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Ophiolite-hosted Copper and Gold Deposits of Southeastern Turkey: Formation and Relationship with Seafloor Hydrothermal Processes

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Abstract: The paper documents evidence about the physical and chemical controls on the behaviour of Au and Cu sulphide deposits in fossil seafloor hydrothermal systems of SE Turkey. Observations from actively forming sulphides at mid-ocean ridges (MOR) and in back-arc environments are compared briefly with ancient analogues of gold and pyritic copper deposits such as Kisecik, Ergani and Siirt-Madenköy, formed at mid-oceanic ridges, or possibly at seamounts and back-arc settings.

Many ophiolite-hosted Au- and Cu-deposits, of various sizes, are known to exist along the Bitlis-Zagros Suture Zone (BZS), the boundary between Anatolian and Arabian plates in SE Turkey. These deposits are associated with Cretaceous intra-oceanic supra-subduction zone ophiolitic slabs, such as Kızıldağ, the Bäer-Bassit massif (the southern extension of the Kızıldağ Massif in Syria), and the Yüksekova and Berit ophiolite bodies, which tectonically overlie the Mesozoic platform carbonates and Palaeozoic sediments of the Arabian plate. East of the BZS, ophiolitic segments of Tertiary age are strongly mineralized. Several Au and Co-Ni bearing pyritic Fe-Cu oxide and sulphide deposits associated with chloritized and spilitized basaltic pillow lavas or sheeted dykes crop out along the BZS. Volcanics associated with mineralisation closely resemble MOR sequences, sedimented ridges and back-arc environments in spreading centres of island arc systems. Ophiolitic rocks and the mineralogy of associated alteration are similar to characteristics of modern mid-oceanic ridge mineralization along the East Pacific Rise (EPR), Mid-Atlantic Ridge (TAG hyrothermal field) and Red Sea (Atlantis-II Deep).

Key Words: mid-oceanic ridge (MOR), pyritic copper-gold mineralisations, alterations, exploration tools

Türkiyenin GD'sunda Ofiyolitlere Bağlı Bakır ve Altın Yatakları: Oluşumları ve Deniz Tabanındaki Hidrotermal Sistemlerle İlişkileri

Özet: Bu çalışma, deniz tabanında oluşan GD Anadoludaki fosil hidrotermal sistemlerle ilişkili Au ve Cu yataklarının davranışları ile ilgili fiziksel ve kimyasal kontrolların delillerini ortaya koymayı amaçlar. Günümüzde halen okyanus ortası sırtlarda ve yay gerisi ortamlarında oluşmakta olan altın ve piritik Cu-sülfid yataklarında yapılan gözlemler Kisecik, Ergani, Siirt-Madenköy gibi eskiden okyanus ortası sırtlarda, ve denizaltı tepelerinde (?) veya yay gerisi ortamlarda oluşmuş eşdeğer yataklarla kısaca karşılaştırılmıştır.

Ofiyolitlerle ilişkili, çeşitli ebadlardaki birçok Au- ve Cu-yataklarının Bitlis-Zagros Sütür Zonu (BZS) – GD Anadolu'da Anadolu ve Arab plakaları arasındaki sınır hattı boyunca yer aldığı bilinmektedir. Bu yataklar, Kretase yaşlı, okyanus içinde oluşmuş Kızıldağ Masifi, Baer-Bassit masifi (Kızıldağ'ın Suriye deki uzantısı) Yüksekova, ve Berit gibi supra-subduction zonu ofiyolit dilimleriyle ilişkilidir. Ofiyolitik kütleler tektonik olarak Arab plakası'nın platform karbonatlı sedimanlarını üzerler. BZS doğuya doğru bölümlerinde, Tersiyer yaşlı ofiyolitik dilimler kuvvetli bir şekilde mineralize olmuşlardır. En az birkaç Au ve Co-Ni içeren piritik Fe-Cu oksid ve sülfid yatağı BZS boyunca yüzeyleyen kloritleşmiş ve spilitleşmiş bazaltik yastık lavlar veya sıralı dayklar (sheeted dykes) ile ilişkilidir. Cevherleşmelerle ilişkili volkanik istif ada yayı şeklindeki yayılma sistemlerinin okyanus ortası sırt istifleriyle, sedimanlarla örtülmüş sırtlar veya yay gerisi ortamlarla benzerlik gösterir. Ofiyolitik kayaçlar ve bununla ilgili ayrışmanın mineralojisi Doğu Pasifik Yükselimi'ndeki (EPR), Atlantik Ortası Sırtlardaki (TAG hidrotermal sahasındaki) ve Kızıl Deniz'deki (Atlantis II Çukuru'ndaki) modern okyanus ortası sırt cevherleşmeleriyle benzerlik gösterirler.

Anahtar Sözcükler: okyanus ortası sırtlar, piritik bakır-altın cevherleşmeleri, ayrışmalar, arama yöntemleri

Introduction

Ophiolite-hosted copper and gold deposits have been mined since 2500 B.C. in Cyprus (Bear 1963) and 2000 B.C. in SE Turkey during the period of the Assyrian Empire or even before (Ergun Kaptan, 2004, pers. comm.). They occur in a very complex geological environment controlled by various tectonic elements.

Anatolia (the mainland) is an east–west-trending important component of the Alpine-Himalayan orogenic system which marks the boundary between Gondwana to the south, and Laurasia to the north. The neotectonic history of Anatolia is primarily linked to the continental collision between the Eurasian and Arabian plates, which occurred along the Bitlis-Zagros Suture Zone. Southeastern Turkey was squeezed between the northeasterly moving Afro-Arabian (African) plate in the south and the Eurasian plate in the north during the consumption of the southern branch of the Neotethyan Ocean. The collision caused the formation of two intracontinental transform faults, the North Anatolian fault (NAFZ; dextral strike slip) and East Anatolian fault (EAFZ; sinistral strike slip) systems, along which the Anatolian plate has been escaping westwards since the Pliocene (5 Ma) (cf. Bozkurt 2001 and references therein). The subduction-related movements of the oceanic crust of the Neotethys and mineralizations along the mid-oceanic ridges resulted in a very complex geology in this part of Turkey: the region is also an important oil field on the northern edge of Arabian promontory platform.

Recent developments and findings in present-day hydrothermal discharge areas of mid-oceanic ridges (e.g., TAG, EPR, ATLANTIS II), the structure and formation mechanisms, associated alteration types, sulphide-, Mn-, Au-mineralizations and the distance between the discharge points along the same MOR call for an urgent new interpretation of pyritic copper-gold deposits along the BZS, associated with ancient analogues of ophiolitic bodies of mid-oceanic ridges. One of these deposits is associated with the sheeted dykes and, on a small scale, with pillow lavas of the Kızıldağ Massif sections that show a full pseudostratigraphy. Other deposits occur in disconnected segments of MOR sections which greatly resemble Cyprus-type ores, typified by up to 90 sulphide deposits in the Troodos Massif, and in Oman and Newfoundland (Moores & Vine 1971; Constantinou & Govett 1973; Dilek & Eddy 1992).

Although some deposits have been mined for a long time and developed with some drilling activities after the 1970s, only 3 deposits along the 500-km-long suture zone are important and economically noteworthy. Published literature in the last 50 years about the origin and mineralogy of these deposits contribute little new evidence about the regional and environmental relations of these deposits.

As indicated by Hannington *et al.* (1995a) ‘physical and chemical processes of seafloor mineralization in the early oceans were fundamentally the same as those observed on modern mid-oceanic ridges and direct comparison can be made between the formation of modern and ancient... analogues of... sulphide deposits’.

I re-evaluate the data gathered from the mineral association, host rocks, type of alterations and the relation between discharge zones, tectonic setting and basin characteristics of the SE Anatolian pyritic copper and gold deposits. Intensive hydrothermal alteration and spilitization observed around SE Turkish copper-gold deposits indicate that all the mineralization results from interaction between circulating sea-water deep in the crust and the crustal rocks that provide the metals. It is therefore suggested that there is a striking similarity between Cu-Au deposits in SE Turkey and present day MOR mineralization. The aim of this paper is to provide insight for the future exploration programmes in the region. If new exploration programmes and projects are planned and follow the guidelines carefully, new sulphide deposits can be found along the 500-km-long ophiolitic belt and suture zone. The region is also known as the copper province of SE Turkey and has several known potentially economic sulphide deposits.

Geology of Southeastern Anatolia and the Setting of Ophiolites

Although major revisions have been made during the past 40 years (Okay & Tüysüz 1999), Turkey simply divided into 3 major tectonic units. These are, from north to south, the Pontides, Anatolide-Tauride Platform and Border Folds or Arabian Platform (Ketin 1966; Okay & Tüysüz 1999; Bozkurt & Mittwede 2001; Erendil 2003).

The Pontides are an orogenic belt divided into two parts, each having distinct geological characteristics. The *Western Pontides* is the area to the west of Samsun as shown in Figure 1 and is characterized by unmetamorphosed Palaeozoic units around İstanbul and older massifs, such as Strandja, Bolu and Kargı, and mélanges exposed along by the İzmir-Ankara Suture Zone (Figure 1). The *Eastern Pontides* are part of the Alpine-Himalayan Metallogenetic Belt. Numerous Kuroko-type Cu-Pb-Zn massive sulphide and porphyry Cu-Mo-Au deposits are associated with calc-alkaline-tholeiitic, volcano-sedimentary complexes of Jurassic–Paleocene age (Akıncı 1980, 1985; Mitchell 1996; Jankovic 1997). These are underlain by the Tokat metamorphic basement of the eastern Pontides which can be correlated with the Karakaya Complex, the Ağvanis and Pulur crystalline massifs, volcano-sedimentary units and intrusives of Palaeozoic and Mesozoic age, and cross-cutting Tertiary intrusives (Akıncı 1985).

The 2000-km-long İzmir-Ankara-Erzincan Suture (İAES) Zone forms the boundary together with right-lateral North Anatolian Fault System, NAFS, between the Pontides and the Tauride-Anatolide Platform or Block (Okan & Tüysüz 1999). It is also the collision zone between Laurasia and Gondwana. Arc and fore arc structures to the north of İAES and terrigenous and shallow marine Jurassic rocks along the suture indicate north-directed subduction in the Senonian, while erosion and compression in the Paleocene mark the final collision with the Sakarya Zone being the upper plate (Okan & Tüysüz 1999).

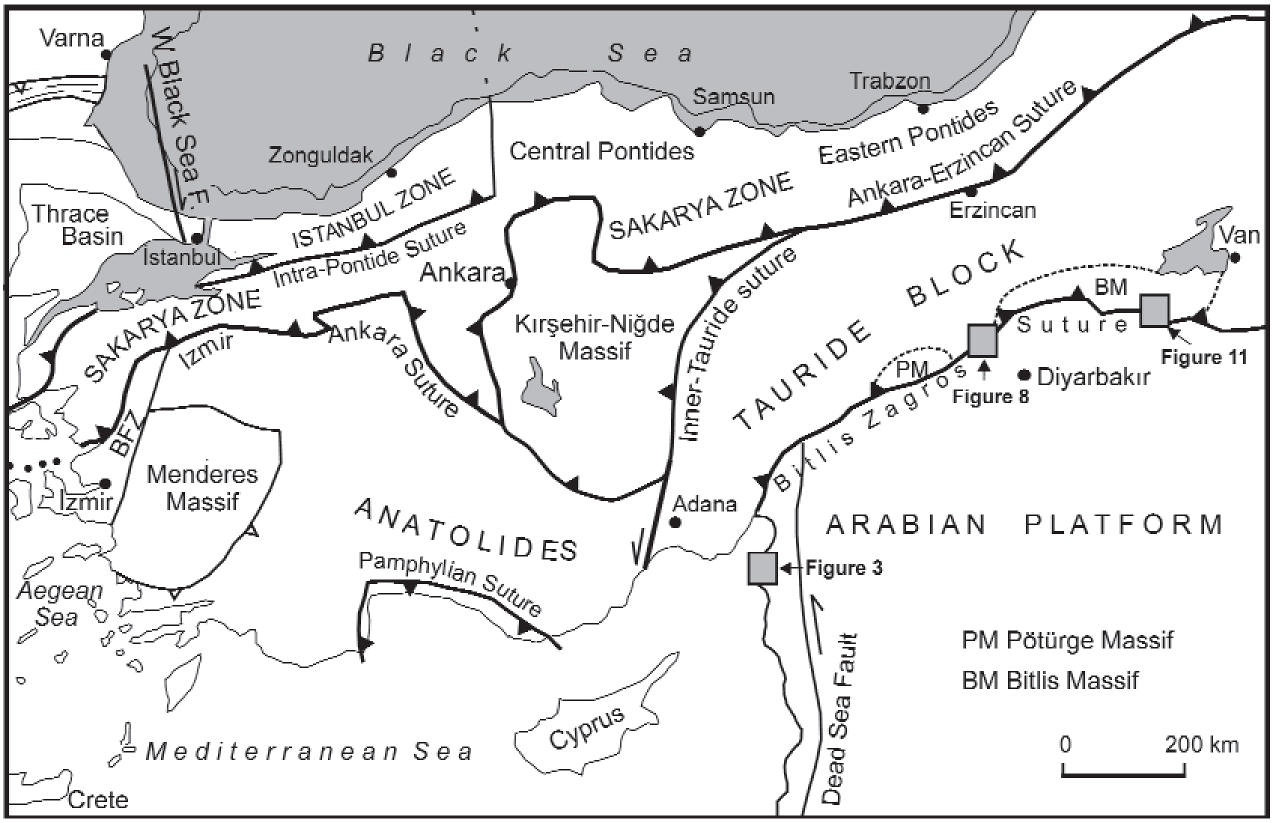


Figure 1. Location of the major tectonic units and suture zones of Turkey (modified after Okan & Tüysüz 1999). Three mineralized areas studied along the BZS Zone are indicated on Figures 1, 2, 3 (insets) and in the cross section presented in Figure 2B.

The Kırşehir (and Niğde) Massif and its magmatic, metamorphic and ophiolitic units form the Central Anatolian Crystalline Complex (Göncüoğlu *et al.* 1994; Whitney & Dilek 1997; Gautier *et al.* 2002).

The Anatolide-Tauride Block (ATP) is represented mainly by the Menderes Massif with accompanying E–W- and NE–SW-trending horst and graben structures in the west (e.g., Bozkurt & Park 1994; Bozkurt 2001, 2004; Bozkurt & Oberhänsli 2001; England 2003; Westaway 2003; Karamanderesi & Helvacı 2003; Bozkurt & Sözbilir 2004; Erdoğan & Güngör 2004; Koralay *et al.* 2004 and references therein) and carbonate platform rocks in south and east-northeastern Turkey (Figure 1).

The Taurides are made up of platform carbonates with carbonate type Pb-Zn and Al-Ba, and skarn iron ore deposits and nappes occurring especially on both sides of Antalya Bay and along the Pamphylian Suture which, as the characteristic structure of the region (Çelik & Delaloye 2003), extends eastwards to the north of the BZS (Figure 1). The southern boundary and eastern extension of ATP is displaced northward by the sinistral Ecemiş Fault between Adana and Kayseri (Koçyiğit & Beyhan 1998).

The Tauride ophiolites represent remmants of the Mesozoic Neotethyan Ocean which started closing in late Cretaceous time. However the Pamphylian Suture (Figure 1) marks a short lived Triassic rifting. As indicated by Robertson (2002), three settings have been reported: (1) MOR type; (2) transitional between MOR and subduction-related; (3) subduction-related. A brief description of these structural settings follows.

The Tauride ophiolite belt of the Neotethyan ocean, with an amphibolite-greenschist facies metamorphic sole at the base (Çelik & Delaloye 2003) east of Ecemiş Fault, forms huge thrust sheets emplaced onto the Mesozoic carbonate platforms along the Mediterranean coast of S Turkey. Cr-enriched spinels, whole rock analyses of peridotites, and immobile trace element analyses of dolerite dykes showing a marked Nb depletion, indicate a SSZ origin (Collins & Robertson 1998; Elitok 2001).

The most northerly ophiolites of the eastern Taurides overlie the Munzur platform carbonates (Figures 1 & 2A) south of Erzincan and are assumed to have been transported from the south by the unexposed Senonian thrust – the first thrust cycle in the region (Figure 2A, C). The ophiolites comprise the north-dipping, intra-oceanic SE Anatolian supra-subduction zone, SSZ, ophiolitic belt, consisting of the Berit (S of Afşin), İspendere (ENE of Malatya) and Guleman ophiolites (N of Ergani) and the amphibolitic Kömürhan metaophiolite (NE end of Pötürge Massif), together with the non-metamorphosed Permo–Carboniferous Keban unit (N of Pötürge Massif) and the Andean-type Late Cretaceous Baskil arc (SW of Elazığ), tectonically overlain by the Munzur and (Binboğa) platform carbonates (Figure 2A, B; Robertson 2002).

A second intra-oceanic subduction zone might have led to the formation of the SSZ components of these ophiolites and also to the formation of the Baskil Arc between Malatya and Elazığ cities and the Yüksekova arc near the Turkey-Iran-Iraq border (Parlak *et al.* 2004).

At the Turkish (Anatolian)-Arabian plate boundary, the approximately E–W-trending Malatya-Pötürge-Bitlis Massif is underlain by HP/LT metamorphics, and thrust over an imbricated accretionary complex, the Lice formation at the western end of the Bitlis Massif (Figure 2B), and on to Tertiary sediments of the north Arabian plate margin (Aktaş & Robertson 1984).

Ophiolites on the margin of the W Arabian plate include Kızıldağ, and its southern extension the Baer-Bassit Massif on the Turkish-Syrian border (Morris *et al.* 2002), and Koçali, near the town of Adıyaman (Figure 2A, B). These are considered to be a continuous large slab of oceanic crust generated above a northward dipping intra-oceanic subduction zone (Parlak & Robertson 2004).

The Kızıldağ and Baer-Bassit ophiolites (Figure 3), with the underlying mélange, are characterised by boninite-type volcanics. Tuff-bearing cover sediments of the Koçali ophiolites (SW end of the Pötürge Massif) indicate proximity to a magmatic arc. Collision with the Arabian margin first commenced in Late Senonian time, reached its peak in the Miocene and is still active (Robertson 2002; Figure 2B).

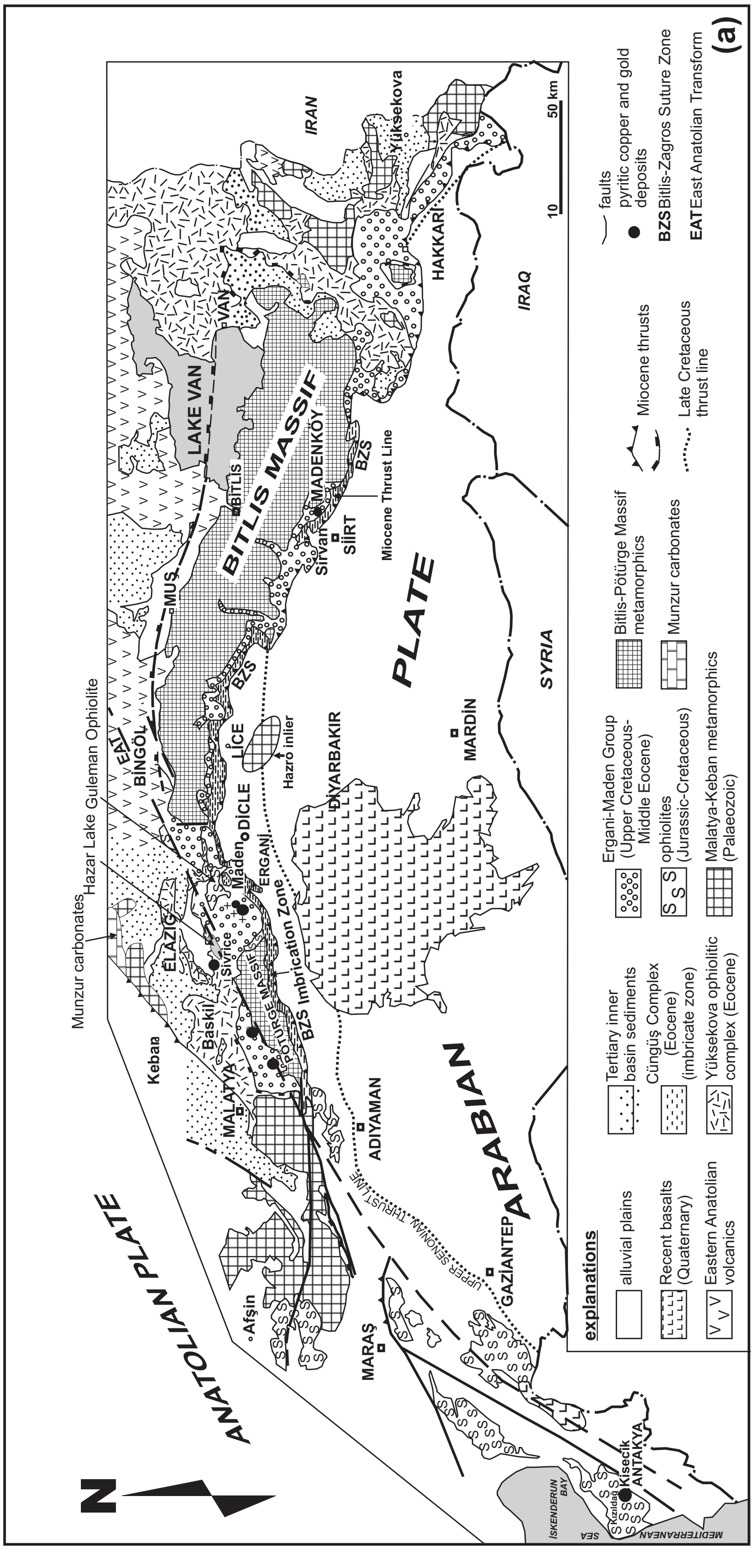
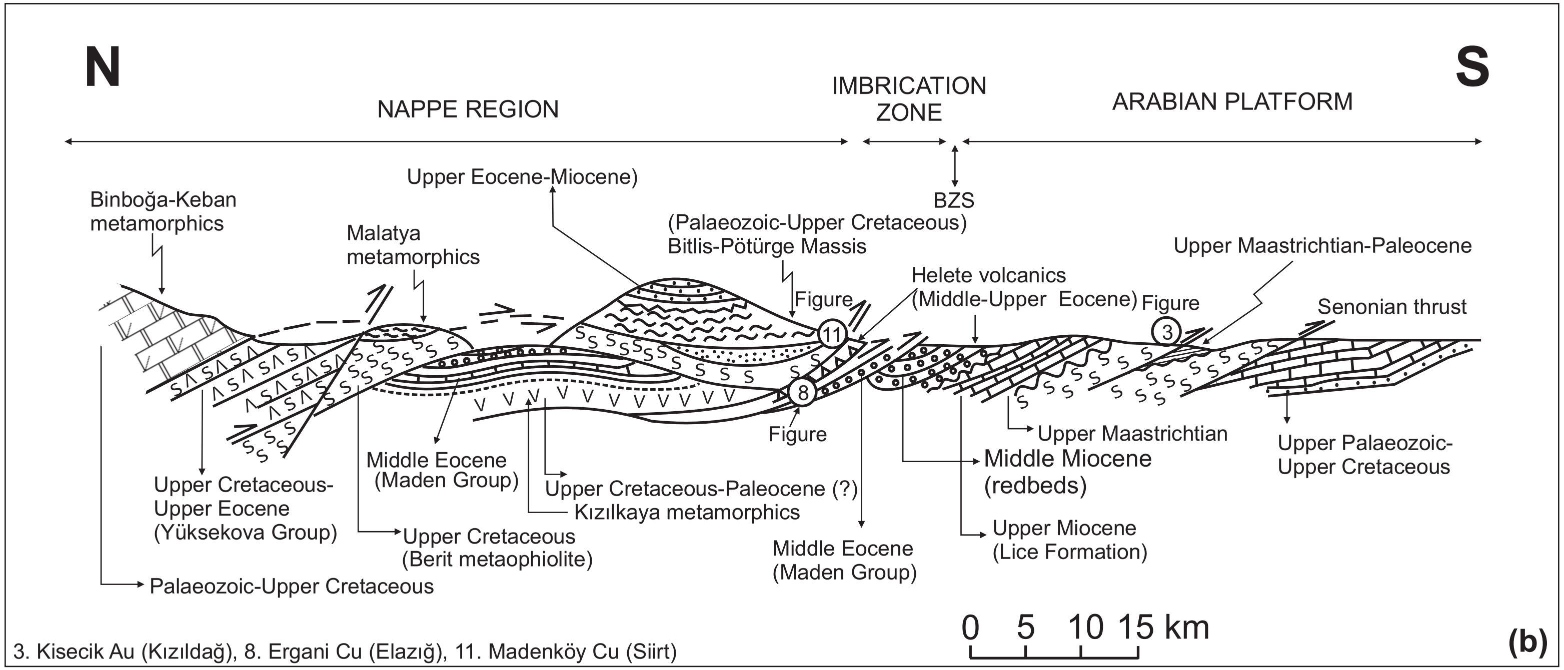


Figure 2. **(a)** Geological map of southeastern Anatolia and **(b)** cross-section showing the thrust and nappe structures and imbrication zone across the BZS; **(c)** geochronological sequences of the Arabian Plate (Ketin's Border Folds Region). **(b, c)** modified after Yilmaz (1993).



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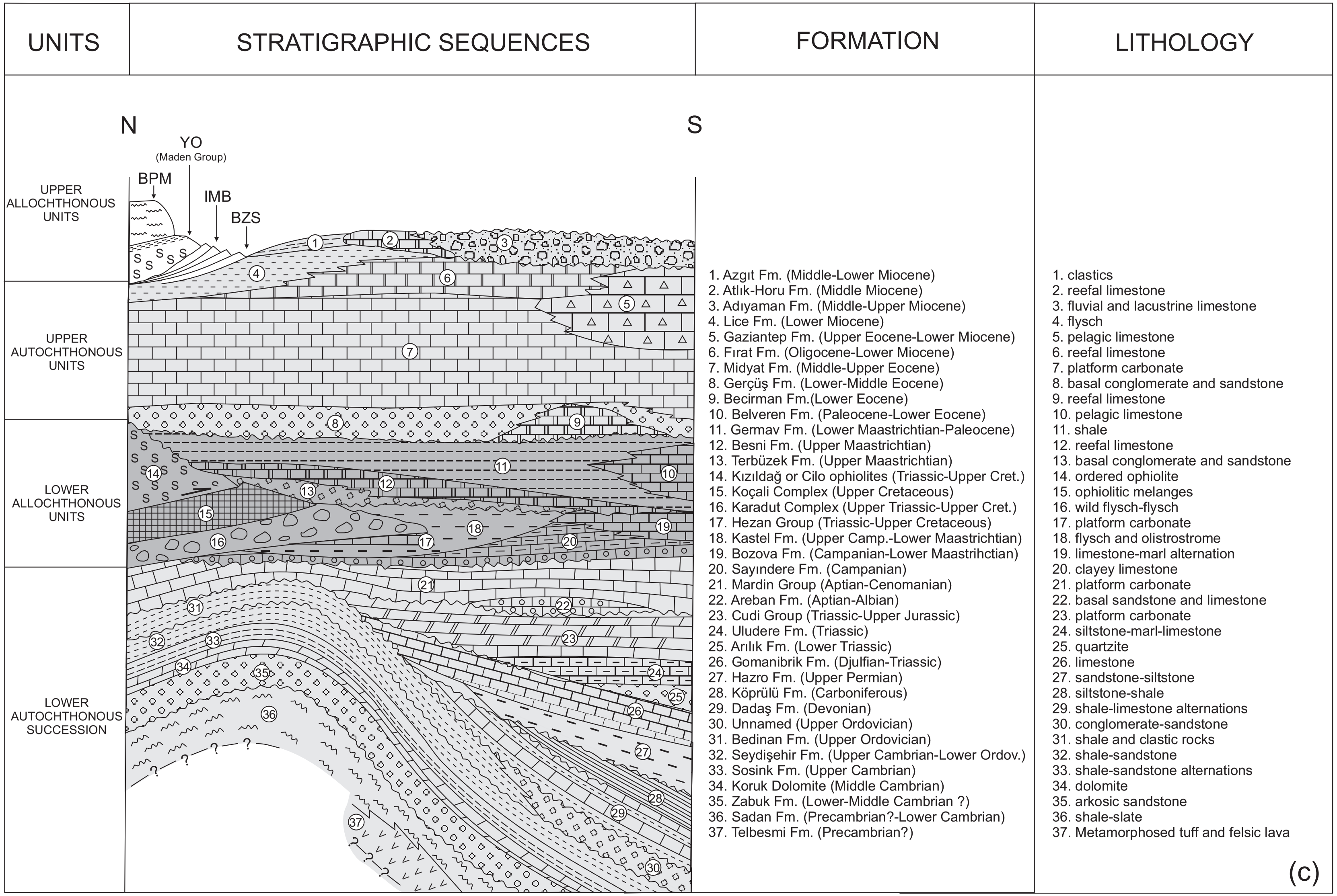

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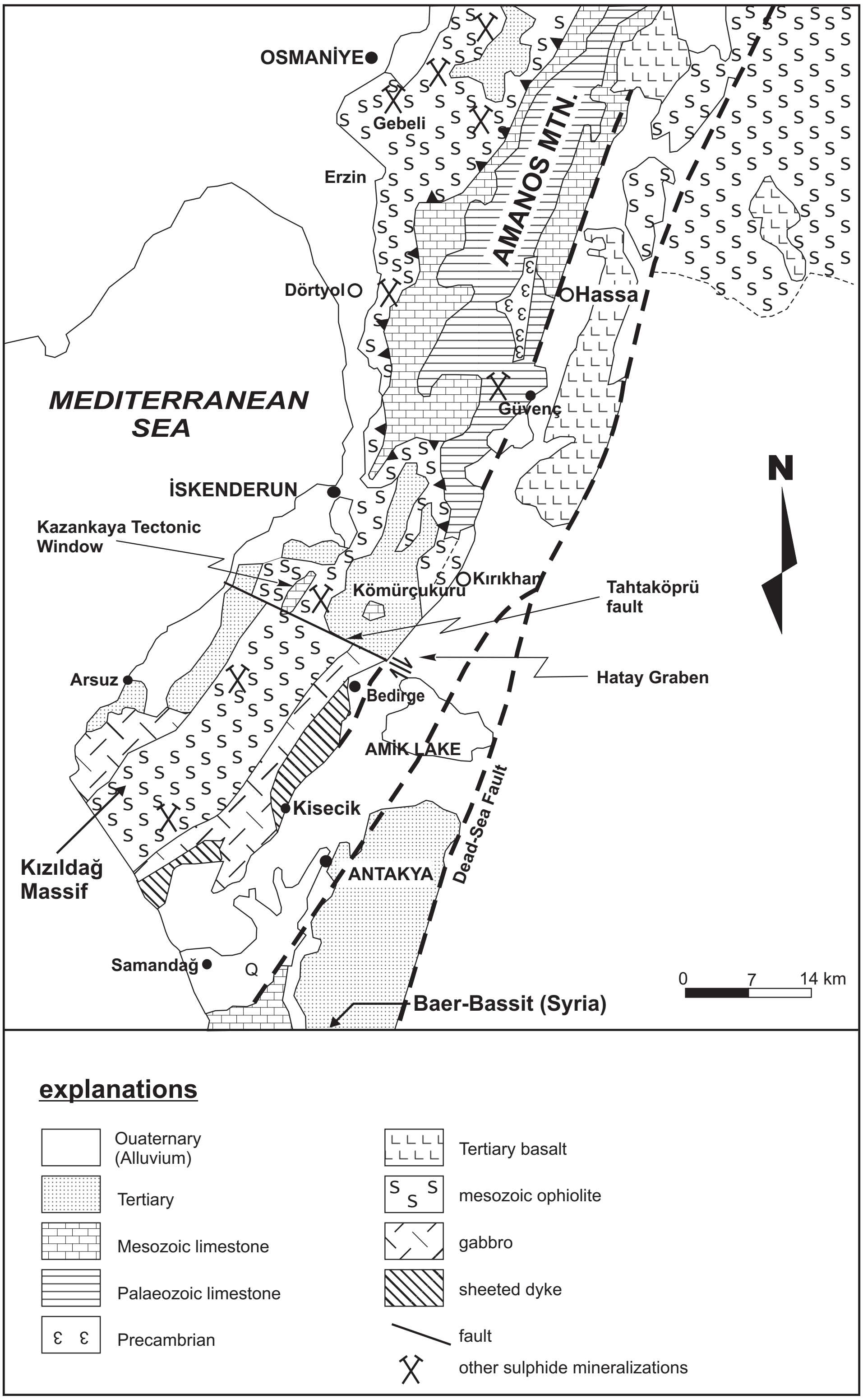

Figure 3. Geological Map of the Kızıldağ Massif and northern ophiolites thrust onto platform carbonates of the Arabian Plate (modified from Tekeli & Erendil 1993).

The area to the south of the Bitlis-Zagros Suture, BZS, was called 'Border Folds' by Ketin (1966) and mainly comprises folded young sediments within Turkish Territory at the northern edge of the Arabian Platform (Figures 1 & 2A) and Mesozoic platform carbonates underlain by Palaeozoic sediments (Figure 2C).

The Bitlis-Zagros Suture Zone

In southeastern Anatolia, an arcuate suture zone (Figure 2A), termed the 'Croissant ophiolitique peri-Arabe' by Ricou (1971), extends eastwards from the Kızıldağ Massif through Ergani (Maden) and the Siirt Madenköy-Yüksekova Complex, and includes the Zagros and Oman ophiolites. This zone contains many economic massive sulphide Cu deposits to the south of Pötürge-Bitlis Massif (Figure 2A).

Although many reports on the geology and mineral deposits of southeast Anatolia and BZS already exist (e.g., Whitechurch *et al.* 1984; Yılmaz 1993; Aktaş & Robertson 1984; Griffiths *et al.* 1972; İleri *et al.* 1976; Karul 1978; Akıncı 1980, 1983; Çalgın 1980; Erdoğan 1982; Engin 1983), the major characteristics of the mineral deposit-rich zone will be outlined before the geology of the ore deposits is described.

The BZS zone is also part of a south-directed imbricated thrust zone with the thrust planes dipping 10° to 30° north (Yılmaz 1993; Robertson 2000). It is characterized, from south to north, by three distinct structural units:

(1) The '*Arabian Platform*' or '*Arabian Foreland*', known as '*Border Folds*' (Ketin 1966; Yılmaz *et al.* 1993) consists mainly of Middle–Upper Eocene autochthonous marine and platform carbonates (Midyat Group) overlain by flysch of the Lice Formation; these units altogether form the *Upper autochtonous succession* at the top (Figure 2C).

Beneath this succession is the *Lower autochtonous succession* represented by platform carbonates (Jurassic–Senomanian Cudi-Mardin Group) and the folded Bedinan-Sadan-Telbesmi formations. The basement comprises Palaeozoic–Precambrian shallow marine sediments (exposed in the Hazro inlier, Figure 2A) and volcanics. In between these two successions, the *Lower allocthonous units (LAU)* are locally exposed (Figure 2C).

The passive margin of the Arabian plate gave way to a foredeep (Kastel Formation) on to which ophiolites of the LAU were thrust southward during the Late Cretaceous. Subsidence along the northern margin of the carbonate platform was followed by the deposition of Maestrichtian terrigenous sediments overlain by sedimentary mélange, forming a *subduction accretion complex*. These units overlie an ordered ophiolitic sequence, represented by the Kızıldağ and Cilo ophiolites (ESE of Hakkari; Yılmaz 1993); which were obducted on to the platform carbonates of the LAU along the southern margin of the Neotethyan Ocean during the Senonian and this obduction is not exposed in the central region of BZS.

(2) North of the Arabian Platform and BZS, a narrow '*zone of imbrication*' (Figure 2B, C), 1 to 5 km wide, consists of a number of south-vergent thrust slices on the Lice Formation. They include Upper Cretaceous to Lower Miocene units (Yılmaz 1993; Yılmaz *et al.* 1993). Yiğitbaş *et al.* (1993) stated that rifting during the early Middle Eocene formed the Maden (Group) Basin, which was followed by deposition of deep sea sediments. It was located behind the Helete volcanic arc above the Arabian platform and represents a back-arc basin; the unit is tectonically overlain by the Berit and Yüksekova ophiolites (Figure 2A, B).

(3) Lower Palaeozoic–Upper Cretaceous Keban-Malatya metamorphic rocks and the Pötürge-Bitlis massifs form a '*nappe region*'. The high-grade metamorphic schists and gneisses are surrounded by an envelope of low-grade slate, phyllite, marble, and metacherts (Figure 2B). These metamorphic rocks form an *upper nappe* and tectonically overlie the Berit and Yüksekova ophiolites and the Maden Group (Aktaş & Robertson 1984; Genç *et al.* 1993; Yiğitbaş *et al.* 1993) comprising the lower nappe north of the BZS zone (Figure 2B); these units together form Upper allochthonous units shown in Figure 2C.

Geology of Kızıldağ Massif and Maden Group and Related Mineral Deposits

Two major groups, together with the BZS zone, include all the major mineralizations, such as the

Kisecik gold, Ergani copper and Siirt-Madenköy copper deposits in the region.

Maden Group

The most important unit, in terms of close association with mineralization, is the *Maden Complex* as defined by Aktaş & Robertson (1984, 1990) for the lithologic associations exposed at the Ergani (Maden) copper mine. The Maden Group includes the Maden Complex and crops out over large areas between the Bitlis and Pötürge massifs and along the BZS. The unit is transgressed by Eocene sediments. The 17-km-thick sequence consists of imbricate thrust sheets and mélange of Upper Cretaceous ophiolitic rocks. In general, it is divided into two parts: a lower volcano-sedimentary unit at the bottom and an upper volcanic unit at the top. The group overlies slightly metamorphosed rocks consisting of pillow lavas and pelagic sediments. Sedimentation commenced with transgressive shallow sea sediments and reef carbonates, and grades upward into argillaceous and volcanogenic deep-sea sediments and basic lavas that suggest rifting and subsidence (Yılmaz & Yiğitbaş 1990; Yiğitbaş & Yılmaz 1996; Robertson 2000).

The Upper Jurassic–Lower Cretaceous age *Guleman Ophiolite* of the Maden Complex (Engin 1983; Figure 2A) is divided into 3 units; these are, in ascending order: (1) serpentinized peridotite grading upward, through a transition zone of peridotite-pyroxenite alternations with increasing amounts of gabbro, into banded gabbro; (2) banded gabbro (with pegmatitic dykes) that grades upward into a microgabbro-diabase dyke zone; (3) tholeiitic-basaltic lava flows, pillow lavas and diabase dykes that cut across basaltic lava flows.

East of Hazar Lake (SE Elazığ, Figure 2A), tectonites (harzburgite, dunite) occupy the central parts in and around the Guleman chromite mine, whilst cumulates (dunite, pyroxenite, wehrlite, troctolite and gabbro) encircle and overlie the tectonites. Contact between the two is interpreted to be tectonic. Pyroxenite, dolerite and plagiogranite dykes are also common, but sheeted dykes were not observed. Pillow lavas are found in neighbouring areas. A brief explanation about Maden Complex from west to east along BZS zone is given below.

Volcanic rocks of the Eocene Maden Complex at the western end of the Pötürge Massif, the Helete volcanics (Figure 2B), are composed of andesite and associated pyroclastic rocks. They were interpreted as part of a volcanic arc by Yılmaz (1993) and formed before collision and final thrusting. However, Aktaş & Robertson (1984) suggested a transtensional pull-apart basin setting for the formation of the similar Karadere volcanics that crop out near Lice in the central part of the BZS zone.

Maden Complex volcanic rocks in the central parts of the BZS, the Karadere Formation (Figure 2A, ENE of Lice), form a Middle Eocene thrust sheet of subalkaline mafic volcanic rocks, interbedded turbidites and overlying pelagic carbonates. These volcanic rocks were probably formed above subduction zones in marginal basins (Aktaş & Robertson 1984). However, varying degrees of alteration obscure the environmental setting in Karadere, and the available data is insufficient for speculation as to whether the width of Neotethys was adequate for subduction and/or back-arc rifting.

In the east of the BZS zone, altered basaltic-spilitic pillow lavas of Eocene age are overlain by nummulitic limestones at Siirt-Madenköy (Figures 2A & 11) and indicate a ridge-type stratigraphy or a seamount before thrusting, but there is insufficient reliable chemical analysis to support this setting.

Kızıldağ Massif

The Kızıldağ Massif is a product of Cretaceous oceanic spreading that resulted in a series of E–W-trending ophiolitic slabs, such as Cyprus and Kızıldağ; they were segmented by NW–SE-trending transform faults in the Tethyan ocean (Robertson 2000). These slabs were emplaced during the Late Campanian to Early Maastrichtian (Yılmaz *et al.* 1993). Different aspects of the Kızıldağ ophiolite were discussed by Vuagnat & Çoğulu (1968) who first decribed the sheeted dyke complex (Engin 1974; Selçuk 1981; Dilek & Moores 1990; Dilek *et al.* 1999; Figures 3 & 4A–F).

The Kızıldağ Ophiolite rests, regionally, on autochtonous Arabian Platform carbonates and overlies an olistostrome. In the main outcrop area, only grey-black dolomitic limestones and olisthostromal rocks made up of ophiolitic and limestone blocks within a highly sheared serpentinite matrix are present (Yılmaz & Yiğitbaş 1990). The tectonic contact between the ophiolite and the carbonate platform is best seen in the Kazankaya tectonic window (Figure 3), north of the Kızıldağ Massif and Tahtaköprü fault, where it is overlain by transgressive Maastrichtian sedimentary rocks (limestone, conglomerate and sandstones). These sedimentary rocks are overlain respectively by an upper Maastrichtian sequence (Yılmaz 1993), then unconformably by Paleocene limestones, marl/sandstone, and Miocene sandstone, clays, marl, marly limestones, gypsum, reef limestones and sandstones (Selçuk 1981; Dilek *et al.* 1991; Yılmaz 1993). Basaltic Quaternary lavas occur in the Hatay graben area east of the Massif (Figure 3).

The NE–SW-trending massif is divided into two parts by the high-angle oblique-slip Tahtaköprü fault at its northeastern boundary (Figure 3). The main part of the massif to the SW of the Tahtaköprü fault consists of a serpentinized core of harzburgite with some dunite lenses and chromite mines (Figure 4A) and overlying crustal plutonic gabbroic rocks (Figure 4B), sheeted dyke complex (Figure 4C–E) and pillow lavas on top (Figure 4F). This complete MOR sequence can be clearly seen between Arsuz and Samandağ along the coast line. East of the Tahtaköprü fault, the massif consists of faulted blocks of extrusive volcanic rocks, dykes and plutonic gabbroic rocks directly overlying serpentinized peridotite (Dilek *et al.* 1999). Sheeted diabase dykes, metamorphosed under lower greenschist facies conditions (mainly zeolite alteration), form a 40-km-long SW–NE-trending zone from Samandağ through Kisecik to Bedirge at the SE flank of the massif (Figure 3). Pillow lavas are locally cut and displaced by high-angle faults along which mineralization is pronounced. In scale and occurrence, its internal and structural features most resemble modern sea-floor spreading structures in oceanic crusts at slow-spreading centres (Dilek & Delaloye 1992). No metamorphic sole is reported at the base of the massif. This contrasts with Bäer-Bassit, which has very strongly depleted ophiolitic lava chemistry, suggesting affinities above a subduction zone rather than MOR (Parrot 1980; Al-Riyami *et al.* 2000) possibly related to later stage subduction in front of MOR.

The Kızıldağ Massif has various mineral occurrences or deposits of economic size. The Hatay-Kisecik gold, the mined out Ergani–Maden copper deposit, and the Siirt-Madenköy copper deposit (yet to be mined) are amongst the numerous sulphide bodies of varying size aligned along the BZS (see Figure 2A). Kızıldağ, a 45-km-long and 25-km-wide massif, is also an example of a complete ophiolite situated west of the Hatay Graben and east of İskenderun; it covers an area of 950 km^2 (Tekeli & Erendil 1985; Figure 3). At the southern extension of the massif, near the Syrian border, the Bäer-Bassit ophiolitic complex consists of harzburgitic tectonites, peridotitic cumulates, layered gabbros, diabase dykes, two levels of pillow lavas and an amphibolitic metamorphic sole (Dubertret 1955; Delaloye & Wagner 1984).

Kisecik Gold Mine

Placer gold deposits around Kisecik and neighbouring villages, 13 km NW of Antakya, have been known since antiquity, but the sulphide-associated gold veins were only recently explored. Major gold-bearing sulphide veins mined also by the Romans are found within E–W-trending sheeted diabase dykes located on the southeast flank of the massif, delineated by the Hatay Graben in the east and controlled by local high-angle faults (Figures 3 & 4D, E). The best gold mineralization is seen in the Kızıl Tepe-Delikli Tepe area, NW of Kisecik village (Figure 5), and many veins of varying sizes have been mapped in the mineralized area. However, the gabbro contact is very close to the surface on Delikli Tepe and the veins do not show much continuity, unlike veins that occur close to the gabbro-diabase transition zone. Gold mineralisation is associated with brecciated, altered gabbro, diabase-diorite, and sheeted-dykes, and in places with pillow lavas. The veins mostly trend NW–SE, while some veins in Delikli Tepe trend NE–SW and dip at 70 to 85° to NW or SE (Figure 5). Enrichments are seen in places where veins intersect, and breccias are also mineralized in tectonized zones.

Mineralization may extend down to the upper tectonic zones (or transition zones of diabase-gabbro) of the isotropic gabbros. There are two dyke

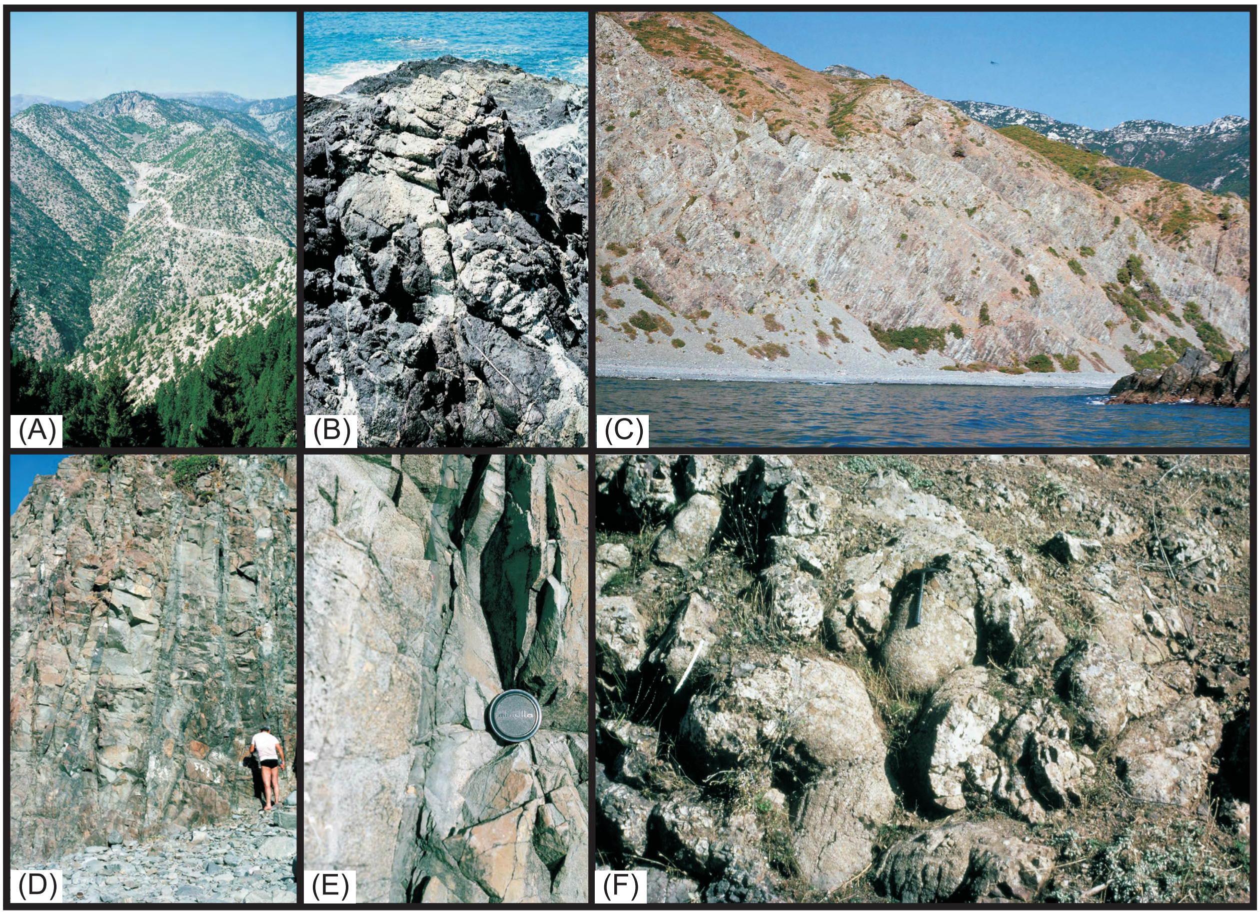

Figure 4. Mid-oceanic ridge units of the Kızıldağ Massif. **(A)** Peridotites (and chromite mines), **(B)** gabbros, **(C)** sheeted dykes, **(D)** sheeted dyke zone, **(E)** close-up photo of a sheeted dyke showing glassy rims of the dykes, **(F)** pillow lavas.

groups, with different plagioclase compositions. Green unmineralized sheeted dykes of the first group crop out south of Arsuz village (Engin 1974); they have sharp fracture surfaces with chilled margins (Figure 4D, E). However, dykes of the second group are brown to light yellow and are extensively altered; they are poor in titanium (Aydal 1989; Figure 6). In places these dykes are found cross-cutting the first group.

Veins, occurring close to diabase and/or gabbro, are enriched in As, Zn, Cu, S, and P_2O_5. Aydal *et al.* (1992) suggested that the introduction of gold was not related to the presence of gabbro and diabase dykes; as the field relations in the Kisecik area show that many of the sheeted dykes found are either concordant with, or slightly truncate the Au-bearing sulphide veins. This is also supported by a zonal arrangement of sulphide-quartz and clay minerals in the gold and quartz-rich veins parallel to the sheeted dykes (Figure 7), indicating that the mineralization resulted from hydrothermal processes along sheeted dykes which served as channels for the solutions.

Alteration– Hydrothermal alteration of iron-bearing sulphide minerals is intensive and striking, with red, yellow and white colours (Figure 6). The following variable alteration is seen at the Pamuk and Kıraç Ali pits (Figure 5), where argillization, chloritization and sericitization are weak, but silicification and limonitization are well developed. However, in areas/veins where argillization, chloritization and sericitization are strong (including veins# 5, 12, 13, 14, 18 and 19; Figure 4), silicification and limonitization are rather weak (Yıldız 1991). As seen in Figure 7, the gold and quartz-rich zone (~4 m

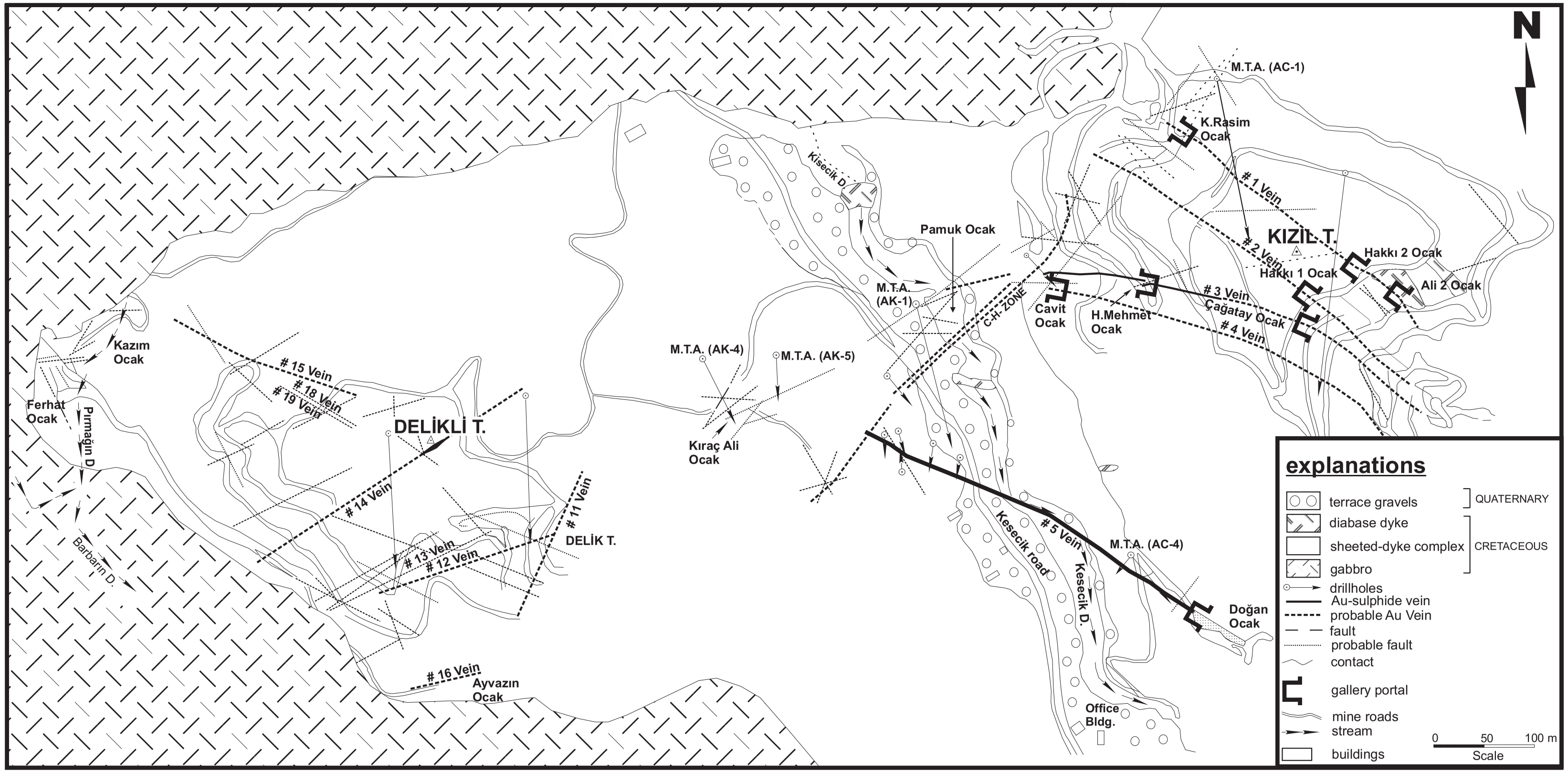

Figure 5. Geological map of the Kisecik gold mine showing parallel vein systems, exploration galleries driven along veins and drill hole locations (Simplified after Yıldız 1991).

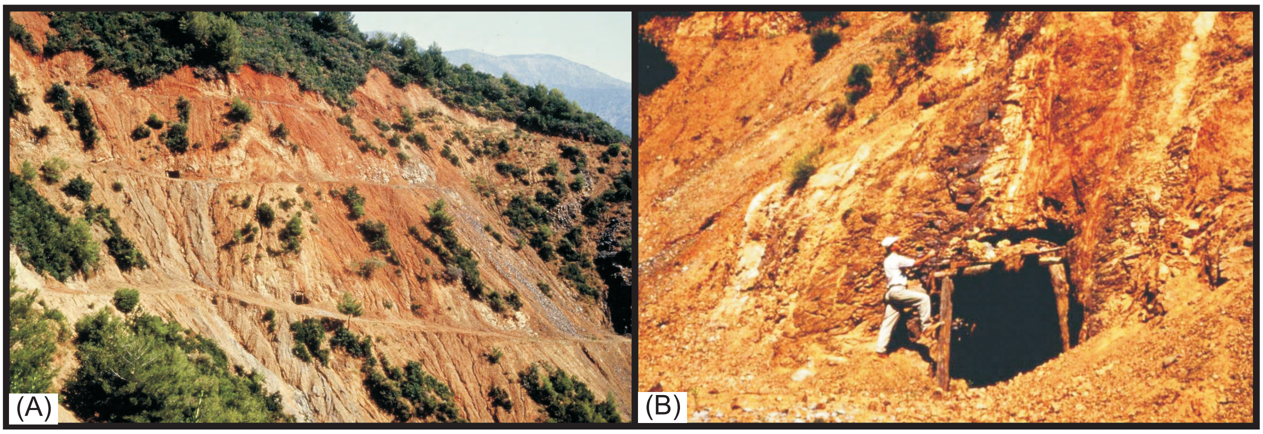

Figure 6. Extensive limonitic alteration developed parallel to the sheeted dykes above the adit entrance and sulphide veins.

wide) is bounded by massive sulphide veins (10–15 cm wide), which, in turn, have a clay alteration zone (2–5 cm wide) on both sides, flanked by a zone of intensely limonitized hematite (20–30 cm wide) that passes gradually into fresh sheeted dykes.

Gold-bearing quartz and arsenopyrite veins (0.01 m to 10 m thick) can be followed up to 500 m along strike and 400 m down dip, surrounded by an argillised zone, which grades laterally into hematitized and limonitized alteration zones.

Mineralogy– The gold in quartz veins occurs within pyrite, chalcopyrite and arsenopyrite accompanied by hematite and sphalerite. In places where sulphides are altered, the gold may be found as 5–20 µm-sized free grains enriched in silver (Aydal *et al.* 1992). Higher concentrations occur in places where two veins intersect or where faults cross veins. Faults controlling the mineralization around the Kızıltepe-Delikli Tepe area are, in many cases, parallel to N45–70°W–trending sheeted dykes (Figure 5): for example, next to the Ali-2 Adit (driven along No.1 at the eastern end). In many places like the Kızıltepe 1, 2, 3 and 4 vein groups, a parallel vein sytem is striking (Yıldız 1991); and adits with different names, as seen on Figure 5, driven in different levels of the same vein due to steep topography (Figure 6), may be confusing. Two groups of veins with different characteristics occur in the mineralized area (Table 1).

Aydal (1989) suggested that formation temperatures for the first group of veins are 160 to 170 °C and that of second group, 270 to 400 °C. Since chalcopyrite contains sphalerite inclusions as oleander-leaf-type exsolution stars; occurrences of high-temperature minerals, such as cubanite and valleriite, are also common. Çağatay *et al.* (1991) documented the names of many high-temperature minerals and suggested that they are consistent with temperatures of 250–350 °C.

Aydal (op.cit) stated, based on the As, Cu and Zn values, that the trace element contents of the gold-bearing sulphide (rich) and gold-bearing quartz veins are different. However, Özkoçak (1993) argued that the gold occurrences are related to thermal waters and siliceous sinters similar to the Buckhorn Au-Ag deposits of Nevada.

The gold grade averages 3 ppm, but in the Kıraç Ali pit east of Delikli Tepe it is around 140–156 ppm (Özkoçak 1993). Overall ore reserve estimates made so far are about 5 million tonnes, with a grade of 0.78 ppm gold and around 573,000 tonnes of 0.8 % Cu (Yıldız 1991). However, the author argues that the actual reserves may be more than estimated figures since the mineralized areas are incompletely explored.

Furthermore, Özkoçak (1993) reported metalliferous occurrences other than gold in different parts of the massif: these include oxidized pyrite veinlets with gossan in harzburgites, Pb-Zn mineralisation within serpentinites, some chalcopyrite and pyrite occurrences, and some partly altered sulphide mineralization of pyritic copper in gabbros. However, none of these metalliferous occurrences have been studied in detail.

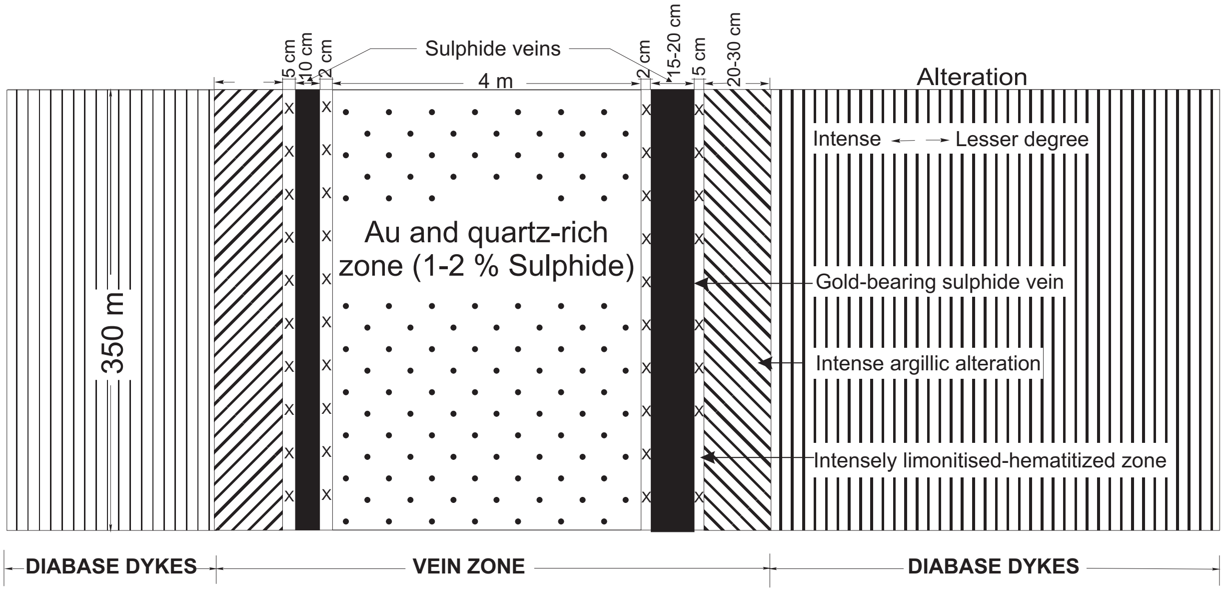

Figure 7. General structure of the Kisecik gold-bearing sulphide veins showing the relationship between sheeted dykes and various alteration bands enveloping veins and gold rich zones parallel to the dykes (modified after Aydal 1989).

Table 1. Mineral association of Kisecik (Hatay) Gold Veins.

Vein Type	Main Ore Minerals	Ganque Minerals	Accessory Minerals
gold-bearing quartz (Delikli Tepe type)	arsenopyrite, gold	quartz, chalcedony	pyrite, marcasite, pyrrhotite, galena, sphalerite, chalcopyrite, covellite, malachite, valleriite, leumontite, heulandite, erionite, smectite, hematite, rutile, anatase, titanite, chromite, limonite, scorodite
gold-bearing sulphide (Kızıltepe type)	arsenopyrite, native gold, chalcopyrite, sphalerite, pyrite	quartz, calcite, dolomite, ankerite, siderite, chlorite, clay, muscovite, sericite, titanite	pyrhotite, marcasite, löllingite, fahlerz, galena,valleriite, cubanite, covellite, neodigenite, chalcosite, tenorite, azurite, malachite, Bi-tellurites-hessite, cinnabar, rutile, anatase, chromite, ilmenite, hematite, magnetite limonite, scorodite

The Ergani Copper Deposit (Anayatak, Maden)

The Anayatak (main orebody) is located in Maden town, 50 km SE of Elazığ and NW of Ergani in SE Turkey, but is known as the Ergani copper mine throughout its history; it has been mined for the last 4,000 years. The mine is the only economic deposit along a 20-km-long narrow belt parallel to the thrust faults within the BZS zone. Other smaller bodies, such as Kısabekir, Mergen Tepe and Mızır Tepe (Figure 8) have been mined out several decades ago, but a smaller reserve still exist NW of Anayatak in the Weiss Pit (Figure 8), to be minable by underground methods.

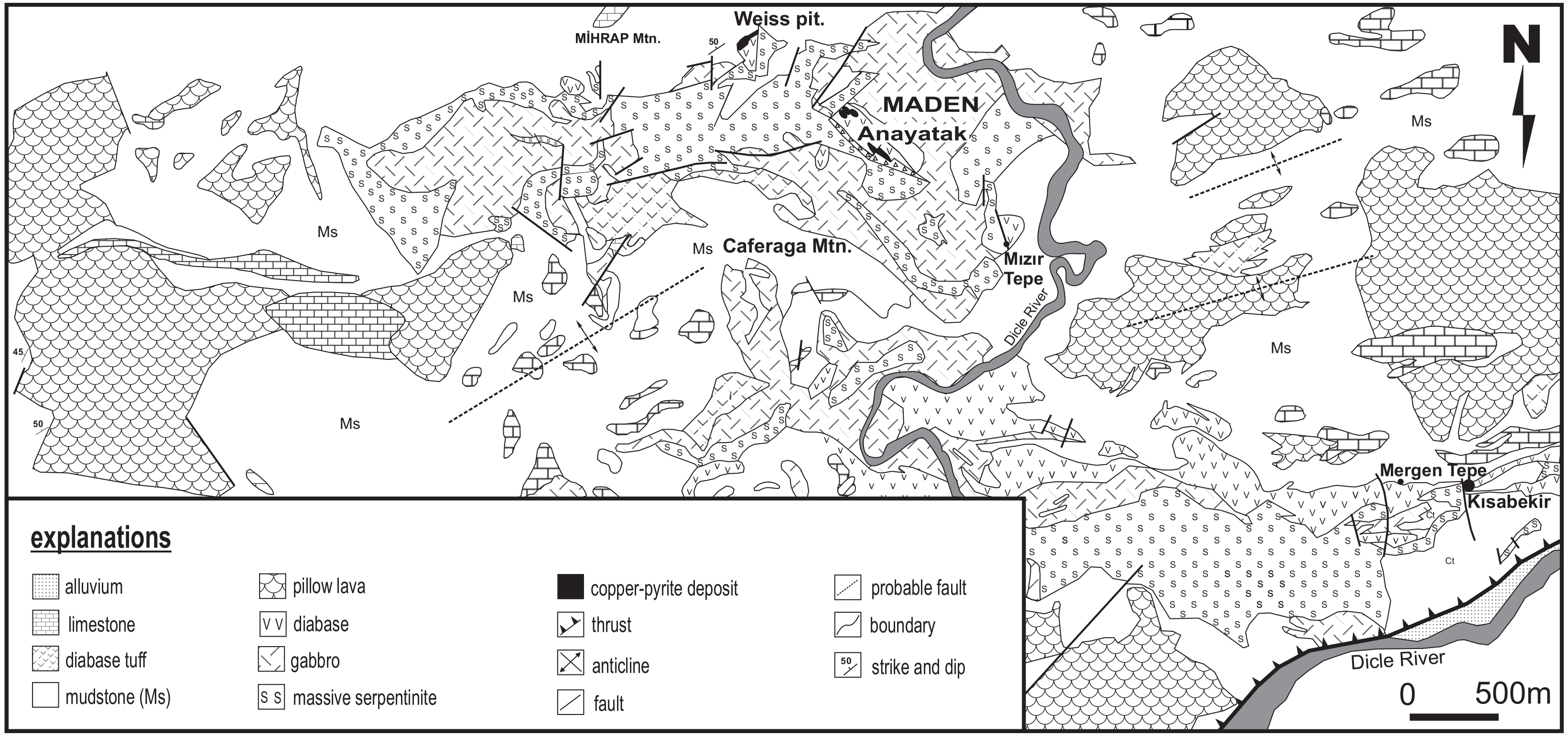

Figure 8. Geological map of the Ergani copper mine and neighbouring areas showing the Maden succession and NW–SE-aligned sulphide mineralization from the Weiss Pit in the NW to Kısabekir in the SE through Anayatak, Mızır Tepe and Mergen Tepe (Maden Town, Ergani) and the MOR succession from serpentinite and gabbro at the base, to pillow lavas and sediments at the top (Simplified after Karul 1978).

This mineralized 20-km-long belt constitutes the central part of the Upper Cretaceous ophiolitic zone of imbrication (basalts, intrusives and serpentinite intercalated with deep sea argillaceous, calcareous and volcanogenic sediments) and consists of two members of the Maden Complex; the Guleman ophiolite (SE of Elazığ) at the base (Figure 9), and the Maden succession (NW of Ergani) on top.

The lower volcano-sedimentary part of the Maden Complex begins with (and the Guleman ophiolite is overlain by) a 15-m-thick basal conglomerate. Pebbles, indicating an extensive period of erosion before deposition of the Maden Complex, are derived from basalt, gabbro and peridotites of the Guleman ophiolite, the host of well known Alpine-type chromite deposits scattered throughout the peridotite (Erdoğan 1982; Engin 1983). Basaltic lava pebbles of the Guleman ophiolite can be distinguished from the similar porphyritic volcanics of the Maden Complex by their aphanitic texture. The basal conglomerates are metamorphosed to greenschist facies, whereas the overlying Maden volcanics are in prehnite-pumpellyite facies. There is no basal conglomerate of the Maden complex above the Guleman ophiolite in the area between Maden town and the Anayatak pit. There, the Guleman ophiolite is represented by an almost complete ophiolite pseudostratigraphy ranging from peridotites to uppermost pillow lavas and sediments, except for sheeted dykes; it is attributed to effective erosion. Conglomerates pass upwards into subaerial reddish alluvial sediments and a flysch-like unit formed in a block-faulted subsiding basin. Reddish and greyish mudstones, in places, either interfinger with basaltic volcanics, basaltic tuffs and mudstones with tuff lenses, or overlie these rocks. For detailed information about the tectonic setting of Maden Complex see Perinçek & Özkaya (1981), Şengör & Yılmaz (1981), Aktaş & Robertson (1984), Yiğitbaş & Yılmaz (1996), and Yiğitbaş *et al.* (1993).

Vertical magma flow at spreading centres and subsolidus flow zones along the mantle-crust boundary can be indicated by foliated serpentinite according to Nicolas *et al.* (1988). In a similar manner strongly foliated serpentinite occurs, in places, at the base of the Anayatak orebody. It is not clear whether this indicates tectonic obduction or a sea floor related structure. It is more likely that this foliated serpentinite is related to faulting separating basement serpentinite or peridotite from the overlying ore-bearing sequences. Just south of Anayatak, unaltered dunite and pyroxenites (inclusions?) also occur within the serpentinites cut by rodingite dykes.

At the southwestern boundary of the Anayatak open-pit, serpentinites are brought to the surface along a N45°W-trending pre-mineralization fault (Figure 10A); the fault separates serpentinites from massive diabase (below the orebody) and overlying mudstones, and a diabase breccia zone with gabbro. Werhlite and spilite clasts are exposed along this fault.

Although outcrops of gabbro occur at many localities throughout the mineralized zone (e.g., the Hacan area in the west, SSW of Mihrap Dağ near the Weiss pit in the centre, and south of Kısabekir, in the east), the largest outcrops occupy the central part of the mineralized zone around Maden (Figure 8). Massive saussuritized and schistose gabbros were also reported by Bamba (1974), and pegmatitic gabbros are quite common.

Gabbros in the Anayatak pit area were thought to be intrusive by Griffiths *et al.* (1972, Figure 9a, b), but later mapping at 10,000 scale, together with drilling by MTA, the General Directorate of Mineral Research and Exploration (to estimate remaining reserves), showed that this is not so (Karul 1978). A section including boreholes 17, 18, 19 and 31 (Figure 9c) clearly shows that the orebody is hosted by intensively altered diabase and tuffs (chloritized, containing disseminated sulphides and quartz-veined), which represent the upper parts of the discharge zones. These rocks grade downwards into gabbros, and the boreholes (10, 17, 18) intersected serpentinites beneath the gabbros (Figure 9d).

Diabase, exposed as disconnected outcrops, is the main host for the ore, and locally grades downwards into extensively chloritised gabbros. Diabasic tuffs of the ophiolitic suite may be seen, in places, interfingering with mudstones, whilst some isolated diabase dykes occur to the SW of Anayatak Pit (Figure 10B). Fresh diabases are also found in the vicinity of serpentinites.

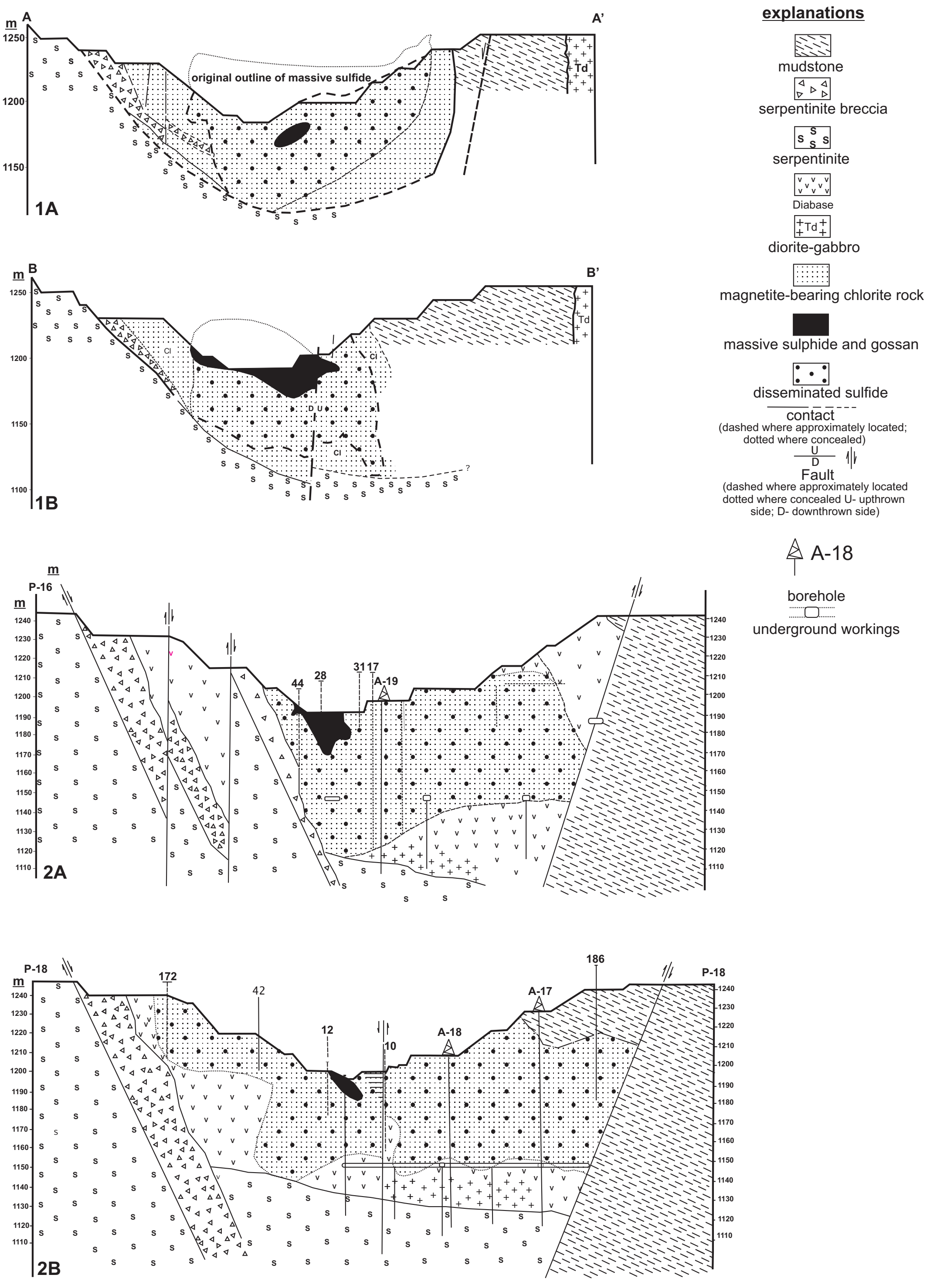

Figure 9. Geological cross-sections of Anayatak (Ergani-Maden) showing two different interpretations. **(a)** and **(b)** indicate gabbros intruding the sediments (modified after Griffiths *et al.* 1972), whereas **(c)** and **(d)** show the present author's interpretation (modified after Bamba 1974) of gabbros forming the basement of a MOR sequence. The uppermost two figures also show the flat tops of the orebody and tectonically uplifted basement serpentinites seen in Figure 10b.

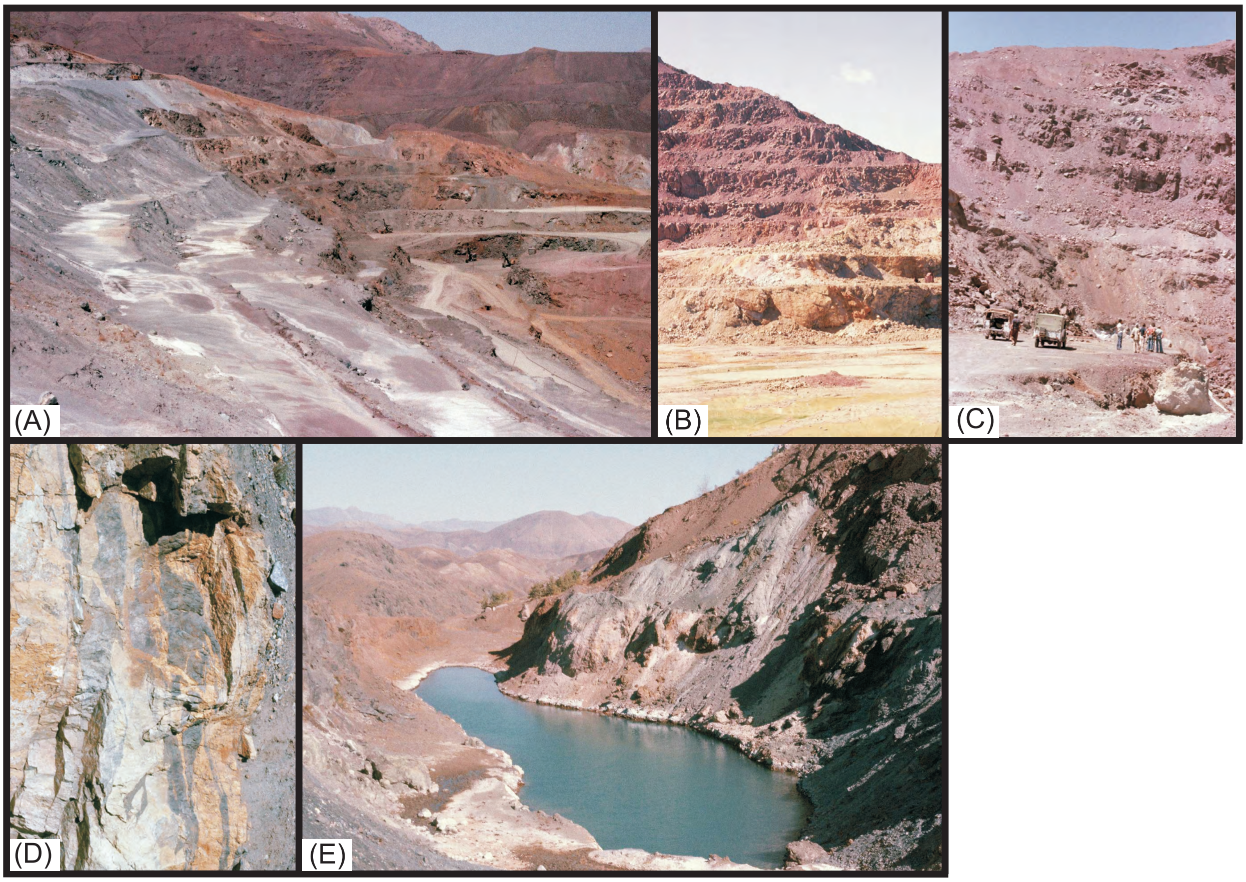

Figure 10. Peridotite-diabase-sediment sequence in Ergani-Maden. **(A)** Altered Serpentinites brought to the surface by a fault exposed in Anayatak; **(B, C)** altered, ore-bearing basaltic lavas and calcareous mudstones overlying the Weiss Orebody (whitish areas); **(D)** massive Chalcopyrite Vein in Anayatak; **(E)** Kısabekir Mine, small pond formed after mined out orebody site.

Pillow lavas are alkali-basaltic (Bamba 1974) and exposed throughout the mineralized areas. They are spilitic and amygdaloidal with glassy outlines, and are cut by post-tectonic keratophyre and sulphide-bearing quartz-epidote veinlets (Çağatay 1977). South of Maden, unaltered pillow lavas and volcanics are exposed above the serpentinites, but a sheeted dyke complex cutting, or associated with, the mineralized zone like in Kızıldağ Massif is absent.

The upper volcanic unit is mainly basaltic and basaltic-andesitic in composition, and consists of pillow lavas, basaltic agglomerates and tuffs, the latter two being more widespread than the lavas. In other parts of the region the Maden Group is overlain, with a subhorizontal tectonic contact, by the Berit meta-ophiolite.

On the northern benches of the pit, a reddish-green calcareous mudstone and sandstone unit unconformably overlies the ore-bearing rocks, and contains no ore minerals other than some disseminated pyrite (Figure 10c). The fossil content of this unit (*orbitoides sp., siderolites sp., rotailidae and gastropodas*) indicates Maastrichtian age; silicified and pyritised *Gastropoda* sp. fossil casts suggest Senonian age (İleri *et al.* 1976). The presence of *gastropoda* fossils in the ore-bearing chlorite rock which passes laterally into fresh mudstones let Griffiths *et al.* (1972) to suggest that these chlorite rocks, which occupy a large part of the Anayatak Pit area, were originally black mudstones similar to fresh reddish-black units overlying the orebody at Weiss pit (Figure10b, c), but they differ in texture and mineral associations, and grade into one another. The fossil content of this unit (*orbitoides sp., siderolites sp., rotailidae and gastropodas*) indicates Maastrichtian age (İleri *et al.* 1976). The reddish and greyish mudstone also passes vertically and laterally into calcareous shales and well-bedded lenticular pelagic limestone that contains *nummulites*, indicating a Maastrichtian (?) to Middle Eocene age (Erdoğan 1982; Aktaş & Robertson 1984).

Anayatak is an about 1-km-long, 0.5-km-wide, N55°W-trending roughly elliptical or elongate orebody. The main sulphide body ends abruptly against a roof of chloritised sedimentary rocks and has a reasonably flat upper surface, suggesting long-term exposure (+alteration and erosion) on the sea floor (Figure 9a, b). The original outline of the massive sulphide orebody was boat-shaped (Griffiths *et al.* 1972; Figure 9b). The importance and characteristic shapes of sulphide orebodies at seafloor spreading centres were pointed out by Rona (1988), and Constantinou & Govett (1972, 1973); most sulphide deposits at seafloor spreading centres were found to be mound-shaped with a convex top: in contrast, Cyprus massive sulphides are concave at the bottom and planar at the top like the Anayatak orebody.

Northwest of the Maden mineralized area, the East Anatolian Fault System (EAFS) and NE–SW-trending faults between Elazığ and Maden define a 10 km wide depression, named the Hazar Lake pull-apart basin (Hempton & Dunne 1982).

Alteration– Outside the Anayatak open pit, mudstones and pillow lavas cover the mineralized zone in about equal amounts. The volcanics, greenish black due to extensive chloritization, and reddish mudstones are distinctive in the area. In different parts of the mineralized areas, only chlorite of possible diabasic origin can be identified; otherwise chlorite is found cementing quartz-sandstones. These chloritic rocks (possibly corresponding to epidosites in other ophiolite suites of the world) include quartz-chlorite, phyllite, siltstone-sandstone and arenite. Within the ore zone, there are only chlorite-bearing rocks that cannot easily be distinguished from diabase and pillow lava. An iron-chlorite, pyrite, quartz, sericite, anatase, rutile assemblage is dominant in the ore-bearing alteration zone.

Mineralogy– The mineralization usually follows the fine-grained upper parts of the chloritized diabases. In the pit area, there are also magnetite-bearing blocks of varying sizes. Layers rich in Fe- and Mn-oxide associated with cherts contain no magnetite, but pyrite and chalcopyrite are common. A massive magnetite body, common in this type of ophiolite-associated deposit showing mineralogical zoning in SE Turkey, was found below the 1143 Level Gallery; it is collapsed and inaccessible at present. A small flat-lying sulphide body within the pillow lavas consisting of colloidal pyrite and bornite (+chalcopyrite-chalcocite-covellite and insignificant sphalerite) has been reported by Çağatay (1977). Four main different types of mineralization can be observed in the pit area: (1) fracture-filling, (2) disseminated, (3) spotty–flow textured, and (4) conglomeratic. The first two types are mainly restricted to the lower parts of the orebody, the third occurs in the middle, and the fourth comprises a mixture of ore and rock fragments in the uppermost levels.

Three large ore and gossan masses are exposed at the northern edge of the pit and dip gently south and southwest. Romieux (1940) mapped a gossan, much more extensive than the present day limited outcrops at the north rim of Anayatak, and reported opaline silica as overlying the massive sulphide. The massive sulphide ores pass abruptly downwards into disseminated ore, in which stringers and blebs of sulphide minerals and veins up to several centimetres thick are enclosed in chloritic rocks. The boundaries of this disseminated ore are not as regular as those of the massive sulphide orebodies (Griffiths *et al.* 1972).

Magnetite, the earliest-formed mineral, is the dominant component of two reasonably large masses in the northwestern part of the pit (Griffiths *et al.* 1972, Figure 3) and is cut by veinlets of pyrite and, less commonly, chalcopyrite or pyrhotite. In polished sections studied magnetite usually is associated with ilmenite, Cr-spinel and chromite and is seen cut by Cu-Fe-Co sulphide veinlets altered to hematite. Molybdenite occurs only within the magnetite, and the gangue is generally made of chlorite and carbonate with some barite, actinolite, tremolite and quartz. Major ore minerals identified in outcrops are chalcopyrite, pyrite and magnetite.

Chalcopyrite forms large masses in both the northern and southeastern parts of the pit. A massive chalcopyrite vein, observed and photographed earlier by the author, was removed by mining operations in the 1970s (Figure 10d). Some fault controlled, dyke-like, apophyses of massive sulphides were also reported by Griffiths *et al.* (1972), and possibly were the hottest parts of the feeder or discharge zones at the sea floor. Enrichment of the copper sulphides, with chalcopyrite being replaced by chalcocite, covellite, digenite etc., is obvious from microscope studies and field observations. The chalcocite is sometimes altered to malachite and can occur together with specular hematite (Table 2).

Pyrite is locally Co-and Ni-rich and is the dominant and/or only sulphide in the eastern and northwestern parts of the pit and birds-eye or sieve-like colloform, framboidal and roughly spherical textures also occur and may be bacteria-derived. Pyritized fossil casts, in the form of some *gastropoda* and other fossils are also common. Amongst the minerals identified (Table 2), fine-grained pyrite within a chalcopyritic groundmass constitutes 85% of the main orebody and the remaining 15% is made of coarse-grained sulphide minerals; the former was termed 'yellow ore' and the latter 'black ore' by Çağatay (1977).

Sphalerite is found in greater amounts in the Weiss pit than in Anayatak and shows some exsolutions of pyrrhotite and chalcopyrite. Silver-bearing sphalerite occurs rarely. Pentlandite is seen as exsolution lamellae in pyrrhotite.

Chromites are altered to magnetite and Cr-spinels. Co-bearing pentlandite is the most common cobalt mineral and occurs in minor amounts within pyrrhotite as exsolution lamellae. Where it is altered to cattierite as flames or fibres together with chalcopyrite, secondary copper sulphides also occur. Cubanite and valleriite are not seen in the black ore; they occur only in trace amounts in chalcopyrite. Ilmenites, which are usually seen in gangue and locally in sulphides, are partly altered to rutile and leucoxene.

Native gold occurs within glauconite, chalcopyrite, pyrite, sphalerite, pyrrhotite and galena (Çağatay 1977). A similar mineral association is reported from the Limassol Forest sulphide-arsenide deposit (Panayiotou 1980), which occurs in deformed serpentinites. Ergani-Anayatak, Turkey is associated with the Limassol Forest Plutonic Complex of the Troodos Massif.

Usually there is a mineralogical zonation, similar to that in the Siirt-Madenköy deposit, from the base to the top of the orebody. Generally, magnetite (accompanying chromite, pyrrhotite and the Co-Ni mineral association) passes upwards to pyrite and chalcopyrite, then to Cu-sulphides with subordinate sphalerite and galena. As a result of drilling activities carried out by MTA in the mid-1970s, 11.7 million tonnes of proven reserve was established at Anayatak with an average grade of 1.77% Cu. At around 2000 B.C., ore as rich as 97% Cu was mined, whereas in the 19th Century, the minable grade was over 5% Cu (Chancourtois 1844). Griffiths *et al.* (1972) report

Table 2. Mineral association of Ergani copper mine.

Ore Minerals	Accompanying Minerals	Gangue Minerals	Alteration Minerals
chalcopyrite, bornite, pyrite, native gold, silver (SULPHIDES)	(1) sphalerite, galena, molybdenite, marcasite, linneite, pyrrhotite, cubanite, valleriite, Co- pentlandite, melnicovite –pyrite (SULPHIDES)	chlorite, baryte, quartz, opaline silica, siderite, limonite, dolomite,calcite,	chalcocite, covellite, digenite, cuprite, tenorite, malachite, azurite, cattierite, limonite hematite, maghemite, rutile, anatas, leucoxene titanite, glauconite
	(2) magnetite, chromite, ilmenite, Cr-spinel (OXIDES)	ilvaite, tremolite, actinolite, talc,	

that between 1939 and 1969 6.1 million tonnes of Cu ore were produced with an average grade of 6.5% Cu. If an average grade of ca 1.8 % Cu is taken as the basis for reserve estimation, the total ore produced to date is estimated at around 40 million tonnes, which is larger than many known VMS deposits (cf. Galley & Koski 1998). The reserve of the flat-lying Weiss orebody, located between serpentinites and overlying mudstones to the NW of the main pit, was estimated to be 270,000 tons grading 1.43 % Cu (Akıncı 1983).

Anayatak is located at the NW end of a 20-km-long mineralization zone. If the Topal Uşağı mineralization, which lies just outside the western end of the map area shown in Figure 6 is excluded, from northwest to southeast, the Weiss (1 Km NW of Anayatak), Anayatak (Main Pit) and Mızırtepe (1.5 Km SE of Anayatak) in the central parts, and Mergentepe and Kısabekir mineralizations (Figure 8) at the SE end, are aligned along a NW–SE-trending line which is thought to be surface projection of an old fault (Figure 8).

These characteristics of the Anayatak orebody suggest a rift-type deposit in a back-arc environment like Siirt-Madenköy (Robertson 2002), but unlike the Kisecik gold deposit which has the characteristics of MOR with full pseudostratigraphy.

Siirt-Madenköy Copper Deposit

The mineralized area is located NW of Siirt, at the eastern end of the Bitlis Suture Zone (Figure 2a). The Siirt-Madenköy deposit (Figure 11) occurs within pillow lavas intercalated with Eocene sediments. In places, these sediments overlie pillow lavas in a manner similar to that of the Anayatak (Ergani, Elazığ) copper deposit. Lower Eocene flysch is exposed to the west and southwest of the mineralized area (Yıldırım & Alyamaç 1976). The stratigraphic sequence comprises autochthonous Tertiary units overlain by allochthonous thrust sheets of the Palaeozoic Bitlis Massif metamorphics (Yiğitbaş *et al.* 1993). The deposit was discovered by MTA during exploration carried out in the early 1970s, and the discovery was followed by a drilling programme between 1973 and 1977. The orebody occurs in a zone of very intensely altered spilites, 400–500 m long and 50–200 m wide.

In this area, Palaeocene–Lower Eocene flysch sediments, consisting of sandstone, mudstone, marl, and fossiliferous limestone containing *nummulita, discocyclina, alveolina rotalidae and bryozoa* pass laterally into, or are overlain by the ophiolites (Alyamaç 1979). The ophiolitic sequence has gabbros at the base, followed by diabase, (some sheeted or isolated diabase dykes) spilitic pillow lavas and mudstone of Middle–Late Eocene age. This unit was overthrust by Bitlis Massif metamorphics as well as by gabbros and serpentinites to the west of Madenköy (Erler 1980). The Bitlis Massif metamorphics in this region comprise amphibolites and chlorite schists overlain in turn by quartzite and sericite schists, then recrystallized, brecciated, calcite-veined Permo–Carboniferous limestone with nodule lenses (Figures 11 & 12A, B).

Gabbros have not been identified with certainity in the mineralized area, but Yıldırım (pers. comm.) states that rocks mapped as '*undifferentiated basics*' by Alyamaç (1979; MTA Map arch., No. 36103) at 1/5,000 scale) are, in fact, gabbros, which crop out where the Sümbül and Yol streams join near MTA Drillhole No.5, next to an old collapsed gallery (Figure 11 SE corner of the geological map).

Pillowed spilite and porphyritic spilite flows are the host rocks for the sulphide ore (Figure 12). Their outcrops extend in an E–W direction and, together with alteration area, form a tectonic window surrounded by recrystallized limestones of the Bitlis Massif. These rocks are basic lava flows interbedded with mudstone and conglomerates (which consist of volcanic material) and show no indications of terrigeneous origin. The pillows are 25–250 cm across, amygdaloidal with ophitic textures. A porphyritic texture, common only in the presence of 0.5-cm-long feldspar crystals, occurs extensively in the south of the mineralized area (Figure 12C). Contacts between porphyritic and ophitic textured spilites are either gradational, or discontinuous and sharp. Drill holes show that these rocks may be up to 450 m thick (Ulutürk 1999). The pillows have a 2-mm-thick glassy crust, with coarser-grained inner zones; they commonly dip 50–60° NE and show exfoliation . The spilites also contain reddish jasper and fine-grained tuffaceous horizons. Middle Eocene fossils were reported by Yıldırım & Alyamaç

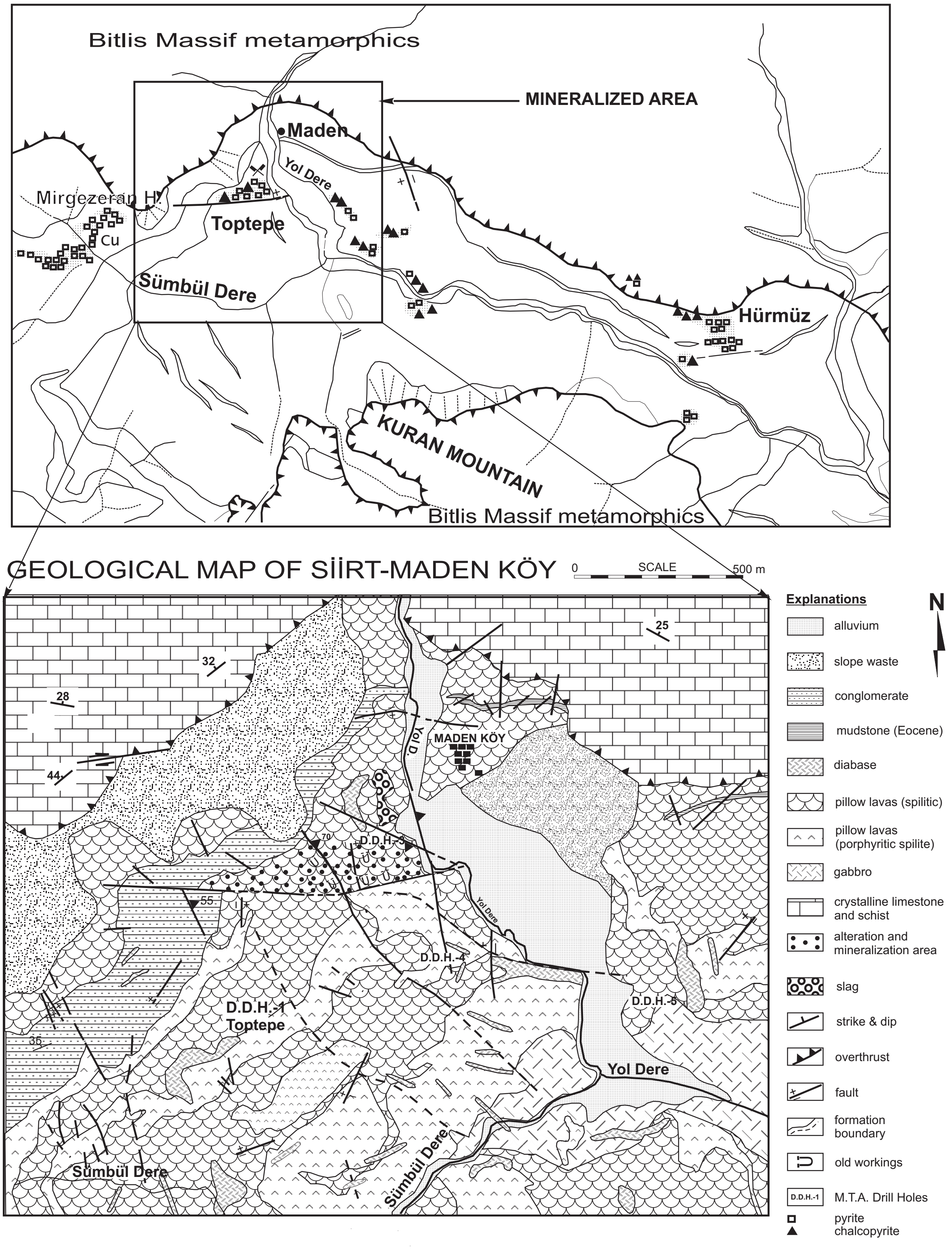

Figure 11. Location and detailed geological map of the Siirt-Madenköy copper mine and mineralized area exposed in between metamorphic units of the Bitlis Massif (simplified after Alyamaç 1979).

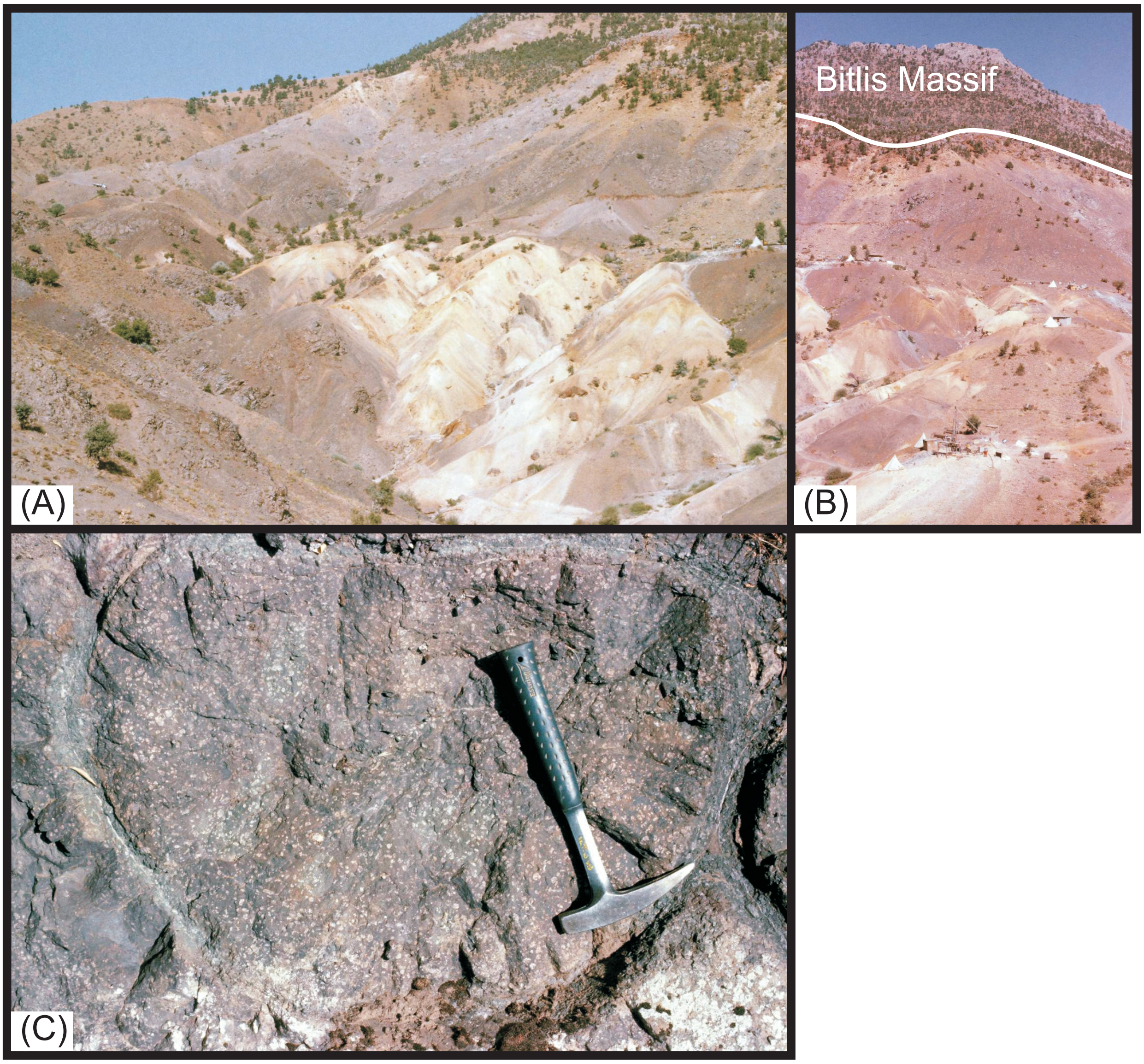

Figure 12. Altered pillow lavas forming the Siirt-Madenköy orebody **(A)**; drilling tents in foreground and Bitlis Massif metamorphics at the background **(B)**; Close up photo of a fresh pillow lava showing albite metasomatism (spilitisation) and glassy rims **(C)**.

(1976) from mudstone intercalations between pillows. The sequence is cut by diabase dykes, which contain small amounts of magnetite, hematite and leucoxene.

The diabases at Madenköy are exposed to the north of the mineralized alteration area and are generally fine-grained. They occur as sheeted dykes in the southwest of the area (Ulutürk, pers. comm.), although they are also found as closely spaced isolated dykes (Erler 1980). They contain hematite, rutile, ilmenite, calcite and quartz as accessory minerals.

Mudstones, closely associated with the pillow lavas, show vertical and lateral gradations or interfinger with conglomerates composed of recrystallized limestone fragments. Some sandy lenses are also common, but are not very extensive. Yıldırım & Alyamaç (1976) reported Middle Eocene fossils in biomicritic or micritic mudstones.

An E–W-trending, near vertical major fault (Figures 11–13) between boreholes M-84 and M-6, divides the mineralized and altered area into two blocks and delineates the footwall block of a major ore lens that has been displaced to the SW. The lens-shaped orebody clearly dips at 50–60° to NE in cross sections, and at the western end is delineated by a NNW–SSE-trending fault which partly follows the Yol stream to the north (Figure 11). Sixty-six holes, several made for geotechnical investigations, totalling more than 18,500 m, have been drilled by MTA, mainly seeking sulphide mineralisation; and a further 7 boreholes were drilled for mining preparations by the Preussag Company.

Alteration– The Siirt-Madenköy sulphide mineralization follows closely an extensive E–W-trending alteration zone traceable for at least 10 km from Maden to Hürmüz village at its SE end near the thrust zone (Figure 11). Pillow basalts are also extensively spilitized in the mineralized area and, around the orebody, chloritization, argillization, silicification and sericitization are seen to varying degrees. Vesicles in the spilites are filled with secondary zeolite, quartz and calcite. Albitization of the feldspars and chloritization of the mafic minerals are extensive, in places showing sericite and clay alteration. A detailed alteration study of Madenköy deposit by Erler (1980) indicated that:

(i) there is no significant chemical difference between the normal spilites and porphyritic spilites. Chlorite, calcite, epidote, quartz and actinolite minerals formed by alteration, in addition to the albite metasomatism.

(ii) the chloritized rocks are either light green with argillized pillow forms (consisting of plagioclase, chloritized pyroxene, and are calcite-bearing with disseminated pyrite and limonite concentrated along fractures), or dark green to green-black chlorite-rich rocks with sericitized plagioclase, calcite and pyrite and/or magnetite disseminations. Compared with reasonably fresh spilites in the mineralized area, the chloritized rocks are depleted in Si, Ca and Na, but enriched in Fe and Mg.

(iii) the argillized rocks, consisting of kaolinite and montmorillonite, are enriched in Si and K, but depleted in Fe and Mg when compared with the chloritized rocks.

(iv) sericitized rocks are seen to be associated with massive pyrite lenses or pyrite disseminations, and illite, montmorillonite, kaolinite and quartz-bearing rocks. They are seen the alteration form nearest to the orebody and show a distinct K- enrichment relative to silicified rocks.

(v) silicified rocks, found below the massive pyritic zone or/at the surface, are grey, and quartz, sericite and montmorillonite-bearing with pyrite disseminations.

Chloritized rocks with pyrite/ magnetite disseminations pass laterally and vertically into spilite with a decrease in the chlorite and magnetite contents, and are within an argillized zone at greater depths. The outer zones of the massive orebody are relatively rich in barite (and Zn), similar to mineralization in the outer rims of sulphide mounds or chimneys at spreading centres (Figure 13).

The sulphide mineralization is completely enclosed in altered pillow lavas where, despite ubiquitous alteration, pillow outlines are well preserved. The spilites contain varying amounts of sulphide disseminations and veinlets; mainly of pyrite though in places, partly oxidized chalcopyrite is present. Ore lenses in pillow forms, either due to complete replacement of pillows or direct discharge of hot sulphide fluid into the cold sea bottom, are also common. Chloritization is extensive but is not directly related to the sulphide mineralization.

Mineralogy– Ore microscopy works on core samples collected exclusively from boreholes indicates the presence of the following minerals: pyrite, chalcopyrite as ore, quartz, chlorite, baryte, siderite and calcite are gangue minerals. Various Cu-Fe-Ti oxide, sulphide and carbonate minerals occur as gangue minerals accompanying the ore and. A variety of minerals (Table 3) were identified by Çağatay (1977).

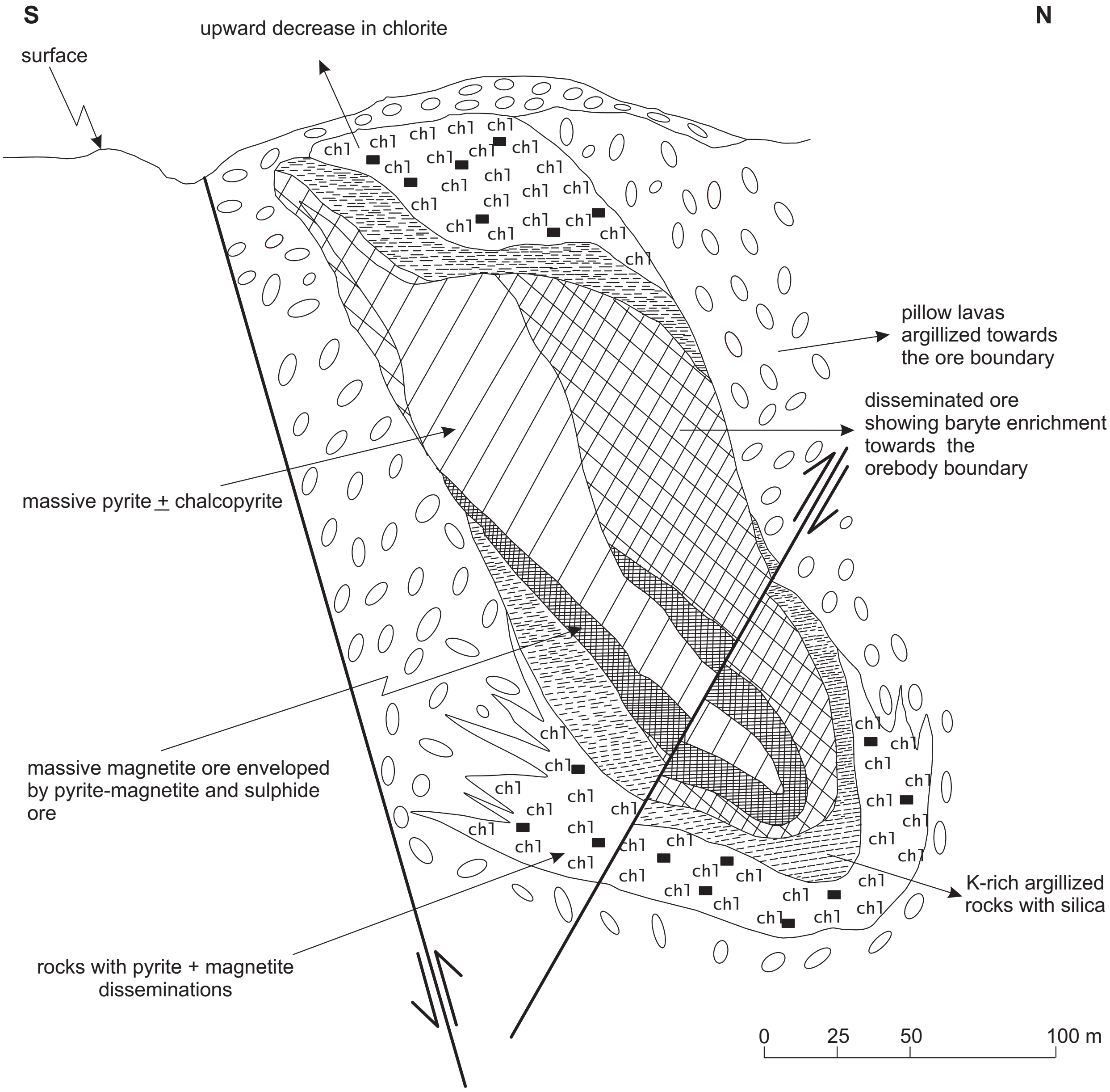

Figure 13. Schematic cross-section showing mineralogical zoning and wall-rock alteration of the Madenköy orebody. The major E–W-trending fault which limits the mineralization in footwall side and post ore, crosscutting fault displacing the orebody in the hanging wall side which are seen in Figure 11.

Magnetite is replaced by, or altered to hematite (martitization) along cleavage planes and maghemite is accompanied by ilmenite laths altered to leucoxene and rutile along crystal outlines. Other accessory minerals are very similar to those in the Anayatak (Maden, Ergani) ore, including gangue minerals such as chromite, Co and Ni-sulphides.

Mineralogical zoning in this orebody is similar to that observed in the Anayatak Pit (Ergani, Elazığ) copper mine and comprises, from top to the bottom: (1) pyrite (seen as euhedral and subhedral grains with some small magnetite, chalcopyrite, sphalerite and rutile inclusions and replaced by chalcopyrite and gangue minerals along fractures); (2)

Table 3. Mineral association of the Siirt-Madenköy copper mine.

Ore Minerals	Accompanying Minerals	Ganque Minerals
pyrite, chalcopyrite,	magnetite, sphalerite, galena chalcocite, covellite, bornite, fahlerz, native silver,	quartz, siderite, calcite, dolomite, marcasite, pyrrhotite, linneite, limonite, malachite, maghemite, hematite, ilmenite, rutile, leucoxene, chromite, Cr-spinel, chlorite, sericite, barite, titanite

chalcopyrite + pyrite (in places altered to secondary copper minerals such as chalcocite and covellite and also accompanied by fahlerz, bornite and with some linneite) + sphalerite (with some chalcopyrite inclusions); (3) magnetite (± pyrite and chalcopyrite).

A schematic cross-section, from a near-vertical dipping massive orebody as seen in sections through bore holes completed, was drawn to show mineralogical zoning. Massive magnetite is enveloped by (1) chloritized and argillized rock with disseminated pyrite and magnetite in which magnetites are in the form of fracture-filling at the bottom, then upwards by (2) massive pyrite and chalcopyrite, followed by disseminated sulphide ore at the top near the surface (Figure 13).

Zn contents range up to 2.75 wt%, Pb up to 0.3%, Cu from 0.3–8.55% and Cd from 5–140 ppm. According to Ulutürk (1999), the average grade of 20 Mt of proven ore reserves is 2.33% Cu, 0.67% Zn and 0.059% Pb.

Discussion

Ophiolite-hosted mineralization and accompanying alteration products in SE Anatolia show many similarities to mineralization in present day active ridge systems (e.g., the EPR, TAG and Atlantis II hydrothermal fields).

In world-wide terms, Cyprus-type pyritic copper deposits hosted by ophiolites of various ages, or Kuroko-type VMS are generally considered to be ancient analogues of sulphide deposits forming today at around 350 °C in hot springs (black smokers) on mid-oceanic ridges and in back arc basins (Harper 1998). However, there is a striking difference in the shape of modern volcanic-hosted, mound-shaped massive sulphide deposits at seafloor spreading centres compared with the bowl- or saucer-shaped style of the classic Cyprus- or Ergani-type (SE Turkey) massive sulphide deposits, that formed possibly by the ponding of denser effluents (Rona 1988). In many ophiolite sequences, pyritic massive sulphide deposits are associated with sheeted diabase dykes and pillow lavas, as in the cases of the Kisecik (Kızıldağ) Au and the Ergani-Maden and Siirt-Madenköy Cu-deposits. These associations show the effect of hydrothermal fluids on ophiolitic host rocks and this process is discussed below.

Since these deposits clearly result from metal mobilization in the discharge areas of spreading centres, hydrothermal fluid-sediment interaction studies demonstrated experimentally that greywackes react with saturated NaCl brine at 350 °C and 500 bars to produce an alteration assemblage of chlorite-smectite and albite with significant amounts of Zn, Ni, Cu, Pb, Sb and Cd metals (Bischoff & Dickson 1975; Seyfried & Bischoff 1979; Seyfried & Mottl 1982). This mineral assemblage is common in hydrothermal alteration assemblages around the types of Cu-Au deposits discussed above, suggesting that seawater-rock (+sediment) interactions may be an important source of metalliferous solutions. Work by Bischoff *et al.* (1981) and Thornton & Seyfried (1987) may shed light on the process, and aid exploration for these types of deposits.

As stated by Galley & Koski (1998), 'fault-related crustal permeability and magma chambers at shallow depths within the basalt-dominated extensional sea-floor environments, create favorable conditions for hydrothermal circulation and formation of massive sulphide deposits' along sheeted dykes which form fossilized conduits for magma and fluids ascending to the ocean floor. This statement explains precisely the Au-bearing arsenopyrite veins along sheeted dykes in Kisecik gold deposit.

Mg and SO_4 are removed from seawater or earlier formed evaporites. While seawater is circulating through the crust, SO_4 is reduced to sulphur by reaction with ferrous iron present in the basic volcanic rocks to form H_2S and to be transferred to the crust. Other elements, in particular transition metals, such as Cu, Fe, Mn, Zn and partly Ni and Co, are dissolved from the oceanic crust and transferred to the circulating, heated and saline seawater, thereby converting it to a metal-bearing hydrothermal solution that is vented through chimneys (Rona 1986). Hajash (1975) produced chalcopyrite and pyrhotite during seawater-basalt reactions at 400 °C and 500 °C, whilst the original seawater solution became depleted in SO_4^{-2}. Another possible source of sulphur is that trapped in oceanic basalt, which averages about 800 ppm S.

Koski *et al.* (1984) indicated that hematite, barite and sulphur, common constituents of ophiolite-associated sulphide ores, may be deposited from hybrid fluids with considerably increased oxygen fugacity at the late stage, and also from sea water. Coatings of magnetite and hematite on basaltic volcanics and pillow lava samples suggest that oxidized fluids can mobilize Fe from Fe-bearing sulphides. As temperatures increase, earlier-formed low-temperature colloidal structures (e.g., colloform banded sphalerites) give way to granular sulphide textures, as seen commonly in Kuroko-type VMS deposits.

The reaction of seawater with relatively fresh basalt at high fluid/rock ratios and temperatures above 150 °C will rapidly remove Mg^{+2} from solution to form firstly *Mg-smectite*, then at temperatures above 200 °C, *chlorite* (Seyfried & Bischoff 1981), which is the most common alteration mineral in the Ergani-Maden and Siirt-Madenköy Cu-deposits, and *epidote* at temperatures over 300 °C. This process results in the release of H^+ and a lowering of the pH which accelerates Na-metasomatism of plagioclase *(spilitization through albitization)*. As explained earlier, spilitization of pillow lavas is extensive in the Turkish Cu-Au deposits. The low pH Mg-depleted fluid causes *replacement of chlorite by sericite-illite*, and this can be seen in the core of the Siirt-Madenköy alteration zone. In subsequent stages, the high S/Fe ratio results in the formation of pyrite and chalcopyrite by suppression of Fe-chlorite formation (Rosenbauer & Bischoff 1983; Galley & Koski 1998). Ca and Mg are lost during spilitization and Na, H_2O, and CO_2 are added to the system, whereas levels of Si, Al, Fe, Ti, Mn, and Ti remain unchanged (Boström 1973; Erler 1980).

Cann (1969) stated that spilitization under oceanic conditions involves the loss of Ca and Al with the simultaneous gain of Si, Fe, and Na; chlorite and pumpellyite produced by such alteration can be rich in Fe and Mn (Hermann & Wedepohl 1970). The iron, when remobilized, may be the source of the magnetite that occurs in the lower zones of the Siirt-Madenköy, Ergani and similar deposits. Pillows may also be replaced by manganese minerals that form crusts or veinlets as a result of interaction with manganiferous solutions.

Iron and sulphur are readily oxidized elements in basalts that are present in sufficiently large quantities to control the redox processes. Most of the Fe in basalts is present in magnetite, olivine and pyroxene (Boström 1973); of these, olivine (Fayalite) and pyroxene (Ferrosilite) react readily with oxygenated sea water to form :

$$4FeSiO_3+10H_2O+O_2 \rightarrow 4FeO(OH)+4H_4SiO_4 \quad (1)$$

Ferrosilite + Seawater

$$4FeSiO_3+8H_2O+O_2 \rightarrow 2Fe_2O_3+4H_4SiO_4 \quad (2)$$

Ferrosilite+Seawater Hematite

$$11\,Fe_2SiO_4+SO_4^{-2}+4H^+ \rightarrow 7\,Fe_3O_4+FeS_2+ 11SiO_2+2H_2O$$

(Fayalite + Seawater Magnetite + Pyrite + Silica) (3)

The second reaction, (pyroxenes reacting with sea water) which is the more common in spilites, results in hematite rather than magnetite. As seen in active ridges, Fe and Mn oxidize more readily as a result of reacting with seawater than Ni and Co, and should therefore precipitate first to form Fe-Mn oxides.

It is known from observations at many localities throughout the world (e.g., the Josephine ophiolite and Troodos, Cyprus) and also from laboratory studies, that epidosites (granoblastic epidote + chlorite + quartz + titanite ± magnetite rocks) are the characteristic rock of recharge or fossil reaction zones in some ophiolites (e.g., Troodos) where hot smoker fluids have risen through oceanic crust (Schiffman & Smith 1988; Harper 1998). Although epidosites comprise several percent of the sheeted dykes in MOR ophiolites, despite some epidote-rich rocks reported (Humphris & Thompson 1978; Alt *et al.* 1985; Vanko *et al.* 1992) so far only one sample of ocean crust epidosite has been identified (Alt 1998). Another possible marker for the feeder zone or proximity to the mineralization, may be increased intensity of chloritization (Alt 1998). The alteration zones occupied by epidosite are subjected volume changes in substantial amounts and as a result, high permeability is gained during the Ca-metasomatism (Harper 1998).

Porosity is created during chemical reactions in which albite and chlorite (greenschist facies) assemblages formed before epidotization are replaced by epidote and quartz (Bettison-Varga *et al.* 1995). 'Along with epidosites sheeted dykes and high-level gabbros provide sources for Zn and Cu. Epidote-quartz (±pyrite-chalcopyrite) alteration is predicted to form during the first stage of cooling of an ascending hydrothermal fluid (400 to 380 °C). Subsequent cooling by conduction gives rise to chlorite down to 340 °C and finally paragonite-rich alteration. Reaction of seawater with basalts results also in removal of Mg from seawater, balanced primarily by uptake of Ca. Mg and OH^- are fixed in a Mg-rich phyllosilicates' (Harper 1998). As stated by Seyfried *et al.* (1999), Mg fixation and Mg-rich phyllosilicates characterize the downwelling zones in submarine hydrothermal systems. Ding & Seyfried (1992) also showed that the concentration of dissolved chlorine from 350 to 425 °C greatly enhances the formation of Fe-chlorite complexes. This accounts for differences in the Fe-contents of chlorites in hydrothermal upflow zones and also suggests that significant Fe-rich chlorite can result from the upflow of Fe-rich brines (Saccocia & Gills 1995).

As in the Ergani copper deposit Mg- and Fe-rich chlorite phases are common features of stockwork alteration associated with many VMS deposits. The recorded differences between modern and ancient alteration and ore mineralogy assemblages in MOR analogues or back arc-spreading systems may possibly be due to differences in seawater chemistry in the geologic past, as well as changes in rock compositions.

Gold is a common element in MOR environments (Hannington *et al.* 1991, 1995b; Herzig *et al.* 1991), as it is in pyritic coppers of ophiolitic environments as well as in Kuroko-type VMS deposits. In the TAG hydrothermal field, gold leached from sulphide assemblages during initial sea-floor alteration can be recognized with secondary copper sulphides and abundant jarosite, and is redeposited as native gold at the contact between altered sulphides and Fe-oxides. This gold is thought to be dissolved by pore fluids (of the sulphide mounds or chimneys), which were generated by reactions between oxygen-rich seawater and ascending acidic, metal-rich solutions moving through chimneys that acted as channelways for the solutions (Hannington *et al.* 1995b). The low pH of these pore fluids, and the close association of the gold with copper chloride minerals (e.g. atacamite) suggest that gold is transported as auric chloride complexes $(AuCl_4)^-$ which may be more stable over a much larger temperature range than bi-sulphide, $Au\,(HS)_2^-$, complexes (Gammons & Barnes 1989). Transport of gold at sediment-covered EPR and some other vents is thought to be as $Au\,(HS)_2^-$ complexes in the vent fluids following sustained mixing with seawater (Hannington & Scott 1989; Hannington *et al.* 1991). Secondary gold is redeposited as the pH increases with the mixing of acid chimney pore fluids with seawater (Herzig *et al.* 1991).

Another type of gold is found in ochres. As stated earlier, in the early stages of mining at Ergani (Turkey) and at Skouritotissa Mine (Cyprus), the sulphide deposits capped by thick ochres were not Au-rich, but those which were were covered by pillow lavas and sediments (Robertson 1976). This suggests that significant enrichment of gold may have occurred during oxidation of the sulphides, whilst they were still being deposited. In the Kisecik gold mine (Kızıldağ Massif), gold is apparently associated with alteration zones and sulphides, formed along sheeted dykes.

At the Ergani copper deposit, as in Cyprus-type and other ancient ophiolite-hosted VMS deposits, the unaltered tholeiitic basalt has a high magnetic susceptibility and remnant magnetization due to the presence of Fe-Ti-oxide minerals, whereas in altered basalt, these minerals are replaced by titanite and other alteration products. Rona (1978) stated that distinct lows in residual magnetic intensity mark the Reykjanes, Salton Sea, and New Zealand hydrothermal fields, which are discharge zones of hydrothermal convection systems; the loci of hydrothermal mineral deposition. This characteristically low residual magnetic intensity of discharge zones can be used as a tool for mineral exploration in ophiolitic settings, as happened at Siirt-Madenköy. Other indications of proximity to hydrothermal discharge sites include variations in metal contents and Fe/Mn ratios in metalliferous sedimentary deposits, and the nature of the pelagic sediments and hydrothermal precipitates (Robertson 1976; Boström 1983; Robertson & Boyle 1983; Hannington & Jonasson 1992).

In the early 70s, Lister (1975) predicted that an active hydrothermal area may be expected every 100 km along slow-spreading ridges like the Mid-Atlantic Ridge TAG field and at closer spacing (3 km) along intermediate to fast spreading ridges such as the EPR. Cann (1980) estimated that a 100 km length of oceanic ridge, spreading at a half rate of 1 cm/year should produce a crustal area of 2,000 km^2 (cf. 950 km^2 produced in the Kızıldağ Massif) containing 100 massive sulphide deposits. Rona's (1986) estimate was one massive sulphide occurrence spaced between 15 km to 100 km along slow spreading centres and between 1-km and 100-km-along intermediate to fast spreading centres. However, he warned that the distribution of sulphide deposits is sporadic owing to the special structure and thermal conditions necessary to sustain high intensity hydrothermal systems that concentrate mineral deposits at sea floor-spreading centres.

In Cyprus and elsewhere in the world, most VMS deposits formed at the contact between the compositionally contrasting lower and upper pillow lavas. This distinction may lead to the discovery of new sulphide occurrences in the Kızıldağ Massif where, as expected, Özkoçak (1993) reported some previously unknown occurrences. The 500 km long Bitlis-Zagros suture zone, with its many aligned ophiolitic segments, is likely to contain new deposits waiting to be discovered, particularly taking into account Cann (1980) and Rona's (1986) estimates of massive sulphide deposit spacings along such sutures.

The development of new equipment and techniques for exploration of seafloor hydrothermal mineral deposits was reviewed by Rona (1983, 1999), Tyce *et al.* (1986), Davies *et al.* (1986) and Robertson (1990), Harper (1998), Juteau & Maury (1999) after detailed investigations of the Josephine and other ophiolites. They recommend the following techniques for the exploration of VMS deposits:

- mapping high concentrations of epidosites (i.e., chloritites in Turkey) in VMS deposits.
- since Turkish Cu-Au deposits are also magnetite-bearing or seen in chalcopyrite, pyrite, magnetite paragenesis can easily be detected by geophysical exploration (magnetic) methods
- contouring of δ^{18}O values of epidosites to indicate large upflow zones.
- highly mineralized oceanic fault and breccia zones allow recognition of VMS deposit feeders.
- working out the geometry and timing of structures, including metasomatism, veins, dykes and faults and structural grabens.

Conclusions

Two types of deposit are found in SE Turkey, each representing a distinct tectonic setting. These are: (a) Au-bearing arsenopyrite veins associated with sheeted dykes of the Kızıldağ Massif as in present day MOR areas and (b) Cyprus-type pyritic copper deposits and gold-bearing gossans (which are still forming in TAG hyrothermal field, considered to be analogous to ancient Cyprus ochres). The Cu-sulphide ores of SE Turkey, along the Bitlis-Zagros suture zone, are usually confined to spilitized basaltic pillows truncated by high-angle faults and fine-grained sheet or flow type diabasic lavas possibly formed in back-arc spreading centres.

These deposits are all extensively altered, and are associated with extensive chloritites, in settings similar to those of epidosites from discharge areas of

MOR hydrothermal fields. This close association, between the sulphide deposits and southern Neotethyan supra-subduction zone ophiolitic rocks representing spreading centres (or rifts?) is stated for the first time in this study and suggests that further exploration is warranted along the 500-km-long suture zone. The deposits are also magnetite-bearing (e.g., Ergani and Siirt-Madenköy), Cu-Fe sulphides accompanied by Fe-rich chlorites in contrast to epidosites seen in Cyprus, Josephine ophiolites etc, making them easy geophysical targets. The occurrence of magnetic lows over recent hydrothermally altered mineralization fields such as the TAG, Salton Sea and New Zealand provide useful reconnaissance criteria for exploration.

These deposits so far reported are accepted as formed in simple hydrothermal systems. A close connection with MOR or back-arc settings has never been mentioned. If exploration projects take into consideration the alteration pattern, characteristics and statistical possibilities of this kind of setting there will be a greater chance to find new copper (or gold) deposits in ophiolitic environments in Turkey or elsewhere.

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