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# Porphyry type systems – configuration and distribution in the Chagai metallogenic belt with a reference to the Koh-i-Dalil copper deposit, Balochistan, Pakistan

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ABSTRACT: *The Chagai metallogenic belt, forming the northwestern part of Balochistan, is well renowned for hosting several copper porphyry type systems. The most important and well-studied deposits are Saindak, Koh-i-Dalil / Reko Diq, Dashte-Kain, Durbanchah. These are distributed in the Chagai calk-alkaline magmatic belt and exhibit more or less similar tectono-magmatic and subduction related environments. Hence, the Koh-i-Dalil / Reko Diq Cu+Au porphyry deposit is discussed as a representative study case to understand the other porphyry systems of the Chagai region. The Koh-i-Dalil complex is a large strato-volcano developed during Miocene and is spread over an area of about 25km x 20km. It is encircling a number of closely spaced porphyry systems exposed in the deeply eroded wide valley. These youngest shallow emplaced intrusives are composed of quartz diorite, granodiorite, dacite porphyries whereas the tonalite porphyries are the favourable sites for mineralization. Late andesitic and dacitic dykes are present in a swarm of tangential fractures, resulted due to the intrusion of the tonalite porphyry stocks in the surrounding strato-volcano. The deep erosion of the central caldera has exposed cross sections of the ancient volcanic sequence and, as well as, the intruded tonalite porphyry stocks which are mineralized. The hydrothermal alteration zones overlapping in a concentric manner are very well developed over each mineralized stock. The exposure of the hydrothermal alteration zones depends on the extent of the erosional level of the host porphyry stocks. These alteration zones are distinctly differentiated, from the innermost core to the outer peripheries, into i) potassium silicate zone (K-zone), ii) phyllic/sericitic zone, iii) retrograde zone and iv) propylitic zone. The central K-zone is distinguished by the presence of secondary biotite and occasionally potash-feldspar. The phyllic zone, overlapping the K-zone, is characterized by the presence of sericite and quartz resulting due to the decomposition of feldspar. It displays a milky white halo. The outermost zone of propylitic alteration is marked by the presence of chlorite, epidote and quartz veins.*

*The retrograde alteration is a type of superimposed alteration activity and is not present always. But this type of alteration is well developed in the Koh-i-Dalil (East Main Ore Body) and it is distinguished by the presence of relics of secondary biotite or potash-feldspar. Copper as chalcocite and chalcopyrite is predominantly associated with the K-zone and sericitic alterations. Hypogene mineralization is scarce on the surface owing to its decomposition and subsequent dispersion and leaching. Malachite and goethite are common surface expressions. Magnetite in dissemination and veinlets is common in the sericitic zone and central dacitic core.*

*Geo-chemical anomaly patterns were constructed based on the analysis of more than 1200 rock chip samples for copper determination. The conduction of geophysical surveys including the magnetic, gravity and induced polarization (IP) helped to ascertain the* *subsurface mineralization attribute.*

*A comparative study based on the interpretative results of integrated geological, hydrothermal alterations, geo-chemical anomalies and the I.P. surveys exhibit an excellent correspondence to each other. The anomalous zone of >1000 ppm Cu values coincid well with the K-zone and also with the retrograde zone. The contours of the lowest values of <500 ppm correspond with the late mineral dacite porphyry intruded in the central part of almost each ore body.*

## INTRODUCTION

The occurrence of numerous porphyry Cu ± Mo ± Au type deposits in the Chagai Metallogenic Belt, lying along the northern part of Balochistan Province of Pakistan, is now well established (Fig. 1). The prominent porphyry type deposits distributed in the Chagai area are Saindak, Koh-i-Dalil, Durban Chah, Dasht-e-Kain, Ziarat Pir Sultan, Siah Koh, Missi, Max G. White. The important massive type copper deposits are located at Talaruk, Makki Chah, and iron deposits and Chicken Dick and Chalghazi. The Saindak, Koh-i-Dalil and Dasht-e-Kain Cu ± Mo ± Au porphyry deposits, lying in the northwestern part of Balochistan, have been studied in detail (Ahmed et al., 1972; Farah & Nazirullah, 1974; Sillitoe & Khan, 1979; Ahmed 1993; Karamata et al., 1987; Bhutta et al., 2000). The Saindak deposit is presently in the initial phase of mining. Preliminary exploration and test drilling have been done in Durban Chah (Khan et al., 2000).

The Koh-i-Dalil deposit, also known as Reko Diq, lying between Latitudes 29°05'–29° 10' and longitudes 62° 00'– 62°10', is located at about 500 kms west of Quetta, the capital of Balochistan Province and railway station Nokkundi, which is about 70 kms in the southeast and is connected with Quetta by RCD highway and Quetta-Taftan rail track (Fig.1). The porphyry type mineralization in the Koh-i-Dalil/Reko Diq area was discovered by Geological Survey of Pakistan (GSP) during the geological mapping of the 30 K/4 Quadrangle on 1:50,000 scale (Khan & Ahmed, 1981). Later on detailed studies were conducted by GSP and partly by GSP-UNDP joint projects.

Other deposits present in the Chagai Belt are volcanogenic type magnetite-hematite-chalcopyrite at Pachin Koh, Chicken Dick near Nokkundi and at Chilghazi near Dalbandin and the Manto type occurrence of hypogene chalcocite occur at Makki Chah near Saindak.

## REGIONAL GEOLOGY

The Chagai magmatic belt is a favourable host for sulfide mineralization. Porphyry type mineralization is associated with the calc-alkaline magmatic complexes that constitute the Chagai metallogenic magmatic arc. The origin of these magmatic complexes is related to the northward subduction of the oceanic lithosphere of the Arabian plate beneath the southern edge of the Afghan block (Sillitoe, 1978; Jacob & Quitmeyer, 1979; Dykestra & Burnie, 1979; Arthurton et al., 1979). This zone is believed to be a segment of the Tethyan-Eurasian Metallogenic Belt (TEMB) formed during Mesozoic-Tertiary time along the southern margin of the Eurasian Plate (Jankovic, 1977). The calc-alkaline magmatic complexes comprise igneous rocks, which range in composition from diorite to quartz diorite (tonalite), granodiorite, quartz monzonite to (rare) granite, and from basaltic andesite to dacite and even rhyolite. Quartz diorite and andesite are the dominant members. These were formed in two main periods. The first extended from the Upper Cretaceous to the Lower Miocene, and the second from the Late Pliocene to Quaternary.


Fig. 1. Distribution of copper mineralizattion in the Chagai District, Balochinstan, Pakistan.

The oldest magmatic rocks exposed in the Chagai arc belong to the Sinjrani volcanic group of the Cretaceous age. However, volcanic activity continued into the Tertiary as evidenced by the presence of volcanics in the Juzzak and Rakhshani formations of Paleocene age. The Sinjrani volcanics comprising andesitic volcanic rocks interbedded with minor flysch-type and calcareous sediments are present in the north-west of the deposit, while bioherms of hippuritic limestone of Humai Formation, representing Upper Cretaceous, are present in the east of the study area.

The Juzzak Formation, representing the Paleocene sequence of rocks, consists of volcanic flows, tuffs, and breccia with minor volcanic clastic rocks. The dominant lithology is of andesitic composition. The upper sub-unit of the Juzzak Formation consists mostly of flysch type clastic and volcanic clastics sediments of interlayered shale, sandstone, conglomerate and minor mudstone. The Saindak Formation consisting of turbiditic shale, sandstone and limestone with some volcanic material belong to Eocene age.

The sub-aerial volcanism and cogenetic intrusive rocks mapped as Reko Diq Formation (Khan & Ahmed, 1981) of Oligo-Miocene age consist of andesitic agglomerate, flows, fine-grained and porphyritic andesite. The intrusive rocks include tonalite, diorite with andesitic dykes. The brick red, buff to dirty white gypsiferous clay and conglomerate alongwith thin beds of sandstone and shale of Dalbandin Formation represent Mio-Pliocene age. The Quaternary deposits comprise volcanic rocks, older alluvial travertine marble deposit, alluvial fan deposits and dunes of eolian sand.

Batholiths and stocks intrude the volcanic and locally sedimentary sequences. Their composition range from gabbro to granite but dominantly are composed of quartz-diorite and granodiorite. The youngest composite intrusions emplaced at shallow depth in stratovolcanoes structures are granodiorite porphyries, quartz-diorite porphyries and granite porphyries. These intrusions provided favourable conditions for Koh-i-Dalil porphyry copper mineralization in the Chagai district.

## GEOLOGY OF THE AREA

The sulfide mineralization distributed in the Chagai belt exhibits characteristic features of the porphyry type system. The mineralized stocks exhibit the alternation facies resulted due to the hydrothermal activity of varying degree of intensity. These deposits occur in the same region, hosted in the suit of rocks of almost similar lithology and age and are usually formed by the same tectono-magmatic activity and subduction related magmatism. As these deposits are commonly similar in many respects owing to their existence in similar environments, the Koh-i-Dalil deposit is discussed here as a representative example to understand the geological setting, lithology of the host stocks, attitude of mineralization and the pattern of hydrothermal alteration facies of the other porphyry type deposits present in the region.

The Koh-i-Dalil area is formed of a huge strato-volcano, which is a conspicuous structure in the region. The strato-volcano complex covers an area of about 25 kms x 20 kms with a caldera of about 10 kms x 7 kms in size exposed in the central wide-open valley (Fig. 2). This strato-volcano was built during Miocene on the Paleocene Juzzak Formation base. Sinjrani volcanics of Cretaceous age, Chagai intrusive and volcanics of Miocene age compose the volcano-intrusive complex.

The development of the Koh-i-Dalil complex occurred through a number of evolutionary phases. Five phases of evolution are noticed to trace the evolutionary trend which led to the development of the Koh-i-Dalil volcano-intrusive complex (Karamata et al., 1987). The initial evolutionary phase relates to the development of the strato-volcano. The second phase marked the collapse of the central part of the volcano and also the formation of a caldera that was followed by the igneous activity. The later events of this phase corresponded with brecciation, fragmentation of the base of the cauldron followed by the intrusion of the concentric and radial dacitic and andesitic dykes. The third phase designates the rise of tonalite type porphyries. The fourth phase is marked by the occurrence of the dacite porphyries which are intruded into the already existing tonalite bodies. The final phase of the igneous activity pertains to the formation of andesitic and dacitic dykes. These phases were followed by the erosional processes as a result of which the intrusive facies and the associated mineralization are exposed with the development of a widely open, almost flat, valley.

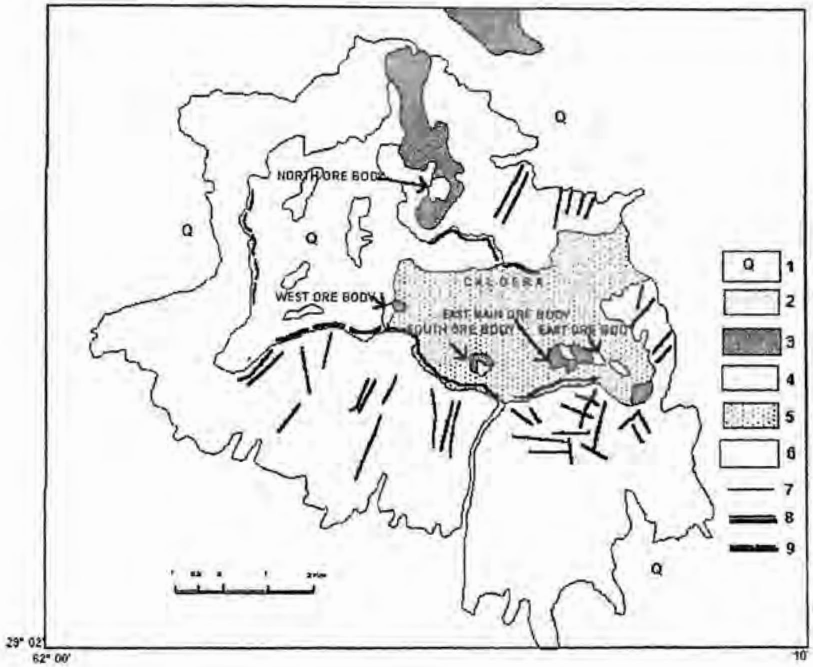


Fig. 2. Geological sketch map showing the Koh-I-Dalil volcano-instrusive complex and the positions of Ore Bodies.

1. Quarternary sand and debris;
2. Dacite porphyry;
3. Tonalite porphryries granodiorite to quartzdiorite);
4. Explosive quartz-tourmaline breccia;
5. Volcano clastics of the base of caldera;
6. Volcanic agglomerates, clastics and lava flows;
7. Dykes;
8. Caldera wall;
9. Relics of an ancient caldera wall (?)

## MINERALIZATION

The mineralization distributed in the Chagai belt exhibits characteristic features of a porphyry type system. Chalcopyrite is the main copper ore and is associated with the K-zone and the retrograde zone spread over the tonalite porphyry (Bhutta & Jaleel, 2000). Hypogene mineralization is scarce on the surface because of its alteration and subsequent leaching. Goethite is also present mainly in the intense K-zone. Malachite is wide spread and is particularly abundant in association with the quartz-magnetite facies of the K-zone and the fracture zone. Magnetite in the form of veins and as dissemination is associated with the central alteration zones, usually with the neo-biotite. It occurs commonly in the silicified zones and also with the quartz-tourmaline veins. Hematite is the common alteration product of magnetite. Quartz is mostly associated with the magnetite – hematite assemblage.

### Mineralized bodies

The mineralized intrusive stocks are composed of tonalite, quartz-diorite, monzonite and grano-diorite porphyries. These stocks are mainly exposed along the southern wall of the inner rim of the caldera, intruding the pre-existing rocks. The deep erosional processes, activated during the various development phases of the strato-volcano, have exposed the mineralized bodies in the broad low-lying valley.

The Koh-i-Dalil deposit consists of five mineralized bodies, in addition to many a small, low-lying, partially exposed altered zones scattered in the caldera. The mineralized bodies termed as East -, East Main -, South -, and West body are exposed along the east-west trending fault running along the southern margin of the inner rim of the caldera, whereas the fifth North body lies within a large pluton on the northern side (Fig. 2).

These mineralized bodies occur in the same general region, hosted in the suit of rocks of almost similar lithology and age and are usually formed by the same tectono-magmatic activity and subduction related magmatism. A common feature with all the ore bodies is the emplacement of late dacite porphyry bodies that have partly destroyed the potassium silicate alteration zones and also the associated cupriferous zone.

As these deposits are commonly similar in many respects owing to their existence in similar environments and composition, therefore, the East Main Body is discussed here as a representative example to understand the geological setting, lithology of the host stocks, attitude of mineralization and the pattern of hydrothermal alterations facies of the other mineralized bodies exposed in the strato-volcano.

**East Main Body:** Among the five mineralized bodies identified in the Koh-i-Dalil area, the East Main Body is the most promising owing to its extent, grade of mineralization and degree of hydrothermal alterations. This ore body, 1200m x 1000m in size, is dominantly composed of quartz-diorite/tonalite porphyry intruded by dacitic – andesitic volcanics. The tonalite porphyry is dark to dark-grey with phenocrysts of quartz, plagioclase (andesine), biotite, and hornblende present in a fine-ground mass. The variation in texture is quite common varying from medium- to coarse-grained. Partial assimilation of sedimentary rocks have generated some hybridized rocks on the southern side of the East Main body. Tonalite stock is intruded by the dacitic porphyry bodies in the later stage which is a unique feature with almost all the mineralized bodies in the Koh-i-Dalil area. The largest dacite intruded in the central part measures about 400 m x 300 m across and the smallest is 60 m x 50 m across on the margins of the East

Main body. The dacite porphyry is light to dark-grey, consisting of quartz, plagioclase in a light colour aphanitic ground mass with minor specularite.

**Hydrothermal alteration facies**

The zonal pattern and the regularity of the alteration facies and the associated assemblage of mineralization developed in the region are characteristic of a porphyry type system. The alteration zones, indicating the varying degree of the intensity of hydrothermal activity ranging from intense to moderate and/or to weak, are developed in a concentric enveloping pattern over the mineralized bodies. The hydrothermal alteration zones are well developed and quite distinct. These alteration zones in the Koh-i-Dalil area, starting from the innermost core towards the outer peripheries, can be distinguished into i) Potassium silicate (K-zone); ii) Phyllic/Sericitic; iii) Popylitic; and iv) Retrograde alteration zone.

**Potassium silicate alteration zone (K-zone):** The K-zone, exposed in the central part of the alteration system, is well developed in the intrusive rocks (Fig. 3). This type of alteration is characterized by the presence of secondary biotite or neo-biotite of dark-brown or pale-brown color. The neo-biotite, the brown color of which may be due to the richness of iron and titanium, occurs in aggregate of unoriented small flakes. Another distinguishing product of this zone is the presence of potash feldspar, but it is very rarely observed in the Koh-i-Dalil area. The degree of biotization ranges from strong to weak. Secondary biotite is a diagnostic mineral constituent of this zone and it is generally associated with dioritic stocks. Development of fine flakes of the altered biotite with the complete alteration of the primary minerals is also a distinguishing feature of the central K-zone.

**Phyllic / sericitic zone:** The phyllic or sericitic zone occurs as a halo around the K-zone (Fig. 3). This is a feldspar destructive zone where the feldspar is altered and replaced by sericite and quartz. Argillization and kaolinization is also common in this zone. The phyllic / sericitic alteration exhibits a prominent milky white halo around the dark-grey K-zone. The sericitization is partly superimposed on and surrounded by the largely spread propylitized volcanic rocks.

**Propylitic alteration zone:** The propylitic alteration surrounding the phyllic zone and is marking the outermost peripheries of the mineralized body. It is generally extending towards the caldera wall. This type of alteration is represented by the presence of chlorite, epidote and quartz veins. Chloritization is well developed and prominent whereas the epidotization and calcitization is weak.

Similar type of chloritization $\pm$ epidotization occurs in the dacite porphyry bodies as well as in the andesitic and dacitic dykes. These alterations are not considered to have any genetic relationship with the mineralization. Such alterations result due to the interaction of primary mafic minerals with the water remaining in an almost closed system.

**Retrograde alterations:** The retrograde chloritization / sericitization, a very characteristic alteration in this area, is a type of superimposed alteration related to the later phase of hydrothermal activity. The pervasive chloritization, minor sericitization, argillization and abundant silicification are commonly observed. Small remnants / relics of biotite and K-silicate alteration are locally preserved in the zone of retrograde alteration. The relics of the neo-biotite and sericite, which are the distinguishing features of this zone, suggest that the tonalite porphyry was subjected to K-alteration prior to the superimposition of sericitization.

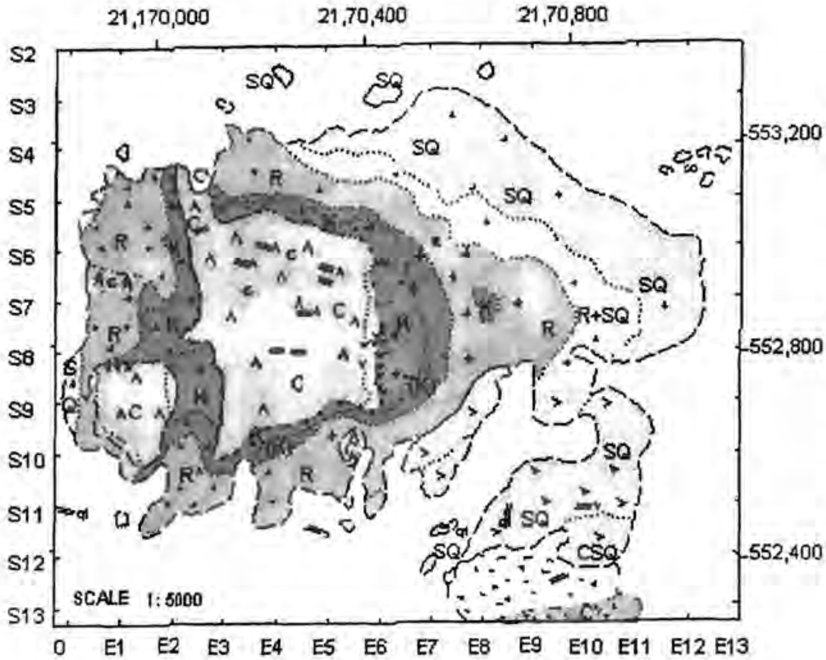


Fig. 3. Geological map showing the lithology, hydrothermal alterations in the East Main Body, Koh-I-Dalil, Chagai District, Balozchistan.

Another type of alteration noticed in the area, which could be related to the final events of the post volcanic activity, shows the development of quartz, quartz-tourmaline and jasper-like veins. However, owing to the subsequent erosion of high level the jasper veins are rare but quartz and quartz-tourmaline veins or impregnations are common.

## GEO-CHEMICALS STUDIES

More than 1200 rock chip samples were collected from 50 m x 50 m grid intersections from all over the mineralized bodies of the Koh-i-Dalil area to define their geochemical behavior. A total number of 440 rock chip samples collected from the East Main Body, were analyzed to determine the values of copper and molybdenum present in that body. The analytical values deduced from these samples were plotted on a grid based map to construct a geochemical anomaly map showing the distribution of copper in the East Main body (Fig. 4). The contours on the geochemical anomaly map show the copper values ranging from $<500$ ppm to $>3000$ ppm. Distribution of copper in the surface rocks of the East Main body reveals several anomalous zones in excess of 1,000 ppm Cu that cover an area of about 1 sq.km.

**Correlation of geology and chemical values**
Consedering the copper concentration and the alteration facies, it is observed that a positive correlation exists between the mineralized areas and the hydrothermal alterations associated with the tonalite porphyries in the East Main Body. Correlating the copper values with the alteration facies revealed that

the highest copper values coincided with potassium silicate alteration and retrograde chloritization alteration. The geochemical concentration correspond positively with the alteration patterns. The geochemical anomalous zones of >1000 ppm Cu (1000 – 3000 ppm Cu), having maximum dimension of almost 1sq.km, are confined to the K-zones and retrograde alteration zones of the East Main Body. The lowest closures of <500 ppm of Cu relate to the central post-mineralization dacite porphyry intrusion. It is also interesting to note that the induced polarization values, when correlated with the geology and geochemical maps, strongly endorsed the high Cu values and the K-zone of the East Main Body.

The geochemical assays have, in fact, been found to be a direct indication of the grade of the underlying hypogene copper mineralization, as in the case of Saindak Deposit (Sillitoe & Khan, 1977). As such the correspondence of the distribution of the high copper with the tonalite intrusives and the associated K alterations over the East Main body are indicative of the subsurface ore body.

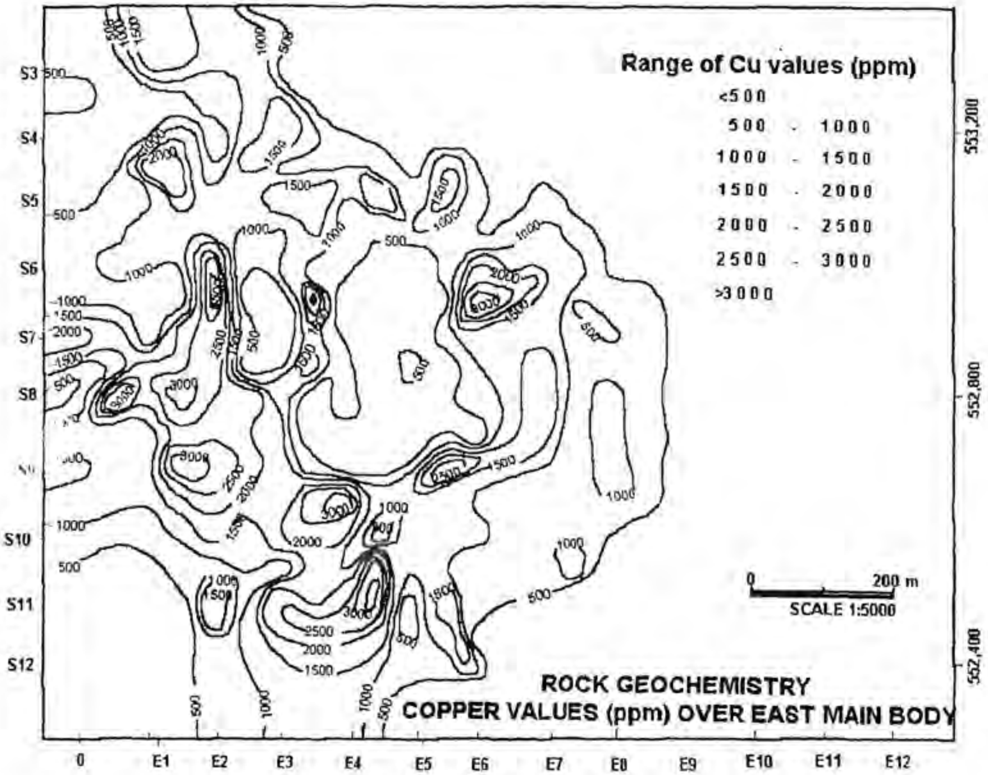


Fig. 4. Geochemical anomaly map showing the distribution of copper (ppm) in the East Main Body, Koh-I-Dalil Deposit, Chagai District, Balochistan.

## CONCLUSIONS

The integrated geological and geochemical investigations conducted in the Koh-i-Dalil area lead to the conclusions that the porphyry type mineralization is associated with Chagai calc-alkaline magmatic suit of rocks. The shallow emplaced tonalite porphyries are the favourable host rocks for copper mineralization and the associated alterations.

The hydrothermal alterations are distinct and well developed and show regularity in their occurrence and dispersion. The type of mineralization characterized by such hydrothermal alteration pattern / zonation, is typical of porphyry copper type mineralization.

The distribution of the geochemical values of copper corresponds very well with the rock units and the relating hydrothermal alterations. The high-grade copper values follow the potassic alterations precisely, whereas, the closures of lower copper values are restricted to the outer propylitic zones and the dacite porphyry bodies. The significant lateral extension and magnitude of the surface geochemical copper anomalies are associated with the areas of potassium silicate alteration and the retrograde chloritization.

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