Tab. 5: Overview about important mineral phases, aqueous species and oxidation processes.

Primary minerals
galena (PbS), sphalerite (ZnS), pyrite (FeS_2), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), quartz (SiO_2)
Precipitating minerals
gypsum ($CaSO_4 \cdot 2H_2O$), ferrihydrite* ($FeO[O,OH_{1-x},Y_x]$, goethite ($FeO(OH)$), hematite (Fe_2O_3), jarosite ($KFe_3(SO_4)_2(OH)_6$), smithsonite ($ZnCO_3$), hydrozincite ($Zn_5(CO_3)_2(OH)_6$), hemimorphite ($Zn_4Si_2O_7(OH)_2{}^*H_2O$), willemite ($Zn_2SiO_4$), anglesite ($PbSO_4$), cerrusite ($PbCO_3$), hydrocerussite ($Pb_3(CO_3)_2(OH)_2$) , anglesite ($PbSO_4$), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), schwertmannite ($Fe_{16}O_{16}(OH_{12})(SO_4)_2$), magnesite ($MgCO_3$), aragonite ($CaCO_3$)
Main aqueous species
Fe^{2+} , Fe^{3+} , H^+ , Ca^{2+} , Mg^{2+} , Zn^{2+} , Pb^{2+} , $O_{2(aq)}$, $CO_{2(aq)}$, CO_3^{2-} , HCO_3^- , OH^- , HSO_4^- , SO_4^{2-} , $Fe(OH)_{3(aq)}$, $Fe(OH)_2^+$,$ZnOH^+$, $ZnHCO_3^-$, $ZnCO_3^0$, $PbOH^+$, $^-$, $PbCO_3^0$
Gases (equilibrium)
CO_2 , O_2

3 Geological situation of Iran

The geology and especially the tectonic style of Iran is highly influenced by the development and history of the Tethyan region (Fig. 2). The tectonic events, which occurred around the Iranian Plate margins, are related to rifting processes of Gondwana and subsequent collision with the Arabian plate from the WSW. These important processes affected the Iranian Plate and the adjacent plates, such as the African, Indian, Arabian, and Eurasian Plates, during Mesozoic to Tertiary times (ALSHARHAN ET AL., 2001; ALAVI, 2004).

The Tethyan region, which includes the Iranian Plate and the adjacent areas, underwent three major evolutionary stages. The first stage was the closing of the Paleo-Tethys and rifting of the Neo-Tethys from early Permian to late Triassic times. With the second stage, the subduction process of the Neo-Tethys and the collision of the Indian Plate with the Eurasian Plate from the Jurassic to the early Lower Tertiary began. The third and last stage is associated with the collision between the Arabian plate and the Eurasian plate from early Tertiary to the present (SHUFENG, 2002).

The first step, the Gondwana break-up, was associated with tensional basins and basement highs. The central Iranian segment separated from the Arabian plate along the line of the present High Zagros Zone (ALSHARHAN ET AL., 2001). The result of this process was the opening of the Neo-tethys. The closure of Neotethys started with the Late Cretaceous and proceeded into Cenozoic times. This phase is marked by the emplacement of a number of prominent ophiolithes in Oman, Iran, Syria, and southeast Turkey.

The final orogenic phase is due to the Arabia–Eurasia convergence and takes place first in southern Iran starting at the end of Eocene (HESSAMI ET AL. 2001). This process affected the Arabian and Iranian Plates and results in the Zagros orogenic phase of Late Miocene to Pliocene age. The suturing began approximately 12 Ma in Turkey and subsequentely progressed southeast. The suturing process has not yet occurred along the Gulf of Oman and the Makran. In these regions the subduction continues (McCall, 1998).

Latest Tertiary to Holocene events included strong uplift processes (Fig. 3), magmatism (Alavi, 1994) and volcanism, erosional processes, and the associated deposition of extensive alluvial fans from the uplifted mountains (ALSHARHAN ET AL., 2001).

The non-sulphide zinc deposits at Iran-Kuh, and Mehdi Abad studied and analysed in this thesis, are each situated in different tectono-sedimentary units. STÖCKLIN, 1968 and others have presented detailed investigations about the tectonic and geological setting of the Iran. Most of the tectono-sedimentary units are distinguished from the adjacent regions by faults and transitional zones (RASTAD, 1981). Mainly three structural trends (Fig. 4) can be distinguished in Iran: (i) a N-S trend, (ii) a NW-SE trending system, which follows the alpine trend, and (iii) a NE-SW trend.

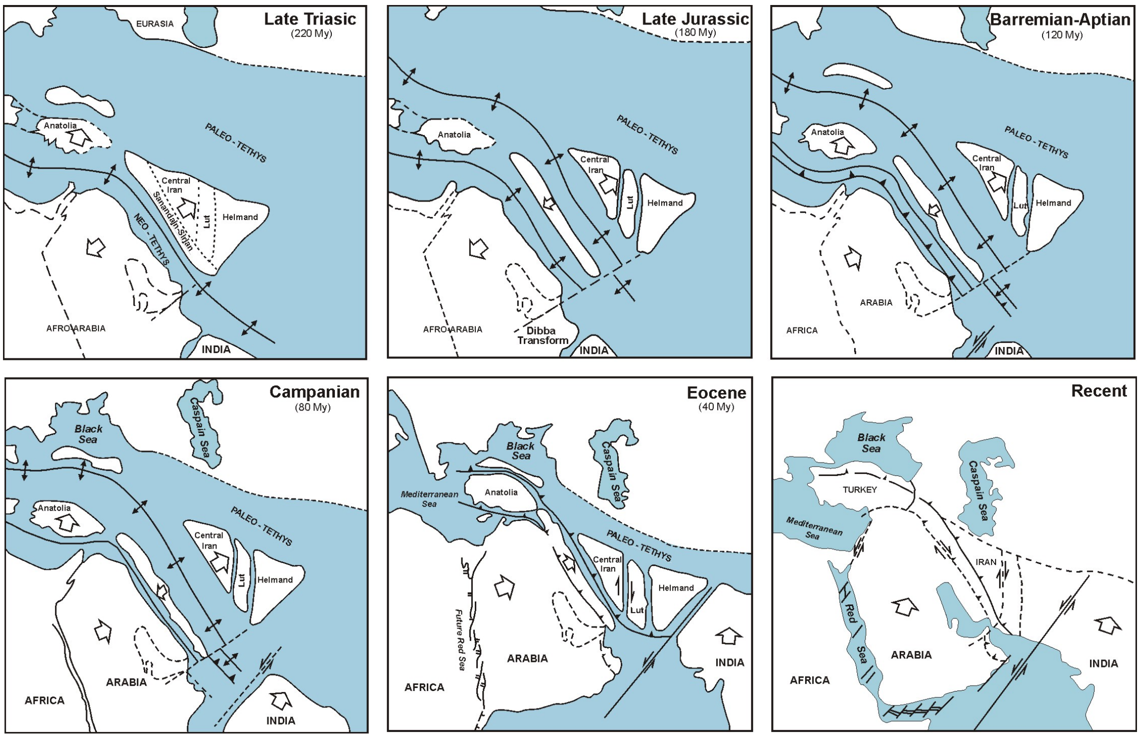

Fig. 2: Continental Drift of the Arabian Plate beginning in late Triassic to present. (modified from GLENNIE, 1992)

The following major structural zones can be distinguished in Iran (STÖCKLIN, 1968; BERBERIAN & KING, 1981) (Fig. 4): Folded Zagros, High Zagros, Sanandaj-Sirjan Ranges, Central Iran, Alborz Mountains, Kopet Dagh, Lut Block, and East Iran/Markran Ranges. The Mehdi Abad Zn-Pb deposit is located at the Central Iranian zone and the Zn-Pb deposit Irankuh is located at the Sanandaj-Sirjan zone (Esfandagheh-Marivan), whereas the Kuh-e-Surmeh is located in the Folded Zagros zone. These deposit-specific zones will be explained in more detail due to their relevance for this research project.

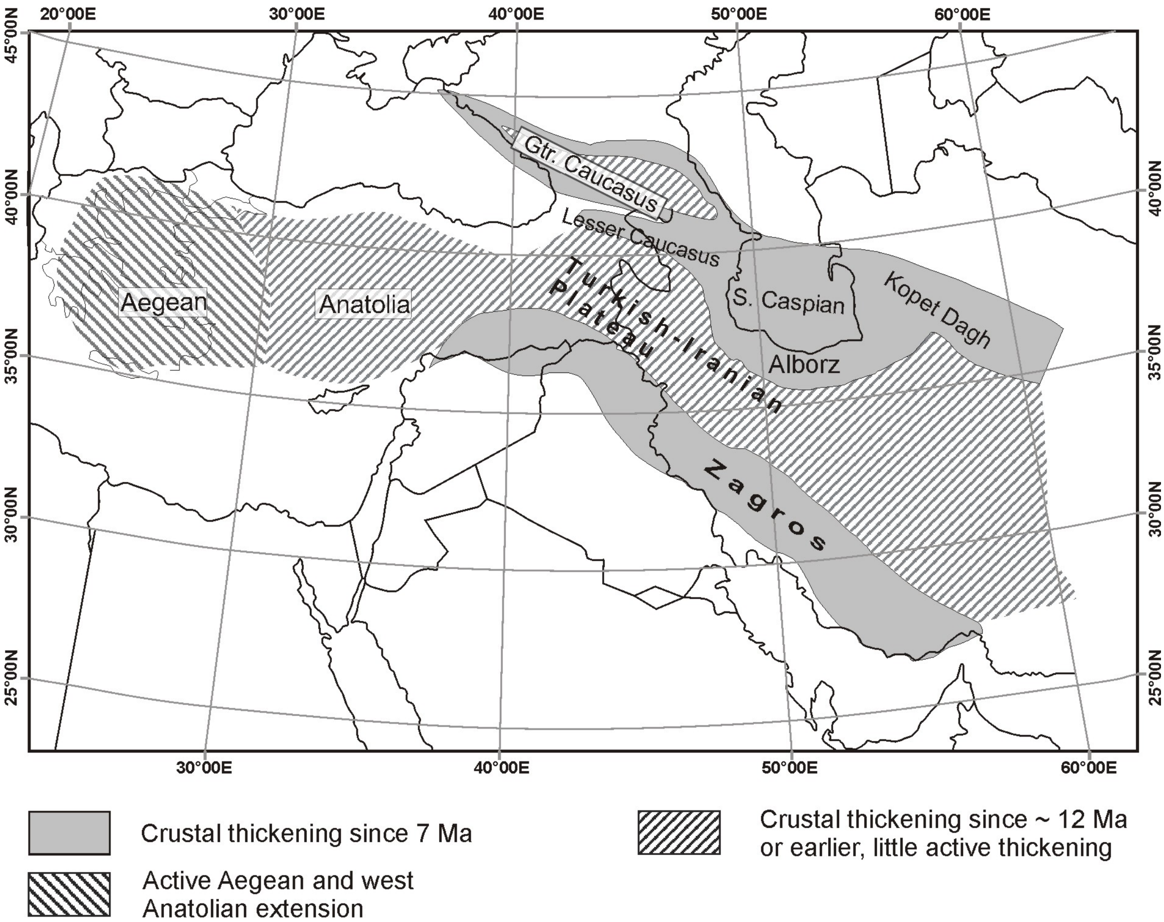

Fig. 3: The Arabia-Eurasia plate collision resulted in crustal thickening and uplift. The crustal thickening in the 12Ma highlighted area show no significant thickening processes at present (e.g. Turkish-Iranian plateau), whereas the 7 Ma marked area is still active (e.g. Zagros Simple Folded Zone, Alborz) (After ALLEN ET AL. 2004)

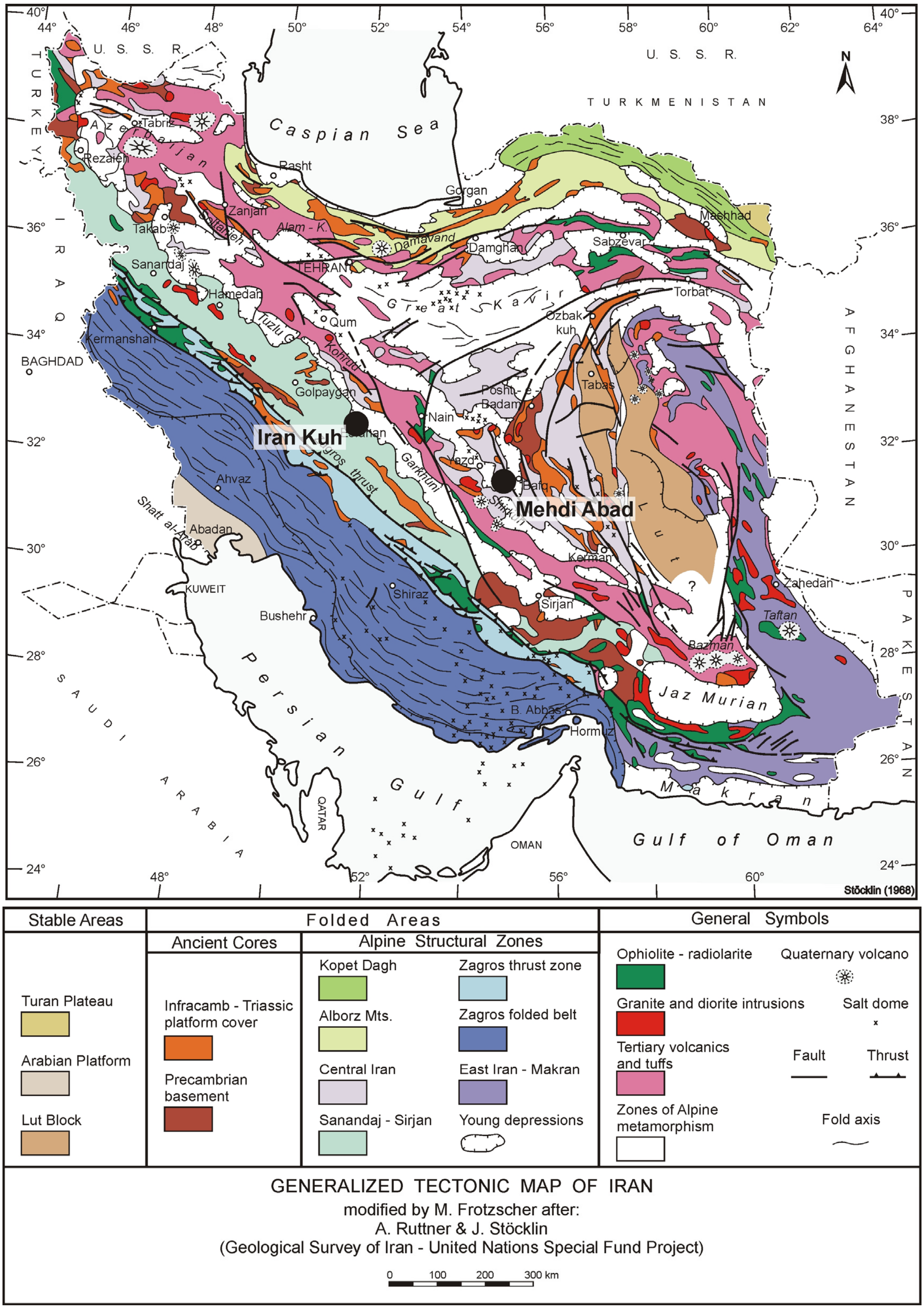

Fig. 4: Generalised geological and tectonical map of Iran with the location of the examinated non-sulphide zinc deposits: Mehdi Abad and Irankuh. Modified after STÖCKLIN (1968).

3.1 The Zagros structural zone

The predominant structural style of the Zagros Mountains is a characteristic set of NW-trending open, parallel anticlines and synclines. The main orientation of the fold-axis is NW-SE, which reflects the characteristic orientation of the Zagros Fold Belt. The Zagros Structural Zone comprises the main structure units: Folded Zagros in the southwestern part of the Zagros, the High Zagros, and following to Northeast the Sanandaj-Sirjan Ranges (Fig. 5).

The Zagros Mountains are the result of complex deformation processes, which started in Late Cretaceous time. These deformations are due to the collision of the Arabian and Iranian Plates. The deformation rate increased during the Pliocene time due to increased convergence rate by the opening of the Red Sea (SATTARZADEH, 2002). The sedimentary cover and the underlying metamorphic basement decouple along an important detachment horizon, the Hormuz Salt Formation. The irregular distribution and the thickness of this horizon play an important role in determining the geometry of the deformation belt (SATTARZADEH, 2002).

The Folded Zagros consists mainly of thick marine sediments of several thousand meters depth. The stratigraphic sequence comprises sediments of Mesozoic and Neogene ages, which have been deposited in a basin. These sediments were folded and uplifted mainly during the Upper Miocene/Lower Pliocene (ALLEN ET AL. 2004) to the Pleistocene. As a result, the Zagros fold-belt has been formed.

The High Zagros (historically known as Zagros Crushed Zone and Zagros Thrust Zone e.g. STÖCKLIN, 1968) marks the plate boundary between the Arabian Plate to the west and the Iranian plates to the east. The Arabian plate is subducted beneath the Iranian plate along the High Zagros zone. Both, the Central Iranian strato-volcanoes and important ore deposits are related to this High Zagros thrust zone (DABIRRAHMANI, 1984). Sedimentation and magmatism within the High Zagros are similar to those of the Folded Zagros (BERBERIAN & KING, 1981). The width of this structural zone varies around 10 to 65 km.

This collisional setting and the thrust- and folding-processes caused a rapid uplift of the overriding Iranian plate and high level magmatic-volcanic activity along the Urumieh-Dokhtar Volcanic Belt as well (STÖCKLIN, 1968; ALAVI, 1994). This uplift and provided a favourable environment for the exhumation and oxidation of several primary sulphide ore bodies and the preservation of the resulting non-sulphide ore.

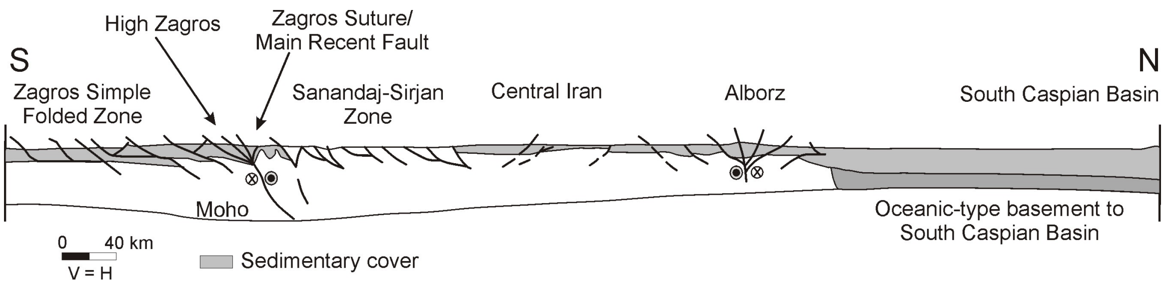

Fig. 5: Structural units of Iran and tectonic relations (after ALLEN ET AL. 2004)

The Sanandaj-Sirjan Zone (SSZ) extends over 1200 km length and is located between the Central Iranian zone to the northeast, and the Tethyian ophiolitic zone of Zagros in the south-west. The SSZ has been formed in the late Cretaceous during the closure of the Neo-Tethys and the subsequent collision of the Arabian- with the Iranian plate. The SSZ can be subdivided in several zones, which comprise Triassic to Cretaceous shallow to deep marine sediments, ophiolit^ es, volcanics (MOHAJJEL, 1997).

3.2 Central-Iran structural zone

The Central Iranian Terrane is located northeast of the Zagros-Makran Neo-Tethyan suture and its sub-parallel Cenozoic magmatic arc, between the convergent Arabian and Eurasian plates. Thus, due to the collision setting, continuous continental deformation processes affect Central Iran. The Central Iranian platform was a stable platform during Paleozoic times, but late Triassic movements caused the creation of horsts and grabens. Central Iran comprises three major crustal domains: the Lut Block, the Kerman-Tabas Block, and the Yazd Block. The area of the Central Iranian terrane is surrounded and limited by faults and fold-and-thrust belts and Upper Cretaceous to lower Eocene ophiolite and ophiolitic melange (DAVOUDZADEH, 1997). Adjoining fault separated areas and tectonical units are the Alborz and Kopeh-Dagh region, which ranges to the north, Makran and Zagros ranges to the west and south, and the East Iran Ranges, which borders this terrane to the east.

The structural components (Lut Block, Kerman-Tabas, Yazd) of the Central Iranian Terrane are characterised by distinct horst (e.g. Lut block) and graben (e.g. Kerman-Tabas region) structures. The grabens are characterised by fillings of thick Jurassic sediments. However, the stratified cover rocks are largely correlatable among these blocks, but with locally significant facies and/or thickness variations across the block boundaries. The Blocks are characterised by an individual deformation style and seismicity, which makes them distinguishable from the adjacent regions (BERBERIAN, 1981).

3.3 Magmatic intrusions

In Mesozoic and Tertiary times tectonic activities affected particularly Central Iran. These movements were accompanied by folding, uplift processes, metamorphism, and magmatism (KHALILI, 1997). In Late Jurassic times, the tectonic activity affected a great part of the Iranian region, which resulted in regional unconformities. In some areas, such as Central Iran, the Sanandaj-Sirjan belt and the Lut block these tectonic movements were associated with felsic intrusions (KHALILI, 1997). The most important intrusions of the Lut block are the granodiorites of Kuh-e-Bidmeshk, Shah-Kuh, and Sorkh-Kuh, where the Shah-Kuh granite represents the largest intrusion in the Lut region. Other important intrusions, especially in Central Iran are the Shir-Kuh granite, the Esmael-Abad biotite granite, the Airakan granites and the Kolah-Quazi S-type granitoides, located 50 km SE of Esfahan. These intrusive bodies intruded in Jurassic sediments and were overlain by basal conglomerate of Cretaceous age.

Tectonic movements in Late Cretaceous and Tertiary times were accompanied by magmatism and metamorphism as well. The Tertiary plutonic activity had a climax in the Eocene and continued into Neogene and Quaternary times. This activity caused numerous felsic intrusions (granites and diorites) in the Sanandaj-Sirjan Zone/Esfahan, Central Iran zone, the southeast areas, and the north and north-west areas of Iran.

Tectonism, magmatism, and implications for metallogenetic processes

Iran and the adjacent areas are composed of composite subduction-collisional belts. These collisional belts are the result of the closure of the (Neo-) Tethys and successive episodes of volcano-plutonism. As the result of these tectonics and magmatism the Tethyan Eurasian Metallogenic Belt (TEMB) was formed during Mesozoic and post-Mesozoic times. The TEMB is located in the area of the former Tethyan Ocean on the southern margin of Eurasia and extends from the western Mediterranean to the Alps and southeastern Europe, the lesser Caucasus, the Hindu Kush, and the Tibet Plateau, Burma, and SW Indonesia (Fig. 6).

In Triassic times, the Neo-Tethys began to open as a series of back-arc basins. Subduction activities during Cretaceous times and extensive submarine volcanism and collisional tectonics between the Arabian and the Iranian plates began to result in formation of important ore deposits.

The most important types of deposits relating to these collisional processes are: (i) Porphyry copper, (ii) chromite and related deposits, (iii) lead-zinc deposits, and others (DIXON & PEREIRA, 1974).

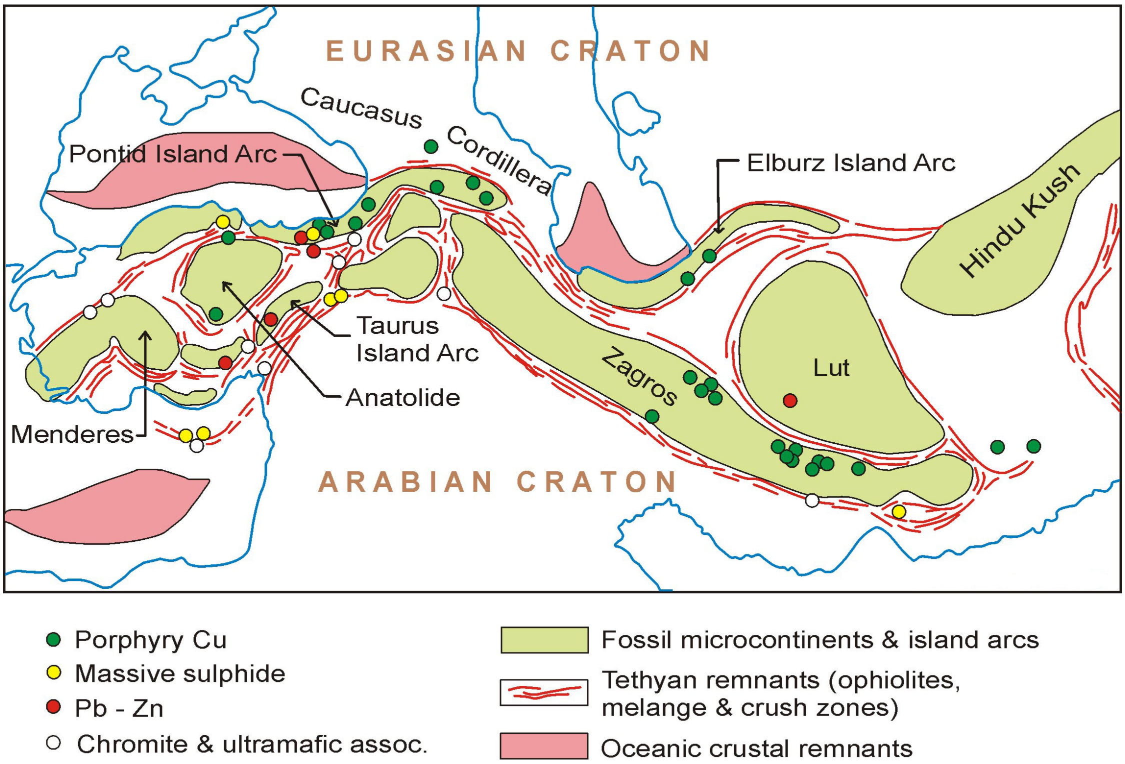

Fig. 6: Microcontinents in the Tethyan region and their relationship to important mineral deposits. (modified after DIXON & PEREIRA, 1974)

(i) Porphyry copper deposits

The emplacement of large porphyry copper deposits in Iran is the result of major mineralising events in Late Oligocene-Miocene times. These events are caused by the continental arc-style tectono-magmatism (LEAMAN & STAUDE, 2002). This zone extends through Turkey and into the Balkan as the north Anatolian Metallogenic Belt. Important Iranian porphyry copper deposits are Sar Cheshmeh, Meduk, Kal-e-Kafi, and the Sungun deposit, which is located in the Azerbaijan-Tarom belt in the north of the Iran. Sungun contains a resource of 860 Mt @ 0.6%Cu. Other Tethyan-related porphyry copper deposits are Gumushane, Guzelyayla, Derekoy, Ulutas (Turkey), and Saindak, and Reko Diq in Pakistan.

Some other deposits are probably associated to these porphyry copper systems. DALIRAN & BORG (2004) have suggested that the primary sphalerite-rich ore of the important (non-sulphide) zinc deposit Angouran is probably related to a hidden porphyry copper system.

(ii) Chromite and related deposits

Peridotites are common both in the melange zones and in the ophiolite complexes and are often associated with lens-shaped massive or disseminated bodies of chromite. However, in contrast to the porphyry copper deposits the occurrence of chromite deposits is much less common. Nevertheless, several distinct provinces occur in the Taurus zone in Turkey, and some small deposits in Iran, such as Fariab, Esfandoqeh, Makran, Khash-Nehbandan belt, Sabzevar, and Neyriz.

(iii) Lead-zinc deposits

Lead-zinc deposits occur widely in Iran and presently about 600 Zn-Pb deposits and occurrences are known. Only a small portion of these ist actually explored and/or exploited to variable degree and 10 deposits are actually mined (GHORBANI ET AL., 2000). It is probable, that the full range from exhalative sedimentary to Mississippi Valley types occur (DIXON & PEREIRA, 1974). The most important metallogenetic provinces for zinc mineralisation are Central Iran, the Sanandaj-Sirjan zone, and the Alborz region (GHAZANFARI, 1999). The time for the mineralisation events ranges from Upper Proterozoic, Upper Cretaceous up to Tertiary (Oligocene-Miocene). The age of the host rocks ranges from Upper Proterozoic up to Tertiary rocks. However, most of the host rocks are Paleozoic and especially Cretaceous carbonates. Provinces with the greatest potential for zinc-lead mineralisation are Central Iran and the Sanandaj-Sirjan Zone.

In the past, the exploration and scientific interest has been focussed mainly on sulphide ore deposits. Only a small amount of non-sulphide zinc deposits is actually in an active mining process, such as Angouran, Iran-Kuh, Kuh-e-Surmeh (REICHERT & BORG, 2002). Thus, the scientific data about non-sulphide zinc deposits in Iran are very preliminary (DALIRAN & BORG, 2004). However, numerous non-sulphide zinc deposits are known at this time in Iran (Fig. 7) and several of these prospects can be probably turned into significant resources of zinc, and thus they hold an enormous economic potential.

Literature research of DALIRAN & BORG (2004) has showed that most of the non-sulphide zinc deposits have been formed in Jurassic to Cretaceous carbonate rocks within the overriding Iranian plate. This overriding plate has undergone strong uplift and exhumation, which are an important factor for the formation of non-sulphide zinc deposits.

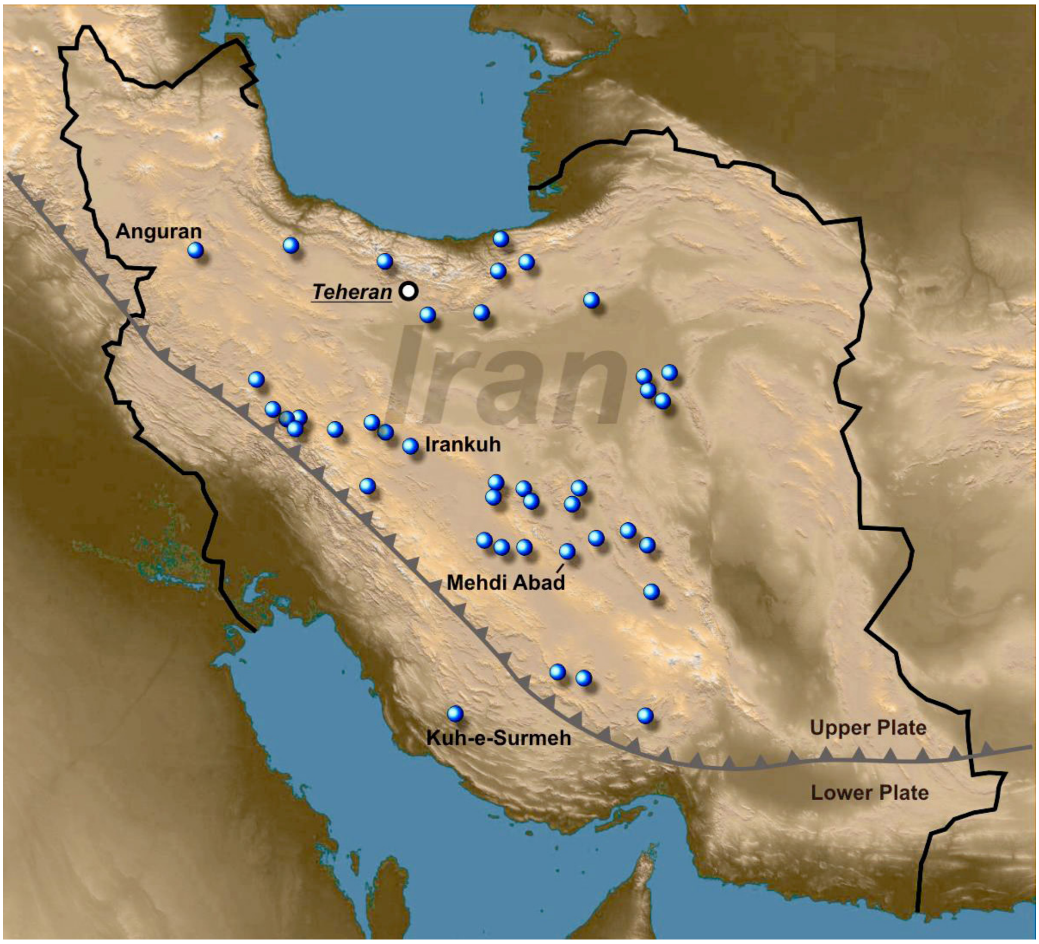

Fig. 7: Regional distribution of the non-sulphide zinc deposits. Most of these deposits are located on the upper (Iranian) plate. This plate has undergone strong uplift, exhumation, and erosion. (BORG ET AL. IN PREP.)