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Metallic and non-metallic mineral resources in SE Anatolia

Érces és nemérces ásványi előfordulások DK-Anatóliában

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(10 figures)

Key words: Chromite deposits, Massive sulphide deposits, Phosphate, Asphaltite seams, Eastern Taurus fold belt, Southeastern Anatolian thrust fault, Turkey

Abstract

The southeastern part of the Anatolian Peninsula comprises a large number of ore deposits showing the well-preserved sedimentary and magmatic textures connected with their origins. The whole region has undergone extensive deformations and corresponding high-grade metamorphism during the Alpine Orogeny. From oldest to youngest, the known metallic and non-metallic deposits are scattered over a large area of various rocks in the interior of the Eastern Taurus fold belt of southeastern Turkey. Most are essentially small deposits on a commercial scale and are of varying degrees of importance. The age of mineralization differs from place to place across the region and ranges from Paleozoic to Tertiary.

The metallic ore deposits of the region nearly always seem to be associated with the evolution of the Eastern Taurus fold belt, part of the Alpine tectonic system. This belt is dominated by upper Cretaceous–Oligocene eugeosynclinal lithologies and much ophiolite and blueschist, especially at its central part. The ultramafic and mafic members of the ophiolite suite contain the large chromite deposits and Cyprus-type massive sulphide deposits. The deposit at Guleman, Elaz constitutes one of the most important chromite deposits in Turkey and has yielded roughly one-third of the country's total chrome production. All the deposits are of podiform type and are associated with ocean-floor spreading areas. The most important example of the massive sulphide deposits is that at Ergani, Elaz. These are essentially sea-floor pyritic copper sulphides which occur within the ophiolite complexes. The Keban Pb-Zn deposits form other productive metallic deposits of the region and occur as vein fillings, cavity fillings in breccias, and stockworks in the pneumo-hydrothermal stage of the intermediate and acidic magmas. Generally, the lead-zinc deposits are polymetallic vein systems developed in backarc environments. In addition to these deposits, replacement of the country rocks by high-temperature hydrothermal solution has given rise to some metallic orebodies emplaced especially within limestones.

The productive sedimentary deposits known in the region are the phospate deposits at Mazidag, Mardin and asphaltite seams at Sirnak. They are found in the various sedimentary formations ranging in the stratigraphical scale from Cambrian to Quaternary. These formations are metamorphosed in the greenschist or amphibolite facies in many places, as in the Avnik area, and convert to the metamorphic rocks such as gneiss, schist, phylite, and marble. The phosphate deposits occur as beds in shallow marine environments and are associated with the segregation of phosphoric acid in the sea-water. The economic importance of metamorphic massifs is essentially restricted to some apatite rich iron deposits and several epitermal veins formed along the main faults.

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Introduction

The southeastern part of Anatolia, as a whole, is one of the most productive mining districts in Turkey, especially for Cr, Cu, Pb, Zn and Fe mineralizations (*Fig. 1*). The region is thought to be one of the sectors of the Tethyan Eurasian metallogenic belt (JANKOVIC 1997), which is characterized by some specific features. Most metallic ore deposits are emplaced within the Eastern Taurus fold belt formed during the Mesozoic and post-Mesozoic ages in the area of the former Tethyan Ocean on the southeastern margin of Eurasia. The general geotectonic evolution of this belt is closely connected with the movement of the Arabian Plate towards the Eurasian Plate in the Alpine Period.

The emplacement of ore deposits along the southeastern Anatolian thrust fault at the boundary between the Anatolian and Arabian plates signifies a structurally controlled deposition (*Fig. 1* and 2). The thrust of metamorphic massifs over sedimentary rocks of the Arabian foreland has led to the development of appropriate depositional environments in which many mineralizations are formed related to the fracture systems. In general, hydrothermal ore deposits are associated with these types of structural elements. However, the ones that are associated with the ultramaphic rocks and large metamorphic massif have more important economic significance than the others. Although some have been rapidly exhausted, as in Ergani and Keban, there is still a large potential.

The development of metallic ore deposits in the region is based on specific tectonic settings such as Cretaceous oceanic closing ophiolite complexes (particularly podiform chrome and cyprus-type massive sulphide deposits) and subductionrelated settings including volcanic rock-hosted vein-type deposits, and lesser skarn deposits accompanied locally by Pb, Zn of replacement type. The non-metallic deposits are essentially of chemical sedimentary type in origin and occur within the foreland sediments of the Arabian plate. These deposits are not common in the region and have been mined from time to time on a large scale.

This report is mainly the outcome of two separate investigations, one by the Mineral Research and Exploration Institute of Turkey and the other by a working group, which participated in a research project entitled "Mining Potential of SE Anatolia". As a result of these investigations, the metallogenic map of the region has been prepared using various scales, especially a scale of 1: 2 500 000, and the relations between the Alpine deposits and tectonic settings have been revealed. Although several unpublished reports have been used by the authors for further information in this study, they do not contain comprehensive information. Therefore, the present study chiefly combines data from both sources in order to report the geological, mineralogical and geochemical aspects of some deposits which are critical in interpreting their genesis.

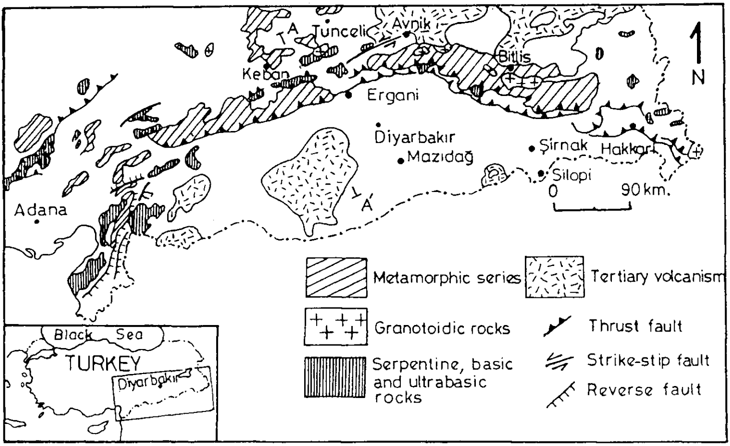

Fig. 1 Distributions of the magmatic and metamorphic rocks of the southeastern part of Anatolia

1. ábra. A magmás és metamorf kőzetek eloszlása Anatólia DK-i részén

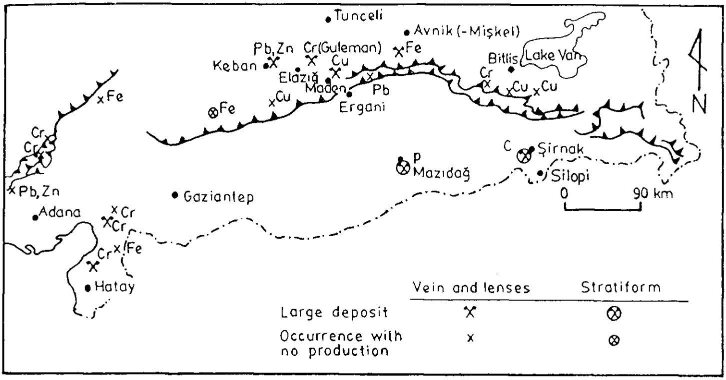

Fig. 2 Metallogenic map of southeastern Anatolia

2. ábra. DK-Anatólia metallogéniai térképe

Geology

The southeastern part of the Anatolian Peninsula forms a transition between the high East Anatolian plateaus and the Arabian plate. It consists mostly of folded and faulted magmatic and sedimentary rocks lying on a basement of Precambrian age (*Fig. 1*). All the region has been affected by the late Mesozoic compressional regime during the Alpine orogeny. The general geology of this region has been described by many authors (BARNES 1963; KIPMAN 1976; BÜRKÜT 1977; SAGIROGLU 1990).

The early attempts to determine the geological relationships between the deposits of the region revealed the presence of small to large acidic intrusive rocks. The investigated region is mainly made up of ultrabasic magmatic, volcanic, metamorphic, and sedimentary rocks of the Paleozoic, Mesozoic, Tertiary, and Quaternary ages. A cross-section of the spatial relations of the major units is shown in *Figure 3*.

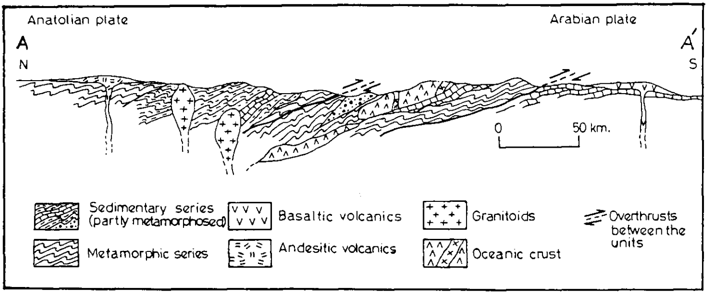

Fig. 3 Simplified cross-section along the line A – Á in Figure 1

3. ábra. Egyszerűsített A – Á keresztszelvény ld. 1. ábra

The metamorphic rocks range from Precambrian to Tertiary age and consist of gneiss, mica schist, amphibolite, blue schist, phyllite, and various complex units that have been intruded from the oldest to the youngest by the acidic and intermediate plutons. These rocks are typically seen in the Bitlis massif. The Bitlis massif is a large area of Paleozoic metamorphic rocks within the Eastern Taurus fold belt (ETFB) lying from Hakkari in the east to Hatay-Adana in the west and characterized by apatite-rich iron deposits. In the light of some information from the southeastern Anatolian deposits, HELVACI (1977) suggested that the age of these rocks is about 450 m.y. The glaucophane-bearing metamorphic rocks, many of which were emplaced along the thrust plane occur, within a narrow zone. These rocks, that exhibit well-developed mylonitic textures, were folded into large-scale interference patterns and deformed to various degrees. The metamorphic rocks are mostly underlain by the marbles and fusilinid-bearing metacarbonates of the Cambrian age.

The fossiliferous unit of the Cambrian age, lying on the Precambrian formations, generally outcrops within the deep valleys that cut across the region. The field studies suggest non-conformity between the Cambrian and Precambrian units. Most of the unit is based on exposures at Derik where the rocks are best preserved; there the unit is comformably overlain by Ordovician, Silurian and Devonian formations. In addition, Permo-Carboniferous units, including calcareous and dolomitic facies, are also observed within the thick Paleozoic sequences of the region. These rocks are unconformably underlain by Mesozoic units.

The Mesozoic units, as seen on the Munzur Mountains, are separated by a marked lack of conformity from the Permo-Carboniferous rocks that acted as the floor for the Mesozoic rocks. These units started with basal conglomerates lying directly upon the limestones of the Permo-Carboniferous age. The basal conglomerate beds are, locally, several metres, or at least several decimetres, thick and contain pebbles from the Permo-Carboniferous units. In general the deposition of this initial formation was followed by the filling up of the geosynclinal formation consisting mainly of submarine lava, shale, limestone, dolomite and chert. The well-bedded volcanoclastic sediments and submarine flows and breccias of spilitic composition are interbedded with the limestones of Mesozoic age. The shales represent flysch sediments of the geosynclinal sedimentation. The limestones have been noted for the small bauxite occurrences in the western part of the region.

The geological history of the serpentinized ultramafic rocks appears to be restricted to the Upper Cretaceous period. These rocks that belong to extensive ophiolite complexes of the ETFB form a part of the active tectonic system and exhibit well-established mechanic contacts. In some places the ophiolitic complexes have been cut by plutons of dioritic composition. The presence of these plutons is probably associated with a hybrid magma containing both the continental crust and oceanic crust materials. Many studies have focused on the ophiolite complexes in recent years (ALTINLI 1966; BÜRKÜT and TURUNÇ 1981; SAWKINS 1990). They indicate that the emplacement of major ophiolite complexes has typically involved an arc-continent collision event, and under normal conditions of subduction, slivers of oceanic material tend to be incorporated in imbricate, forearc melange terraines. In other words, the ophiolite complexes of the region essentially represent the forearc limbs of island arc complexes. Furthermore, the petrochemical results obtained from the lavas and associated ophiolitic units formed in marginal basins, appear to support the emplacement above active subduction systems. Generally dunite, harzburgite, and gabbro constitute the common rocks of the southeastern Anatolian ophiolite complexes.

The Cenozoic units appear to be widespread throughout the region. The oldest dated rocks are the Paleocene–Eocene calcareous and dolomitic marl and sandstones, and the youngest are subaerial volcanic rocks which erupted in historic times. In many places, the Paleocene–Eocene units lie directly on the Mesozoic units. Of the Cenozoic units, the rocks of the Oligocene–Miocene age appear to be very wide; this is a feature common to many areas of the southeastern part of Anatolia. These rocks include chert, evaporitic clastics, and reef facies and represent the shallow water environment. The tertiary formations lying around Bitlis are made up by turbiditic shale-siltstone-sandstone units. In contrast to the older preorogenic rocks, the regional deformation of these rocks is slight or absent. The clay, sand and gravel accumulations form the youngest units of the region.

Tectonic evolution

The general tectonic evolution of southeast Anatolia where the ETFB was formed, is closely connected with the history of Tethys (e.g. its opening, development of island arcs, closing, welding of microplates with Eurasia, subduction of oceanic crust(s), and collusion of continents). The simplified tectonic map of Turkey is given in *Figure 4.*

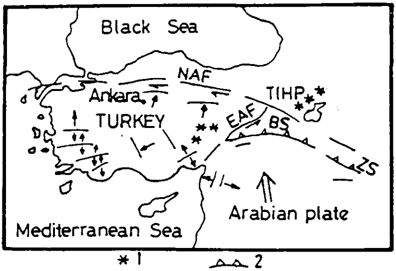

Fig. 4 Tectonic map of Turkey. Key to lettering: NAF – North Anatolian Transform Fault, EAF – East Anatolian Transform Fault, TIPH – Turkish Iranian high plateau, BS – Bitlis suture, ZS – Zagros suture, 1 Ancient volcanic activity centres, 2 Main Miocene thrust

4. ábra. Törökország tektonikai térképe. Jelmagyarázat: NAF - Észak-anatóliai transzform törés, EAF - Kelet-anatóliai transzform törés, TIPH - Török-iráni plató, BS - Bitlis szutúra, ZS - Zagros szutúra, 1. Egykori vulkáni központok, 2. Fő miocén feltolódás

The ETFB, an Alpine metallogenic unit, is the last peripheral folding caused by strong N–S compression during Miocene period, due to the continuing convergence between the Anatolian and Arabian plates (DEWEY and SENGÖR 1979; YILMAZ 1990). This E–W-trending fold belt is situated south of the line of the southeast Anatolian Thrust between Hatay and Hakkari and forms part of the Arabian block, constituting the foreland of the Alpine geosyncline. The compressional regime related to the plate movements has led to the development of normal, reverse, and strike slip faults, as well as the concentric fracture systems within present metamorphic massifs, both in the eastern and the southeastern parts of Anatolia. In fact, the northeast- and northwest-trending fracture systems are most common in the region and have formed important channelways for post-orogenic volcanism, as infered from the geographic distribution of volcanic centres.

In general, the region from Precambrian to the late Mesozoic is very calm with regard to the tectonic situation, although the small granodioritic and dioritic plutons in the crystalline Bitlis massif date from Paleozoic age. At the end of the Mesozoic age, the entire region began to be affected by relatively strong compressional tectonics linked with the movement of the Arabian plate towards the north. The first folding developed in the Austric stage, although the main episode took place during the Laramide, Pyrenean and Helvetic phases. The Laramian magmatism involves both the Senonian volcanics (andesite, dacite, locally rhyolite) and Campanian Paleocene intrusive rocks (essentially ultramafic and mafic rocks, locally small granodioritic and dioritic plutons). The ultrabasic rocks emplaced along present thrust planes were serpentinized and deformed to various degrees. These rocks exhibit well-presented textures, formed simultaneously with the plate movements. In the Late Oligocene–Early Miocene ages, a large section of the ETFB emerged as a response to the collusion of the Arabian plate with the Anatolian plate along only the Bitlis- Zagros suture zone. The closure of the southern branch of Tethys during the Miocene age was followed by subduction of oceanic lithosphere under the Anatolian Torid platform, resulting in the generation of numerous volcanic rocks of calc-alkaline suites, locally alkaline, situated along the main Miocene thrust over the Arabian platform. The post-collusion magmatic activity which is dominated by volcanic rocks, such as basalt and basaltic andesite, occupied the large area in the Late Miocene–Early Pliocene ages, but this magmatic activity at present is restricted to the waterand volatilerich solutions in the vicinity of volcanic eruption centres and adjacent areas.

Chromite deposits in the ultrabasic rocks

The Upper Mesozoic activity attributed to the Cimmerian age in the region has been responsible for many chromite deposits associated with the ocean-floor spreading areas. The chromite orebodies occur within the serpentinized complexes which form part of a broad band of Tethyan ophiolites running from the Alps through the Balkan Peninsula to Turkey and beyond. These complexes rarely exhibit a full suite of ophiolitic rock types from pelagic sediments down through pillow lavas, dykes, gabbros, and ultramafics. The ultrabasic rocks, together with the present mineralizations, have been subject to intense deformations in many places. The deformation of the orebodies and the associated rocks is explicable in terms of the subcrustal environments below the spreading ridge systems where solid state ductile movement predominates. All the chromite deposits are of podiform type, due to their tendency to form lensoid bodies. Some authors have suggested that podiform chromite concentrations form within convecting dyke like bodies of basalt magma - and

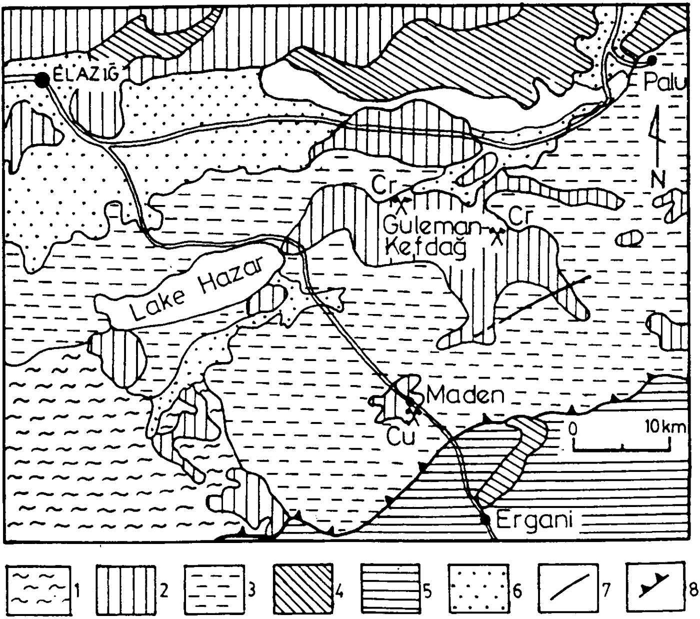

Fig. 5 Geologic map of the Guleman-Kefdag and Ergani-Maden districts; slightly modified after ERENTÖZ (1964). 1 Gneiss and schist, 2 Serpentine, ultrabasic and basic rocks, 3 Upper Cretaceous sedimentary units, 4 Eocene flysch, 5 Miocene flysch, 6 Alluvium, 7 Fault, 8 Thrust fault

5. ábra. Guleman-Kefdağ és Ergani-Maden környékének földtani térképe ERENTÖZ *(1964) szerint, kissé módosítva. 1. gneisz és pala, 2. szerpentin, ultrabázisos és bázisos kőzetek, 3. felső-kréta üledékes egységek, 4. eocén flis, 5. miocén flis, 6. alluvium, 7. törés, 8. feltolódás*

these crosscut harzburgite within peridotite diapirs (LAGO et al. 1982; SAWKINS 1990). It is thought that the collapse of the accumulated chromite grains and nodules formed along one side of the magma chamber produced the various types of chromite ore.

Of the chromite deposits known in SE Anatolia, the ones found around Elazig constitute the most significant deposits. Others are concentrated in the western portion of the ETFB, mainly in the Hatay and Adana districts (*Fig. 2*). The deposits at Elaz are in the Guleman-Kefdağ district, about 70 km southeast of Elazig (*Fig. 5*). This district is one of the oldest and most productive mining districts of southeastern Anatolia. The production began at the beginning of the 1930s and has continued without interruption to the present. The total reserves of the commercial chromite ore have been estimated to be about 50.0 million tons for all the region, when the adjacent eluvial chromite placer deposits are included. The chrome contents of the deposits vary from 30.0 per cent to 55.0 per cent Cr_2O_3 and the ratio is generally 1:3.

The Guleman-Kefdağ district consists of six disconnected mining areas in which concentrations of chromite are sufficiently large to merit production. From north to south they are the Sasin, Tosin, Gölalan, Şimalyarmasi, Soridağ, and Kefdag mines. All of the deposits are in a long tabular mass of serpentinized ultramafics which trend north to northeast. The Gölalan deposit is more important than others and furnished nearly one million ton of chromite ore during the 20-year period from 1940 to 1960.

The oldest rocks of the Guleman-Kefdağ and Ergani-Maden districts are gneiss and mica schist of the Paleozoic age, and these are strongly folded (*Fig. 5*). These rocks are intruded by great masses of Cretaceous serpentine, and ultrabasic and basic rocks which occupy a quarter of the area. The upper Cretaceous units are represented by sedimentary rocks, consisting of limestone, dolomite and chert, and are overlain by an Eocene sequence that begins with serpentine- and limestone rich conglomerates lying on Upper Cretaceous units and continues upward through normal conglomerate, sandstone and siltstone. In the southeast part of the region, these rocks are directly overlain by Miocene flysch, which is locally cut by diabase and spilite dykes. The alluvium of the Quaternary age is the youngest unit of all the region.

Ultrabasic rocks containing the podiform chromite ores, which are typically of either harzburgite or dunite type, but the latter is the predominant type in the region. In many places, the chromite deposits are only in dunite lithologies whose relative ages are thought to be Late Cretaceous – Early Tertiary, on the basis of stratigraphic control from under- and overlying sedimentary units. The ultrabasic rocks hosting the ores invariably exhibit tectonite fabrics, and in some instances these are of considerable complexity and are locally cut by small mafic dykes that are resistant to weathering; despite this, however, the chromite concentrations over the entire region do not exhibit well-defined layering. On the basis of geological and petrological investigations, it can be said that the region is rich in these types of deposits and the number and distribution of the known economic and subeconomic chromite deposits attest to the tremendous amount of chrome within the region. The distribution of the deposits, the volume of the ultrabasic rocks, and the tonnage of ore show a laterally located, highly mineralized zone that is emplaced along the main Miocene thrust.

The southeastern Anatolian chromites possess excellent metallurgical properties and are characterized by the presence of uvarovite and kammererite. Martitization, a deuteric alteration of chromite, always seems to be one of the most important features of the chromite deposits. Deuteric alteration suggests that the chromite deposits have been affected simultaneously by regional forces and hydrothermal solutions. The mineralizations of kammererite, uvarovite, and chrome tremolite found within the fissures, are essentially a response to these processes. The main ore minerals of the deposits are chromite and minor amounts of pycotite. Magnesite, talc, and other minerals of deuteric alteration occur locally in very small amounts. Magnesite and talc may be recovered as by-products, but kammererite, uvarovite, and chromium tremolite are only interesting for mineralogical studies.

The chromite orebodies contain five different types of ore: i.e. massive, nodular, disseminated, vein-like, and much less linear banded. In addition, breccia-type chromite ore has been observed within the contact zone between the ore and host rock. Their distribution varies considerably in individual deposits, but massive ore is common over the whole region. In massive ore, there is no apparent arrangement of chromite grains, and all possible gradations, from a few scattered grains in dunite to an aggregate of pure massive chromite. Euhedral chromite is common in the disseminated ores, but most of the chromite is subhedral to anhedral. Nodular ore consists of rudely spherical or ellipsoidal nodules of chromite which are surrounded by partially serpentinized olivine. Linear banded ore appears to be restricted to the Pozant-Adana district, and together with the planar banding, characterizes a few per cent of the ore in the deposits. When observed parallel to the strike, linear banded ore has the same appearance as the planar banded ore, but when viewed across the strike it is seen that the banding is formed by a series of parallel rods of chromite in nearly parallel layers.

The chromite deposits of the region occupy various positions within the serpentinized peridotite masses. They essentially occur as lensoid bodies varying in thickness from a metres to 30.0 metres. In some places, the lens-like structures laid end to end in the peridotite masses form well developed examples resembling a string of sausages. Such structures are chiefly developed under conditions of regional stretching and are directly associated with the fault mechanism. In general, the chromite bodies are more rigid than the overlying and underlying layers. They have broken and formed lenticular structures, while more mobile beds surrounding them show an elastic character under conditions of stretching. These types of occurrence, developed simultaneously with serpentinization, are essentially a common feature of Turkey's podiform chromite deposits.

Massive sulphide deposits

The ophiolite complexes of southeastern Anatolia contain many massive sulphide deposits of the Cyprus type. These are essentially sea-floor pyritic copper sulphides formed in the volcano-sedimentary units. In general, the deposits bear close similarities to the sulphide material which collects at the base of, and below black smoke chimneys at modern vent sites (ROSS 1977). In many places, the upper parts of the ophiolite complexes contain listric faults related to shallow detachment zones. It is generally accepted that all the deposits are coeval with the enclosing submarine volcanics (BÜRKÜT 1984; SAIROLU 1990), and were deposited either near or at the rock-water interface. On the basis of composition, age, and rock association, the deposits belong to the copper-rich, lead deficient ore type of massive sulphides which have been formed within basic-ultrabasic rocks of ophiolitic affinity. In most cases, the deposits exhibit a structurally controlled occurrence and weak mineralogical zonation from stratigraphic footwall to hanging wall. The ophiolite complexes, at least those including massive sulphide deposits, do not contain a typical sequence of litho-units from peridotite - through gabbros and sheeted dykes to pillow basalts - due to the absence of the sheeted dykes and pillow lavas which occur in many places. The deposits are epigenetic, although there are some disputed features in terms of their emplacement mode and time. It is more common, however, that the age of mineralization dates from the Cretaceous or Eocene periods. Examples of this type include deposits in Elmali-Kahramanmaras, Halezur-Elaziğ, Çüngüs-Diyarbakir, Ergani-Maden, and Madenköy-Siirt. All the deposits are emplaced along the Southeast Anatolia suture zone, and are also noteworthy in terms of their relatively high gold content, which occurs as small particles within sulphide minerals (BÜRKÜT 1984). The deposits occur in the form of lens- or slab-shaped bodies, more or less elongated in the direction of the local linear structure.

The Ergani-Maden massive sulphide mineralization is the most important deposit on a commercial scale, and constitutes the oldest mine of the region. Others are of subeconomic size, but locally they contain massive concentrations of high-grade ore, raising up to 3.0% Cu. Since the content is large, this study is focused on only the Ergani massive sulphide deposit.

The Ergani massive sulphide deposit is located about 1 km northwest of Maden, Elaziğ province (*Fig. 5*). As noted above, the deposit is thought to be a Cyprus-type massive sulphide deposit, on the basis of mineralization, wall-rock alteration, and rock association. The mining activity in the district goes back up to 2000 years, but modern production began in 1937. Today, the deposit has nearly been mined out.

The Ergani district contains igneous and sedimentary rocks of the Cretaceous, Tertiary and Quaternary ages. The geologic relations of the major rock units to the mineralization are shown in *Figure 6*. The massive sulphide orebody occurs sporadically in the gabbro and diabases connected with Maastrichtian-Eocene volcanism in the suture zone. The associated ultramafic rocks are represented by serpentinized peridotites, and there are local dunites which also contain a considerable amount of chromite ore. The serpentinized peridotite forms a basement in the Ergani distict, and passes upward to the pyroxenites and the olivine-bearing gabbros. The gabbroic rocks are covered by diabases consisting essentially of labradorite and pyroxene in composition. These rocks have been extensively silicified and chloritizated by the hydrothermal solution and capped by pillow lava flows in some places. All the ultrabasic and basic rocks are underlain by various sedimentary units of the Tertiary age. These units in the Ergani district consist of the following succession grading upward:

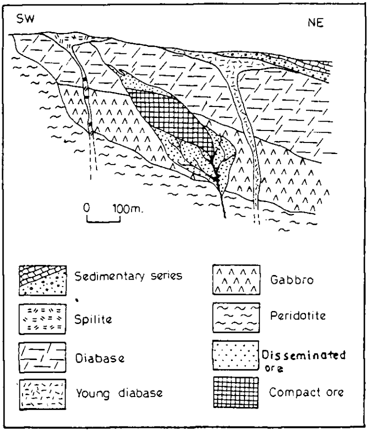

Fig. 6 Schematic cross section of the Ergani-Maden Cu deposit shown in the *figure 5*

6. ábra. Az 5. ábrán látható Ergani-madeni rézérc telep egyszerűsített keresztszelvénye

red limestone, fossil-rich upper Cretaceous limestones, limestone-schist intercalations, and grey-brown Eocene sandstone and siltstone (HELKE 1964). The district is characterized locally by radial and concentric fractures, and hydrothermally altered rocks believed to be related to the unexposed acidic or intermediate plutons.

The Ergani district consists chiefly of four economic orebodies such as the Mihrapda, Arpa meydani, Ana yatak, and Kisabekir mines. The Ana yatak mine is more important than the others and has supplied a few million tons of ore since 1937. The ore is a lensoidal massive sulphide body with a strike length of 1000 m, and a maximum of 400 m wide. In some places, it is surrounded by alteration zones, but copper minerals related to these zones are very rare. Ore textures range from massive to granular and disseminated, and include colloform and nodular varieties believed to have formed at a low temperature by open-space filling. Disseminated ore surrounds the massive ore and esentially occurs within the gabbro.

The main sulphide minerals are pyrite, chalcopyrite, pyrotite, sphalerite, and pentlandite. Magnetite, rather than pyrite, is the principal iron-bearing phase in the mineralized zones. The gangue is largely quartz, barite, chlorite, sericite, and the variety of host rocks for the ores. In addition to the major metallic constituents – Cu, Zn, Fe, Ni – the commercial ores contain up to 1–2 g of Au per ton, 10–15 g Ag per ton and a maximum of 0.5% cobalt. The cobalt content of the ore is probably associated with such minerals as cobaltite, cobalt pentlandite, valerite, cubanite and smaltite. The presence of valerite and cubanite suggests that the mineralization took place at the deeper levels under high-temperature conditions. The distributions of Cu, Zn, Fe, Ni, and Co in the deposit are related to both the country rock-type and the stratigraphic position of the massive ore. The highest concentrations occur in diabases, sulphide-bearing rocks and the upper part of massive ore, but the rock types themselves are no sure indication of the presence of these metals. In general, the metal concentrations are controlled by processes of partitioning of Cu, Zn, Fe, Ni, and Co between silicate, oxide and sulphide phases. The average contents of these elements in a stratigraphic column probably reflect the overall results of the evolution of the parent solution from which these elements were successively derived. The Ergani massive sulphide deposit was formed by hydrothermal solutions that travelled through and deposited their loads in discreet sheetlike fractures such as fault zones. The emplacement of the mineralizing fluids is chiefly controlled by the southeast Anatolian thrust fault and the secondary fracture systems.

Arc-related Pb-Zn Ore Deposits

The lead-zinc deposits associated with asitic and intermediate intrusive rocks of calc-alkaline and alkaline suites embrace a variety of deposit types from skarns to replacement ore and veins. The vein deposits are essentially related to polymetallic vein systems containing silver-lead-zinc (±copper) and mostly characterize the backarc environments. In many places, such vein deposits occur intermixed with the contact metasomatic ores, as seen in Keban.

Where zoning is well developed in backarc mineral districts, distal veins represent the typical epitermal vein deposits. The replacement deposits are hosted in Jurassic and Eocene carbonate rocks, which exhibit a complex history of dolomitization on a regional scale. Therefore, it is thought that they are connected with Alpine activity. The association of distinctive lead-zinc ores with alkalic and calc-alkalic igneous activity in backarc environments in southeastern Anatolia strongly suggests a tectonomagmatic control of this type of mineralization.

The Keban Pb-Zn deposit is one of the most important deposits of this type. The deposit is located about 40 km NW of the city of Elazig (*Fig. 7*) and has been well investigated by many authors (POLLAK 1957; BARNES 1963; KUMBASAR 1964 and ÇAGLAYAN 1979). Its mining history goes back to antique times when the mine probably supplied the first known lead and zinc products to nearby civilizations. It was mined on an industrial scale from 1953 to 1982 by the Turkish public company Etibank. During that time the total output of Keban was over 1.0 million metric tons of ore, producing several hundred thousand tons of lead and several hundred thousand tons of zinc metal. Today, this deposit has nearly been mined out.

The local geology is restricted to the metamorphic rocks of the Paleozoic age and intermediate intrusive rocks of the Tertiary age (*Fig. 7 and Fig. 8*). The metamorphic rocks of the Keban area are divided into lower and upper units. The lower unit, so-called Nimri Formation, consists of calc-schist, white and grey marble, brown dolomitic limestone, and recrystallized Keban limestone

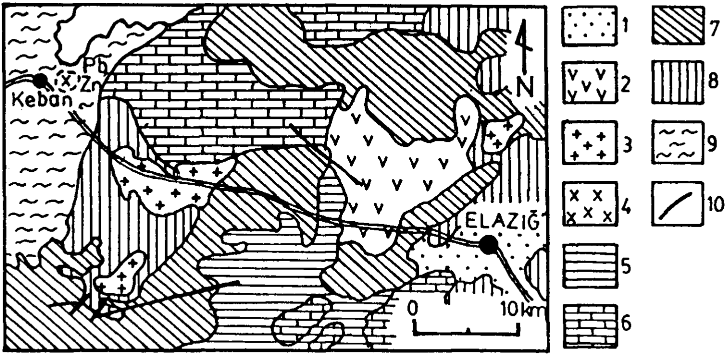

Fig. 7 Simplified geologic map of the Keban region (based on C. ERENTÖZ 1964). 1 Alluvium, 2 Basalt and dolerite, 3 Granite and granitoid, 4 Syenite porphyr, 5 Neogene sedimentary units, 6 Limestone, 7 Eocene flysch, 8 Serpentine, ultrabasic and basic rocks, 9 Gneiss, schist with marble interbedded, 10 Fault

7. ábra. Keban terület egyszerűsített földtani térképe (ERENTÖZ 1964 alapján). Jelmagyarázat: 1. alluvium, 2. bazalt és dolerit, 3. gránit és granitoid, 4. szienitporfír, 5. neogén üledékes egységek, 6. mészkő, 7. eocén flis, 8. szerpentin, ultrabázisos és bázisos kőzetek, 9. gneisz és márga betelepüléses palák, 10. törés

which were folded during the Hercynian and Alpine orogeny. The crystallized limestone, which varies in thickness from 150 to 400 m, has a number of carstic cavities. A mechanic contact has been observed at the boundary between calc-schist and recrystallized limestone.

The upper unit consists mainly of calc-phyllite, called the Delimehmet formation. This formation is unconformably underlain by the Bagdiçlar formation, consisting of the Cretaceous fylisch and various rocks of the Tertiary age. The lower part of the upper unit is mainly metaconglomerate: it contains pebbles of the lower unit rocks and is interpreted as a basal conglomerate. The thickness of the upper unit is over 1500 m. In the Keban area, there is a local non-conformity between the upper unit and the Keban limestone (KIPMAN 1976).

All the metamorphic rocks are intruded by the Keban syenite porphyr intrusion, a homogeneous and extensively faulted rock which has gradational contacts with the calc-schist and calc-phyllite. The Keban syenite porphyr intrusion is characterized by 1 to 5 mm megacrysts of K-feldspar in a fine grained groundmass which has very irregular micro structures. Its chemical composition suggests that the syenite porphyr was derived from a grano-syenitic magma and strongly foliated. It is dominantly intermediate in composition and consists of albite, oligoclase, orthoclase, sanidine, hornblende, biotite and minor pyroxene, apatite, zircon, and sphene. The main tectonic elements of the Keban area are associated with the southeast Anatolian thrust. The complicated structural pattern of the area is possibly due to recumbent folding during both the Hercynian and Alpine orogenies. The general strike directions of observed faults are NNE–ENE, and NW–WNW. The mineralization in the Keban area almost entirely seems to be associated with these faults, within which ore-bearing solutions derived from syenitic magma have deposited their loads.

The Keban area consists mainly of three economic orebodies, namely the Keban anayatak, Nalliziyaret, and Bamas mines. The Keban anayatak mineralization occurs as metasomatic type in the limestones. The main ore minerals are galena, sphalerite and pyrite. Some of the ore occurs as a vein type within fractures. The average Pb and Zn contents in the deposit are about 4.38 per cent and 4.70 per cent, respectively.

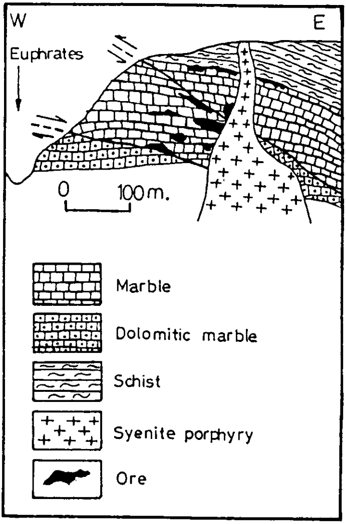

Fig. 8 Schematic cross-section of the Keban Pb-Zn deposit

8. ábra. A kebani ólom- és cinkérctelep egyszerűsített keresztszelvénye

In the Nalliziyaret mine, the mineralization is of skarn type in the contact area between limestone and syenite porphyr. The important primary ore bodies are several hundred metres below the present surface where the contact metamorphic reactions formed the ore bodies – as much as 10 m thick – that contain substantial quantities of Mo, Cu, and W. The thickness of the ore increases towards the northeast part of the area in which limestones have been locally metamorphosed to dense, hard, apple-green rocks similar to hornfels, composed principally of tremolite, chlorite, and epidote. It is important to note that these rocks are unevenly distributed and associated directly with ore. Similarly, some limestones have also been recrystallized to marble containing hydrothermal biotite and skarn minerals. The characteristic sulphide mineral assemblage of the skarn zone consists of molybdenite, chalcopyrite, and pyrite. Minor components are wolframite, bornite, magnetite, haematite, fluorite, and sulfosalts. The gangue mineral assemblage is strongly influenced by the limestone country rocks and consists mainly of garnet, epidote, quartz, calcite, dolomite, tremolite, and chlorite.

The Bamaş mineralization occurs as stockwork and vein types within the calc- schist. The characteristic mineral assemblage consists of sphalerite and galena, sphalerite, molybdenite, fluorite, and chalcopyrite. The gangue minerals are mostly quartz and calcite. The average Pb and Zn contents are similar to those of the Keban Anayatak mine.

In addition to the minerals mentioned above, the Keban Pb–Zn deposits have been noted for their Au and Ag contents and for the well-developed vanadinite crystals. The Au and Ag contents are 2.5 grammes per ton and 300 grammes per ton, respectively. The vanadinite occurrences are of no economic importance.

Avnik - Miskel iron deposits

The Avnik - Miskel iron deposits hosted in the high-grade metamorphic rocks of the Bitlis Massif are located just south of Avnik (*Fig. 1 and Fig. 2*), and are generally formed as lenses several hundreds metres long. Magnetite is the predominant ore mineral, but apatite and haematite in minor amounts accompany this mineral as a by-product. Pyrite, chalcopyrite, ilmenite, and lepidocrocite are minor components of the ore. The grades of the deposits vary from 50 to 65 per cent Fe_2O_3. The apatite-rich ore contains an average 4.42 per cent P, 0.5 per cent Ti and 0.3 per cent S. According to Ouz and others (1975), the total reserves of the deposits are over 3.0 million tons. The deposit consists of 10 separate occurrences and these are located in three zones extending to an area 9 km by 1 km wide. Taking into consideration the three zones, the total reserves are 7.64 million tons.

In the Avnik-Miskel area, apatite-rich iron deposits are mostly interbedded with gneisses and are intermediate to felsic calc-alkaline metavolcanics of the Bitlis massif; these deposits show some well-preserved porphyritic, spherulitic, and volcanoclastic textures. Some of the ore occurs in the granitoid (*Fig. 9*). The Bitlis massif is a large area of Paleozoic metamorphic rocks in the interior of the ETFB of southeastern Turkey. The Avnik-Mikel area is the western part of the massif. The southern edge of the Bitlis massif is the southeast Anatolian thrust fault, at the boundary between the Anatolian and the Arabian plates along which the Bitlis massif has been thrust southward over sedimentary rocks of the Arabian foreland (ALTINLI 1966; KETIN 1966; HELVACI 1984). The iron deposits and associated metamorphic, metavolcanic, and igneous rocks are overlain in an uneven way by micaschist and Permian marble, which were folded and metamorphosed during the Alpine orogeny. The metamorphic rocks of the massif are intruded by acid intrusive rocks (350 million years old). The metavolcanics, the granitoids, and the overlying mica schists have been extensively feldspathized and silicified.

According to HELVACI (1984), the deposits contain banded, massive, or disseminated ore and are located in a gradational zone between the gneisses and better preserved parts of the metavolcanic rocks. The massive ores are

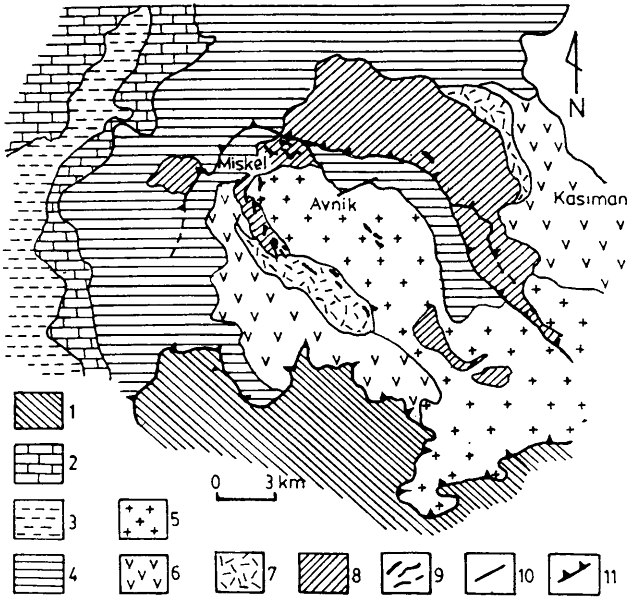

Fig. 9 Geological map of the Avnik-Miskel deposits (After HELVACI 1984). 1 Miocene flysch, 2 Marble, 3 Marble and schist, 4 Mica schist, 5 Granite and granitoid, 6 Metavolcanic rocks and metaaglomerate, 7 Metatuff, metavolcanic rocks and amphibolite, 8 Gneiss, 9 Apatite-rich banded and massive iron ore, 10 Fault, 11 Thrust fault

9. ábra. Az Avnik-miskeli telep földtani térképe (HELVACI 1984 szerint). 1. miocén flis, 2. márga, 3. márga és pala, 4. csillámpala, 5. gránit, és granitoid, 6. metavulkáni kőzetek és metaagglomerátum, 7. metatufa, metavulkáni kőzet és amfibolit, 8. gneisz, 9. apatitban gazdag szalagos és tömeges vasérc, 10. törés, 11. feltolódás

commonly fine-grained and the banded ore zones show magnetite–apatite laminations. Massive and banded ores range in thickness from several centimetres to several metres and form a lens-like orebody that is generally concordant with the wall rocks. Disseminated iron ore mainly occurs in the gneiss and the metavolcanic rocks and appears in the form of euhedral to subhedral grains that are relatively homogeneously distributed through the country rock.

In general, the rocks of the Avnik-Miskel area are divided into two sub-units, (1) The lower unit is a series of intermediate to felsic calc-alkaline metavolcanic rocks, (2) The upper unit consists of the metamorphic and sedimentary rocks.

The interbedded banded and massive apatite-rich iron deposits are associated with the lower unit. This unit consists of quartz-feldspar gneiss, amphibole-rich gneiss and amphibolite, metavolcanics-metatuffs, and metavolcanics-metaagglomerates. The gneisses alternate with amphibolite-rich gneiss and amphibolite. The rocks are strongly foliated, recrystallized and albitized felsic metavolcanics. The lower unit, as a whole, is intruded by the Avnik granitoid, a heterogeneous and strongly albitized rock, and by the Yayla granite, which has sharp contacts with the surrounding rocks. The upper unit consists of garnet-biotite micaschist, grey fossiliferous Permian marble, marble-schist intercalations and white marble. There is local non-conformity between the garnet-biotite mica schist and grey marble.

The Avnik-Miskel apatite-rich magnetite deposits are very closely associated with a dominantly intermediate to felsic calc-alkaline volcanic sequence. The formations of magnetite and apatite are initially linked with the immiscible liquids that were separated during the fractional crystallization of the magmas that produced the Avnik-Miskel volcanic rocks. As a result of this, the magmatic injections into fractures have caused the Paleozoic mineralizations in the felsic volcanic rocks. During the intrusion of granitoids, the deposits have been remobilized to stockworks by fluids derived from the granitoids. Both rare earth element contents and the Sr isotope data support the remobilization process (LEEMAN 1983; HELVACI 1984). These and other geochemical data, such as negative Eu anomalies and lack of negative Ce anomalies, indicate that the deposits are neither sedimentary nor volcanic-exhalation type in origin. In general, the rare earth element values are similar to those of the metavolcanic rocks, suggesting a genetic relationship. On the other hand, rare earth element patterns in apatites of the iron deposits are very similar to those of apatites that would crystallize from a hypothetical mafic magma in immiscible liguid equilibrium with the Avnik-Miskel volcanics (PARAK 1973; HELVACI 1984). When all the geochemical results, together with field evidence, are considered, it can be said that the Avnik-Miskel deposit is a stockwork iron deposit, remobilized by fluids derived from a magma of granitoid.

Phosphate

The low-grade phosphate occurrences hosted in the Turonian series – the so-called Tat Formation – lie about 10 km west of Mazda and contain an average grade of 20.0 per cent P_2O_5. The most common ore minerals are dahllite and collophanite (SHELDON 1964). The Mazda phosphate deposits occupy an area of about 4 sq. km and consist of various phosphate zones varying in thickness from several centimetres to 12 metres. In some places, these phosphate zones are underlain by sedimentary rocks of an average 85 metre thickness that contain 2 to 5 per cent P_2O_5. In particular, the Tasit formation has been noted for the U, V, Mo, Cd, In and Y that show remarkable concentrations throughout the formation (BÜRKÜT 1977). In general, these deposits are similar to those of Morocco and Algeria, but the content of P_2O_5 is somewhat lower. The average P_2O_5 content of the ore is approximately 20.0 per cent. Although total reserves have not been estimated, the low-grade reserves are as much as 2.0 million tons.

The phosphate deposits of the region are marine concretionary beds in which the phosphates occur disseminated in small quantites, in part as small concentrations, in part remaining in shell fragments. In many places, they appear in more concentrated form and characteristically contain the forms of nodules, or concentrations, in part of concentric and fibrous structure. The nodules often have a shell nucleus and, as a result of enrichment, may contain more phosphate in the peripheral than in the central parts. The deposits are developed at moderate depths, or in the shore facies where the marine life is most abundantly developed. Thus, it is believed that the phosphor initially is in the form of ammonium phosphate in the organic matter and then converted to calcium phosphate by chemical reactions. These processes are likely to continue for some time, at least after the sedimentation, in the still soft sediments. Although there is some evidence of enrichment, due to weathering the Mazda phosphate deposits are directly related to the segregation of phosphoric acid by the inhabitants of the sea.

Asphaltite occurrences

The Sirnak and Silopi asphaltite occurrences in the southeastern part of Anatolia are genetically related to the formations of the Upper Cretaceous and Pliocene ages and occur along a length of several hundred kilometres (ÜNALAN 1990). In the area they appear to be directed towards northeast–southwest. The Silopi asphaltite occurrences lie in the Gürçüş Formation of Eocene age (*Fig. 10*). The ash and sulphur contents of the deposits vary from 30 to 60 per cent and from 4 to 8 per cent respectively. Due to high ash and sulphur contents, their calorific values are always low and range from 3000 to 5000 Kcal/kg. In addition, they contain 0.2 to 0.5 per cent V_2O_5, 0.2 to 0.6 per cent NiO, 0.1 to 0.8 per cent MoO_3 and 60 to 500 ppm U_3O_8. The conversion of the asphaltites to synthetic natural gas seems to be the best way to use them for commercial purposes. On the other hand, the trace elements mentioned above can be produced from their ashes as a by-product. In the light of the studies conducted up to now, it can be said that the total reserves are more than 100 million tons.

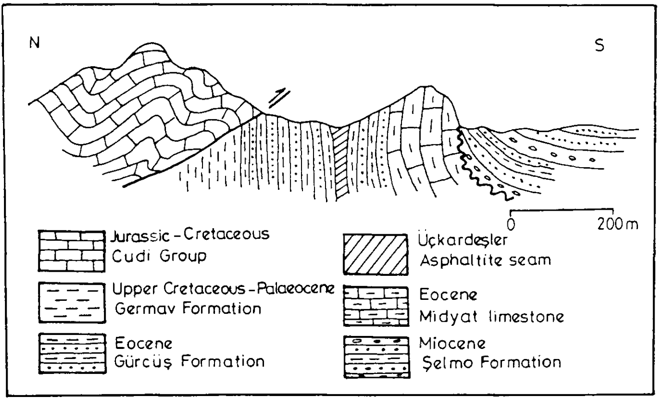

Fig. 10 Cross-section of the Silopi Asphaltite occurrences (after ÜNALAN 1990)

10. ábra. A silopi aszfaltit előfordulás keresztszelvénye (ÜNALAN 1990 szerint)

Conclusions

The magmatic mineralizations associated with the southeast thrust fault are characterized by a wide distribution in both geological time and space, and they occur in large- and medium-sized deposits. The chromite and massive sulphide deposits of the region form the most important mineralizations with respect to the grade, reserve and minable ore potential.

The sedimentary deposits have a restricted distribution in geological time and are usually formed in only small deposits or prospects. The deposits occur as non-metallic mineralization in limestone, rare sandstone and siltstone. The Mazidağ phosphate deposit, hosted in the fossiliferous limestone, is a well-established deposit of this subtype. The deposit is the only large phosphate deposit known in Turkey, but its prospects are of low economic importance, due to the grade ore.

The metamorphic massifs of southeastern Anatolia have been noted for their iron deposits. Despite the many problems which still exist, it is thought that these deposits are associated with magmatic processes. However, the metamorphic massifs have not been investigated in detail in many respects. Probably, there are still large areas that may contain the iron deposits of a magmatic type as well as various metallic mineralizations. Similarly, the detailed geological and geochemical studies, focused on ultramafic and mafic intrusive rocks, would expose the mineral potential of the region in terms of massif sulphide and chromite deposit.

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