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PORPHYRY COPPER DEPOSITS OF THE URUMIEH-DOKHTAR MAGMATIC ARC, IRAN

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Abstract - Three of the major copper provinces of the Tethyan metallogenic belt lie within Iran. Two of these, the southeastern and north western provinces, contain the major Sar-Cheshmeh (1.2 Gt @ 0.7% Cu, 0.03% Mo) and Sungun (500 Mt @ 0.75% Cu, 0.01% Mo) porphyry copper deposits respectively. The copper mineralisation of these provinces bears a direct relationship to the evolution and closure of the Neo-Tethys Ocean and the collision of the Iranian and Afro-Arabian plates. All of the significant porphyry type copper deposits in Iran are associated with granitoids of the subduction-related, Eocene to Miocene age, volcanism and plutonism in the northwest-southeast oriented Central Iranian Volcano-Plutonic Belt (better known as the Urumieh-Dokhtar Magmatic Arc). The peak of mineralisation was during the Miocene. The Urumieh-Dokhtar Magmatic Arc developed in parallel with the collisional Zagros Fold and Thrust Belt to the southwest, and the intervening Sanandaj-Sirjan Metamorphic Zone. Although many examples of porphyry copper mineralisation are known within these provinces, potential still remains for large discoveries in several prospective districts through further studies and systematic exploration.

Introduction

Iran is a one of the major copper provinces in the Tethyan metallogenic belt. Ancient mine workings and records indicate that copper mining was an important industry in Iran, and that its peoples have had exploration, mining and metallurgical knowledge of this metal for a long time. Exploration has been undertaken by the Geological Survey of Iran (GSI), Yugoslavian, Australian, Canadian and French mining companies, and the National Iranian Copper Industries Company (NICICO) between 1966 and 2003. This work has identified many copper deposits and occurrences in various parts of Iran, especially along the Central Iranian Volcanic-Plutonic Belt, better known as the Urumieh-Dokhtar Magmatic Arc (hereforth referred to as the UDMA). About 250 copper deposit and occurrences associated with vein type, porphyry, skarn, skarn-porphyry, or massive sulphide genesis have been described in reports (e.g., Bazin and Hubner, 1969; Forster et al., 1972). The most important mining districts and the significant currently mined copper resources in Iran are porphyry copper style deposits located within the UDMA. Almost all known porphyry type copper deposits in Iran are associated with Cenozoic granitoids within the UDMA (e.g. Bazin and Hubner, 1969; Jankovic, 1984). The volcanism, plutonism and associated mineralisation in the UDMA are considered to be the result of subduction (e.g. Berberian and King, 1981) within the collisional Zagros belt. The main known porphyry copper deposits and porphyry occurrences of Iran are located in the north western and central-south eastern sections of the UDMA, respectively (Fig. 1).

Regional Geologic Setting of Iran

The geotectonic setting of Iran with respect to the Scytho-Turanian plate in the north and the Arabian plate (Gondwana) in the south is still a matter of controversy (e.g. Soffel *et al.*, 1996). Subduction between the Iranian and Afro-Arabian plates during the Mesozoic defined three main parallel tectonic zones: i) the Zagros fold and thrust belt, ii) the Sanandaj-Sirjan metamorphic zone, and iii) the UDMA (Fig. 1). Most Iranian igneous rocks associated with copper mineralisation are in the UDMA. This magmatic belt is considered to be an integral part of the Zagros orogenic belt (e.g., Stocklin, 1968; Alavi, 1994), which is in turn part of the Alpine–Himalayan orogenic/ metallogenic belt. The Zagros orogenic belt extends from the Eastern Anatolian Fault in eastern Turkey, to the Oman line in southern Iran, a distance of over 2000 km. Early studies suggested either a subduction model (e.g., Takin, 1972; Forster, 1978; Niazi and Asoudeh, 1978, Alavi, 1980; Berberian, *et al.*, 1982) or a continental rifting model (e.g., Sabzehie, 1974; Amidi, 1975) for the tectonic setting and formation of the Zagros orogenic belt. According to the subduction model, a small continental block (the Central Iranian Block, CIRB) separated from Gondwana in the early Mesozoic and formed the Iranian plate and the intervening Neo-Tethys basin, floored by oceanic crust (Alavi, 1980; Sengör, 1990). In the early Cretaceous, movement of the Iranian plate and expansion of the Neo-Tethys oceanic crust ceased and was then reversed. This resulted first, in the subduction of the Neo-Tethian oceanic lithosphere below the CIRB, and subsequently, in collision between the Afro-

Arabian and Iranian plates. In contrast, the continental rifting model assumed that magmatism in the Central Iranian block was the result of episodic opening of a continental rift zone during the Eocene. Most recent work however, fully supports the subduction model (e.g. Alavi, 1994), and also emphasises the tectonic effects of oblique subduction (Sokoutis *et al.,* 2000) in the generation of parallel strike-slip and reactivated structures in the UDMA.

Geological Framework of the Urumieh-Dokhtar Magmatic Arc

Early studies of the UDMA generally suggested that it represents an Andean type magmatic arc formed by subduction along the active continental margin of the Central Iranian Block during the Alpine orogeny (Takin, 1972; Berberian *et al.,* 1982; Sengör, 1990; Alavi, 1994). However, other workers proposed that the belt was formed by post-collision magmatism related to orogenic collapse (e.g. Stocklin, 1974; Berberian and King, 1981). Within the UDMA, Late Mesozoic and Palaeogene plutons intruded sedimentary rocks of Cretaceous age (Nabavi, 1976; Alavi, 1980). Magmatic activity peaked during the Eocene, leading to widespread extrusion of volcanic rocks consisting of trachy-basalt, andesite and dacite lavas, domes, ignimbrites and tuffs (Alavi, 1980). These rocks were in turn intruded by granitoids of Oligocene-Miocene age, which in many parts of the UDMA are spatially associated with copper mineralisation (Jankovic, 1984). Based on geochemical investigations (e.g., Forster *et al.,* 1972; Berberian *et al.,* 1982; Shahabpour, 2004) volcanic and plutonic rocks in this belt are mainly calc-alkaline and related to subduction between the Arabian and Iranian plates. Young alkaline volcanic rocks in some parts of this belt may be the result of melting of the broken oceanic crust slab after collision and the cessation of subduction (Berberian and Berberian, 1981).

The metallogenic characteristics and copper occurrences of the UDMA have been described by many authors (e.g., Bazin and Hubner; 1969; Forster, 1972; Jankovic, 1984; Shahabpour, 1999, 2004; Yaghubpur, 2003; Richards, 2003). These studies indicate Cenozoic granitoid and volcanic bodies related to subduction played a key role in the formation of different types of copper-mineralisation in the UDMA, particularly porphyry style occurrences. Porphyry style mineralisation accompanied the final phases of arc magmatism in the Middle Miocene, following the peak of arc magmatism in the Eocene (Richards, 2003). Development and evolution of the UDMA is coeval with magmatic up-welling and crustal thickening, and in several parts of the belt, was accompanied by Miocene age reactivation of older structures and tectono-magmatic zones parallel to the Zagros orogenic belt (Zarasvandi, 2004).

Urumieh-Dokhtar Magmatic Arc and Porphyry Copper Deposits

The UDMA is subdivided into a number of separate copper provinces by a series of structural feature, including major strike-slip faults and long lived structural lineaments. Remote sensing studies (e.g., Ranjbar *et al.,* 2004;

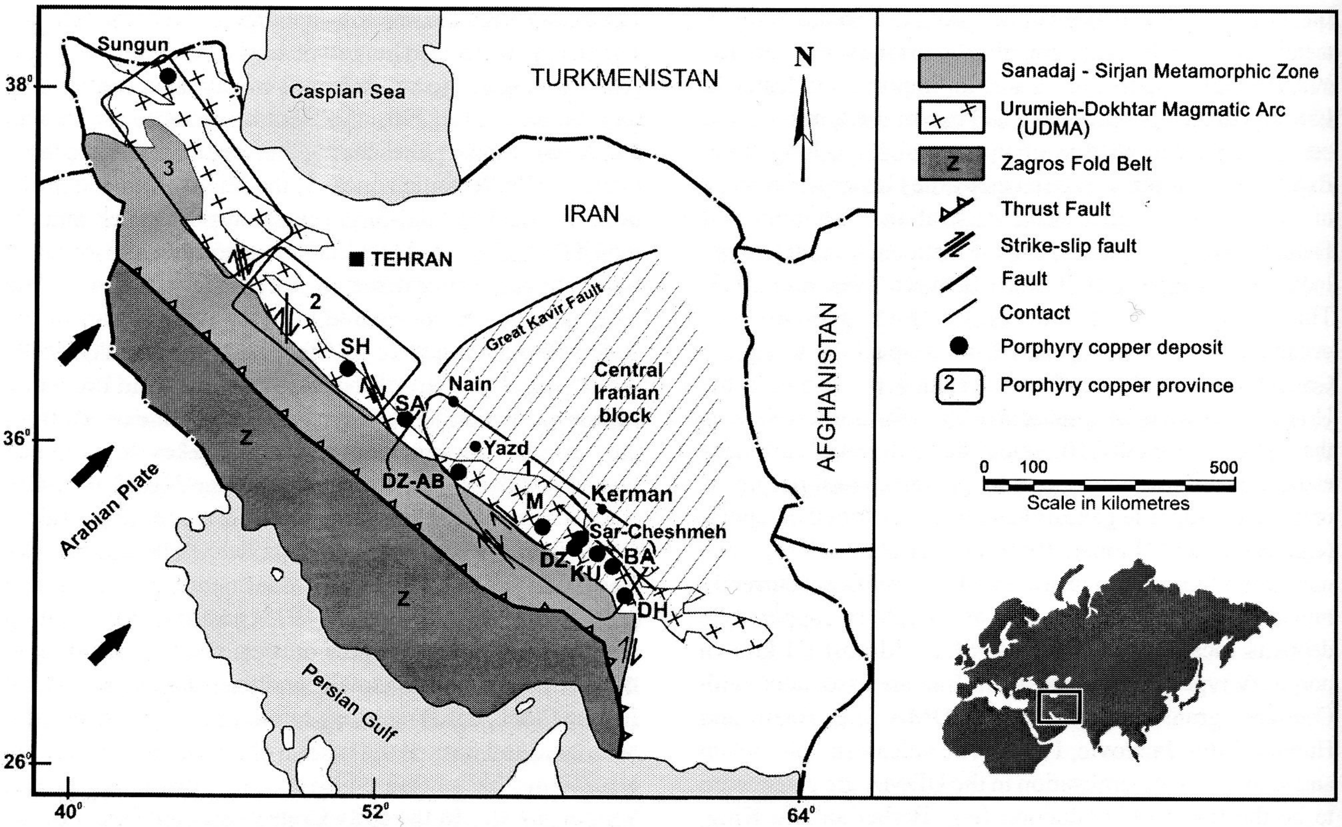


Figure 1: ***Index map showing the geographical position and main tectonic zones of Iran.*** Dashed area is Central Iranian Block (CIRB). Porphyry Copper Provinces are: 1. The Ardestan-Sarcheshmeh-Kharestan region; 2 The Saveh-Ardestan district; 3 The Takab-Mianeh-Qarahdagh-Sabalan region. Porphyry copper deposits are: M = Meiduk; SA = South Ardestan; SH = Sharifabad; DZ-AB = Darreh-Zerreshk and Ali-Abad; DZ = Darreh-Zar; KU = Kuh-Panj ; BA = Bahr-Aseman; DH = Darreh-Hamzeh. Black arrows indicate relative plate motion from Sokoutis *et al.* (2000).

Tangestani and Moore, 2002), field mapping by the Geological Survey of Iran and NICICO, and geochemical, petrological and geochronological studies by many authors (e.g., Aftabi, 1999; Shahbpour, 2004; Zarasvandi *et al.*, 2005; Hezarkhani and Williams Jones, 1998; Calagari, 2004; Karimzadeh, 2004) indicate that most of the copper deposits (skarn, porphyry, skarn-porphyry and vein-type) in the copper provinces of the UDMA share direct, or parental genetic relationships.

The copper deposits in this belt are related to a common calc-alkaline magmatism, and are developed in a similar crustal thickness and structural regime. They also share a common, time of emplacement and the same range of mineralisation styles. These relationshipos may be the result of their common subduction history, including the time of collision, and the trend and angle of subduction subduction between the Arabian and Iranian plates (Berberian and King, 1981; Shahabpour, 1999; Richards, 2003; Yaghubpur, 2003; Zarasvandi *et al.*, 2005; Richards, 2003; Shahabpour, 2004).

Geological studies undertaken by numerous authors and companies between 1969 and 2003 indicate that the bulk of the exposed porphyry copper deposits are concentrated in three major copper provinces within the UDMA (Fig. 1). Erosion and good exposure of the lithostratigraphy and magmatic sequences in these provinces has assisted in the discovery of most of the porphyry copper mineralisation. Although many deposits have been outlined, there are still prospective districts that may be considered promising for further studies, systematic exploration and discoveries.

The three main porphyry copper bearing provinces within the UDMA (Fig. 1) are:

1) The Ardestan-Sarcheshmeh-Kharestan region in the centre and southeast, which includes the major Sar-Cheshmeh and Meiduk porphyry copper deposits. Both are currently being mined by separate companies under the supervision of NICICO. Many of the other deposits in this district, such as those at Darreh-Zerreshk, Ali-Abad, Abdar, Darreh-Zar, Saridoon and Kharestan are either being explored or developed by Iranian and foreign companies.
2) The Saveh-Ardestan district in the central sections of the UDMA does not contain any known major copper deposits.
3) The Takab-Mianeh-Qarahdagh-Sabalan region in the northwest of Iran is the second most important copper province in the UDMA, containing both porphyry and other styles of copper deposit, including the Sungun porphyry copper orebody, the second largest in Iran. This deposit is currently being developed by a subsidiary of NICICO. No detail is available of exploration or development programs at the other porphyry copper deposits in this province, although some could be targets for future mining operations.

Most of the important porphyry copper deposits and occurrences in the major copper province of the central Iranian volcano-plutonic belt and their characteristics are listed in Table. 1. A summary of the geology of the major porphyry copper deposits in the UDMA follows.

Sar-Cheshmeh Porphyry Copper Deposit

Sar-Cheshmeh is the largest porphyry copper deposit in Iran, and one of the largest in the world, containing 1200 Mt of sulphide ore at an average grade of 1.2 % Cu, 0.03 % Mo, 0.27g/t Au, and 3.9 g/t Ag (Ellis, 1991). The deposit is located 60 km south of the city of Rafsanjan in southwest Kerman Province, at an altitude of approximately 2500 m above sea level. It is elongate in shape, with dimensions of around 2000 m in length by 1000 m in width and trends northeast-southwest. There are two low grade porphyry copper deposits to the south and north of the Sar-Cheshmeh mine which NICICO plans to develop in the future by extending the current open pit.

Waterman and Hamilton (1975), and Shahabpour and Kramers (1987) classified Sar-Cheshmeh as a porphyry copper-molybdenum-gold deposit. Rapid erosion has exposed the magmatic sequence both at the deposit and in

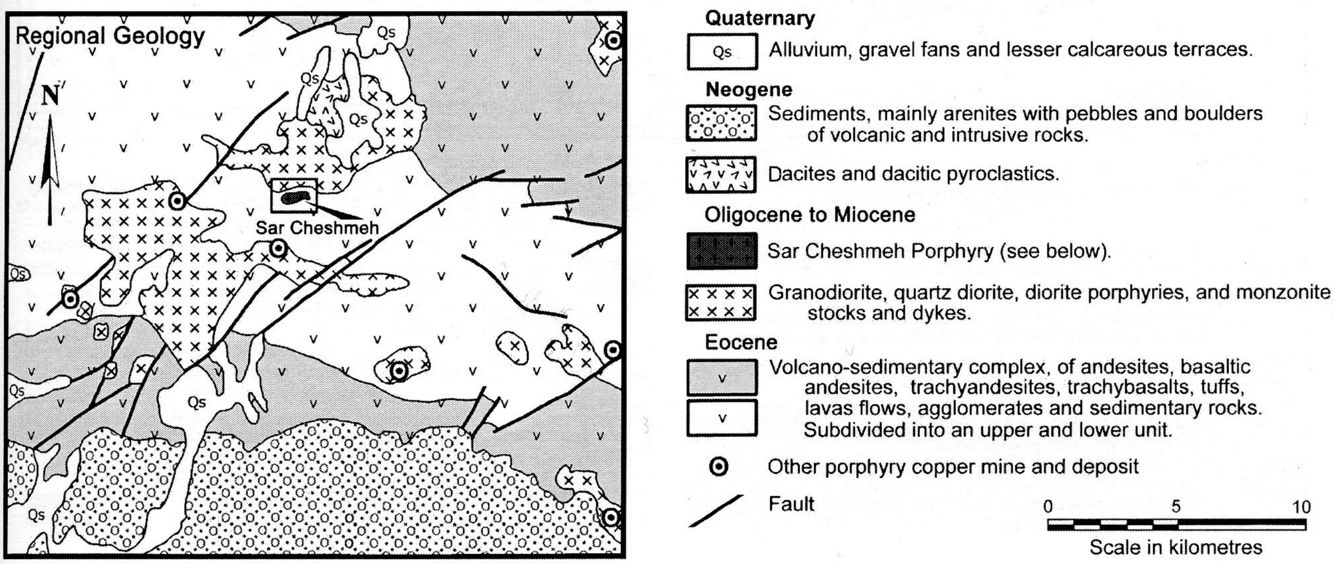


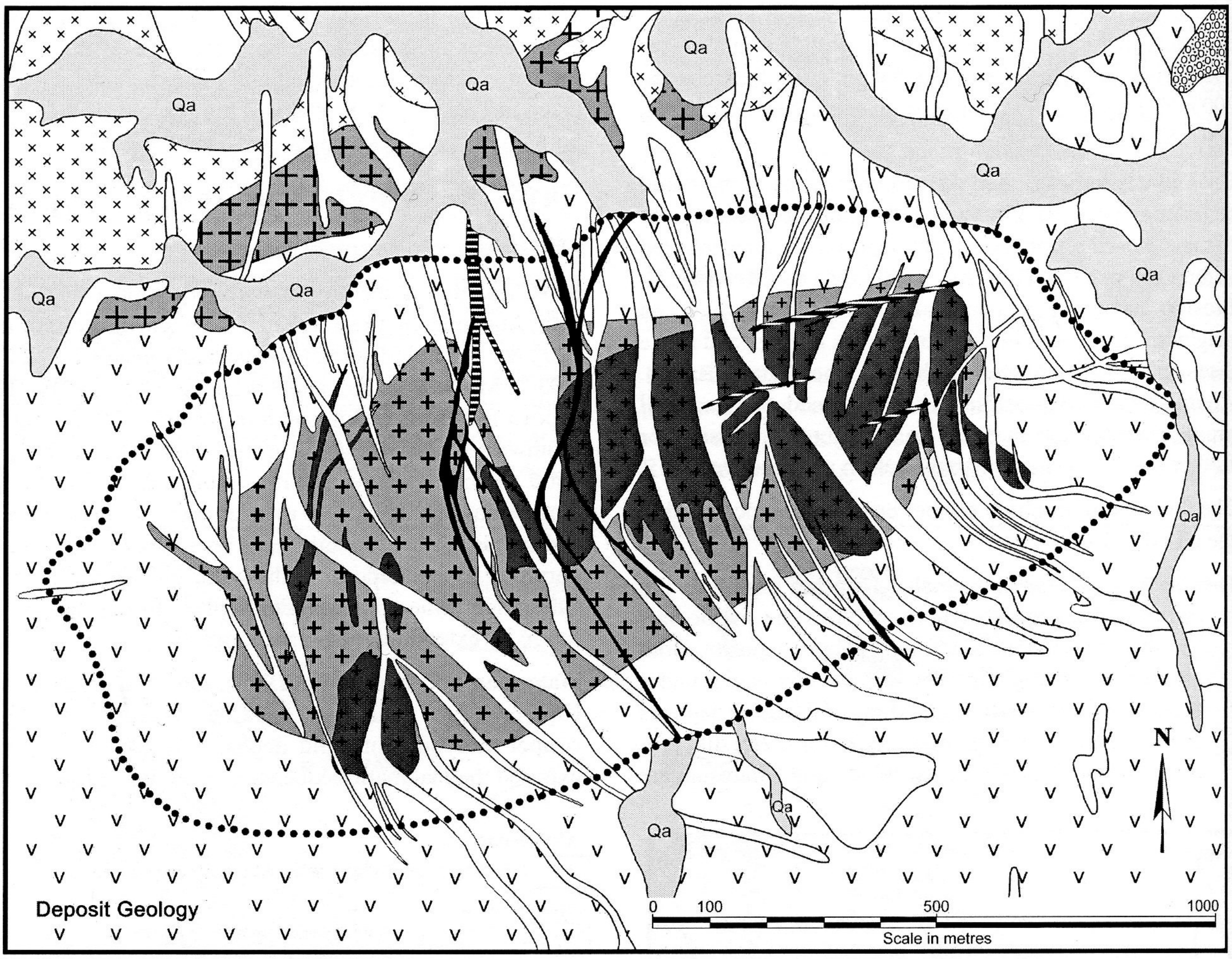
Figure 2: ***The regional scale geological setting of the Sar Cheshmeh porphyry copper deposit, southeastern Iran.*** After Honarmand *et al.*, (2002) and Ranjbar *et al.*, (2004). The rectangle surrounding the Sar Cheshmeh deposit is the area of Figs.3 and 4.

the surrounding area, where the Miocene Sar-Cheshmeh granodioritic porphyry has intruded Eocene andesites (Waterman and Hamilton, 1975; Ellis, 1991 Shahabpour and Kramers, 1987). This granodiorite stock and biotite altered andesites are the main hosts to mineralisation (Waterman and Hamilton, 1975).

Waterman and Hamilton (1975) and Shahabpour and Kramers (1987) have reported six magmatic units in the Sar-Cheshmeh deposit, namely: i) Sar-Cheshmeh granodiorite porphyry stock; ii) Late feldspar porphyry; iii) Early hornblende porphyry; iv) Late hornblende porphyry; v) feldspar porphyry dykes; and vi) Biotite porphyry dykes (Fig 2).

Intrusion of the Sar-Cheshmeh porphyry stock into the Eocene andesitic wall rock created four alteration zones associated with the deposit. These consist of a core of strong biotite alteration, grading out to weak biotite, followed by a strong phyllic zone and an outer peripheral halo of pyrophyllite.

The intense biotitisation and overprinting, abundant phyllic zone are the most important features in the alteration pattern at Sar-Cheshmeh. Different zones of mineralisation include hypogene chalcopyrite, molybdenite and magnetite, with minor bornite, which have been replaced in the supergene blanket by chalcocite. These sulphides occur both as disseminations and in veinlets.



Quaternary

Qa — Alluvium (only shown outside mineralised area).

Neogene

Dacites, dacitic pyroclastics and arenites with pebbles and cobbles of volcanic and intrusive rocks.

Oligocene to Miocene

Post-mineral biotite porphyry dykes - biotite books in fine grained, generally flow banded feldspathic groundmass.

Intra-mineral feldspar porphyry dykes - large plagioclase widely dispersed in a feldpathic groundmass.

Intra-mineral hornblende porphyry dykes - large euhedral plagioclase, biotite and hornblende phenocrysts set in a dense, fine grained groundmass.

"Late"-mineral porphyry and breccia - irregular shaped masses, dykes and breccias with fragments of older rock types. Sparse plagioclase laths, thin biotite and quartz eyes ina fine grained feldspathic groundmass.

Oligocene to Miocene (continued)

Sar Cheshmeh Porphyry - variable in composition, but generally euhedral to subhedral plagioclase phenocrysts and a few quartz eyes, thin biotite books and minor hornblende in a medium grained aplitic groundmass of mainly quartz and K feldspar.

Quartz-eye porphyry - near contemporaneous with Sar Cheshmeh Porphyry. Intrudes granodiorite. Phenocrysts of euhedral plagioclase, K feldspar, biotite and erratic quartz-eyes in an aplitic groundmass.

Granodiorite - pre-mineral, near batholith sized mass, variable in composition, from extremes of gabbro to aplite.

Eocene

V — Andesitic volcanics - mainly fine grained andesitic porphyries.

•••• Outer 0.4% Cu cut-off contour.

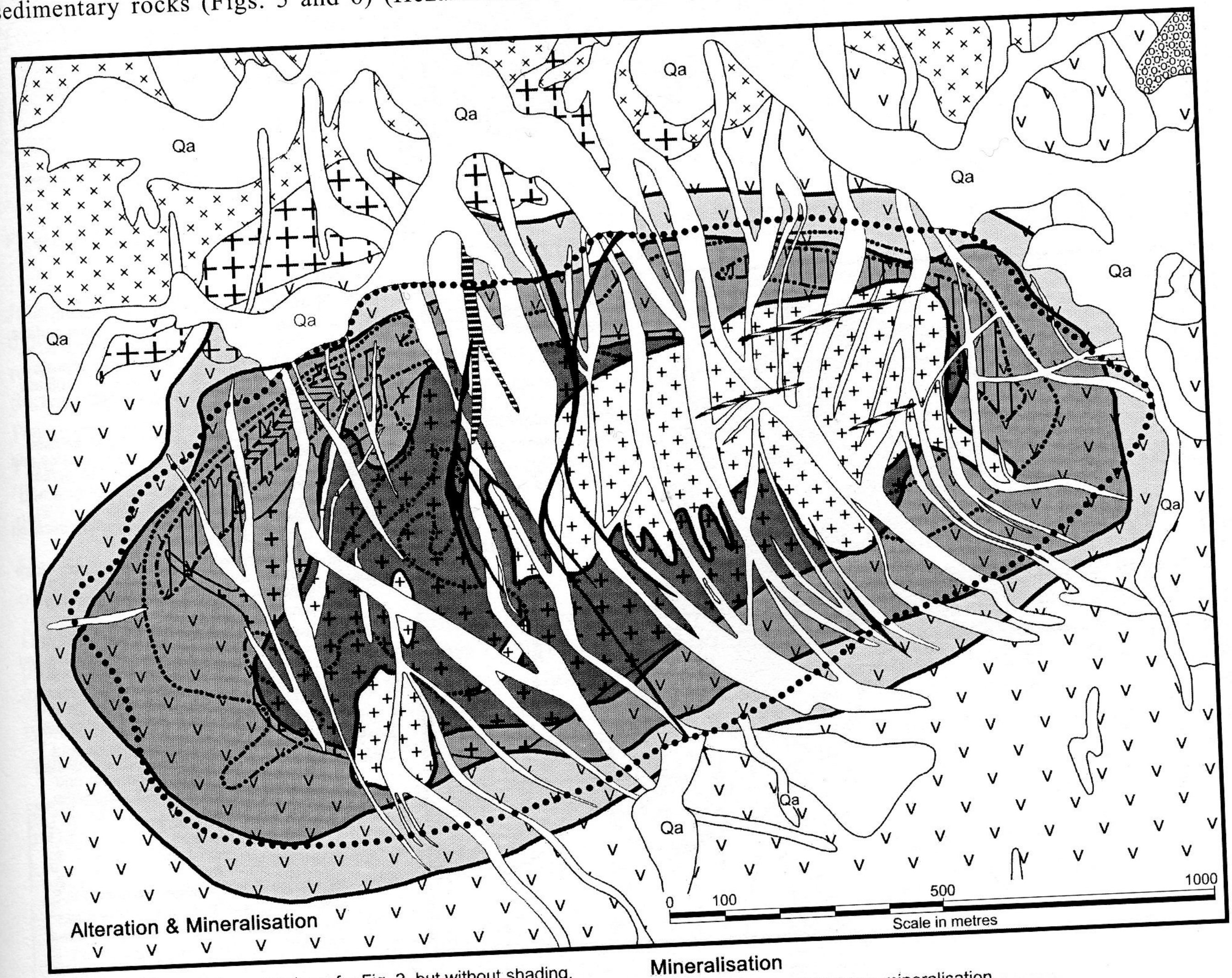
Figure 3: ***The deposit scale geological setting of the Sar Cheshmeh porphyry copper deposit, southeastern Iran.*** The detail within the 0.4% Cu contour on the deposit scale plan is the interpreted geology on the 2400 m elevation level. After Waterman and Hamilton (1975) and Ghorashi-Zadeh (1979).

The first geochronological study of the deposit was undertaken by Shahabpour and Kramers (1987). $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ isotope ratios yielded ages of 18.580±0.005 and 15.581±0.004 Ma respectively for the Sar-Cheshmeh porphyry.

Sungun Porphyry Copper Deposit

The Sungun porphyry copper deposit is located 75 km northwest of Ahar in Azarbaijan Province of northwestern Iran. It is currently being developed by NICICO and it will commence production in the near future. The host porphyry stocks are Oligocene-Miocene in age and were intruded into Cretaceous carbonate and Eocene volcano-sedimentary rocks (Figs. 5 and 6) (Hezarkhani and Williams-Jones, 1998). Sungun contains more than 500 Mt of hypogene sulphide ore at 0.75 % Cu and 0.01% Mo (unpublished data, NICICO).

Bazin and Hubner (1969) classified the Sungun deposit as skarn-type mineralisation at the contact between a granodioritic stock and Cretaceous carbonate rocks. More recent studies (Etminan, 1977; Hezarkhani and Williams Jones, 1998; Calagari, 2004; Hezarkhani, 2004) have, on the basis of alteration and mineralisation patterns and magmatic petrogenesis, concluded that it is a porphyry-related copper deposit. The Sungun Oligocene-Miocene porphyries occur as stocks and dykes, and were derived from a calc-alkaline, syn-collisional magma that was generated in a continental arc (Hezarkhani and Williams



Geological Legend - symbols as for Fig. 2, but without shading.

Boundary of alteration zone. Mostly gradational, except at contacts with the predominantly unaltered Intra-mineral dykes and Late-mineral porphyry and breccias.

Alteration Zones

- Weak to un-altered rocks with only low grade copper mineralisation in the Intra-mineral dykes and Late-mineral porphyry.
- Propylitic zone - altered andesitic volcanic rocks peripheral to the phyllic (sericitic) zone. Contains pyrite and rare chalcopyrite.
- Sericitic (phyllic) zone - strong sericitisationa with abundant pyrite and minor chalcopyrite.
- Biotite zone - with decreased sericite content and a marked increase in copper grade. Nearer the andesite - Sar Cheshmeh Porphyry contact, biotite is replaced by sericite and a quartz stringer zone with good Cu & Mo mineralisation.
- K-silicate zone - erratic K-silicate alteration within the Sar Cheshmeh Porphyry, grading to sericite on the outer margin.

Mineralisation

Grade contours - hypogene mineralisation

2.0% Cu
1.4% Cu
1.0% Cu
0.4% Cu

Copper mineralisation occurs as fine (a significant percentage of <50 micron) chalcopyrite, pyrite and only minor bornite, as disseminations within the andesite and porphyry hosts. A higher percentage of fine grained sulphide accompanies low grade ore. Sulphides are finer grained in the andesites compared to the porphyry.

>2% Cu

1.4-2% Cu

Molybdenite occurs as disseminated blebs and streaks, generally following the better Cu grades.

A leached capping, which averages 26 m in thickness and generally follows the current topography overlies a supergene enriched sulphide blanket across a sharp boundary. An erratic oxide orebody overlies the sulphide zone. The supergene sulphide zone averages 37 m in thickness It contains disseminated chalcocite overprinting chalcopyrite. Grades are controlled by the hypogene grade and structure, including dyke contacts.

Figure 4: ***The distribution of alteration and mineralisation on the 2400 m elevation level at the Sar Cheshmeh porphyry copper deposit, southeastern Iran.*** After Waterman and Hamilton (1975), Ghorashi-Zadeh (1979).

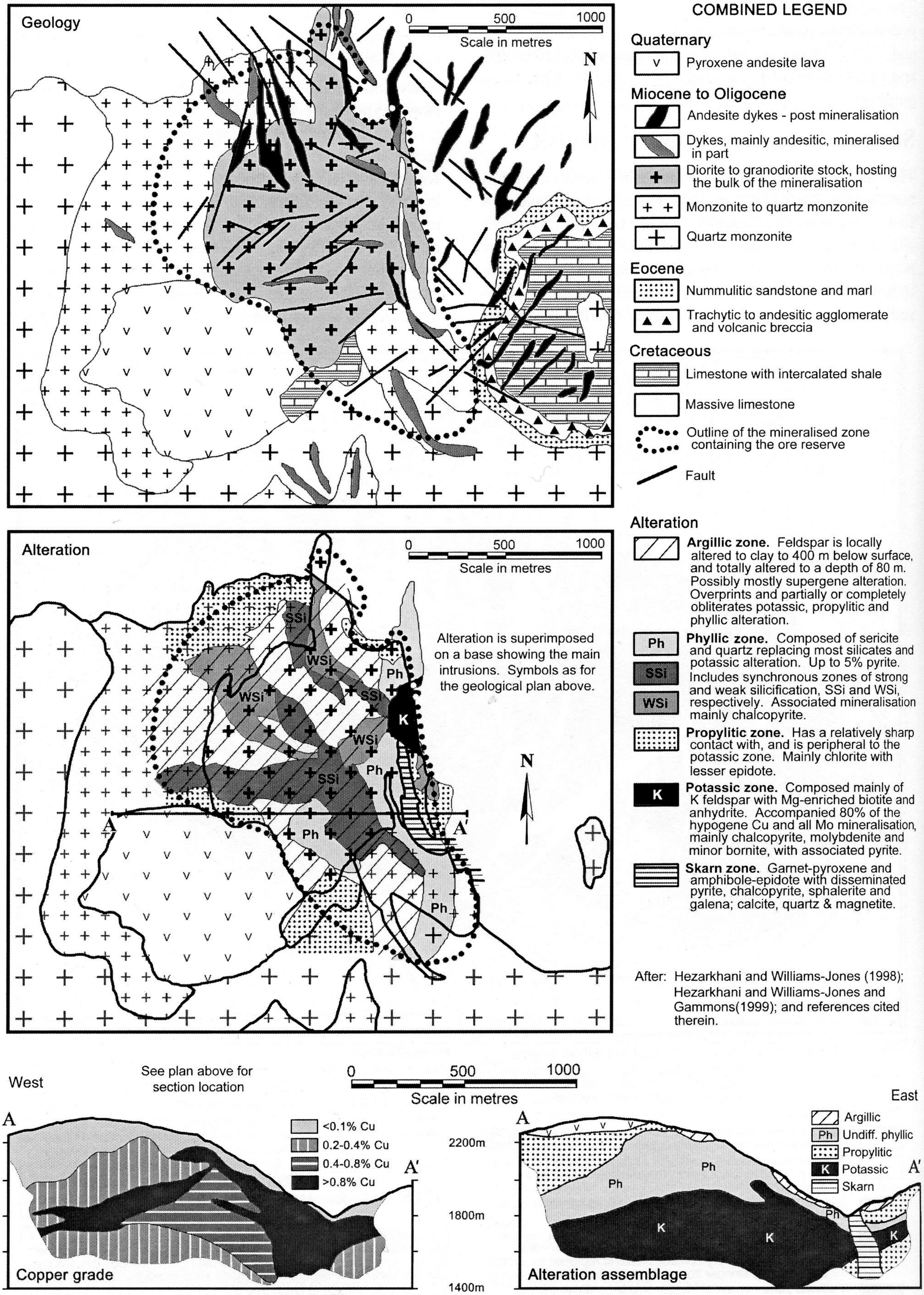


Figure 5: ***The geological setting and distribution of alteration and mineralisation at the Sungun porphyry copper deposit, north western Iran.*** After Hezarkhani and Williams-Jones (1998) and Hezarkhani *et al.,* (1999).

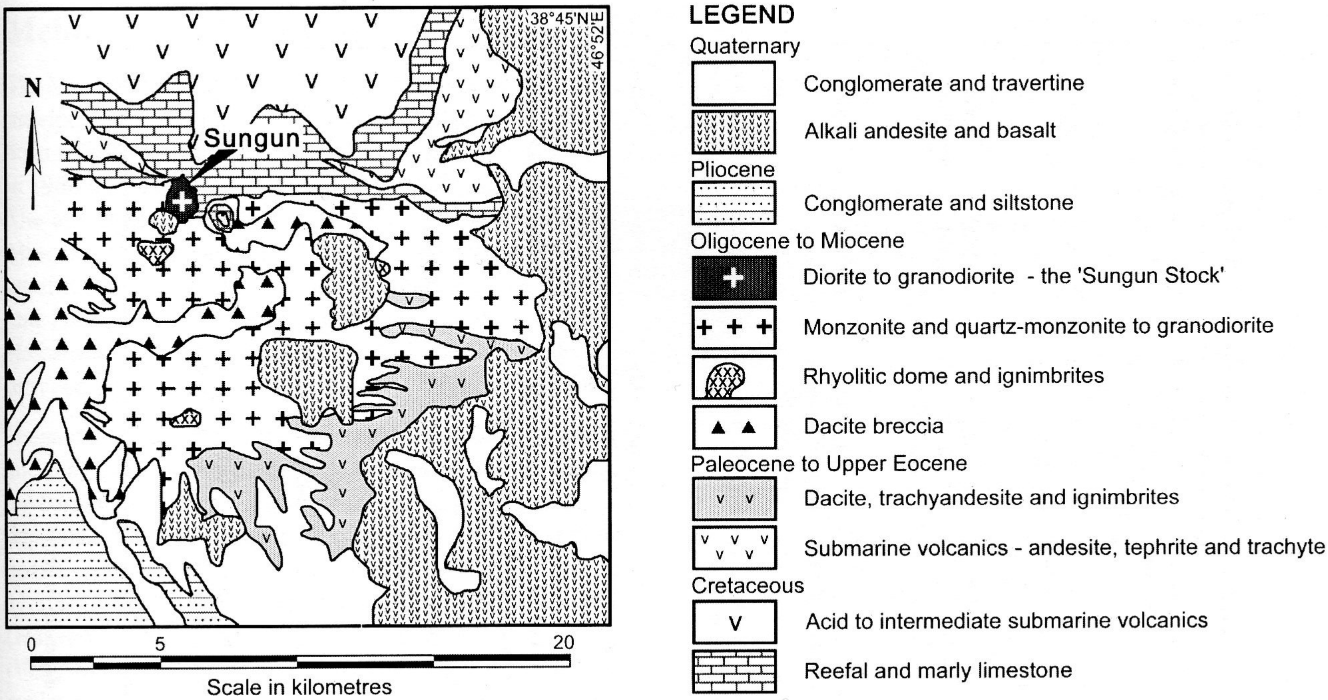


Figure 6: ***The district scale geological setting of the Sungun porphyry copper deposit, northwestern Iran.*** After Hezarkhani *et al.*, (1999) and references quoted therein.

Jones, 1998). The rock composition ranges from early diorite/granodiorite to a later monzonite/quartz–monzonite rock. Calagari (2004) believed that porphyry stocks in the Sungun deposit can be classified in two porphyry groups: Porphyry Stock I (quartz-monzodioritic rocks) and Porphyry Stock II (quartz-monzonite to granitic rocks). These intrusions are situated in the northwestern part of the northwest-southeast trending Cenozoic UDMA.

Fig. 5 summarises the geology, alteration and distribution of mineralisation at the Sungun deposit.

Detailed stable isotope and fluid inclusion studies were provided by Hezarkhani and Williams Jones (1998) and Calagari (2003, 2004). Based on these investigations, typical alteration and mineralisation patterns of porphyry copper deposits were formed by the intrusion of Oligocene-Miocene porphyries in the Sungun porphyry copper deposit. Calagari (2003) suggests that the isotopic data is similar to that reported at El Salvador, Chile and Ajo, Arizona, U.S.A. These stable isotope studies reveal that the alteration and mineralisation at Sungun formed under the influence of magmatic and meteoric waters similar to those reported at other porphyry copper deposits around the world (Calagary, 2004).

Fluid inclusion studies indicate that the temperature and salinity of fluids in the Sungun deposit varies from 160 to 600°C and 2 to 50 wt. % NaCl (Hezarkhani and Williams Jones, 1998; Calagari, 2004). Three types of mineralisation are recognised at Sungun, namely: i) hypogene, ii) supergene, and iii) skarn. Chalcopyrite, molybdenite and pyrite are the most important ore minerals in these zones.

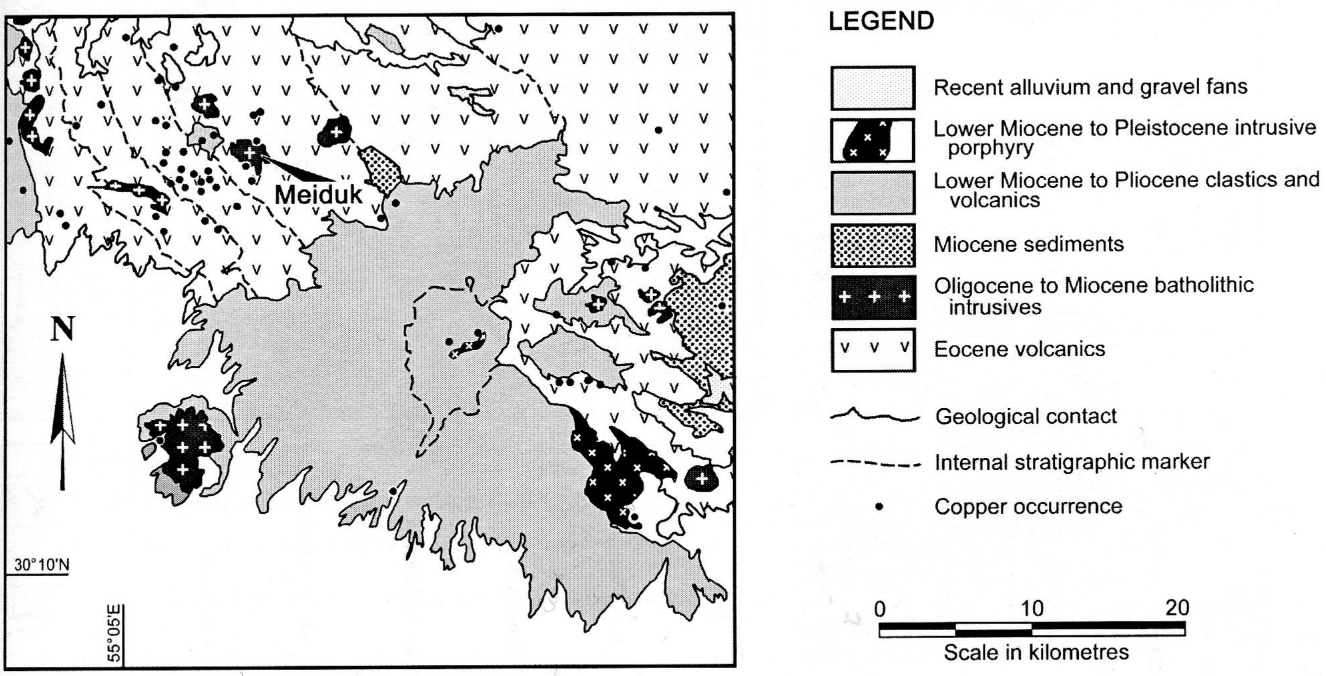


Figure 7: ***The district scale geological setting of the Meiduk porphyry copper deposit, southeastern Iran***

Porphyry	Mineralisation	Tonnage	Grade	Wall rock	Age	Rock type	Alteration	Ore structure	Main minerals	Metallic type	Mining
Sar-Cheshmeh	2 Km^2	1200 Mt	0.7% Cu 0.03% Mo	Eocene andesite	Miocene	Granodiorite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Cpy, mag, chl, bor, py, cov, cup, moly, gal, sph	Cu+Mo+ Au+Ag	Active
Meiduk	2 Km^2	180 Mt	0.83% Cu	Eocene andesite alkali-basalt, pyroclastic rocks	Mid-Miocene	Diorite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Py, cpy, cov, chl, ma, azu, chr	Cu	Active
Sungun	1.5 Km^2	500 Mt	0.75% Cu 0.01% Mo	Cretaceous Limestone, Eocene dacite to trachy-andesites	Upper Oligocene to Mid-Miocene	Diorite to quartz-monzonite, granodiorite	Outward from centre: potassic, phyllic, argillic, propylitic, skarn	Veinlet Disseminated skarn	Cpy, mag, moly, chl, bor, cov, gal, tet, py, sph	Cu+Mo± Au±Ag	Under development for mining
Darreh-Zar	2 Km^2	80 Mt	0.64% Cu 0.004% Mo	Eocene andesite trachy-andesite	Miocene	Diorite to granodiorite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Cpy, mag, chl, bor, py, cov, cup, gal, sph	Cu+Mo	Active
Sara	1.5 Km^2	Unknown	0.15% Cu	Eocene andesite alkali-basalt, pyroclastic rocks	Mid-Miocene	Diorite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Cpy, py, mal, azu	Cu+Mo	Non-active, under exploration
Kuh Panj	3 Km^2	Unknown	0.3% Cu 0.001% Mo	Eocene tuffs	Oligocene-Miocene	Granodiorite to tonalite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Cpy, mag, moly, chl, cov, tet, py	Cu+Mo	Non-active
Darreh-Alu	4 Km^2	Up to 25 Mt	0.4% Cu 0.003% Mo	Eocene andesite	Oligocene-Miocene	Quartz-diorite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Cpy, mag, chl, py	Cu+Mo	Non-active
Darreh-Hamzeh	0.4 Km^2	Unknown	0.3%Cu	Eocene andesite, trachyte, pyroclastic rocks	Oligocene-Miocene	Diorite to granodiorite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Cpy, py	Cu+Mo+Au+Ag	Non-active
Darreh-Zerreshk	1.2 Km^2	23 Mt	0.8-0.97% Cu 0.004% Mo	Cretaceous carbonates, Eocene tuffs	Miocene	Diorite to granodiorite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated skarn	Cpy, mag, chl, py, cov, bor	Cu+Mo+Au+Ag	Under exploration
Ali-Abad	1.6 Km^2	40 Mt	0.7% Cu 0.005% Mo	Cretaceous sediments, Eocene tuffs	Oligocene-Miocene	Quartz-monzodiorite granodiorite granite	Outward from centre: potassic, phyllic, argillic, propylitic	Veinlet Disseminated	Cpy, mag, chl, py, cov, bor	Cu+Mo+Ag	Under exploration

Table 1: ***Summary of the geology and mineralisation of the main porphyry copper deposits in Iran.***

Meiduk Porphyry Copper Deposit

The Meiduk porphyry copper deposit is located in Kerman province, approximately 35 km north of Shahr-e-Babak and 86 km south-southwest of Sar Cheshmeh. It was discovered in 1966 by geochemical and follow-up drilling programs. The ore deposit was formed by the intrusion of a Mid-Miocene dioritic stock into Eocene andesitic and alkali-basaltic volcanics and volcano-sedimentary rocks (Bazin and Hubner, 1969; Geological Survey of Iran, 1973; Hassanzadeh, 1993). All of these lithologies have also been intruded by numerous diorite porphyry dykes (Fig. 7).

Hassanzadeh, (1993) considered that the tectonic setting and magmatic series associated with the Meiduk deposit are consistent with those of diorite related porphyry copper deposits. $^{40}Ar/^{39}Ar$ geochronology of five biotite samples collected from the ore deposit indicate an age of 11.3 ± 0.5 Ma for the emplacement of the Meiduk porphyry (Hassanzadeh, 1993). Studies of Sr isotope ratios ($^{87}Sr/^{86}Sr = 0.40455$; Hassanzadeh, 1993) and the tectonic evolution of the region (e.g., Shahabpour, 2004) indicate that the deposit was formed in the transition between an island-arc and continental margin-arc setting.

Copper mineralisation is hosted by both volcanic and intrusive rocks (Fig. 8), although the bulk is within the main intrusive body (Geological Survey of Iran, 1973). The ore grade in the hypogene zone is between 0.5 and 1% Cu and in the supergene blanket is from 1 to 3% Cu, with an average grade of 1.52% Cu (Geological Survey of Iran, 1973). The supergene zone averages over 50 m in thickness and is characterised by a mineralogy dominated by chalcocite, covellite and chalcopyrite (Geological Survey of Iran, 1973). The total combined supergene and hypogene reserve in 1973 amounted to around 20 million tonnes of ore which was mined and explored on a small scale. Subsequent detailed exploration and development programs undertaken by NICICO in the past seven years have enlarged the reserve to 180 million tonnes with an average grade of 0.83% Cu. This deposit is now the core asset of a new copper complex (the Meiduk mine and Khatoon-Abad copper plant) which commenced operations in December, 2004.

Darreh-Zerreshk and Ali-Abad Porphyry Copper Deposits

Darreh–Zerreshk and Ali-Abad are two relatively small porphyry copper deposits located 60 km southwest of Yazd city in central Iran. Both were discovered in 1972 as the result of geophysical surveys and drilling by the French company COFIMINS. They lie within the central part of the UDMA and are located where the UDMA intersects the Central Iranian block (Fig. 1). In addition to Cu mineralisation, in historical times, several Cu-Fe skarns

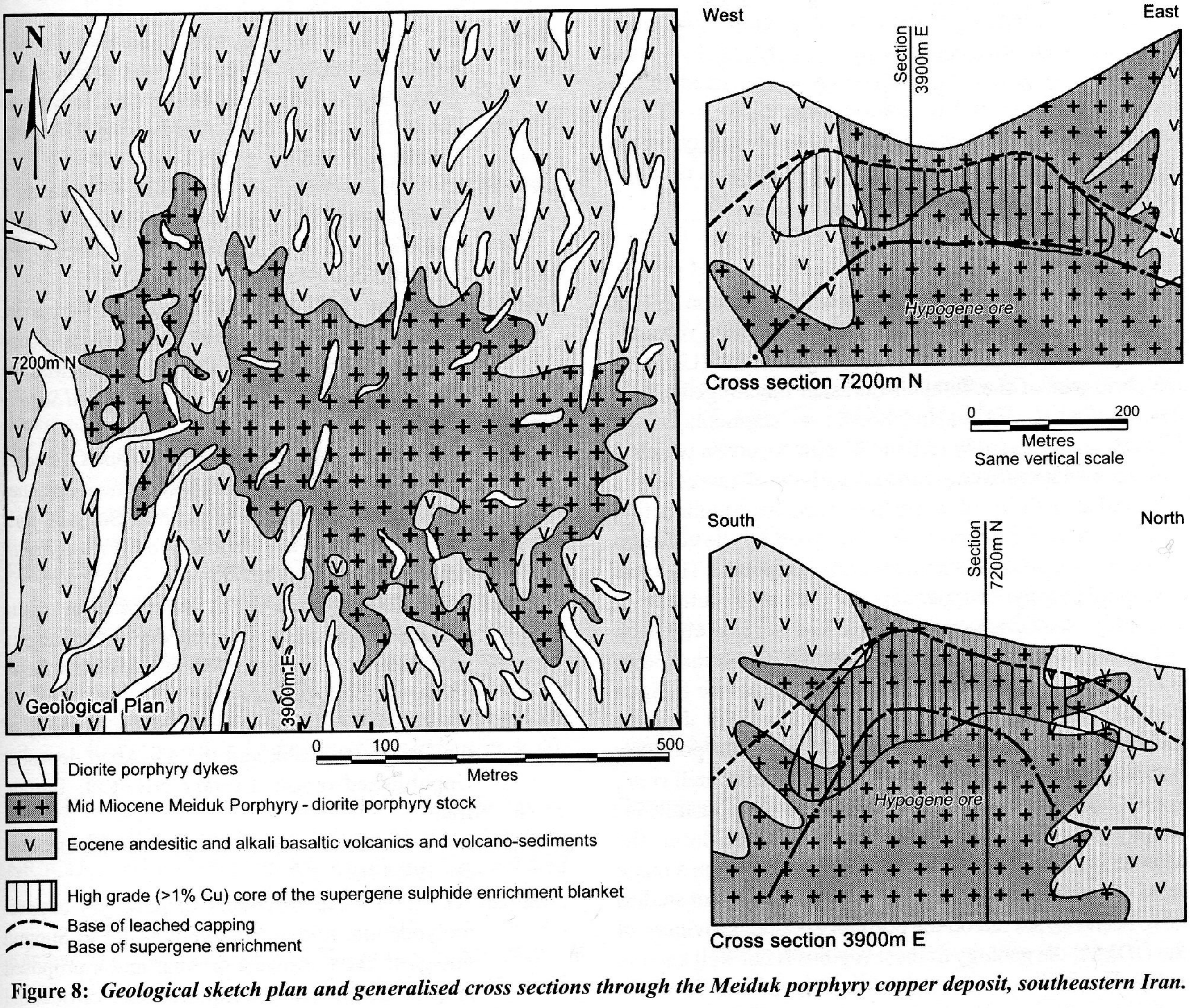


Figure 8: ***Geological sketch plan and generalised cross sections through the Meiduk porphyry copper deposit, southeastern Iran.***

were mined on a small scale, as were minor polymetallic veins, stratabound Pb-Zn (Mississippi Valley Type) mineralisation, kaolin and travertine.

Exploration and assessment of Cu-mineralisation in this area is actively being carried out by NICICO. Drillhole data and surface outcrops were used to produce the first geological reports, which recognised these deposits as porphyry style mineralisation (COFIMINS, 1972; NICICO, 2001). Assessment drilling defined indicated resources of 40 Mt at 0.73% Cu, 0.0059% Mo and 19 g/t Ag at Ali-Abad (NICICO, 2001), and 23 Mt at 0.8 to 0.97% Cu, 0.0040% Mo and 1 g/t Ag at Darreh–Zerreshk (COFIMINS, 1972). Copper ore minerals in the Ali-Abad and Darreh-Zerreshk deposits occur in three main assemblages namely: hypogene sulphides, supergene sulphides, and copper oxides. The total resource at Darreh-Zerreshk is 8.9 Mt of oxide ore at 0.8% Cu and 14.6 Mt of sulphide at 0.95% Cu. At Ali-Abad the total resource consists of sulphide ore averaging 0.9% Cu (NICICO, 2001). The petrology, mineralogy, alteration, structural characteristics, geochronology and geological evolution of the Darreh-Zerreshk and the Ali-Abad copper deposits was discussed by Zarasvandi *et al.*, (2003, 2005). Zarasvandi *et al.*, (2005) concluded from the studies reported that the Cu-Mo mineralisation at both Darreh-Zerreshk and Ali-Abad qualifies the two mineralised systems as probable porphyry Cu (Mo) deposits. Intrusions in the area, a result of subduction related magmatism, range in composition from quartz monzo-diorite to granite, although the porphyry style copper-molybdenum mineralisation is restricted to the quartz monzo-dioritic to granodioritic plutons. These Miocene (16 Ma; Zarasvandi, 2004) mineralising intrusions cut Cretaceous sedimentary and Eocene volcano-sedimentary rocks.

Conclusions

Most of the porphyry copper style mineralisation in Iran has been identified within the Central Iranian Volcano-Plutonic Belt or Urumieh-Dokhtar Magmatic Arc (UDMA), which is part of the Tethyan-Eurasian metallogenic belt. The southeast, central and northwest segments of the UDMA are remarkably rich in Cu mineralisation which is associated with granitoid igneous activity. This activity is believed to be the result of steep northeastward subduction of Tethyan oceanic lithosphere, followed by the collision of the Afro-Arabian and Iranian (Eurasian) plates. The most important porphyry copper deposits are in the southeast of Iran (e.g. Sar-Cheshmeh, Meiduk and several clustered deposits; Waterman and Hamilton, 1975; Shahabpour, 2004) and the northwest of the country (e.g. the Sungun deposit; Jankovic, 1984), while several smaller deposits are found in the intervening central sections of the porphyry belt (e.g., Darreh-Zerreshk and Ali-Abad; Zarasvandi *et al.*, 2004). The peak granitoid magmatism responsible for porphyry copper mineralisation in Iran occurred during the Miocene, although granitoid rocks in the area span a range from Oligocene to Miocene. While many different studies have been carried out on the porphyry copper provinces of the UDMA, the geology of these regions is not well known. However, the current understanding of the tectono-magmatic framework of this magmatic arc indicates potential for further porphyry copper discoveries.

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