Reactivation and polyphase mineralization in Anarak area, Central Iran

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Abstract

The mineralization seemingly occurs at the intersection of Uroomieh-Dokhtar magmatic belt with Doruneh fault as the most important lineament in Iran. Detailed mineralogical, geochemical and geophysical investigations in the vicinity of the Talmessi Mining Area indicate that mineralization had occurred in two separate stages: first stage - fissure-filling copper sulfide mineralization associated with Eocene magmatism (veins, veinlets, stockworks). Major, trace and REE studies show that this high K shoshonite association is subduction related arc magmatic type. The second over imposed stage which occured after a fairly long interval involves the formation of Ni, Co and U minerals. Vein studies show that several time reactivations of NW trending faults play an important role especially in second arsenidic stage of mineralization. Most of the high angle faults are belong to NW category. When these faults reactivated, their high-angle and, hence, small lithostatic pressure of the overlying rocks as well as existence of the pyroclastice facies of the rocks - provide the permeable pathways for ore-bearing fluids in second stage of mineralizaion.

There is a clear zonation of mineral deposits in the Anarak area (Fig. 1b). From west to east, three types of Cu deposit can be distinguished: (1) Cu mineralization (with insignificant Ni, Co and As) directly associated with Eocene volcanics, (2)-Cu-Ni-Co-U) mineralization with Cu/Ni+Co ratios varying from 2 to 50, in association with volcanic rocks, albeit much reduced in thickness (including the Talmessi and Meskani deposits), and (3) Cu-Ni-Co-As mineralization with Cu/Ni+Co ratios varing from 1 to 0.02 and situated 5 to 20 km from the Eocene volcanics. A cluster of lead-zinc deposits are located in the Cretaceous carbonate rocks in the eastern part of the area.

The second type of mineralization has occurred on the Eocene volcanics and far from ultrabasic rocks, but the presence of ultrabasic bodies at depth defined by geophysical investigations,can be related to the upwelling of plastic ultrabasic bodis along the axes of anticlines(now horsts) of Anarak area perpendicular to Arabian plate subduction beneath Central Iran plate. It seems that Talmessi and Meskani deposits are a combination of the first and the third mentioned deposits in which the third one is overimposed on the first after a fairly long interval.

Introduction

Of certain importance in the Anarak area (about 200 km east of Esfahan) are a few compositionally complex hydrothermal Cu-Ni-Co deposits which always attracted attention of scientists (Ladam, 1945; Sarcia and Sarcia, 1960; Bariand, 1963; Schurenberg, 1963; Mir-Mohammedi, 1977; Tarkian et al., 1983; Romanko et al., 1984). They are often referred to in discussions concerning the five-element deposits (e.g. Badham, 1976) but their characteristics are not particularly well-known and their association and genesis are poorly understood. This work presents the results of recent geochemical and structural studies with the aim of elucidating the nature of different stages of mineralization in this area. Apart from Cu, Ni and Co the ores contain As and U and occasionally Pb, Zn, Au and Ag. All these deposits are localized in the same area under similar geological environment along the north-western and western surroundings of Anarak-Khour massif (fig.1).

The only deposits carrying copper sulfides in addition to nickel-cobalt arsenides are Talmessi and Meskani, which occur within 7 km of each other. They are genetically closely related to Tertiary magmatism in Central Iran, whereas other deposits, being localized outside volcanic structures (fig. 1-B), reveal only an indirect association with the Eocene volcano-plutonism.

The deposits of Talmessi and Meskani were mined for copper and nickel until 1960. Mining was then discontinued; recently, however, exploration activities were conducted by the atomic energy organization of Iran in the course of uranium exploration. The Talmessi deposit is accessible through two main shafts and three main adits (18m, 30m and 55m). as well as three ancillary adits on the 6, 42 and 47m levels. In Meskani only the middle of the three main adits (30m, 50m and 75m) is accessible.

Schurenberg (1963) dealt intensively with the microscopy of the entire mineral association. He recognized the host rocks of the deposits as dacite and andesite, and ascribed the Meskani Cu-Ni-Co mineralization to the porphyry copper type (may be due to pervasive stocwork and disseminated mineralizaion form of chalcocite). Tarkian et al.(1983) introduced the volcanic wall rocks as shoshonites and recognized two different structural controles on mineralization in the Meskani deposite.

- Geology:

Two dominant structural features in the Anarak area are; the intersection of Uroomieh-Dokhtar Magmatic Belt (UDMB) and the major Great Kavir –Doruneh fault (GKDF), and the change of direction of Great Kavir - Doruneh fault towards the Nain –Baft fault (fig.1-A). This zone indicates the western rim of the Central –East Iran microplate,. The Central Iranian terrane is an approximately 2300 km^2 region of moderate relief surrounded by fold and thrust belts within the Alpine –Himalayan orogenic system of western Asia. This terrane is an area of continuous continental deformation in response to ongoing convergence between the Arabian (Gondwana) and Turan (Eurasian) plates (Ramezani and Tucker, 2003).

Subduction of the Arabian plate beneath the Iranian one probably commenced in the upper Cretaceous and continued until collision with the Iranian plate in lower Tertiary. The border between these plates is formed by the main Zagros thrust. Continental volcanism along the UDMB and in Central Iran, which also comprises the volcanic rocks of the Anarak area, is related to that subduction (Jung et al., 1976).

Mapping of the mineralized area has revealed an approximately 800m thick, steeply dipping complex of volcanics comprising shoshonitic lavas and tuffs, which have been deposited on the crystalline basement together with Tertiary sediments (figs 1-B and 2).

Stratigraphy

The area of the deposit is underlain by the Upper Proterozoic Anarak Metamorphites – Derakhtak Schists, Lower Cretaceous sediments, Upper Cretaceous – Paleocene Kerman Conglomerate, Lower Eocene Gorgab volcanics, Middle-Upper Eocene rocks of the Sahlab Formation, Eocene Oligocene molasse unit and Quaternary sediments (fig.2).

Upper Proterozoic. Anarak Metamorphites(Derakhtak Schists):

The oldest rocks are exposed in the north-eastern part of the study area, near the Talmessi Mine. They are represented by the Derakhtak Schists consisting chiefly of muscovite, muscovite-carbonate, carbonate-chlorite and muscovite-chlorite varieties that occur in monotonous intercalation with dark grey quartzite. Lenses of marble up to a few meters thick are also present. The basement is represented by a thick (1000-1200 m) sequence of epizonal chlorite muscovite schists and marbles, as well as partially higher grade metamorphic micaschists (Davoudzadeh et al.1981;Tarkian et al. 1983). In terms of their initial composition they correspond to greywakes, arkoses, quartz sandstones, clay rocks and basic volcanics. Mineral associations of relatively high pressures are detected in the metamorphics occurring along the faults (Romanko et al. 1984). The oldest dating of the metamorphism (845 m.y.) was obtained by Rb-Sr method. Radiometric K-Ar ages of 420-270 m.y. testify for later metamorphic processes (Hercynian), while younger dates (183 m.y.) can also be explained by rejuvenation brought about by the Kimerian or Alpine folding (Reyer and Mohafez, 1970). On the basis of geological evidence a Pre –Triassic metamorphism is postulated (Davoudzadeh et al.1981).

Lower Cretaceous:

Lower Cretaceous succession of the sediments consists of essentially carbonate unit that unconformably overlies Upper Proterozoic rocks. Basal beds composed of conglomerate and sandstone, less frequently of sandstone and limestone are recognized at the base of the unit. The carbonate part of succession is made up of rudist limestone. The thickness of the sediments is up to 150m.

Upper Cretaceous-Paleocene(Kerman Conglomerate):

The Kerman Conglomerate is found in the northern part of the area where it overlies unconformably Upper Proterozoic and Lower Cretaceous rocks. The unit consists predominantly of interbedded conglomerate, sandstone and marl. Limestone occurs in thin (up to 2m) lenses. The exposed thickness of the Kerman Conglomerate amounts to 170m.

Lower Eocene, Gorgab volcanics:

During the Eocene similar to other parts of UDMB there was a pulse of intense volcanic activity which led to the extrusion of shoshonitic lavas in the area.

At the deposit, the Gorgab volcanics unit is characterized by prevalence of sedimentary and pyroclastic rocks in its section. Volcanics are less abundant. A conglomerate bed occurs at the base of the section. It rests on the Kerman Conglomerate without angular unconformity and is succeeded by alternating shoshonite, tuff and sandstone. The studied volcanic rocks of the area are alkaline in composition and belong to shoshonitic-ultrapotassic association. Based on their geochemistry, these are similar to those of subduction –related potassic rocks (Bagheri et al., 2005).

The volcanic shoshonitic associations in Iran are limited to volcanic belts of Eocene to recent volcanism (Aftabi and Atapour, 2001).

Foraminifers in the calcareous marls overlying the volcanic complex suggest middle Eocene age. The age of shoshonitic volcanism thus emerges as lower to Middle Eocene. This geological age determination agrees well with the dating of 40 m.y. obtained by fission track method for Talmessi shoshinits (Ahmadi, 2003) and also with the age of andesitic volcanism in adjoining areas (Davodudzadeh,1972; Tarkian,1972), and the radiometric dating of the main phase of volcanic activity in the Lut region of eastern Iran (Tarkian et al.1983).

Shoshonite here is a porphyritic rock. Insets constitute up to 40% of the rock volume. They consist of plagioclase (50-55% An) and mafic minerals after which pseudomorphs of carbonate, iron oxides, chlorite and occasional iddingsite develop. Sometimes clinopyroxene and olivine come into view. Insets usually do not exceed 3mm in size, less frequently they reach 10mm across. The groundmass consists of laths and microlites of sanidine less frequently-plagioclase (which is more acidic than in insets), as well as xenomorphic biotite and a feldspathoid. Individual minutest prisms of clinopyroxene, apatite and isomertic grains of opaque minerals are present. Carbonate, chlorite, quartz, iron oxides, chalcedony, albite, sericite usually develop after groundmass. The thickness of volcanics reaches 550m.

Middle-Upper Eocene, Sahlab Formation:

The rocks of the Sahlab Formation underlie the area to the north-west of the Talmessi Mine. They rest with an indistinct unconformity on the Gorgab volcanics, occasionally - on the Kerman Conglomerate, Cretaceous sediments or ultramafites. There is a bed of conglomerate and gravelstone at the base of the section. This bed is often replaced along the strike by limestone and marl strata. Alternating tuffstone and limestone are noted in the section situated 2km NNW of the Talmessi Mine (Romanko et al. 1984). The thickness of the section is 358m. Tuff is observed in more remote from the mine areas.

Oligocene-Miocene:

The tuff complex is overlain unconformably by coarse grained conglomerates which correspond to the so called lower Red Formation (Davoudzadeh, 1972). Qom Formation (Oligocene) and upper Red Formation (Miocene) are present in fossil –free lagoonal facies (marls, sandstones and gypsum); these are partly intensely folded with a distinct unconformity, then follows horizontal Pliocene conglomerates The conspicuous features are abrupt facial changes of the rocks and significant variations in thickness. The most widespread are cross-bedded sandstone, conglomerate and marl. Gypsum interlayers are noted. The total thickness of the sediments reaches 1000m.

The two unconformities mentioned above can be related to Eocene and Miocene tectonic phases. The sedimentary cover in terms of rock composition as well as of structures formed, is considered to be of a typical platform character (Romanko et al. 1984).

Quaternary:

Old (middle dasth)-alluvial-proluvial sand, boulder pebble beds lying on the bedrock cut high dasht. The thickness of the deposits is 15 to18m.

Recent – proluvial sand and poorly sorted pebble beds filling in the temporary watercourses and their fans. The thickness of the deposits attains a few meters, and in large valleys – 10m.

- **Faults**

Faults play a significant role in the tectonic structure of the Anarak area. A general pattern of the mapped faults of different orientations and categories is, to a greater extent, concordant with the regional structure and, at the same time, governs the tectonic zoning and block structure of the area. The major faults bounding the tectonic zones are deep and have a long history of development. They are traceable for hundreds of kilometers running outside the Anarak area (figs. 1-A and 3). First of all, this concerns the Great Kavir-Doruneh fault with NE trend, whose total extension makes up not less than 1000km. most of the ore deposits in this area are related to its subsidiary faults. It is the most important lineament in central Iran. Another fault system with an NW trend is related to Uroumieh-Dokhtar tectonomagmatic belt. Most of the deposits are located at the intersection of the subsidiary high angel faults, especially in Talmessi and Meskani (fig. 3).

- Spatial distribution of mineral deposits

There is a clear zonation of mineral deposits in the Anarak area (Figs. 1b and 3). From west to east, three types of Cu deposit can be distinguished: (1) Cu mineralization (with insignificant Ni, Co and As) directly associated with Eocene volcanics, (2)-Cu-Ni-Co-U) mineralization with Cu/Ni+Co ratios varying from 2 to 50, in association with volcanic rocks, albeit much reduced in thickness (including the Talmessi and Meskani deposits), and (3) Cu-Ni-Co-As mineralization with Cu/Ni+Co ratios varing from 1 to 0.02 and situated 5 to 20 km from the Eocene volcanics. A cluster of lead-zinc deposits are located in the Cretaceous carbonate rocks in the eastern part of the area (Figs. 1b and 3).

The second type of mineralization has occurred on the Eocene volcanics and far from ultrabasic rocks, but the presence of ultrabasic bodies at depth defined by geophysical investigations, that can be related to the upwelling of plastic ultrabasic bodis along the axes of anticlines (now horsts) of Anarak area perpendicular to Arabian plate subduction beneath Central Iran plate, with about 50 Km long and NW trend.

Characteristics of the Ore Zone and structural controls on mineralization

Ore mineralization of the Talmessi deposit is localized at the eastern termination of the volcanic field. Effusive sequence gradually decreases here in thickness (down to 10m) and disappears farther eastward under Eocene-Oligocene molasse. volcanics and underlying Kerman Conglomerate dip at 50-65° south-westward.

Ore mineralization is concentrated in argillitized and carbonataized lava and subvolcanics that are shoshonitic in composition. Volcanics are leached (argillitized) in the immediate vicinity of the mainly chalcocite-bearing veinlets and clots. Areas of silicification coincide with the more intense metasomatic alteration of the rocks and occur in the zones rich in copper ore. Unaltered greenish lavas are lacking in ore mineralization. Sulfidic ore minerals (mainly chalcocite) occur as thin (up to 2-3cm) stringers forming a dense net. Less frequently small vein bodies composed of massive ores are present. Ni-Co-Cu arsenidic mineralization mainly is associated with carbonate gangues in open spaces especially at the intersection of the fault and fractures which also has mentioned before by Spahbod (1981) and Schurenberg (1963), as the main feature of arsenidic phase of mineralization (fig.4A). Genetic relationship between arsenidic phase of mineralization and open spaces probably is the main reason of increasing of Ni,Co,Cu arsenids toward the upper levels in respect to the sulfidic copper mineralization of the first phase. Judging by plan of mining level –30m, the largest exploitation mine workings (that presumably coincide with the areas of a dense net of veinlets) are slightly elongated lenticular or pipe-like, being 20-40m and sometimes up to 100 m across. At the same time, an intense ore impregnation is associated with the areas of veinlets.

The distribution of ore mineralization was significantly influenced by faults. The ore-controlling structures consist of the system of NW- and NE- trending faults. As a rule the intersections of these faults are marked by the most intense ore mineralization with the development of ore nests. In the other hand these zones which in most cases changed to berecciation zones of volcanics acted as suitable conduits for circulation of meteoric and or shallow marine waters and oxidation of the hypogene ores (fig. 4B).

Ore-bearing zone of the Talmessi deposit is similar in character and distribution of ore mineralization to that of the Meskani deposit. At the surface, it has an oval shape. Its maximum width is 100m, length up to 220m. Parameters of the ore zone are determined tentatively. At the surface the boundaries of the ore zone are delineated by exploitation mine workings and by the presence of visible ore mineralization.

In order to trace the ore mineralization at depth, three boreholes – 6(67.3m), 10(165.2m) and 8(264.7m) – were drilled. The first two boreholes intersected and traced the ore zone as well as old mine workings to the depth of 20 and 60m, respectively. The distribution of the ore mineralization turned out to be as complex and irregular as it is at the surface . Borehole 8(264.7m), that was drilled to intersect the ore-accommodating sequence below the ore zone and to verify possible ore potential down dip the effusive body, did not encounter any mineralization (Romanko net al. 1984). Thus, the ore zone appears to have an intricate configuration on lower levels and is pinching out at a depth of about 60m, at least in the drilled intervals. At the same time, from a number of geologic-geophysical evidences it seems that the ore zone is inclined towards east (Lola et al.1976).

The oxidation zone is developed irregularly at the deposit: on one hand, patches of oxidized ores are noted on level –55m; on the other hand, veins and nests of unoxidized massive sulfide arsenide ores are seen at the surface (in the walls of old quarries). The degree of rock and ore permeability, which is dependent on faulting and hydrothermal alteration intensity, was apparently the main factor controlling the development of the oxidation zone.

Structurally, the area, adjacent to the Talmessi deposit, is a monocline forming the north-eastern limb of the Talmessi graben-syncline. Within the monocline, the SW and SSW dips of the rocks are prevalent, the angles mostly being 50-70°. The monocline is complicated by secondary folds 100 to 150m wide; S-shaped folds are frequent. Besides, in the south-west the monocline is “incised” by a wedge-shaped fault block which must have been developing along the NW-trending reverse fault with left-lateral shift. As a result, the monoclinal portion composed of the rocks of the Sahlab Formation and Eocene-Oligocene molasse was shifted towards east and up thrown.

Two predominant trends of the faults, viz., north-western and north-eastern, are typical of the area of detailed investigations. NW-trending faults show a limited distribution. They are characterized by large amounts of displacement attaining several hundred metres and steep (up to 80°) dip mostly south-westward. They bring into contact different parts of the Sahlab Formation and Eocene-Oligocene molasse or the rocks of the Gorgab volcanics unit and those of the Sahlab formation.

The NE-trending faults are widespread. The greater part of them cut the rocks of the Kerman Conglomerate and Gorgab volcanics units, and Sahlab Formation. Most of them are “dying out” in the basal beds of the Eocene-Oligocene molasse. The amount of displacement along these is small and reaches 200-205m. They chiefly dip north-westward at about 50°.

The Talmessi deposit proper is localized in the area of pinching out the lavas which, along with the Kerman Conglomerate at their base overlie the Anarak Metamorphites (Derakhtak Schists) north-east of the deposit. At the deposit the mineralization is controlled by a series of small, quickly dying out faults of NW and NE trends.

607 fault and fractures has been measured in the Talmessi mine and in surface exposures; they comprise three different systems: 0-40 NE/45-85 NW, 50-85NW/35-80 SW and 40-85NW/40-80NE (fig. 5). 160 measurements from the area of the Meskani deposit by Tarkian et al. (1983) further support these results (fig. 6).

The investigation of the underground (in about 8km tunnel and stops) and surface exposures reveal that most of the first group fractures as transverse faults have been formed before the others. This system is dividable to two categories: 0-10NE/70-90NW youngest one, perpendicular to main fold axes and main strike of the beds which is only filled by calcite+barite gangues. Second group is 10-40NE/25-40NW which mainly is older than the NW faults.

Most of the NE faults are older than the NW one. NE faults are more abundant but it seems that they are minor or secondary in respect to NW faults. Most displacements have occurred along the later one. Sulfidic copper mineralization mainly has occurred in relation to older NE faults. The second arsenidic phase of mineralization is associated with both trends. It seems that this stage is younger than both of fault categories (fig. 7), and younger or contemporaneous in respect to NW trending faults.

Vein studies show that several time reactivations of NW trending faults play an important role especially in second arsenidic stage of mineralization. As it can be seen from fig. 5, most of the high angle faults are belong to NW category. When these faults reactivated, Their high-angle and, hence, small lithostatic pressure of the overlying rocks as well as existence of the pyroclastice facies of the rocks - provide the permeable pathways for ore-bearing fluids in second stage of mineralizaion.

In many cases the reactivation of NW trending faults led to reopening of the older NE faults which in these cases chalcocite has replaced by arsenidic ore minerals, which the remnants of chalcocite is remained in nickelin at the middle part of the vein and also on the walls of the veins with a thin border of arsenidic ores (figs 8A and B)

Some of the samples show widespread fractures and micro fractures in ore minerals which in some cases it led to brecciation of ore minerals of the vein, which is related to reactivation of this veins and in some cases these fractures has filled by secondary minerals.

Underground and surface studies of the fault and fractures revealed that the important mineralized faults are NW trend which occupies 63% of mineralized faults and most of them have high angle dip with NE and SW dip direction, which SW dip direction is more abundant than NE. Some of the NW trending faults with SW dip direction In the studied area, are reverse which can be related to compressional stresses.

It seems that episodic reactivation of NW trend faults in relation to changes in tectonic regime of Great Kavir fault and hence it's subsidiary NW trend faults in Talmessi area has an important role in several different superimposed mineralization in this area.

- Ore minerals:

Mineral composition of the ores, especially in the upper part of the deposits (approximately down to 90 m) has been studied by Bariand (1963) and Schurenberg (1963) and Tarkian et al. (1983). On the whole, over 50 minerals have been diagnosed here includes hypergene ones. Among hypergene minerals Cu sulfides and Cu,Ni,Co arsenides prevail, native Cu and Ag metals, pitchblende, galena,etc. are noted. Typical is the absence of Ni and Co sulfides, sulfarsenides are rare. There are two distinct main associations of ore minerals: Cu – Fe sulfides and Ni – Co arsenides. Uranium mineralization, associated with hematite, calcite and quartz, is linked to the nickel – cobalt – arsenides (Mir-mohammedi and Pedall, 1977) and in some cases replaces them (Tarkian et al., 1983) ; so it has interpreted to be younger. During the final phase of mineralization it followed copper arsenides. The sequence of mineral deposition is not always clearly recognizable, especially as suppergene effects has partly obliterated the primary textures especially after periods of uplifting and tectonic reactivation in the area.

The ore is composed of native minerals (mainly Cu and Ag), sulfides, arsenides and minor oxides and sulfarsenides. As detailed by Trakian et al. (1983) sulfides and arsenids are volumetrically the most important and each of them belong to two distinct phases of mineralization. Sulfides consist primarily of bornite, chalcopyrite, digenite and chalcocite. Main arsenide ore minerals are niccolite, rammelsbergite, safflorite and domeykite. Hematite and pitchblende are the most important oxides and accompanied the arsenids in second phase of mineralization. Carbonates constitute the dominant gangue component and typically accompanied the arsenides. Silicates are ubiquitous but limited in occurrence to thin selvages a few millimeters thick attached and (or) immediately adjacent to vein walls in first phase of sulfide mineralization or as open space filling euhedral aggregates adjacent to carbonates as the last gangue mineral. Barite and chlorite are the other subordinate gangue minerals accompanied by the carbonates in ore veins. The mineralization was preceded by intense silicification that involved a greater amount of rocks than did the mineralization.

The thickness of ore veins varies within the decimeter range. Subordinately there occur thicker irregular orebodies.

Cu- Fe sulfides occur in thin veins, in deeper levels and also as impregnations, preferentially in Eocene volcanic rocks. Mineralization consists of bornite, chalcopyrite, digenite and chalcocite. In addition, there is some fahlore and pyrite. Tarkian et al.(1983) described that in the deepest drill hole, H9 at Meskani, only Cu-Fe sulfides were encountered up to the depth of 350 m, in depths of 200-350 m mainly bornite and chalcopyrite, with subordinate digenite, occur. In the upper levels the proportion of these minerals decreases in favor of low temperature hypogene chalcocite. These observations can be interpreted as hydrothermal zoning.

Nickel – Cobalt arsenides occure as impregnations and veins from millimeter to over than 50 cm thickness in both deposits. This period of mineralization probably commenced with the formation of subordinate amounts of nickel sulfides, millerite and polydymite, which have been only recorded from Talmessi. Then there followed arsenide –rich solutions leading to the formation of the main minerals, niccolite, rammelsbergite and safflorite.in most cases nickline has a rammelsbergite rim and replaced by it. The main gangues in the Ni-Co arsenide veins are carbonates (calcite, dolomite and subordinately Ankerite). pervasive and selective carbonatization of volcanic host rock accompanied this period of mineralization. The main form of mineralization especially in the 18 , 30 and 42 m levels is open space filling (figs. 4A and 9). This phase then follow pitchblende as well as copper arsenids especially domeykite which have been partly affected by suppergen processes. Fig.8B shows a vein with the two mentioned phases of mineralization

Niccolite is the most widespread member of the nickel-cobalt association and accompanied by carbonates (calcite, dolomite and subordinatly ankerite) and in some cases barite, chlorite and quartz (fig. 9). It rimmed by rammelsbergite and safflorite and intergrowthed or replaced by calcite . In many cases there is fine chalcocite relics in niccolite .This reveals a depositional sequence proceeding from NiAs via NiAs2 and CoAs and (NiCo)As3. The ore forming solutions obviously carried increasing concentrations of arsenic and cobalt. It seems that these ore forming solutions were poor in iron especially because of the absence of arsenopyrite and lollingite.

Sarcia and Saricia (1960) reported uranium for the first time from these deposits, they observed high uranium concentrations in the nickel – cobalt – arsenide association. Frequenely close intergrowths of very fine grained pitchblende with copper arsenides or with suppergen chalcocite has been observed by Tarkian et al.(1983), in some of the samples we could find coloform uranium oxides in association with calcite. Aggregate accumulations and single isolations of uranium-bearing (7- 30 %) hard bitumen associating with calcite has also observed(Romanko et al., 1984).

Oxygen, carbon and S isotopic ratios:

Since the veins are typically dominated by carbonates, (especially in second arsenidic stage of mineralization) calcites and dolomites were analyzed for oxygen and carbon isotopes in the department of geology and geophysics of A & M university of Texas. The δ18O values of calcite and dolomite from the veins are given in table 1 and plotted in fig 10. Oxygen isotopic compositions of the hydrothermal minerals are controlled by the isotopic composition of the hydrothermal fluid, the temperature of crystallization, and the extent of isotopic exchange. The carbonates show a range of δ18O values of about 15 to 22.36.‰ This low spread in δ18O values maybe due to low variations in temperature, as well as low changes in the isotopic composition of the hydrothermal fluids during the second stage of mineralization. The isotopic composition of the hydrothermal fluids is calculated using the following equations.

Dolomite – water (Matthews and Katz, 1977):

$1000 \ln\alpha = 3.06 \times (10^6/T^2) - 3.24$

Caleite – water (Bottinga and Javoy, 1973):

$1000 \ln\alpha = 2.78 \times (10^6/T^2) - 2.89$

The temperatures used in the calculation of the above equations were determined by fluid inclusion study .The isotopic composition of the hydrothermal fluids could not be calculated from the δ18O values of the other minerals, as they were not suitable for microthermometric measurments. The calculated δ18O values of the hydrothermal fluids are presented in table 1. The δ13C values of the vein carbonates are given in table 1 and fig.11 .Assuming that the carbon in the hydrothermal fluids was present mainly in the form of H_2CO_3 app (Robinson and Ohmoto, 1973), which may be approximated to be equal to δ13C (CO_2(g)) (Ohmoto, 1972), the δ13C of total carbon in the hydrothermal fluid was calculated using the data of Bottinga (1968). The δ13C values were found to vary between -1.13 and 0.93.

Six samples of chalcocite from different paragenetic stages in the Talmessi mine were analyzed by Bagheri et al., (2005) for $\delta^{34}S$ and the results are presented in Table 2. The values for the two samples of definite hypogene chalcocite are close to zero per mil (-1.4, -3.3) whilst the definite supergene chalcocite has a value of –12.4‰. More negative values are found in samples of unclear paragenesis. Sulphide values close to zero per mil are characteristic of many polymetallic, vein deposits (e.g. Field and Fifarek, 1985) and are traditionally ascribed to a magmatic source for the sulphur. Very light sulphur isotopic values are more difficult to interpret, but are often found in secondary sulphides (e.g. Lawrence and Rafter, 1962). Such values can often be related to bacterial reduction of sulphate in descending solutions (Belogub et al., 2003; Ohmoto and Rye, 1979; see also Sillitoe et al., 1996), so it is possible that these unknown samples are in fact supergene in origin. (Note however that supergene chalcocite which directly replaces chalcopyrite seems to inherit the primary sulphide isotopic values – Field and Gustafson, 1976). However, without a clearer understanding of the conditions of the environment (e.g. O fugacity) during chalcocite formation it is not possible to come to any firmer conclusions.

Fluid inclusions

Fluid inclusion were studied to gain information concerning the nature of the hydrothermal fluids responsible for mineralization and the temperature conditions during hydrothermal activity. More than 65 doubly-polished wafers were prepared for fluid inclusion study.

Fluid inclusions are abundant in calcite from the Ni-Co-As mineralized veins of Talmessi and Meskani. Inclusions in quartz tend to be much smaller and unsuitable for analysis. Most of the inclusions in calcite appear to be secondary or pseudo-secondary, but some which are isolated and occur in irregular and negative crystal shapes are considered to be primary. In most cases the fluid inclusions are of a small to moderate size (typically 5-10*μm,* but up to 30*μm)*. Inclusions are two-phase (liquid plus vapor) and have a high degree of fill (volume liquid/volume liquid + volume vapor; typically 0.9-0.95) but in calcites in domeykite-uraninite bearing veins, monophase liquid fluid inclusions are abundant.

Fluid inclusions in the samples were subjected to heating and freezing studies using a Linkam heating-freezing stage, calibrated with synthetic fluid inclusion standards. Measurements were made of the temperature of homogenization (Th) and the temperature of (final) ice melting (Tm); salinity as wt percent NaCl equivalent was then calculated from the latter measurement. All inclusions homogenized to the liquid phase. The results are reported in figs. 12 and 13.

Measurements of inclusions in samples from Talmessi (-55 m level) and Meskani (-50 m level) give homogenization temperatures of 80° to 420 °C. Most of these samples are calcite from the second stage of mineralization. However, some inclusions in quartzs from the first stage of mineralization gave the highest Th values (up to 420 °C). Stratigraphic considerations and textures in the veins suggest that mineralization took place at relatively shallow depths and so these Th values are considered to be close to the temperatures of mineralization.

The salinity values have a relatively large range, from 1.2 – 18.1 wt percent NaCl (equiv.).

Most of the quartz samples belong to the first sulfidic stage of mineralization and show higher homogenization temperatures with low to moderate salinites (group III – fig.13). But some fluid inclusions in the quartzes belong to sulfidic stage of mineralization show lower temperatures which can be related to the last phases of the first sulfidic stage of mineralization.

-Discussion and conclusion:

Geological and geochemical data indicate that ore association of the Talmessi and Meskani deposits is most probably telescoped as a result of superposition with a time break of relatively later Cu,Ni,Co,AS and U mineralization on the supposed early volcanogenic Cu-Fe sulfidic one. It is suggested that the formation of volcanogenic copper deposition was controlled by the NE trending faults. During the second tectonic stage new NW trending faults has formed and perevious formed faults were reactivated. The high-angle faulting and, hence, small lithostatic pressure of the overlying rocks as well as existence of the pyroclastite facies of the rocks - provide the permeable pathways for ore-bearing fluids.

It seems that the main trigger for these two different stages of mineralization have been two most important thermal events associated with Eocene shoshonitic volcanism and intrusion of granitic bodies in Late-Oligocen (out of the mining area) respectively. However these thermal events might be also related to the effects of orogenic activities. erosion products of the first stage of mineralization occur as ore pebbles in Middle Eocene to Lower Miocene sediments. They do not contain any indications of nickel-cobalt mineralization (Tarkian et al. 1983). In addition of mineralogical studies, this implies a younger age for the Ni-Co arsenide mineralization.

There is a clear zonation of mineral deposits in the Anarak area (Fig. 1b). From west to east, three types of Cu deposit can be distinguished: (1) Cu mineralization (with insignificant Ni, Co and As) directly associated with Eocene volcanics, (2)-Cu-Ni-Co-U) mineralization with Cu/Ni+Co ratios varying from 2 to 50, in association with volcanic rocks, albeit much reduced in thickness (including the Talmessi and Meskani deposits), and (3) Cu-Ni-Co-As mineralization with Cu/Ni+Co ratios varing from 1 to 0.02 and situated 5 to 20 km from the Eocene volcanics. A cluster of lead-zinc deposits are located in the Cretaceous carbonate rocks in the eastern part of the area (Fig. 1b).

The second type of mineralization has occurred on the Eocene volcanics and far from ultrabasic rocks, but the presence of ultrabasic bodies at depth has defined by geophysical studies, that can be related to upwelling of plastic ultrabasic bodis with about 50 Km long and NW trending along the axes of anticlines(now horsts) of Anarak area perpendicular to Arabian plate subduction beneath Central Iran plate . It seems that Talmessi and Meskani deposits are a combination of the first and the third mentiond deposits and the third one over imposed on the first one after a fairly long interval.

S and Pb isotope studies by Yushin et al. (1981) on most of the deposits in Anarak area show scatter values. They belive that This feature can be related to multi-stage or multi source for these deposits (fig. 14).

O isotopic compositions show a nonmagmatic or a very small magmatic water source for the second arsenidic stage of mineralization. But the sulfoure isotopic ratio show a magmatic source for the soulfore in the first sulfidic mineralization stage.

In the other hand fluid inclusion studies support these two different kind of mineralization.

The δ18O values of the hydrothermal fluids of the Talmessi and Meskani are plotted in fig. 10. These values represent the δ18O of hydrothermal fluids calculated from the δ18O values of calcite and dolomite. Also plotted are the isotopic ranges of SMOW, magmatic, meteoric, metamorphic, and formation waters.The δ18OH2O values of -1.1 to 6.16‰ are very much different from those of waters derived from igneous sources which are believed to have δ18O values of around 5.7 to 10‰. This suggests that the contribution, if any, of magmatic water to the second stage fluids was not important.

The source of carbon in the hydrothermal fluids can not be interpreted unambiguously. In hydrothermal systems, the carbon isotopic composition can easily be modified by limestone (Changkakoti et al. 1986). Also the isotopic composition of carbon in hydrothermal fluids of the Talmessi Ni-Co arsenide veins shows a close range, the δ13C's of the hydrothermal fluids in this stage of mineralization mostly fall within the range of limestone and marine carbonate and bicarbonates, which correlates well with the oxygen values of these carbonates. These data suggest that during the second stage of mineralization with incursion of circulating marine or meteoric waters, carbon was probably leached from the carbonate beds of the region, and its isotopic signature was imprinted into the second stage's carbonate gangues (Changkakoti et al. 1986).

From the mineralogical point of view occurrence of pure copper arsenides is of particular interest, because these minerals do not occur in similar deposits. They can probably be attributed to remobilization of copper from country rocks or from the older sulfide mineralization. Ramdohr (1975) explained the formation of copper arsenides occurrences so far known by hydrothermal mobilization of pre-existing copper ores.

Because of prevalent open space filling form of mineralization especially at the intersection of the faults, it seems that it has occurred at low depth below the surface. Calcite and dolomite are the most important alteration products in relation to arsenidic phase of mineralization. Circulation of the ore bearing fluids has been triggered by Oligo-Miocen tectono-magmatic activity which has provided suitable heat source and structural facilities for fluid movments and ore deposition. By considering of these main features, this deposit has many similarities and is comparable with Five-element deposits which their most important features are discussed by Lefebure (1996). Some of the well studied deposits in this category are Cobalt camp, Thunder Bay district (Ontario, Canada) and Freiberg and Jachymov, Erzgebirge district (Germany). As a group, these deposits represent an enigma. Occurrences are relatively rare yet widely scattered throughout the world. They are found in a variety of host lithological environments yet exhibit a striking internal consistency in their mineralogy and textures. Although they are obviously classifiable as a deposit type, they are not clearly related to any readily identifiable metallogenetic province or epoch (Andrews et al., 1986).

The metals in the Talmessi and Meskani Ni-Co-U mineralization are probably derived from basic-ultrabasic rocks and the pre-existing ores. It seems that late-Oligocene magmatic activity has acted as a heat source for the circulation of most probably non-magmatic waters (probably from Oligo-Miocene shallow water basin) through a lattice of fault system in the area.

On the basis of the magmatic segregation rules, hydrothermal mineralization of these ore elements in late stages of magmatic differentiation processes is unlikely. So it seems that alteration of the ultrabasic bodies has an important role in the liberation of the Cu-Ni-Co-As elements from these rocks forming mineral lattices and making them ready for remobilization by these circulating waters.

Emplacement of the area at the intersection of two most important active lineaments especially from Lower Eocene up to now, led to different phases of deformation which led to reactivation of old faults and hence this facilitated different phases of mineralization especially at the intersection of high angel faults. The reactivation and mineralization led to an especial minrealization in Iran which comprises two very different kind of mineralization (one mainly volcanogene and the other mainly non magmatogen) on a same place but in different times.

Groves et al. (1979) described the role of the CO2 rich solutions in the remobilization of the ore elements during alteration of the Mt.KELETH-BETHENO dunites, west of Australia. Keays and Davison, (1976) have suggested that during this process Ni was mobilized while Platinium elements group remained immobile. This might result in the formation of some Au deposits in relation to listwenites. Dunning et al.,(1981) has shown that in fresh ultrabasic rocks, Au, Pt versusCo,Ni changes display a positive correlation which after carbonatization or listwenitization changes to a negative one.

The association of uranium with Ni and Co in the Talmessi deposit is not a unique one. Uranium is an accessory element in Ni and Co Gowganda deposit in Canada, while Ni plays the same role in some of the large unconformity-type uranium deposits.

It is suggested that uranium in these kind of deposits was brought to the depositional site as uranyle carbonate complexes(Guilbert and Park,1986), where first stage sulfide mineralization acted as a reducing barrier and resulted in the destabilization of uranyle carbonate complexes and the deposition of uranium as U^{+4} minerals , most probably after tectonic reactivation of the area and reopening of the sulfidic mineralized veins through the second tectonic stage.

Considering that: main carbonate minerals here (Calcite, Dolomite and Siderite) comprise the main gangues in such deposits, Ni and Co could be leached and removed from the ultramafic rocks by the carbonatic solutions during the listwanitization, and the role of uranyle carbonate complexes in the transportation of uranium to the depositional site - the U, Ni and Co association - could be envisaged and might be related to key direct or indirect role of CO2 bearing solutions.

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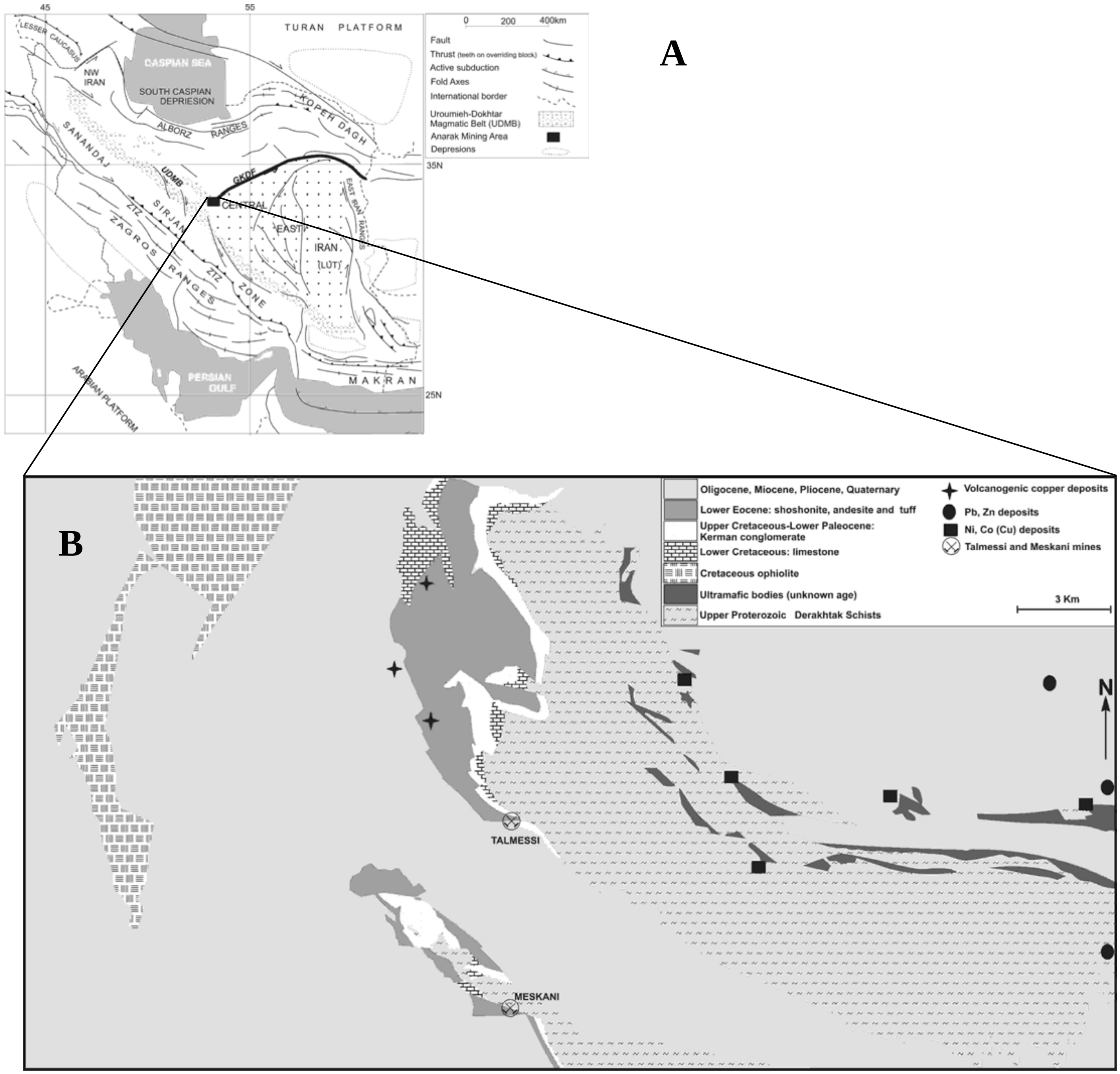
A
45
55
TURAN PLATFORM
LESSER CAUCASUS
CASPIAN SEA
NW IRAN
SOUTH CASPIAN DEPRIESION
ALBORZ RANGES
KOPEH DAGH
SANANDAJ
UDMB
GKDF
CENTRAL
EAST
IRAN
(LUT)
EAST IRAN RANGES
SIRJAN
ZTZ
ZAGROS RANGES
ZONE
PERSIAN GULF
MAKRAN
ARABIAN PLATFORM
35N
25N
0 200 400km
Fault
Thrust (teeth on overriding block)
Active subduction
Fold Axes
International border
Uroumieh-Dokhtar Magmatic Belt (UDMB)
Anarak Mining Area
Depresions
B
Oligocene, Miocene, Pliocene, Quaternary
Lower Eocene: shoshonite, andesite and tuff
Upper Cretaceous-Lower Paleocene: Kerman conglomerate
Lower Cretaceous: limestone
Cretaceous ophiolite
Ultramafic bodies (unknown age)
Upper Proterozoic Derakhtak Schists
Volcanogenic copper deposits
Pb, Zn deposits
Ni, Co (Cu) deposits
Talmessi and Meskani mines
3 Km
N
TALMESSI
MESKANI

Fig. 1

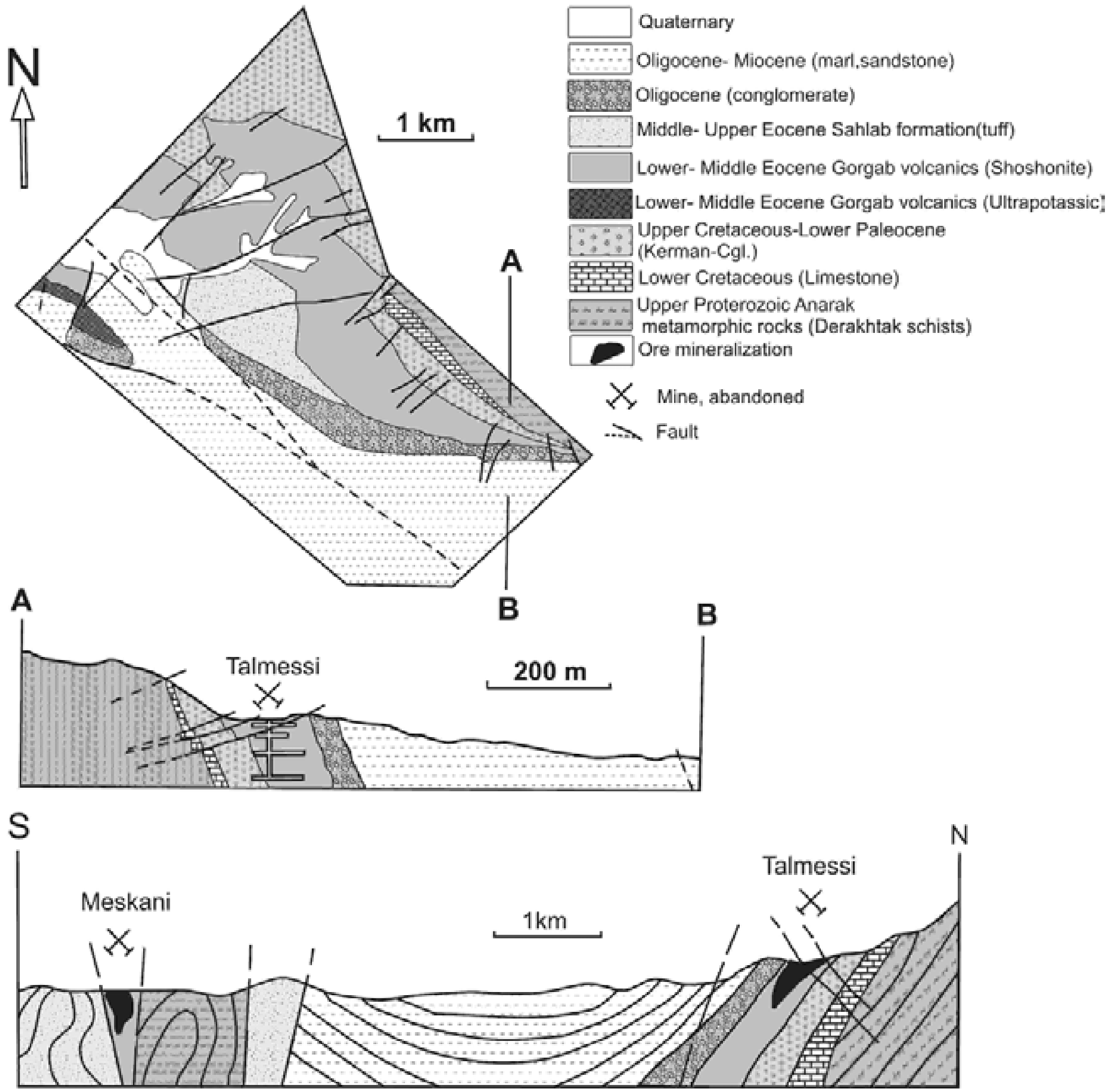
N
1 km
Quaternary
Oligocene- Miocene (marl,sandstone)
Oligocene (conglomerate)
Middle- Upper Eocene Sahlab formation(tuff)
Lower- Middle Eocene Gorgab volcanics (Shoshonite)
Lower- Middle Eocene Gorgab volcanics (Ultrapotassic)
Upper Cretaceous-Lower Paleocene (Kerman-Cgl.)
Lower Cretaceous (Limestone)
Upper Proterozoic Anarak metamorphic rocks (Derakhtak schists)
Ore mineralization
Mine, abandoned
Fault
A
B
A
B
Talmessi
200 m
S
N
Meskani
Talmessi
1km

Fig. 2

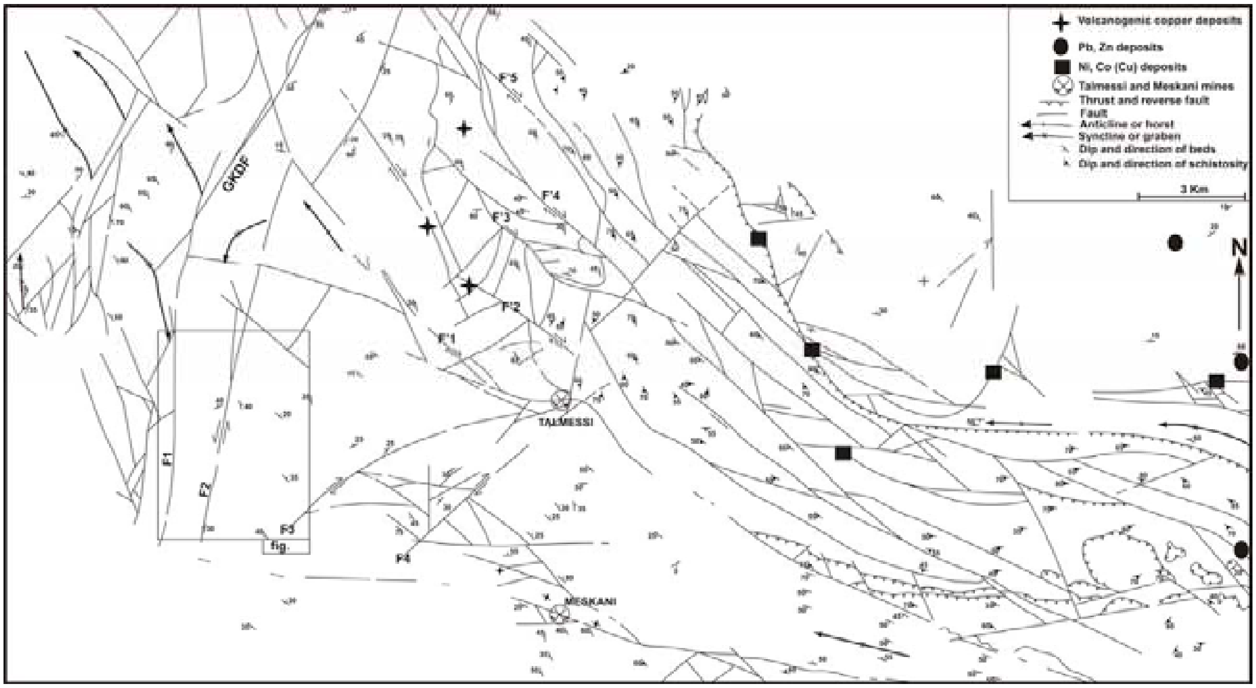
Volcanogenic copper deposits
Pb, Zn deposits
Ni, Co (Cu) deposits
Talmessi and Meskani mines
Thrust and reverse fault
Fault
Anticline or horst
Syncline or graben
Dip and direction of beds
Dip and direction of schistosity
3 Km
N
GKDF
F'5
F'4
F'3
F'2
F'1
TALMESSI
MESKANI
F1
F2
F3
F4
fig.

Fig. 3

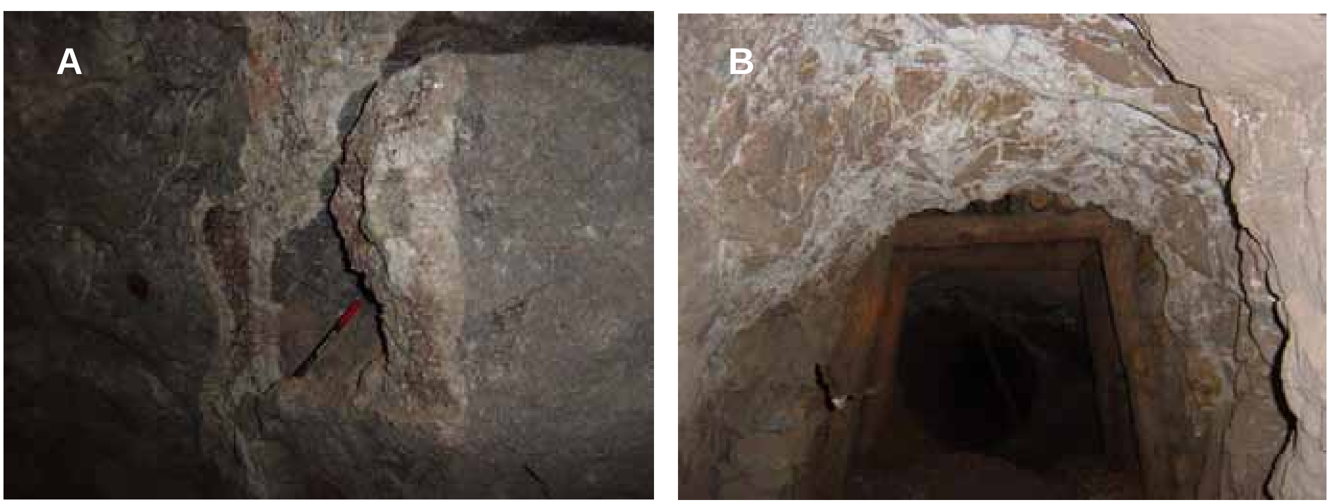
A
B

Fig. 4

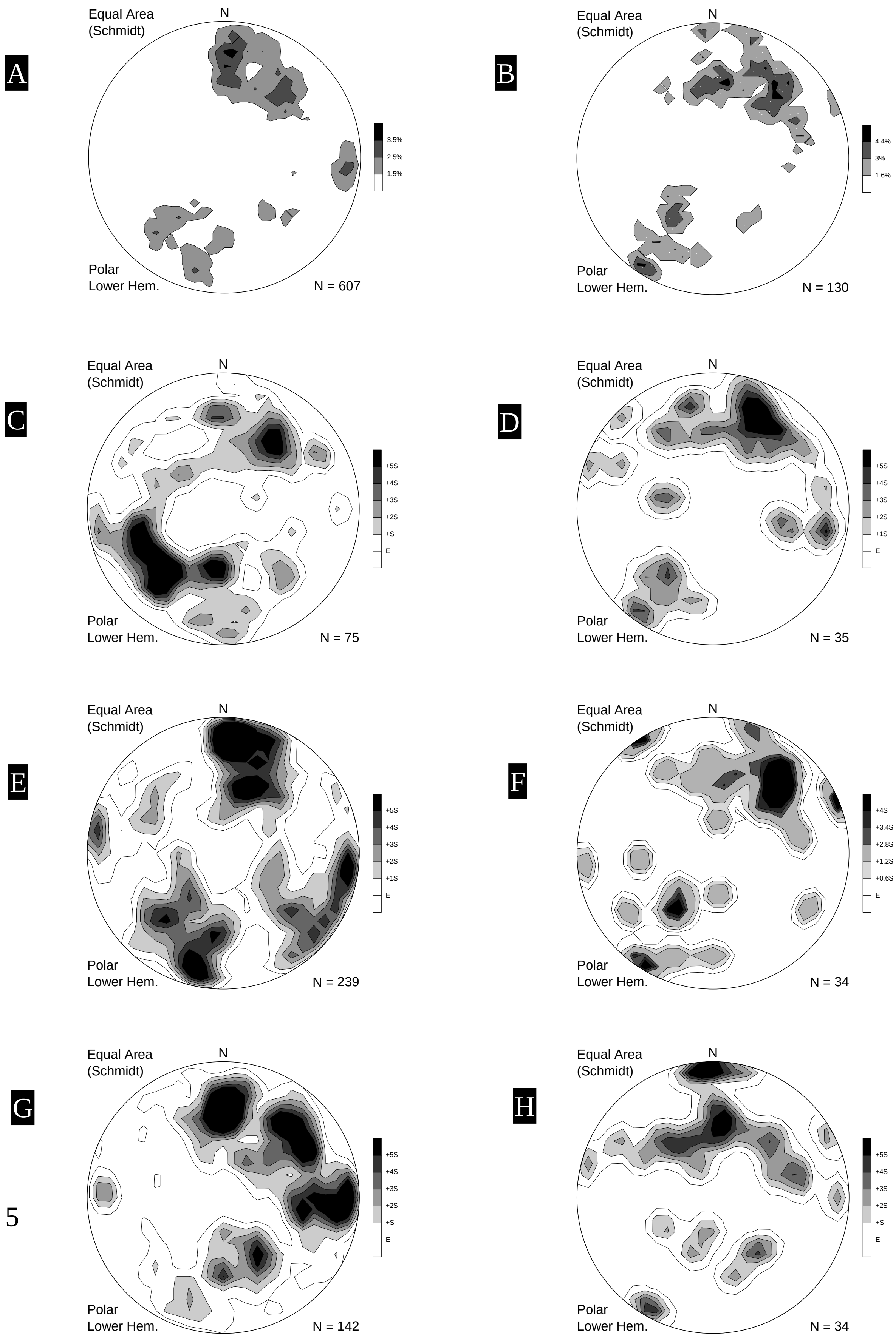
A
Equal Area
(Schmidt)
N
3.5%
2.5%
1.5%
Polar
Lower Hem.
N = 607
B
Equal Area
(Schmidt)
N
4.4%
3%
1.6%
Polar
Lower Hem.
N = 130
C
Equal Area
(Schmidt)
N
+5S
+4S
+3S
+2S
+S
E
Polar
Lower Hem.
N = 75
D
Equal Area
(Schmidt)
N
+5S
+4S
+3S
+2S
+1S
E
Polar
Lower Hem.
N = 35
E
Equal Area
(Schmidt)
N
+5S
+4S
+3S
+2S
+1S
E
Polar
Lower Hem.
N = 239
F
Equal Area
(Schmidt)
N
+4S
+3.4S
+2.8S
+1.2S
+0.6S
E
Polar
Lower Hem.
N = 34
G
Equal Area
(Schmidt)
N
+5S
+4S
+3S
+2S
+S
E
Polar
Lower Hem.
N = 142
H
Equal Area
(Schmidt)
N
+5S
+4S
+3S
+2S
+S
E
Polar
Lower Hem.
N = 34

Fig. 5

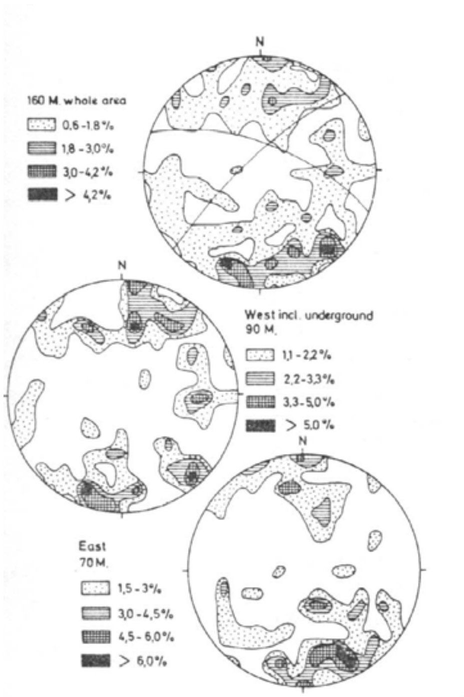
N
160 M. whole area
0,6 -1,8 %
1,8 - 3,0 %
3,0 - 4,2 %
> 4,2 %
N
West incl. underground
90 M.
1,1 - 2,2 %
2,2 - 3,3 %
3,3 - 5,0 %
> 5,0 %
N
East
70 M.
1,5 - 3 %
3,0 - 4,5 %
4,5 - 6,0 %
> 6,0 %

Fig. 6

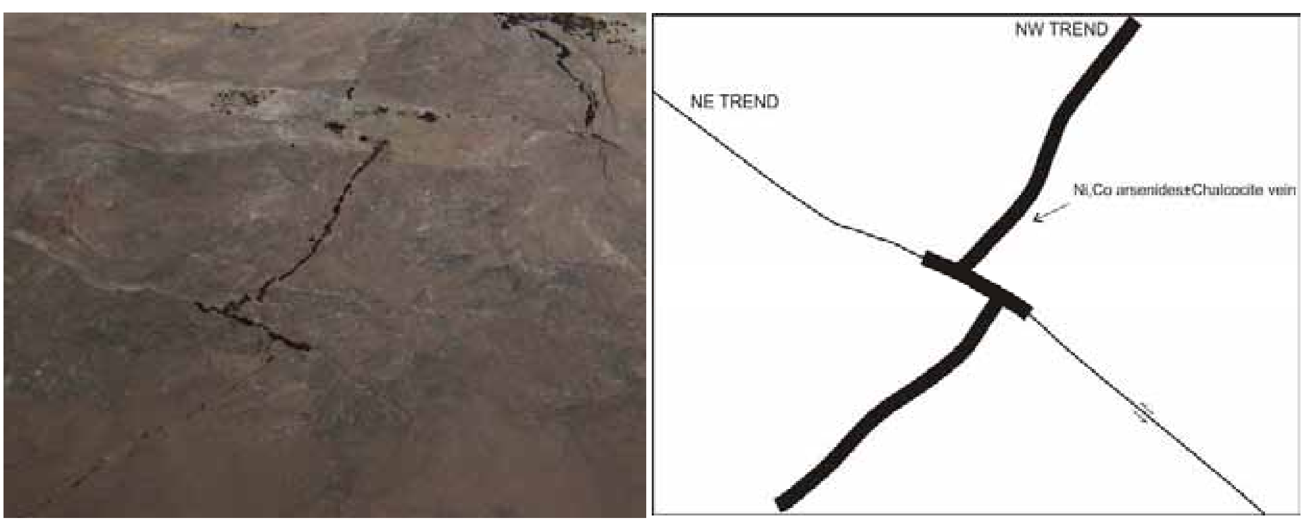
NW TREND
NE TREND
Ni,Co arsenides±Chalcocite vein

Fig. 7

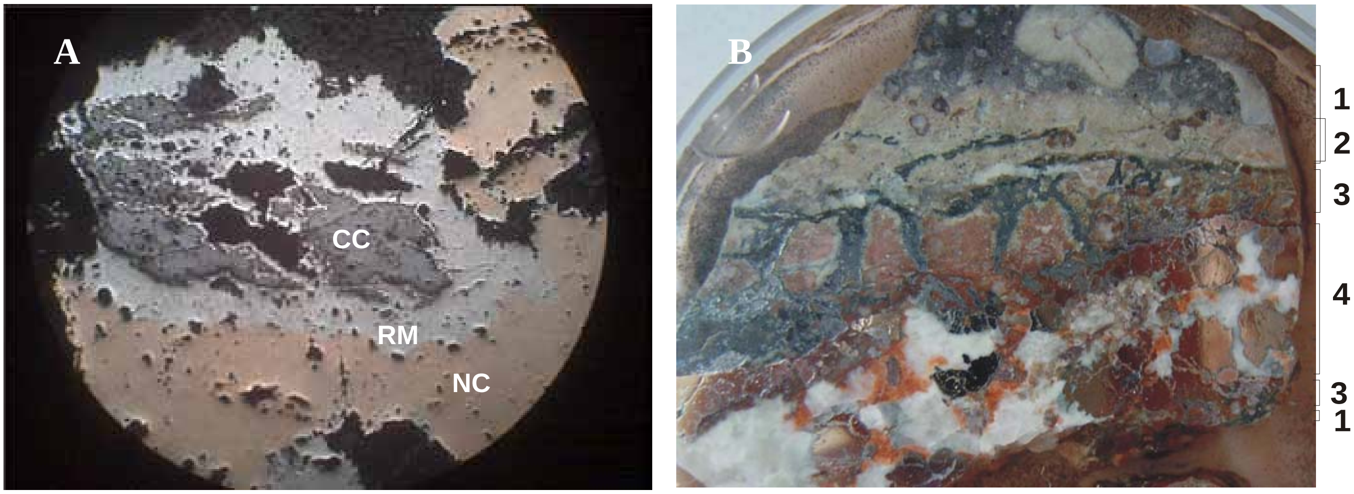
A
CC
RM
NC
B
1
2
3
4
3
1

Fig. 8

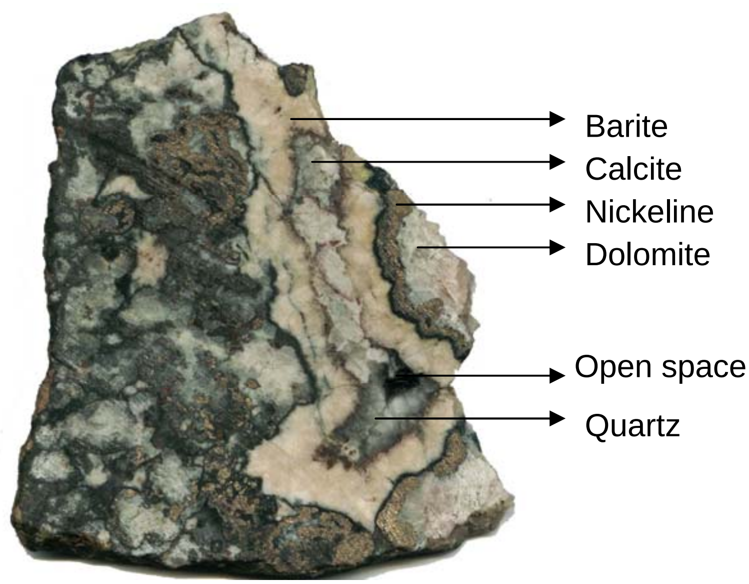
Barite
Calcite
Nickeline
Dolomite
Open space
Quartz

Fig. 9

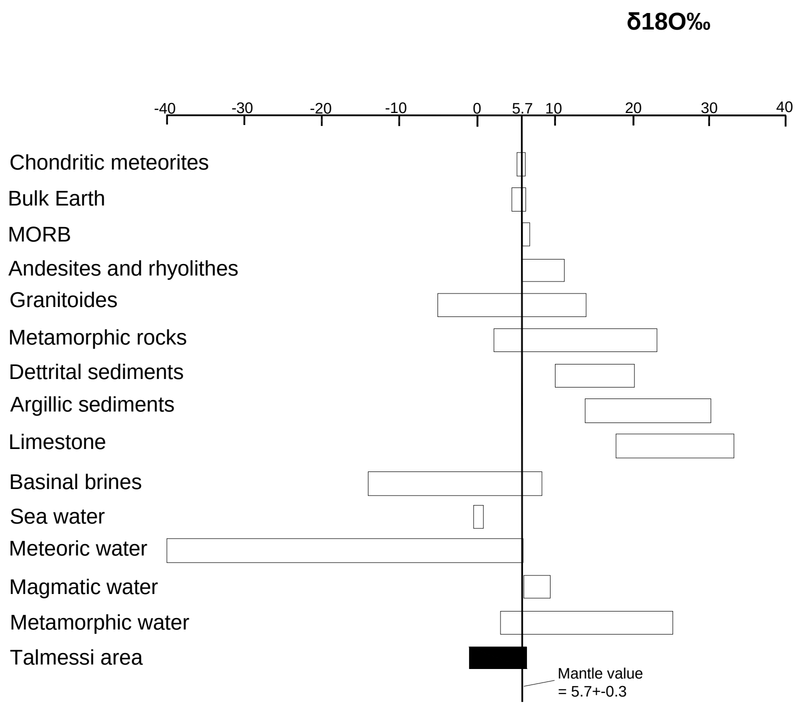
δ18O‰
-40
-30
-20
-10
0
5.7
10
20
30
40
Chondritic meteorites
Bulk Earth
MORB
Andesites and rhyolithes
Granitoides
Metamorphic rocks
Dettrital sediments
Argillic sediments
Limestone
Basinal brines
Sea water
Meteoric water
Magmatic water
Metamorphic water
Talmessi area
Mantle value
= 5.7+-0.3

Fig. 10

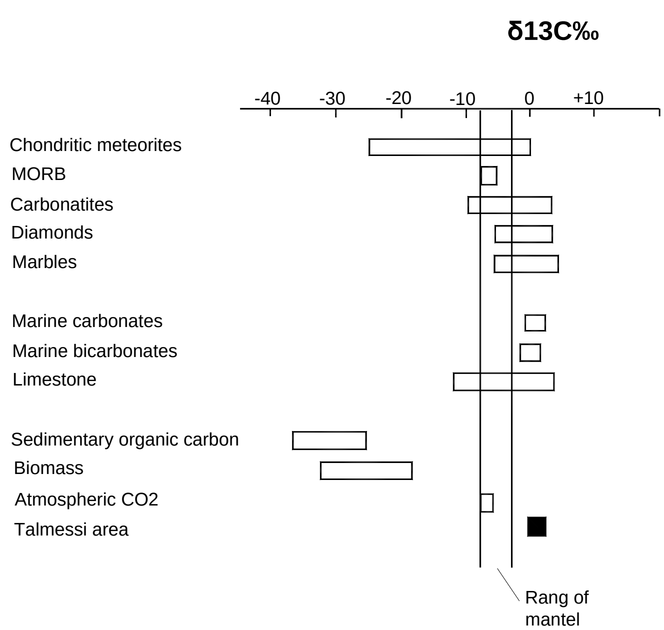
δ13C‰
-40
-30
-20
-10
0
+10
Chondritic meteorites
MORB
Carbonatites
Diamonds
Marbles
Marine carbonates
Marine bicarbonates
Limestone
Sedimentary organic carbon
Biomass
Atmospheric CO2
Talmessi area
Rang of
mantel

Fig. 11

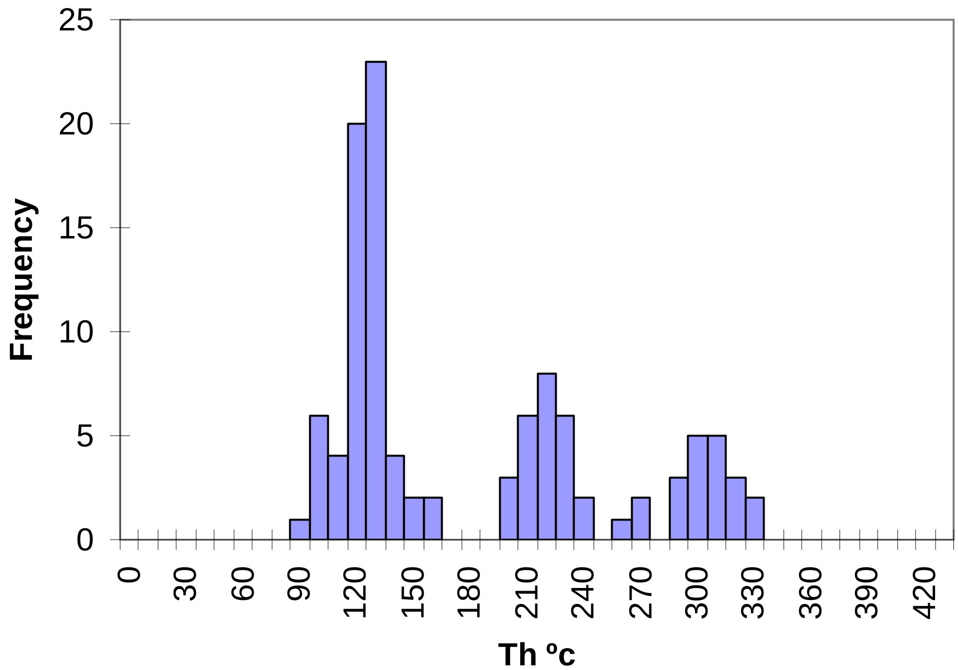
25
20
15
10
5
0
Frequency
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
Th ºc

Fig. 12

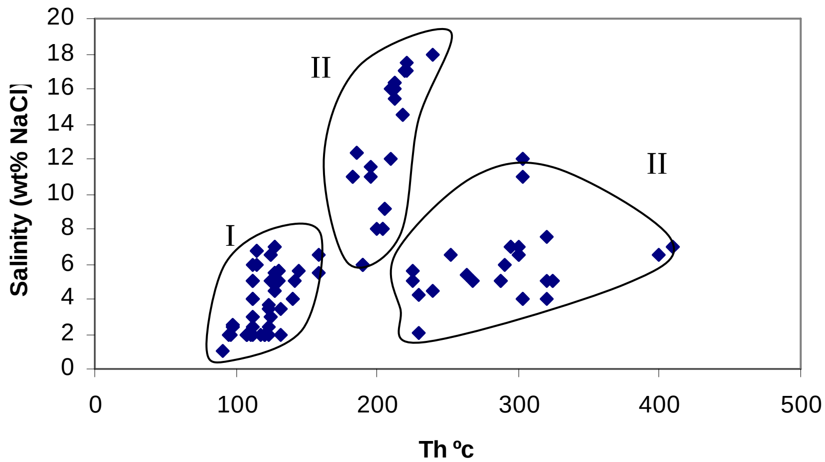
20
18
16
14
12
10
8
6
4
2
0
Salinity (wt% NaCl)
0
100
200
300
400
500
Th ºc
I
II
II

Fig. 13

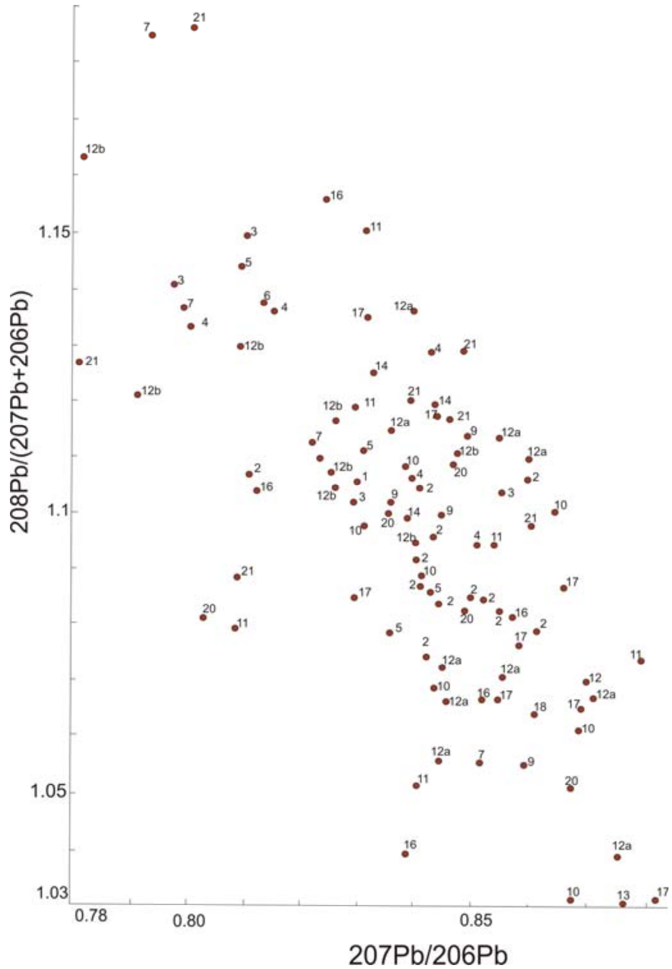

Fig. 14-

Table 1

Sample	Description	δ18O (‰) SMOW	δ13C (‰) PDB	T (ºC)*	δ18O H2O (‰)†
L15	Dolomite	22.36	-0.09	96	3.16
L18	Calcite	17.75	-0.17	156	5.53
L182	Calcite	17.96	-0.76	132	3.9
L184	Calcite	19.08	0.93	125	4.42
L184-1	Dolomite	17.59	-0.32	128	-0.4
M107	Calcite	17.24	-1.13	95	-0.36
T1	Calcite	19.46	-0.84	142	6.21
TP	Calcite	17.6	-0.08	95	-0.04
TP11	Calcite	19.3	0.78	98	1.99
TP12	Calcite	19.49	0.83	108	3.23
TP12-1	Dolomite	15	-0.54	125	-1.1
TX7	Calcite	19.34	0.24	105	2.77
L421	Calcite	19.12	-0.38	102	2.24
TX81	Calcite	19.21	0.26	128	4.81

Table 2

Sample no.	Mineral	Paragenesis	Type	$\delta^{34}S$‰
1	chalcocite	chc, nc, cc,	hypogene	-3.3
L2	chalcocite	chc,cc	hypogene	-1.4
L18-s1	chalcocite	chc,cc	uncertain	-23.3
L18-s2	chalcocite	chc,cc	uncertain	-18.9
M2	chalcocite	chc	supergene	-12.4
L184-6	chalcocite	chc,nc,rm,cc	uncertain	-30.9

Figure captions:

Fig.1: A Main structural lineaments in Central Iran and location of the study area **B** Geological map and spatial distribution of mineral deposits of the Anarak area and location of Talmessi(T) and Meskani(M) mines.

Fig. 2-Geological map and cross-sections of Talmessi mine and Talmessi syncline(modified after Bagheri et al. 2005)

Fig. 3 fault map of the study area

Fig. 4- A) mineralization in the open spaces, carbonates are the main gangues B) brecciation of the volcanic rocks at the intersection of the faults provided suitable sites for mineralization and later supergen activities of the meteoric

Fig. 5 Orientation of joints in the volcanics and Tertiary sediments obtained underground at Talmessi mine and on surface exposures. In all of the mining levels: **A)** Mineralized and unmineralized,B) mineralized. level 18m: C) all data , D) mineralized. Level -30m: E) all and F) mineralized. Level -55: G) all and H) mineralized.

Fig. 6 - Orintation diagrams for joints in the volcanics and tertiary sediments in meskani mine obtained underground at Meskani mine and on surface exposures (Tarkian et al. 1983)

Fig. 7- the youngest stage of mineralization (i.e. Ni,Co,Cu arsenidic stage) is younger or contemporaneous with second main tectonic phase and/or NW trending faults. But the main conduits for ore forming fluids are NW trending reactivated faults.

Fig. 8-A) chalcocite(CC) replaced by nickelin(NC) and both of them replaced by ramelsbergite(RM) **B)-** Two different stages of mineralization in a vein Talmessi mine.(1: volcanic wall rock 2:bleached zone 3:first stage sulfidic mineralization(Chalcocite) with rims of rammelsbergite ($NiAs_2$) 4: second stage Ni-Co arsenides mineralization (nickeline+rammelsbergite+saflorit+calcite) with remnants of chlcocite in nickelin.

Fig. 9- A typical form of arsenide stage of mineralization in Talmessi mine.

Fig. 10 – field of $\delta^{18}O$ changes of Talmessi's fluids in comparison to other cases (after, Rollinson, 1993)

Fig. 11 – field of $\delta^{13}C$ changes of Talmessi's fluids in comparison to other cases (after, Rollinson, 1993)

Fig. 12 histogram of the heating data from studied fluid inclusion from Talmessi mine

Fig. 13 salinity/homogenization temperatures from Talmessi mine
Fig. 14- variations of lead-isotopic ratios in galenas from mineral deposits of Anarak area.(from Yushin et al. 1981)
Numbers belong to different ore deposits studied in the Anarak area: 1-talheh 2-zah 3-ghurchehe berenj 4- dombar 5-pis kuh 6-chika buh 7-rizab e maryam 8- chah sefid 9-negine 10-nakhlak 11-chah mileh 12-gowd (including 12a- homu sector, 12b- beskosh sector) 13-chah gorbeh 14-moala 16-kale kafi 17-arusan 18-western patyar 19-patyar 20-sorb 21-bande gel II 22-seyah kuh (south of the area).

Table 1- Isotopic data for hydrothermal carbonate minerals and fluids in Talmessi deposite.(* Temperature data from fluid inclusions; †Calculated oxygen isotopic composition of the hydrothermal fluids)

Table 2 Sulphur isotope data for samples of chalcocite from the Talmessi mine (chc=chalcocite, cc=calcite, nc=niccolite, rm=rammelsbergite; data from Bagheri et al., 2005)