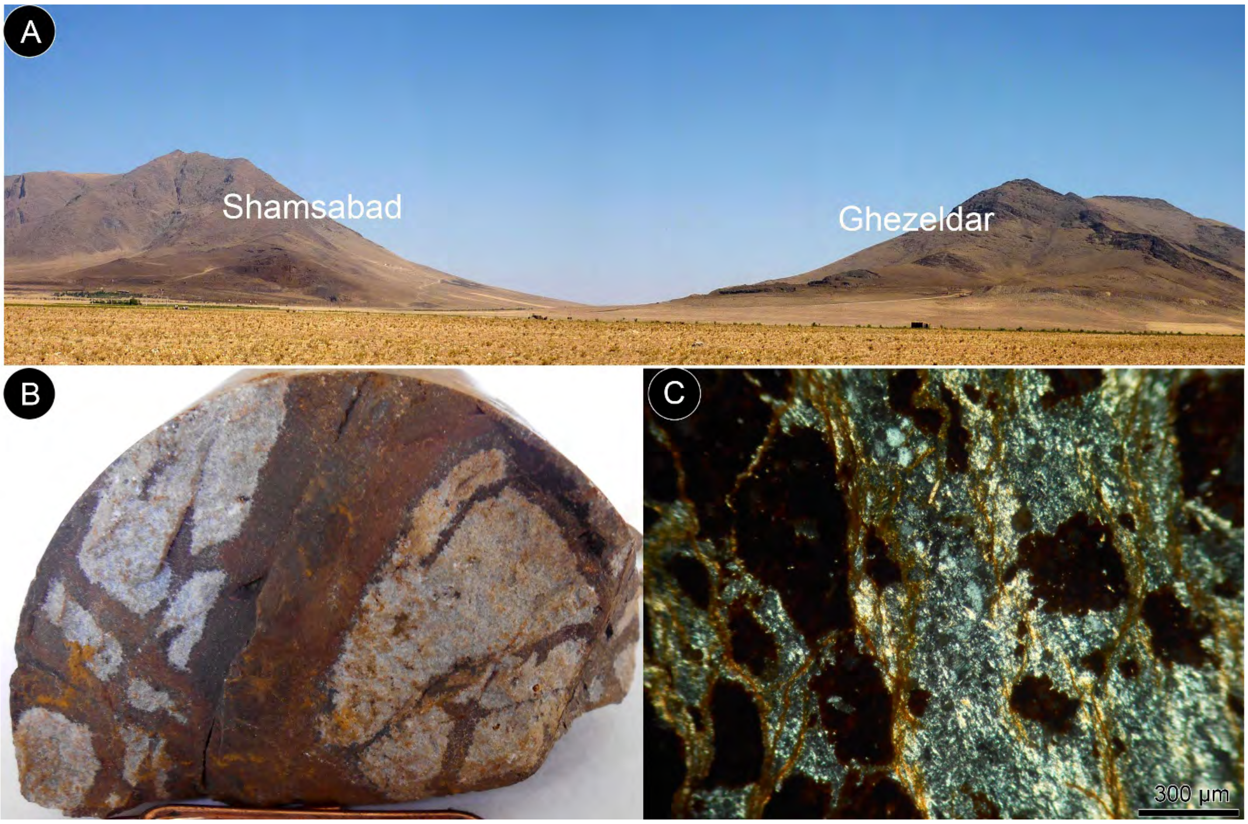

Figure 10: *A) Outcrop views from Shamsabad and Ghezeldar sideritic Fe-Mn-Pb-Zn (±Ag±Ba±Cu) deposits in silicified and dolomitized limestone ("Klsd" unit). B), C) Hand specimen (B) and microscopic (C) photographs of rhyolite with Fe-oxide/hydroxide veins, Shamsabad deposit.*

coronadite, rhodochrosite (Peernajmoin, 2018; Akbari *et al*., 2020). The presence of such abundant Fe carbonates associated with barite and sulphides is not common in MVT deposits but can form by sub-seafloor replacement mineralization in an extensional environment, with associated submarine volcanism, and are most common in sideritic Fe-Mn (±Zn±Pb±Cu±Ba) ore deposits, that are most similar to Irish-type ores. On the other hand, due to the presence of pyroclastic and sometimes volcanic components in their host sequence, they have a transitional state with volcanogenic massive sulphide deposits (Rajabi *et al*., 2019a; Akbari *et al*., 2020).

The sideritic Irish-type Fe-Mn-Pb-Zn (±Ag ±Ba±Cu) deposits are stratabound and occur in "Kc_3" and "Klsd" units (Figs. 3 and 4). The orebodies have tabular to lenticular shapes, which are concordant within the silicified, dolomitized, and sideritic host rocks (Fig. 9).

Among these deposits, Ahangaran is well known and encompasses three distinct ore facies: (1) stockwork zone, (2) massive stratabound oxide-sulphide ore, and (3) massive and banded barite ore. The stockwork zone, which underlies the stratabound massive ore, consists of an irregular network of chalcopyrite, galena, pyrite, tetrahedrite, magnetite, Fe-dolomite, barite and quartz veins cutting the footwall host rocks. The massive ore consists of a high-grade ore body that forms the thickest portion of the deposit and comprises massive zones, replacement patches, brecciated sulphides, and irregular vein-veinlets of sulphides, magnetite, barite, siderite, Fe-dolomite, and quartz. Above the massive ore, massive and banded barite cover the mineralization and includes zebra textures of barite with minor galena, siderite, dolomite, and quartz.

Yazd-Anarak metallogenic belt

The Yazd-Anarak metallogenic belt ("YAMB") in the Yazd Block hosts several carbonate-hosted Zn–Pb deposits, including Irish-type (e.g., Mehdiabad, Mansourabad, and Farahabad), and structurally controlled MVT (e.g., Nakhlak and Darreh-Zanjir) mineralizations. Most deposits (e.g., Mehdiabad, Darreh-Zanjir, Farahabad, and Mansourabad) occur within the early Cretaceous Taft Formation, in the southern portion of the YAMB (Rajabi *et al*., 2012a), but a few MVT deposits are hosted by late Cretaceous carbonate rocks (e.g., Nakhlak deposit).

Mehdiabad (Fig. 11) is a world-class Zn–Pb-Ba-Cu (±Fe±Mn) deposit located in the southern YAMB (Leach *et al*., 2005; 2010; Rajabi *et al*., 2012a). Like Irankuh, early Cretaceous carbonates and sandstones unconformably lie over Jurassic rocks in this deposit. Ghasemi (2006) and Rajabi *et al*. (2012a) reported an oxide reserve of 45.2Mt at 7.15% Zn and 2.47% Pb and a sulphide reserve of 116.5Mt at 7.3% Zn and 2.3% Pb in this deposit. But recent exploration revealed the total geological resource of this deposit of about 630 Mt at 4.2% Zn, 1.2% Pb, 5% Cu and 51 g/t Ag, along with tens Mt of barite (Rajabi, 2022). In the YAMB, the early Cretaceous sequence comprises (bottom to top) the Sangestan, Taft, and Darreh-Zanjir Formations. The Sangestan Formation consists of shales and siltstones with intercalated layers of calcarenites

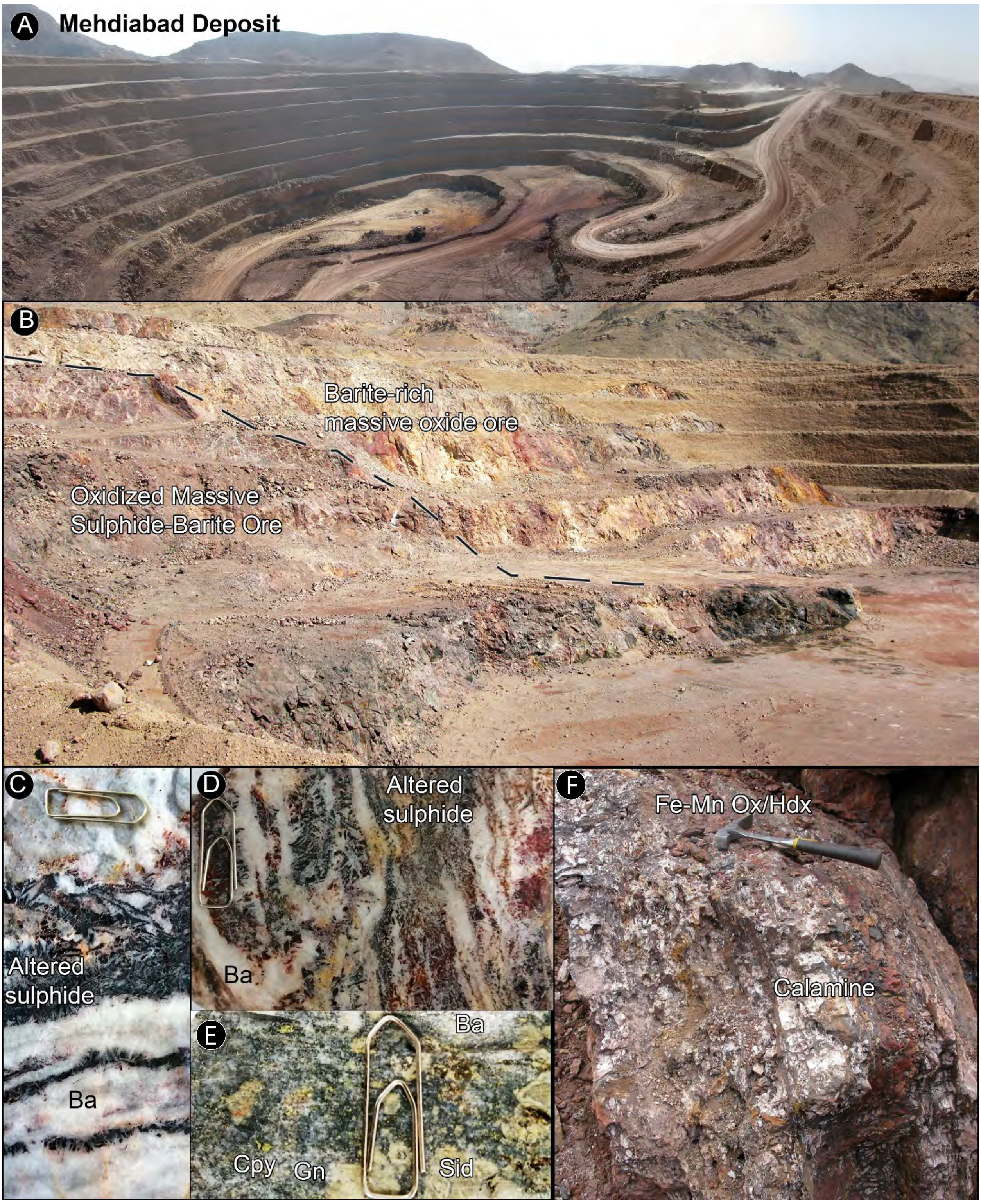

Figure 11:* *A and B) *Outcrop views of the Mehdiabad deposit.* ***C)*** *and* ***D)*** *Zebra texture from the Mehdiabad deposit consisting of interlayered barite and altered sulphides.* ***E)*** *Replacement of sideritic limestone (sid) and barite (Ba) with chalcopyrite (Cpy), and galena (Gn).* ***F)*** *Calamine ore and Fe-Mn oxides/hydroxides, East Ridge orebody, Mehdiabad.*

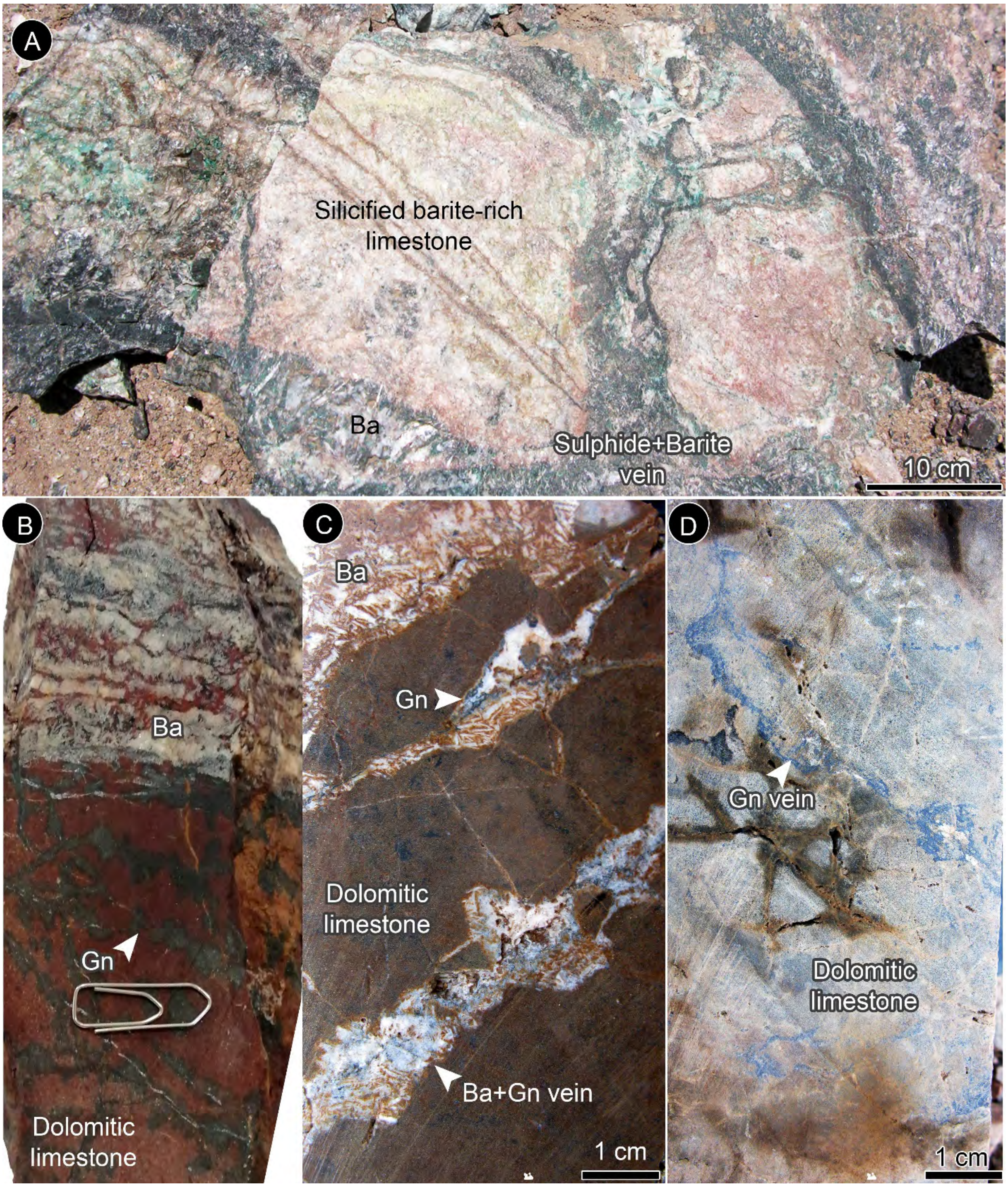

***Figure 12:** Complex veins and veinlets of sulphides and barite in the feeder zone of the Mehdiabad deposit. Gn: galena, Ba: barite.*

and fine-grained to coarse-grained quartz-feldspathic sandstones and sandy shales, and, to the top, changes to limestones with coral fragments (Ghasemi, 2006; Reichert, 2007). The Taft Formation consists mainly of limestones, dolomites, and dolomitic to ankeritic limestones. The upper part of the Taft Formation, known in the Mehdiabad area as the Abkuh Formation (informal name; Babakhani *et al*., 1988), consists of cherty or clayey limestones alternating with massive reef facies and lenses of calcareous shales (Aghanabati, 2004) with calamine mineralization. These sedimentary series are conformably overlain by shales of the Darreh-Zanjir Formation. Ghasemi (2006) investigated the geology and mineralogy of the deposit, and Reichert (2007) provided some geochemical data on the oxide ores and weathering conditions. Rajabi *et al*. (2012a) suggested an Irish-type model for the formation of the Mehdiabad deposit. Maghfouri *et al*. (2019) based on geochemistry and geological evidence suggested the SHMS (SedEx) model for the formation of the Mehdiabad deposit, but

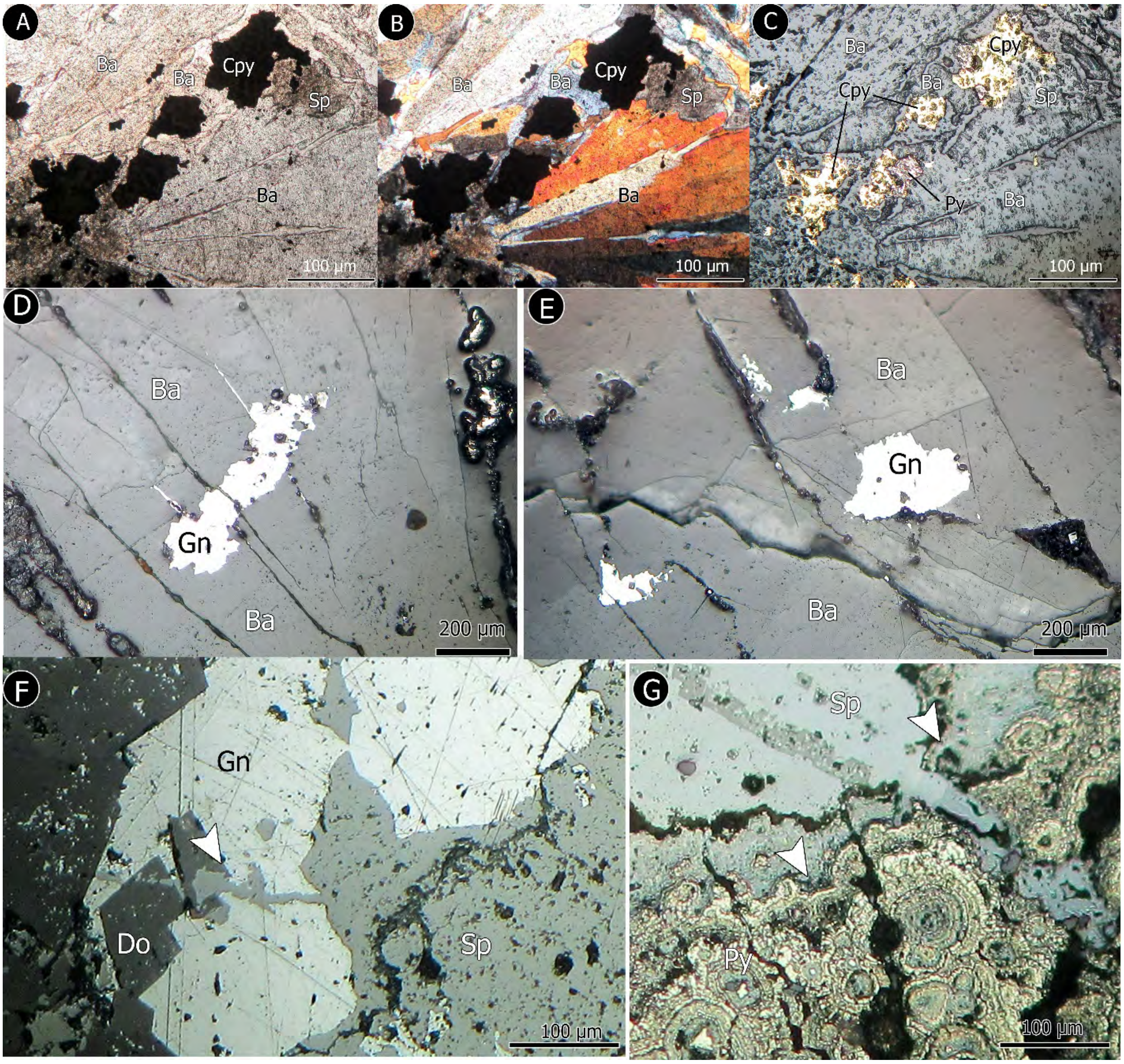

Figure 13: *Photomicrographs of replacement textures of sulphides and barite in the Mehdiabad deposit. A)-C) Replacement of barite with pyrite (Py), chalcopyrite (Cpy) and sphalerite (Sp). D, E) Replacement of barite with galena (Gn). F), G) Replacement of dolomite (Do), galena and pyrite with sphalerite.*

unlike the SHMS deposits, the major host rock of this deposit is dolomitized limestone and represents completely replacement textures. The mineralization occurs in the upper part of the Sangestan (non-economic ore) and Taft (main ore) formations (Ghasemi, 2006). The main orebody of Mehdiabad occurs within a half-graben with a large N–S synform (Ghasemi, 2006; Reichert, 2007; Rajabi *et al*., 2012a) and is laterally limited by faults. The Zn–Pb-Ba-Cu (±Fe±Mn) mineralization of the Mehdiabad deposit occurs along two horizons that extend over a strike length of at least 3.4km (Reichert *et al*., 2013; Maghfouri *et al*., 2019). The lower and main horizon of the mineralization is composed of three parts: the Mountain/Black Hill orebody, the Central Valley orebody, and the East Ridge, hosted in thre Taft Formation, and located in a topographic depression. The second ore horizon is only observed at the Calamine Mine and is hosted in the Abkuh Formation.

Most of the mineralization at the Black Hill and East Ridge deposits were oxidized and consist of smithsonite, cerussite, hydrozincite, and hemimorphite, along with hematite and goethite, but the Central Valley orebody mainly consists of sulphide mineralization (sphalerite, galena, pyrite, chalcopyrite, covellite, and chalcocite). Also, the deposit includes barite, dolomite, siderite, ferrodolomite, calcite, and quartz as waste minerals. Bulk barite in the upper part of the deposit is economic, but in other parts of the deposit, it is considered a gangue mineral. The Mountain orebody is limited to the west by the Black Hill fault and to the east by the Forouzandeh fault. The sulphide ores of both Valley and Mountain orebodies are hosted by dolomites and ankeritic limestones. The Black Hill is a syn-sedimentary fault as evidenced by the occurrence of sedimentary breccias on the west side of the deposit (Ghasemi, 2006; Rajabi *et al*., 2012a; Maghfouri *et al*., 2019).

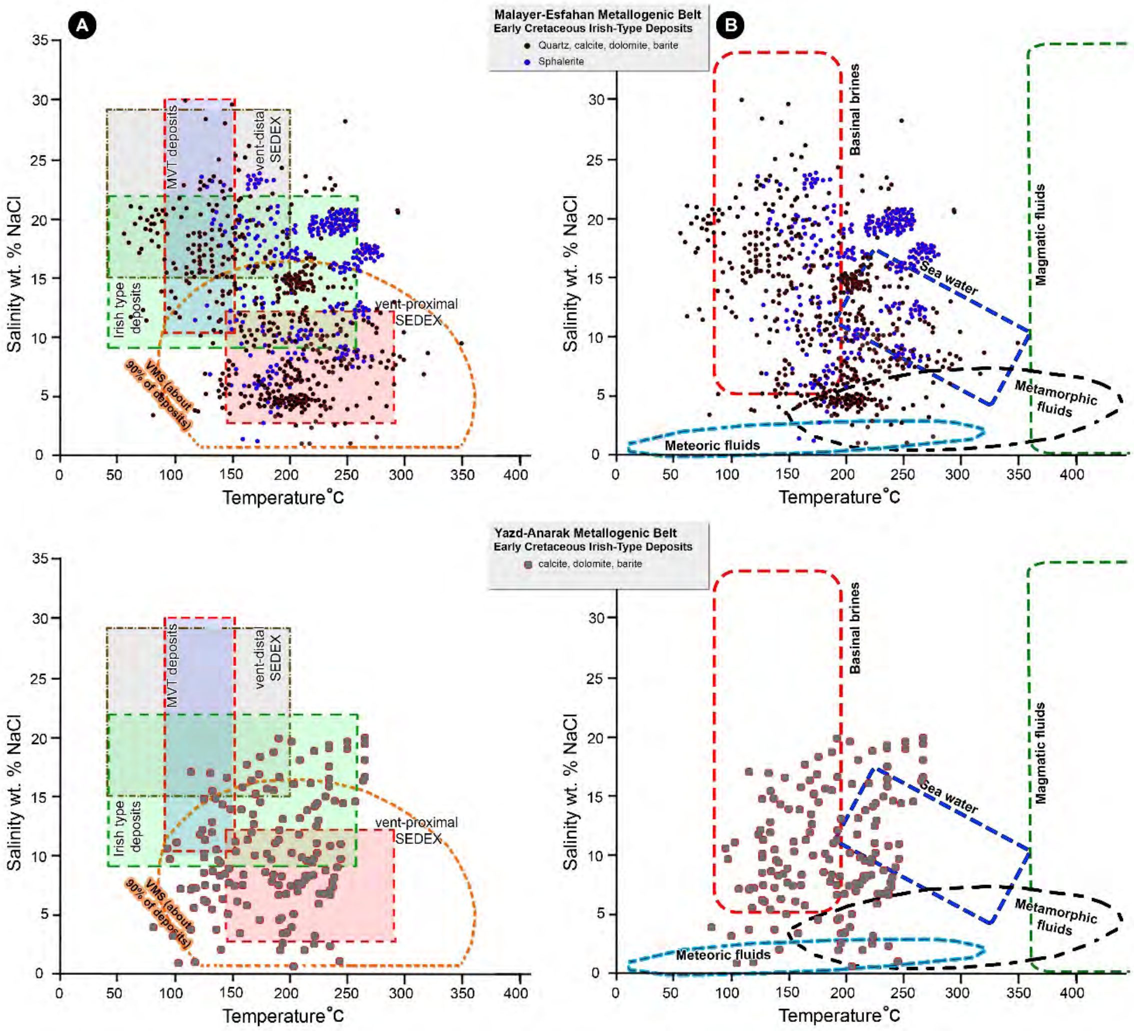

Figure 14: *Summary of published fluid inclusion homogenization temperature–salinity pairs from Irish-type ore deposits of Iran (modified after Rajabi et al., 2019b)*

Moghfouri *et al.* (2019) identified feeder zone facies, massive ore (including sulphide-oxide parts), and massive banded barite ore facies in the Mehdiabad deposit. The feeder zone includes sulphide, quartz, barite-sulphide, and carbonate veins, (Fig. 12). Massive ore includes sulphide at the bottom, sulphide-oxide in the middle part, and massive barite at the top. Massive replacement and zebra textures along with barite and sulphide veins form the main face of this ore facies. The important point in this ore is the development of sulphide mineralization as a replacement in the host carbonate of the deposit, barite, and previous sulphides.

Pyrite is found in framboidal, colloform, and massive textures in different ores of the deposit. Chalcopyrite is observed as a replacement of barite and pyrite, in the feeder zone, and in the massive ore. Galena and sphalerite also replace barite and earlier sulphides in these ore facies (Fig. 13). According to these features, the Mehdiabad deposit can be classified as an Irish-type mineralization that occurred relative to the syn-sedimentary normal fault, in a half-graben structure.

Fluid Inclusion studies

Fluid inclusion studies have played an important part in developing genetic models for different types of ore deposits and identifying the nature of the ore fluids. Extensive fluid inclusion studies in the early Cretaceous Zn-Pb (±Ag±Ba) and Fe-Mn-Pb-Zn (±Ag±Ba±Cu) ore deposits of Iran (Rajabi *et al*., 2019b; Rajabi, 2022, and references therein) show that in the MEMB deposits, fluid salinity values range from 2 to 29 wt% NaCl equiv., with the majority falling between 4 and 22 wt% in hydrothermal gangue minerals (quartz, dolomite and barite). This ranges from 2 to 24 wt% NaCl equiv., with the majority falling between 8 and 24 wt% in sphalerite (Fig. 14). Homogenization temperatures, in hydrothermal gangue minerals, range from 60° to 350 °C (with the majority falling between 150° and 270°C). These data range from 120° to 283°C with the majority falling between 225° and 275°C in sphalerite. Fluid inclusion thermometric data can be largely the result of mixing between moderate-salinity, metal-bearing fluids, and low-temperature, high-salinity brines during ore formation (Rajabi *et al*., 2019b).

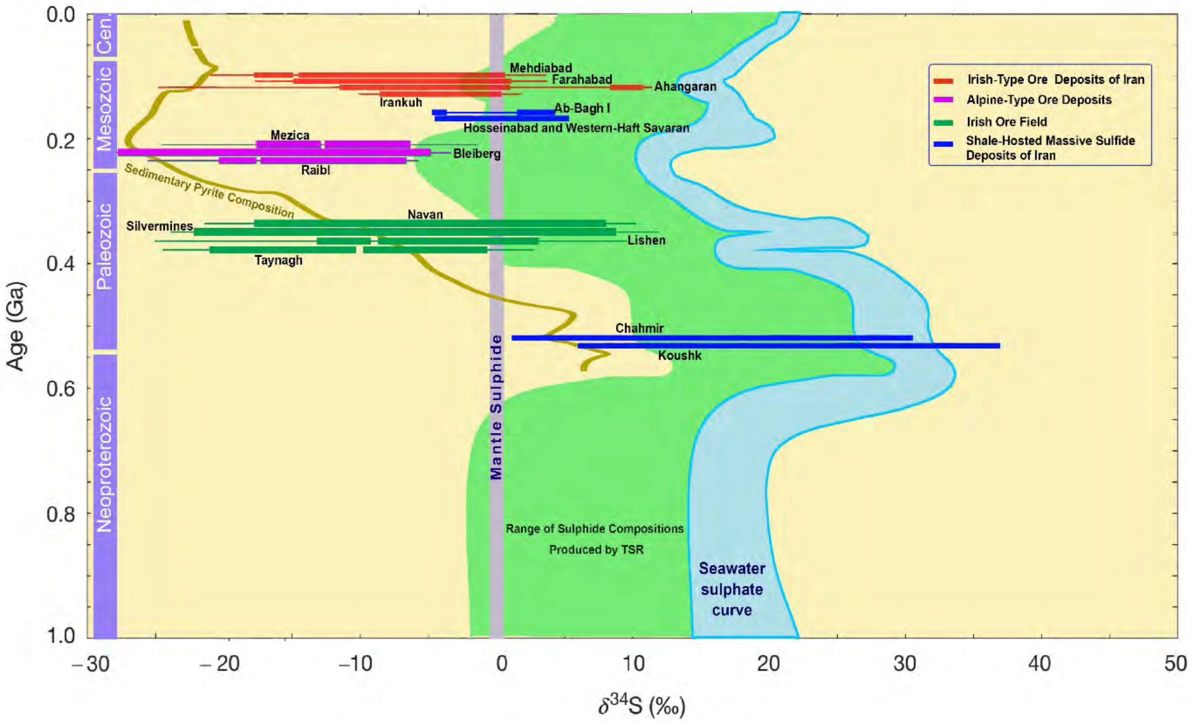

Figure 15: *Diagram illustrating the range of δ^{34}S values of sulphides in selected early Cretaceous Irish-type and SHMS (SedEx) deposits of Iran in comparison with the δ^{34}S values of sulphides in the Irish ore field deposits, and Alpine-Type Zn-Pb ores (Leach et al., 2005; Farquhar et al., 2010; Wilkinson, 2014), seawater sulphate curve (Bottrell & Newton, 2006), mantle sulphide, and mean sedimentary pyrite composition (olive line) as produced by bacterial sulphate reduction (BSR; Wilkinson, 2014). The green-shaded field indicates the likely range of sulphide compositions produced by thermochemical sulphate reduction (TSR) of seawater-derived sulphate at 150°C (Kiyosu & Krouse, 1990).*

In the early Cretaceous Zn–Pb-Ba-Cu deposits of the YAMB, the bulk of the homogenization temperature data from hydrothermal calcite, barite, and dolomite fall in the range of 80° to 250° C, with the majority falling between 120° and 230° C, and their salinity varies from 1 to 20 wt% NaCl equivalent (Fig. 14).

These data represent extensive overlap with other sediment-hosted Zn-Pb deposits (including SHMS or SedEx, Irish, and MVT), and even volcanogenic massive sulphide (VMS) deposits, but most of the data from both metallogenic belts are more like Irish-type ore deposits and represent higher temperature than orogenic MVT ore deposits (Fig. 14). These data indicate a series of basinal brines and seawater for the ore-forming fluid.

Sulphur Sources

Figure 15 illustrates the range and median δ^{34}S values of sulphides in selected early Cretaceous Zn-Pb-Ba deposits in comparison with Irish ore field deposits, Alpine-Type Zn-Pb ores (Leach *et al*., 2005; Farquhar *et al*., 2010; Wilkinson, 2014), and some main well-known shale-hosted massive sulphide deposits of Iran (Mahmoodi *et al.*, 2018; Rajabi *et al.*, 2012b, 2020; Movahednia *et al*., 2020), that are plotted in relation to the age of host rocks, marine sulphate composition (Bottrell & Newton, 2006), and mean sedimentary pyrite composition as produced by bacterial sulphate reduction (BSR; Wilkinson, 2014).

The early Cretaceous deposits in both Malayer-Esfahan and Yazd-Anarak metallogenic belts have light isotopic δ^{34}S values. But SHMS deposits show highly positive δ^{34}S values for hydrothermal sulphides and are consistent with other SHMS deposits around the world.

This light (negative) isotopic composition of the majority of sulphide minerals is one of the very distinctive characteristics of the early Cretaceous Zn-Pb-Ba deposits and is similar to the Irish ore field and Alpine-type ore deposits (Fig. 15). Wilkinson (2014) suggested that the light isotopic composition of δ^{34}S values in Irish deposits is important evidence that shows the development of early seawater convection models for the mineralization and requires a close connection between the seawater and the ore-forming environment in a sub-seafloor (diagenetic) replacement genetic model. But the fluid inclusion microthermometry provides evidence of a steep thermal gradient (120 to 280 °C) within the sulphide ores in the MEMB and YAMB deposits Indeed, in these ore zones, these δ^{34}S values are not consistent with BSR and fluid temperatures are too high for BSR to occur, above 110 °C (Jørgensen *et al*., 1992). Sulphide mineralization with BSR origin in high-temperature environments at these deposits can be explained by the mobilization of older, Jurassic brines that generated or passed from Jurassic organic matter/coal-bearing shales and sandstones (Shemshak Series). Another possible mechanism is the direct replacement of pyrite framboids by later sulphides.

Discussion

Type and origin of mineralization

Early Cretaceous dolomitized carbonate rocks are the main host for Zn–Pb deposits in Iran and are widely distributed in the Malayer-Esfahan and Yazd-Anarak metallogenic belts. Consideration of the geologic and geochemical characteristics operating in the discussed deposits leads to a recognition of the following features in these deposits:

(1) They formed in extensional and passive margin environments that are related to the Nain-Baft back-arc basin undergoing active extensional faulting and subsidence.

(2) Most ore deposits have an indirect temporal link with igneous rocks.

(3) Formation of these deposits is controlled by syn-sedimentary, normal faults that may act as feeder zones and conduits for ore fluids and generated debris flow breccias.

(4) These deposits are stratabound and comprise wedge-shaped to tabular sulphide-barite orebodies, and mineralization occur in several different stratigraphic horizons/strata.

(5) Ore bodies have a high 'aspect ratio' and are dominated by fine-grained massive sulphides.

(6) Replacement textures are common, and orebodies represent complex textures of sulphides and barite, such as brecciated, replacement, colloform, zebra, minor laminated, and banded replacement.

(7) Barite is an important gangue mineral in the MEMB and YAMB deposits, partly replaced by coarse-grained galena and sphalerite.

(8) Sulphur isotope composition reveal light $\delta^{34}S$ values (with the majority falling between -25 to +5 per mil) with mostly BSR origin.

(9) Temperatures of ore deposition are typically 120 to about 280 °C (majority 150-270 °C), and salinities range from 2 to 24 wt% NaCl equiv., with the majority falling between 8 and 22 wt%.

(10) Alteration consists mainly of dolomitization and silicification. Fe-dolomite, siderite and ankerite are common in some deposits.

(11) The dominant minerals are sphalerite, galena, pyrite, and chalcopyrite. Barite is common in most deposits and is replaced by later sulphides.

(12) Laminated sulphides are minor and there is no evidence (or it is so weak) of exhalation in the formation of orebodies.

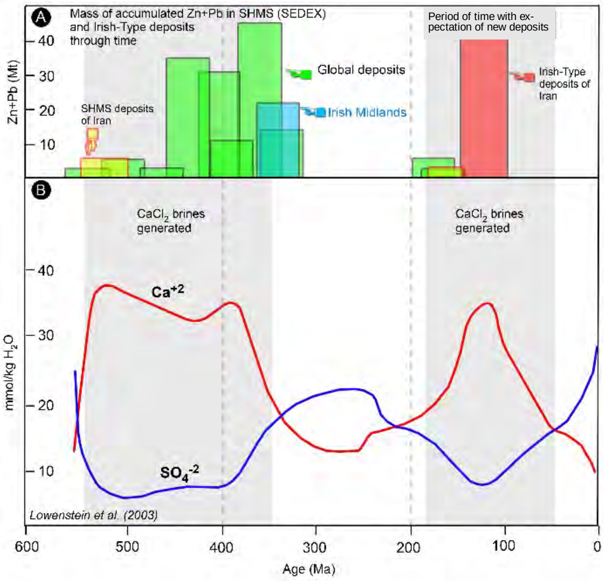

Figure 16: *Age distribution vs. Pb + Zn (Mt) contents for Phanerozoic SHMS (SedEx) and Irish-type ore deposits (data from Leach et al., 2001; Wilkinson, 2014; Rajabi et al., 2012a; Rajabi, 2000) compared with ocean chemistry (Lowenstein et al., 2003). Modified after Wilkinson (2014).*

Given these data and evidence, the early Cretaceous Zn-Pb-Ba deposits of the Malayer-Esfahan and Yazd-Anarak metallogenic belts are more like the Irish Midland ore deposits and show a significant difference from orogenic MVT deposits. Wilkinson (2014) suggested that there is an interesting link between evolving ocean chemistry and the formation of the Phanerozoic SHMS (SedEx) system ore formation (Fig. 16). Plotting of these deposits against the SO_4^{2-} and Ca^{2+} curves for seawater (Lowenstein et al., 2003) demonstrates that the intervals of this mineralization roughly coincide with times when proposed $CaCl_2$-rich seas were predominant (Wilkinson, 2014; Fig. 16). The temporal distributions of SHMS, and Irish-type deposits in Iran and Irish Midlands, also show similar patterns. Wilkinson (2014) suggested that periods of $CaCl_2$-rich seawater are favourable to generate brines via evaporation, which could then change into highly metalliferous ore fluids during convective circulation. This is compatible with the evaporitic brine reflux model for the formation of Zn-Pb deposits in extensional and passive margin environments (Leach *et al.*, 2010). In a reflux model, seawater evaporitic brines infiltrated the underlying rocks of the host basins or fractured basement rocks. Such reflux brines (generated by the dissolution of evaporites) could have provided much of the chlorine necessary as a ligand for large-scale metal transport.

Spatial distribution of deposits and their relation to the tectonic environment

The early Cretaceous Irish-Type deposits of Iran occur around the Nain-Baft suture zone, far from the Zagros thrust zone (i.e., the collision suture between the Arabian plate and Iranian plateau; Fig. 1). If early Cretaceous-hosted Zn-Pb deposits formed due to the collision of the Arabian plate and Iranian plateau, it is difficult to explain the presence of numerous early Cretaceous Zn-Pb (+Ba+Ag) and even VHSMS deposits in the MEMB and also the YAMB, on both sides of the Nain-Baft super-basin (Fig. 3).

Recent evidence based on the study of the Nain-Baft ophiolites shows that the suture between the Sanandaj-Sirjan zone and Central Iran is in fact a major structure resulting from the accretion of a series of back-arc basins (Bagheri & Stampfli, 2008; Moghadam *et al.*, 2009). Rajabi *et al.* (2012a) propose

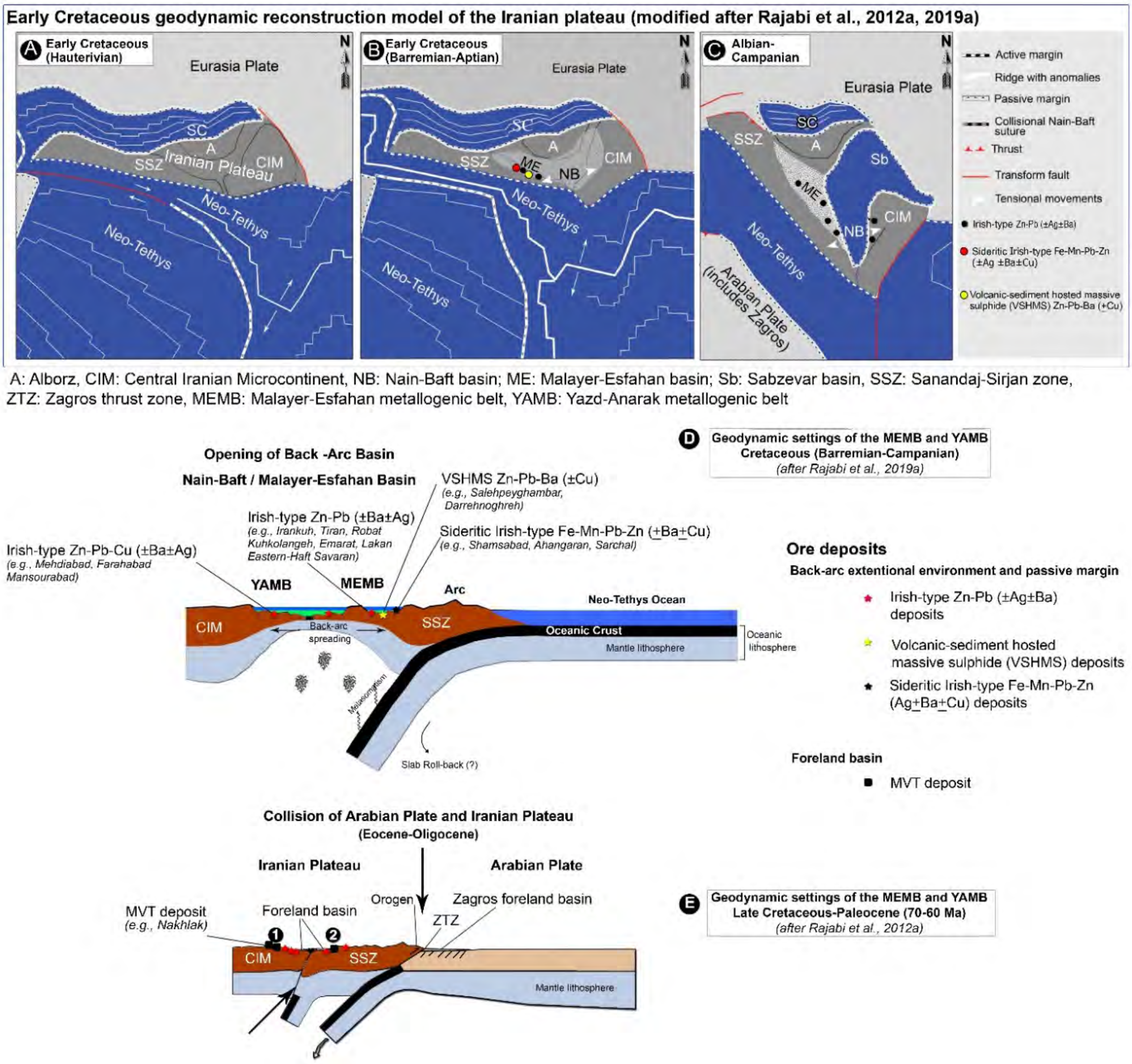

Figure 17: *A)-C) Geodynamic reconstruction model of the Iranian plateau (dark grey) from the early to late Cretaceous (modified after Rajabi et al., 2012a) and Zn-Pb (Ag ± Cu ± Ba) mineralization around the Nain-Baft suture zone. D), E) Comparison of tectonic setting models for Irish-type ore deposits in early Cretaceous extensional environment and orogenic-related MVT deposits of the late Cretaceous and Palaeocene in the MEMB and YAMB of Iran (modified after Rajabi et al., 2012a, 2019a). These deposits are concentrated around the Nain-Baft suture zone in the Iranian plateau.*

that the geodynamic evolution of these basins affected the nature and distribution of the Zn–Pb mineralizations in the Cretaceous carbonate rocks of the MEMB and YAMB, many of which are scattered around the Nain-Baft back-arc basin (Fig. 3), and the geodynamic evolution of this basin can explain both distribution patterns (Fig. 17).

Following the subduction of Neo-Tethyan oceanic crust beneath the southern margin of the Iran plateau in the early Cretaceous, the Nain-Baft back-arc basin began opening, thus separating the Sanandaj-Sirjan Zone from Central Iran (Ghasemi & Talbot, 2005) (Figure 16A-C). In addition, the north of Central Iran (e.g., Sabzevar) was affected by a series of back-arc extensional events (Bagheri & Stampfli, 2008). With the opening of back-arc basins, the Cretaceous is marked in the Iran plateau by a marine transgression (Fig. 17A-C). Deep water sediments, basaltic pillow lavas, and continental slope deposits accumulated in these multi-branched back arcs (Berberian & King, 1981). In addition, Momenzadeh (1976) reported some volcanic lavas and tuffaceous rocks in the Ahangaran and Darrehnoghreh areas within early Cretaceous sediments. Palaeomagnetic data indicate that the Central Iranian Microcontinent rotated counterclockwise with the opening of the Nain-Baft oceanic basin (Ghasemi & Talbot, 2005) (Fig. 17C).

We suggest that the extensional back-arc environment between the Sanandaj-Sirjan zone and Central Iran in early Cretaceous time created favorable conditions for the formation of VHMS ore deposits within the riftogenic sequence and Irish-type deposits in the passive marginal carbonate platforms on both edges of the basin (Fig. 17C, D).

During the late Cretaceous, with the prevalence of a compressive regime and the north and north-eastward migration of the Sanandaj-Sirjan zone arc, the Malayer-Esfahan oceanic crust began to subduct under the Central Iranian Microcontinent (Ghasemi & Talbot, 2005; Moghadam *et al*., 2009). The closure of the back-arc basin generated late Cretaceous to Palaeocene ophiolitic melanges in the Nain and Baft areas (Fig. 1A; Bagheri & Stampfli, 2008). This convergence and magmatism, from the Cretaceous to Lower Miocene, caused regional and contact metamorphism of Palaeozoic and Mesozoic rock sequences in the Sanandaj-Sirjan zone (Mohajjel & Fergusson, 2014). The final collision of the Arabian Plate with the Sanandaj-Sirjan zone is inferred to have been initiated in the Late Eocene, by the closure of the Neo-Tethys Ocean (Allen & Armstrong, 2008). Based on detrital zircon ages, Horton *et al*. (2008) suggested that this collision occurred between the middle Eocene and the late Oligocene. The Late Cretaceous is marked by a major Laramide (Alpine) orogenic event in the Iran plateau and by foreland basin development (Alavi, 1996) on both sides of the Nain-Baft (Fig. 17E). Collision of the Central Iranian Microcontinent with the Sanandaj-Sirjan zone has developed orogenic MVT mineralizations on both sides of the Nain–Baft suture zone (Rajabi *et al*., 2012a). Compressional processes and thrust/reverse faulting may have driven mineralizing fluids toward the adjacent forelands on both sides of the Nain-Baft suture zone (Rajabi *et al*., 2012a; Fig. 17E). This late phase of Zn–Pb mineralization in both belts produced discordant, fault-related, and sometimes stratabound deposits, which differ from the early Cretaceous Irish-Type mineralization and show a close association with faults on both sides of the suture zone parallel to the Nain-Baft suture.

Conclusions

The formation of Irish-type deposits in the Malayer-Esfahan and Yazd-Anarak metallogenic belts is consistent with an extensional environment in the early Cretaceous and the development of Cretaceous passive margins of the Nain-Baft back-arc basin. In addition, the general distribution pattern of MVT deposits in the MEMB and YAMB indicates the direction of fluid flow from foreland basins around the Nain-Baft suture zone towards the north-eastern YAMB and northwestern MEMB after the Laramide (Alpine) event.

Using the criteria outlined in this study for identifying productive basins, we highlight the exploration potential of early Cretaceous extensional sedimentary basins (e.g., Nain-Baft) for discovery of major world-class Irish-type Zn-Pb mineralization. The formation of these deposits corresponds well with the periods of $CaCl_2$-rich brines in the Phanerozoic and fills the interval gap in the Cretaceous period for the formation of Irish-type ore deposits.

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To memorialize Dr. Donald F. Sangster, for his commitment, mentorship, support, guidance, and patience in dealing with the investigation of the metallogeny of the sediment-hosted Zn-Pb deposits of Iran, from 2007 to 2018.

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