Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. **16**, 2007, pp. 57-76.

Sulfur and Lead Isotope Investigations of the Carbonate-Hosted Pb-Zn Deposits in the Yahyalı Region, Kayseri, Southern Turkey

OSMAN KOPTAGEL[1], ULVİ ULUSOY[2] & ANTHONY E. FALLICK[3]

[1] Cumhuriyet University, Department of Geological Engineering, TR–58140 Sivas, Turkey
(E-mail: koptagel@cumhuriyet.edu.tr)
[2] Cumhuriyet University, Department of Chemistry, TR–58140 Sivas, Turkey
[3] Scottish Universities Environmental Research Centre, East Kilbride, Glasgow G75 0QF, UK

Abstract: Carbonate-hosted Pb-Zn deposits are common in the Yahyalı region (Taurus Belt) with galena the most abundant sulfide mineral. The mean $\delta^{34}S$ values for Göynük, Celaldağı Desandre, Demircilik, Tekke, Havadan and Suçatı deposits were +0.2±0.5, +9.3±0.8, +10.7±1.3, +10.8±1.3, +11.5±2.4, –4.2±0.4‰, respectively. The mean $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ measurements for the studied deposits were 18.968±0.005, 15.741±0.005 and 39.074±0.016 for Göynük, 18.702±0.006, 15.715±0.006 and 38.883±0.021 for Celaldağı Desandre, 18.618±0.020, 15.727±0.008 and 38.852±0.032 for Demircilik, 18.808±0.017, 15.751±0.028 and 38.983±0.166 for Suçatı. The sulfur isotope systematics imply that sulfur originated from a mixture of different sources for the Göynük and Suçatı deposits, but was probably derived from seawater for the others. The distribution of lead isotopic ratios had a well-defined cluster for each deposit, but no linear trend defining enrichment in radiogenic lead.

Key Words: sulfur isotopes, lead isotopes, carbonate-hosted Pb-Zn deposits, Turkey

Yahyalı Bölgesindeki Karbonat Yan Kayaçlı Pb-Zn Yataklarının Kükürt ve Kurşun İzotopu İncelemeleri, Kayseri, Güney Türkiye

Özet: Yahyalı yöresinde (Toros Kuşağı) çok sayıda karbonat-yankayaçlı Pb-Zn yatağı yer almaktadır. Galenit yataklarda en bol bulunan sülfür mineralidir. Göynük, Celaldağı Desandre, Demircilik, Tekke, Havadan ve Suçatı yataklarındaki galenitlerin $\delta^{34}S$‰ ortalamaları, sırasıyla +0.2±0.5, +9.3±0.8, +10.7±1.3, +10.8±1.3, +11.5±2.4, –4.2±0.4 bulunmuştur. Bunlardan $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ ve $^{208}Pb/^{204}Pb$ oranları araştırılan yatakların ortalamaları Göynük için 18.968±0.005, 15.741±0.005 ve 39.074±0.016; Celaldağı Desandre için 18.702±0.006, 15.715±0.006 ve 38.883±0.021; Demircilik için 18.618±0.020, 15.727±0.008 ve 38.852±0.032; Suçatı içinse 18.808±0.017, 15.751±0.028 ve 38.983±0.166 dır. Kükürt izotopları incelemeleri, Göynük ve Suçatı yataklarındaki kükürdün farklı kaynaklardan türemiş kükürt izotoplarının karışım ürünü, diğerlerinin ise deniz suyu kökenli olduğunu göstermektedir. Galenitlerdeki Pb izotop oran değerlerinin dağılımı her bir yatak için homojen bir kümeleşme sunarken, radyojenik kurşun zenginleşmesi bakımından bir çizgisellik göstermemektedir.

Anahtar Sözcükler: kükürt izotopları, kurşun izotopları, karbonat yankayaçlı Pb-Zn yatakları, Türkiye

Introduction

Pb-Zn deposits have been mined in Turkey since 7000 BC (Akyol & Pehlivanoğlu 1985). Over 500 Pb-Zn occurrences known in Turkey fall into six generally acknowledged genetic types. The Kuroko (VMS) type is found primarily in northeastern Turkey, the Cyprus (VMS) type primarily in southeastern Turkey, the Red-Bed (sandstone hosted type) is in central Turkey, contact metasomatic (skarn/CRD) deposits are found in central and eastern Turkey, vein-type deposits are found in various locations, and the carbonate-hosted (MVT) type are found dominantly in the south of Turkey. Geological evaluations of Pb-Zn deposits are mostly based on field observation, ore microscopy and some geochemistry. Studies of isotopic systematics are rare and have only been performed for the Kuroko (VMS) type (Gökçe & Spiro 2000), the Cyprus (VMS) type (Koptagel *et al.* 1998), and for the vein-type deposits (e.g., Erler 1979; Efe 1993; Bozkaya 2001), but not for the others.

Carbonate-hosted Pb-Zn deposits are common in the Taurus Mountain Belt, which runs from west to east in the south of Turkey and is geographically subdivided into three parts: the western, the middle and the eastern Taurus Mountains (Figure 1). The boundary between the middle and the eastern part is known as 'Aladağlar' or the 'Zamantı Pb-Zn Province.' Evidence such as primitive hand tools and mining remains confirm that the region has an ancient mining history extending over thousands of years. Demir & Bingöl (2000) reported that the production of Pb-Zn ore from the district was about 2.4 million tonnes grading 21.16% Zn and 3.64% Pb.

The region attracts geological attention due to the widespread occurrence of ore deposits and for clues they may offer for the geological evolution of the area. The basic geological features and evaluation of the area have been comprehensively presented by Blumenthal (1952), Özgül (1976), Tekeli (1980), Tekeli *et al.* (1984) and Ayhan & Lengeranlı (1986).

There are several hypotheses regarding the origin of the deposits in the Aladağlar region. These can be grouped into VMS, CRD/skarn, MVT, syntectonic metamorphic fluids or basinal fluids (Vaché 1964; Türkünal 1965; İskit & Vohyzka 1965; İskit 1967a, b; Ayhan 1983; Ulakoğlu 1983; Tüzün 1985; Lengeranlı 1986; Çevrim *et al.* 1986; Lengeranlı *et al.* 1986; Çevikbaş & Öztunalı 1991; Çopuroğlu 1996; Demir & Bingol 2000). These hypotheses are based only on field

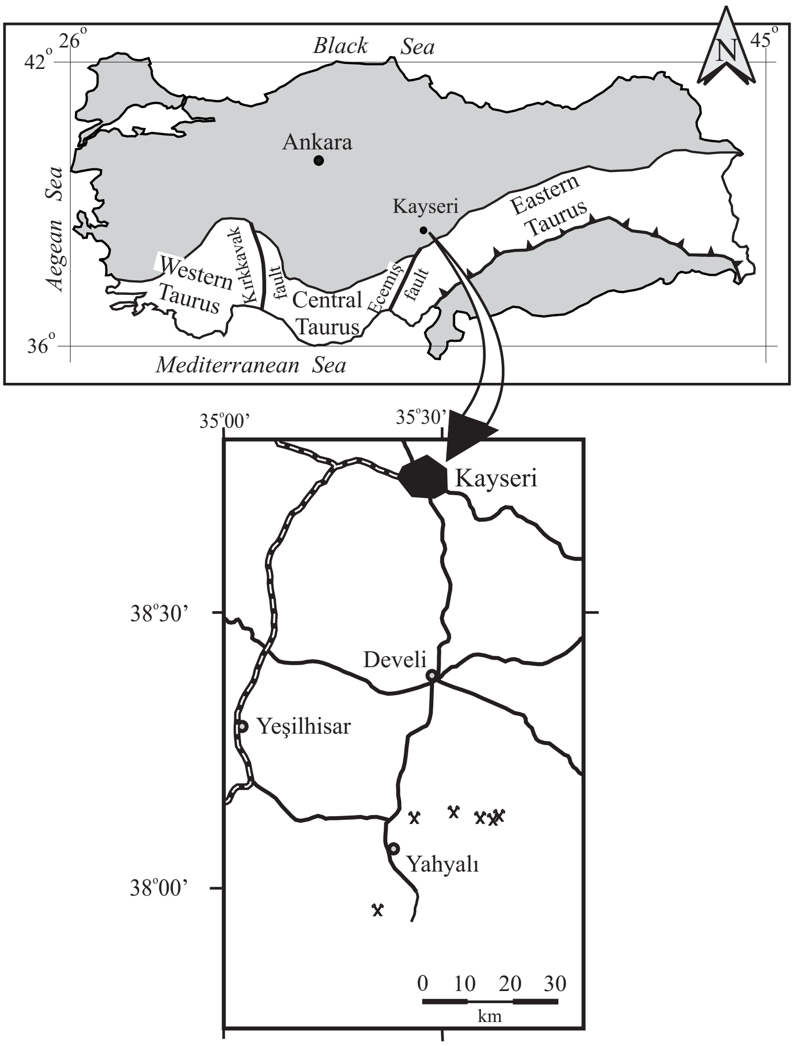

Figure 1. Location maps of the studied Pb-Zn deposits in Taurus Mountain Belts.

observations and ore microscopy; a more complete understanding and genetic models also require consideration of isotopic systematics.

Carbonate-hosted Pb-Zn deposits are common around the town of Yahyalı, in the north of the Zamantı Pb-Zn Province. The aim of this investigation is to use a new approach to understand how Pb-Zn deposits in the Yahyalı region formed. To accomplish this, the relations between ore and host rock, type of deposition, ore microscopy, and sulfur and lead isotope systematics of sulfide minerals are all considered.

Geology

Systematic studies of the geology of the Yahyalı region originated with Blumenthal (1952) and were followed by Özgül (1976), Tekeli (1980), Tekeli *et al.* (1984) and Ayhan & Lengeranlı (1986). Blumenthal (1952) classified the Mesozoic and Palaeozoic limestones with reference to their tectonostratigraphic relations, and divided them into two groups: the 'Beyaz Aladağ Nappe' and 'Siyah Aladağ Nappe.' In contrast, Özgül (1976) defined the rock groups in the Taurus Belt from west to east as the Bolkardağı, Aladağ, Geyikdağı, Alanya, Bozkır and Antalya units in relation to their stratigraphic and metamorphic features, rock types and structural positions. Tekeli (1980) and Tekeli *et al.* (1984) studied the nappe structures of the Lower Devonian to Lower Cretaceous platform-type carbonate rocks around Aladağlar; they delineated from lower to upper the Yahyalı, Siyah Aladağ, Mineratepeler, Çataloturan, Beyaz Aladağ, Ophiolitic Mélange and Aladağ ophiolite nappes (Figure 2). According to Tekeli (1980), the structural evolution of the Aladağlar region occurred in three stages. The first is

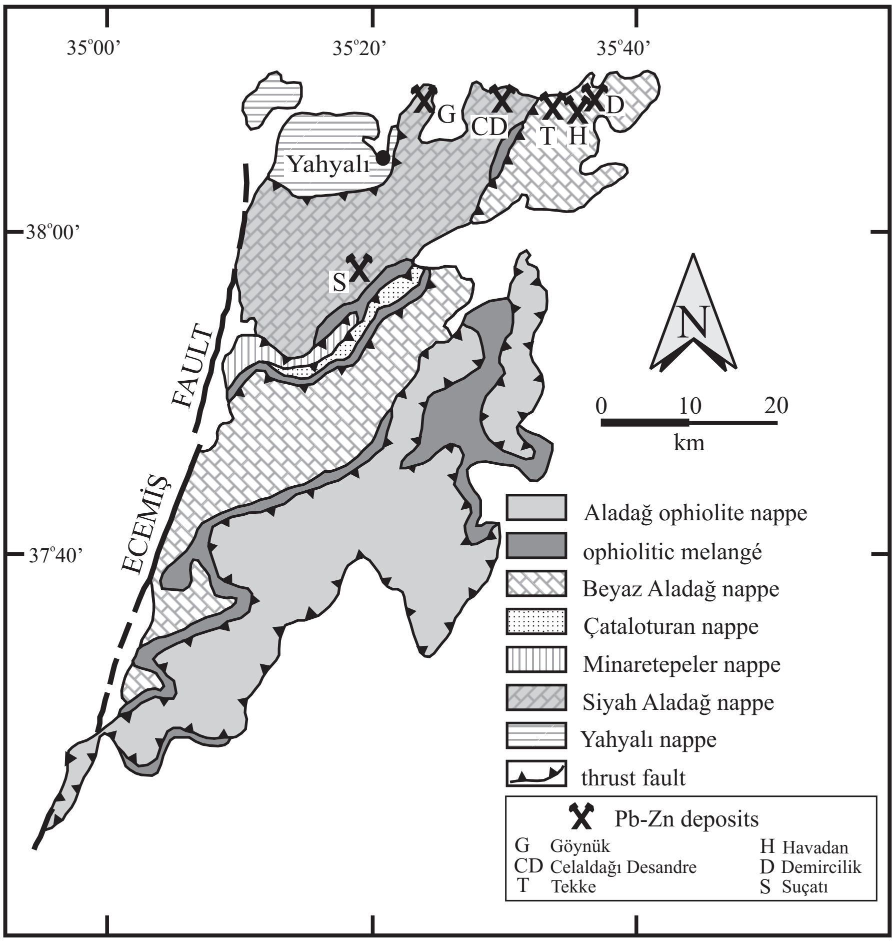

Figure 2. Simplified map of the Aladağ region structural unit (Tekeli 1980; Tekeli *et al.* 1984).

the Late Triassic to Early Cretaceous deposition of carbonate in a shelf environment at a stable continental edge; the second is Late Cretaceous collapse of the carbonate platform by block faulting; and the third is Maestrichtian movement of ophiolitic rocks into the Late Cretaceous basin with nappe development at the continental margin. Ayhan & Lengeranlı (1986) studied the Yahyalı, Siyah Aladağ, Mineratepeler and Çataloturan nappes and described their tectonostratigraphic features in detail.

The mineral deposits in the Yahyalı region are situated in the Siyah Aladağ and Beyaz Aladağ nappes. Geological maps showing lithologic units and the general features of rocks around the deposits are provided in Figures 3, 4 & 5, and Table 1.

Distribution of the Deposits and Mineralogical Features

One of the deposits in the Yahyalı region is near Ağcaşar Village at the contact of the Upper Permian Zindandere and Lower–Middle Triassic Küçüksu formations; two deposits situated around Denizovası and Havadan villages are in the Upper Permian Zindandere Formation, and the others are in the Lower Cretaceous Uzunkoltepe Formation. South of Yahyalı is a deposit located in the Upper Devonian–Upper Permian Siyah Aladağ Formation.

Field observations suggest that the deposits near Yahyalı can be grouped generally into two types: those concordant with their host rocks, and fault-related deposits. The deposits near to Ağcaşar Village (Göynük deposit) and the ones around Denizovası and Havadan villages 500 m south of Celal Mountain (Celaldağı Desandre deposit) are concordant, whilst all the others are fault-related.

The Göynük deposit, situated at the contact between the Upper Permian Zindandere Formation and Lower–Middle Triassic Küçüksu Formation in the eastern part of the syncline axis trending N15°E, is concordant with the sedimentary layering. The strike of the ore body is parallel to the syncline axis and dips 20–25 °NW (Figure 6).

The ore body of the Celaldağı Desandre deposit strikes N60°E and dips 40°NW. The main structural features around the deposits include common strike-slip faults and rare normal faults. Faults striking NW–SE are younger than those trending NE–SW.

The concordant deposits have similar features with respect to bedding and sharpness of the contacts with their host rocks. The ores have a laminated inner structure that is concordant with the host rocks. The thickness of the ore bodies varies from 60–70 cm to a few meters. The ores are coloured yellowish-brownish-reddish and are dominated by carbonate and sulfate ore minerals due to oxidation of primary sulphides. Galena is the only sulfide mineral observed macroscopically. Its presence is concordant with the host rocks and layers, ranging from a few millimetres to centimetres and rarely up to 10–12 cm in thickness. Small galena grains (1–2 mm to several cm in diameter) are also seen as disseminations. The ore bodies are offset by small faults, which postdate the mineralization. The Göynük and Celaldağı Desandre Pb-Zn deposits in the Yahyalı region are probably Sedex-type because of their concordant ore-wall-rock relationship (Koptagel *et al.* 2005).

The fault-related deposits are observed in normal or strike-slip faults of various orientations (Figure 7). Contacts between ore and wall rocks are rather sharp. Most occurrences have karstic cavities filled by the ore. As in the concordant deposits, all fault-related deposits have similar features with regard to bedding and sharpness of host rock contacts. The thickness of ore bodies varies from a few tens of centimetres to metres. The ores are dominated by carbonate or sulfate minerals, have a soil-like appearance and colours ranging from brownish to reddish or yellowish. Galena is the only sulfide mineral on the macroscopic scale and is seen in the ore not only as layers but also as accumulations within the size range of 0.1 cm to 30 cm. Excessive alteration causes variations in the continuity and thickness of galena levels. In faults that developed after ore deposition, clays are also seen with thicknesses ranging from a few mm to tens of cm, and containing ore mineral grains. These deposits resemble the Irish-type, but Hitzman *et al.* (2003) have also generally classified the carbonate-hosted Pb-Zn deposits in Zamantı province as MVT.

The microscopic features are similar in both types of deposit with galena, sphalerite, pyrite and marcasite as the primary sulfide minerals, while smithsonite, cerussite, anglesite, goethite, lepidocrocite, covellite and Ag-sulfosalts are secondary ones. Calcite, dolomite and quartz are the observed gangue minerals. Galena is the most abundant sulfide mineral. Undulation of the triangular polishing pits in galena might be considered as

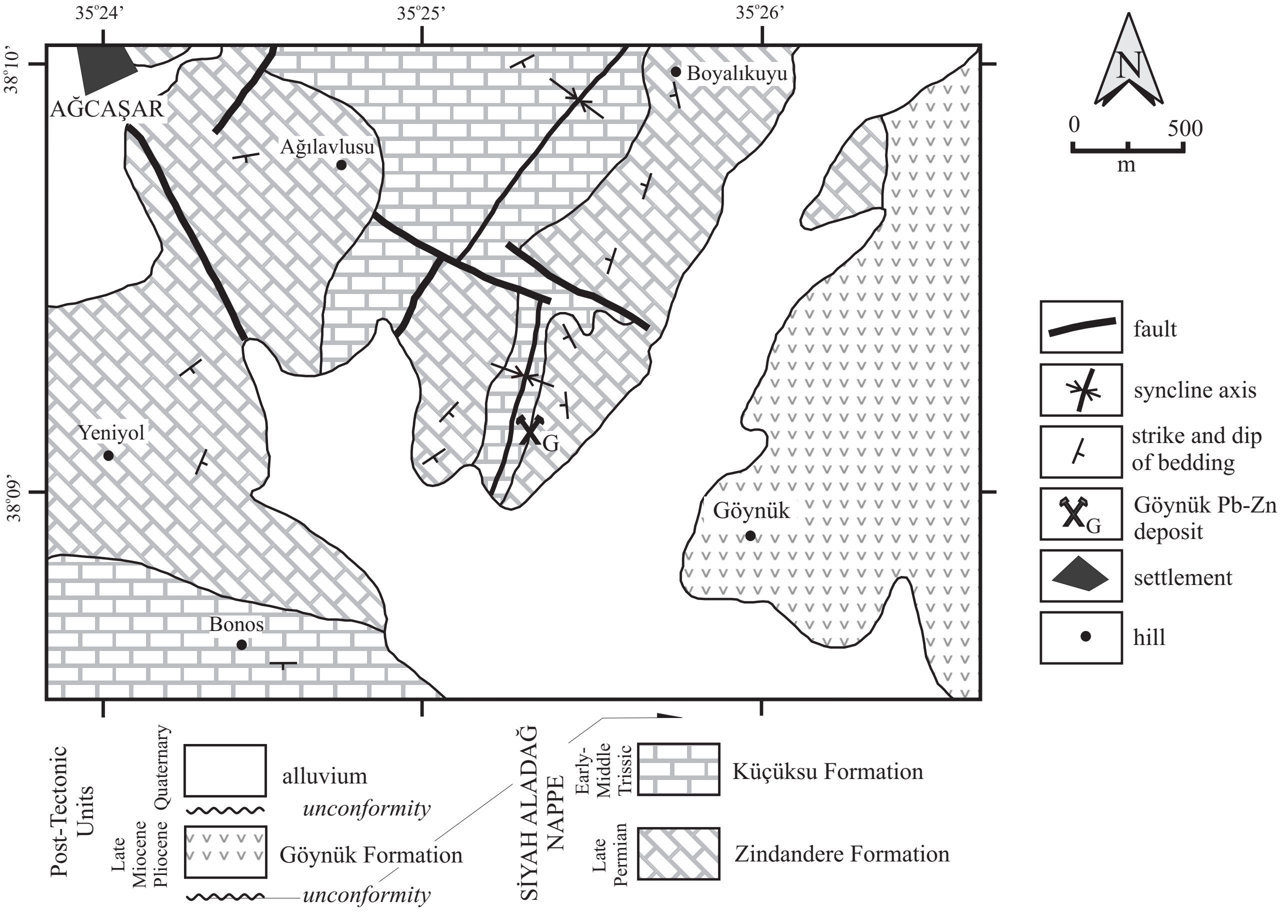

Figure 3. Geological map of the close vicinity of Ağcaşar Village (modified from Lengeranlı 1986).

evidence for deformation effects. Some galena contains unaltered pyrite and marcasite inclusions. Sphalerite, pyrite, marcasite and covellite are rare minerals. Smithsonite, ranging in size from a few tens of μm to 1 mm, is the most abundant secondary mineral in the ores and contains sphalerite relicts in variable proportions and size. Cerussite and anglesite are seen together within fractures in galena and along grain borders. They form mostly in concentric growths, but individual growths containing galena relicts are also seen. Goethite and lepidocrocite are formed from pyrite and marcasite. Covellite and Ag-sulfosalts are usually observed in galena and rarely in sphalerite. The microscopic observations suggested that smithsonite, anglesite-cerussite and goethite-lepidocrocite are the alteration products of sphalerite, galena and pyrite-marcasite, respectively, whilst covellite is produced both from galena altering to cerussite-anglesite and from sphalerite altering to smithsonite.

Hitzman *et al.* (2003) classified nonsulfide zinc deposits into two broad genetic categories, supergene deposits and hypogene deposits. These are genetically different and each deposit type has a characteristic and distinctive mineralogy. Supergene deposits have three subtypes: direct-replacement deposits, wall-rock replacement deposits and karst-fill deposits. Smithsonite is the most dominant mineral in these type deposits. Hypogene deposits have two subtypes: structurally

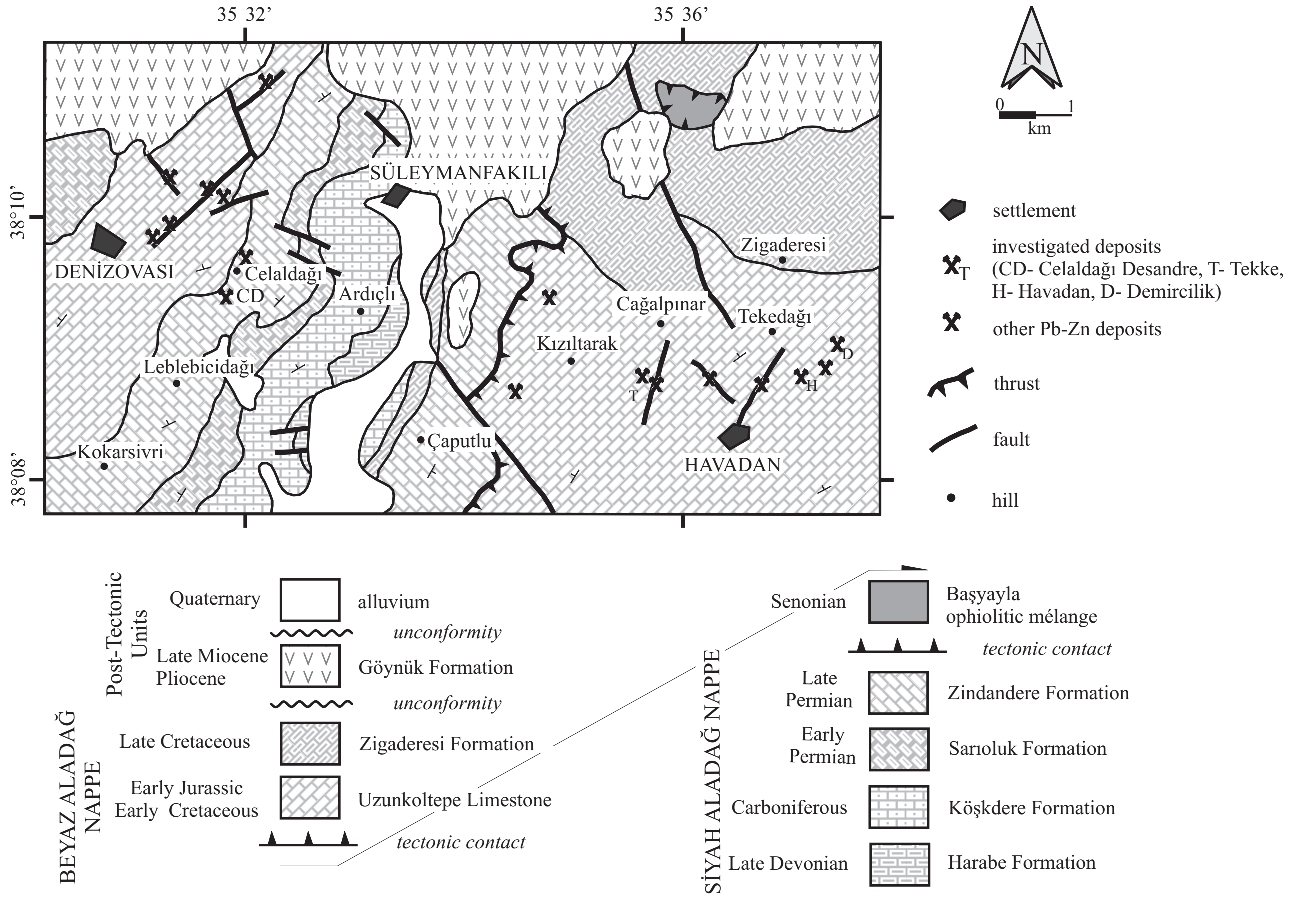

Figure 4. Geological map of the close vicinity of Denizovası and Havadan villages (boundaries of Palaeozoic units designed from Ayhan & Lengeranlı 1986; Lengeranlı *et al.* 1986).

controlled deposits and stratiform deposits. The characteristic and perhaps defining mineral of hypogene nonsulfide zinc deposits is abundant willemite. Yahyalı nonsulfide zinc (and lead) deposits should be considered supergene deposits in the classification of Hitzman *et al.* (2003), since smithsonite is the most abundant mineral (along with the absence of willemite) in the deposits. The deposits have the features of simple mineralogy and deposition observed in karstic cave systems and could be in both 'wall-rock replacement' and 'residual and karst-fill' deposits of its subtypes.

Isotope Studies

Six of the deposits in the Yahyalı region were examined for sulfur and lead isotope systematics. Two were the concordant deposits (Göynük and Celaldağı Desandre deposits) and the others were fault-related (Demircilik, Tekke and Havadan deposits north of Havadan Village and Suçatı deposits south of Yahyalı).

Sulfur and lead isotope analyses were performed only on galena samples since its abundance and microscopic features were more suitable than the other coexisting sulfide minerals in the paragenesis. Special care was taken in sampling galena from both the concordant and fault-related deposits, so that the samples excluded grains affected by any post-mineralization geochemical processes. The samples were finely crushed and galena was separated by hand pickings from the other minerals under a binocular microscope.

Sulfur isotope analysis was performed in the SUERC (Scottish Universities Environmental Research Centre,

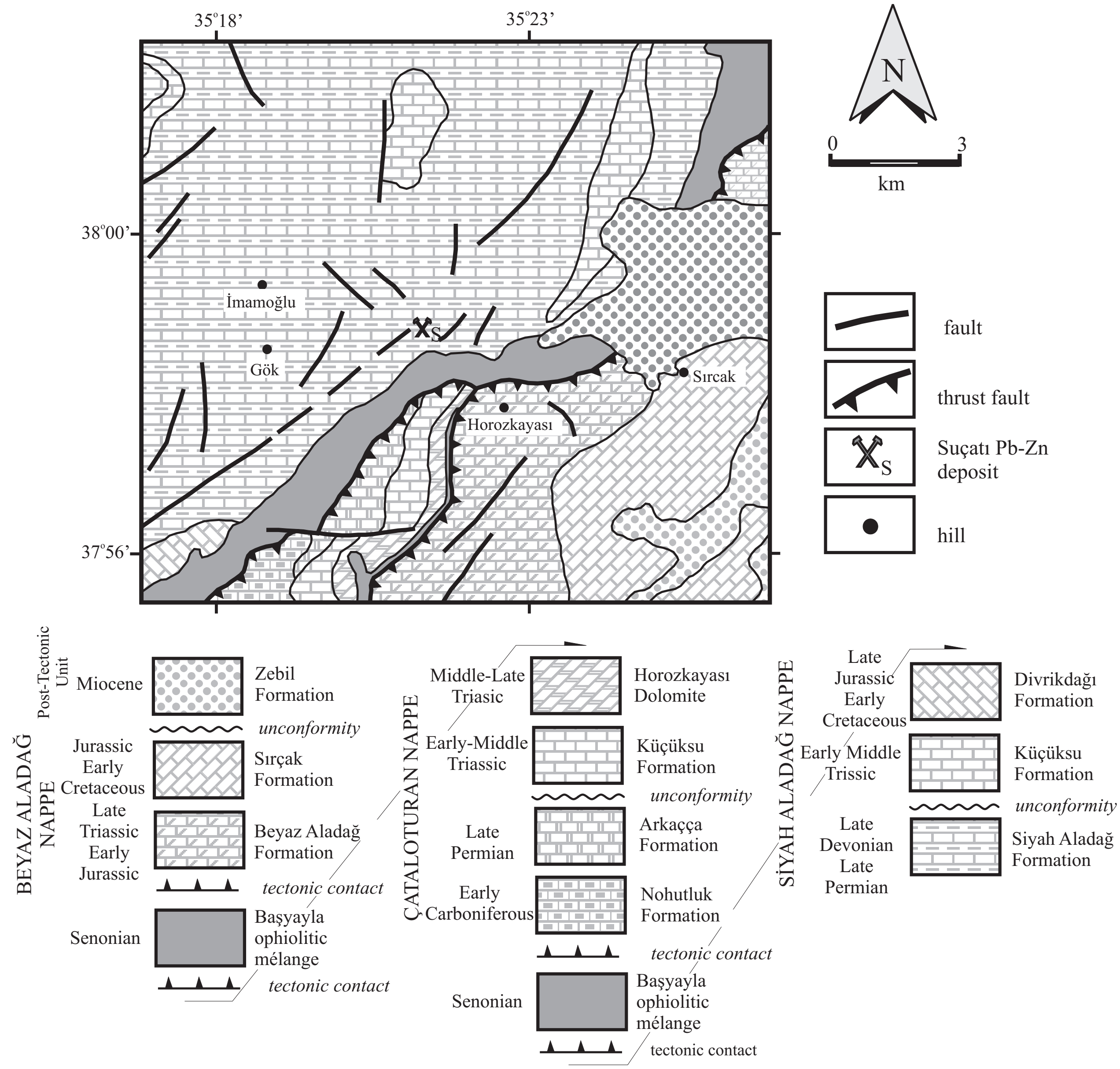

Figure 5. Geological map of the close vicinity of the Suçatı Deposit (modified from Ayhan 1983; Tekeli *et al.* 1984).

Scotland) with a SIRA II mass spectrometer and ACTLABS (Activation Lab. Ltd., Canada) with a VG 602 Isotope Ratio Mass Spectrometer. The SUERC and ACTALABS use methods described by Hall *et al.* (1987) and Ueda & Krouse (1986). The results are presented in standard $\delta^{34}S$ notation relative to the Canyon Diablo Troilite (CDT) standard. Overall precision is ±0.2‰ (1σ) or better.

Lead isotope ratio measurements were also performed by ACTLABS using a Finnigan MAT-261 multicollector mass spectrometer. The Pb isotope composition was corrected for mass fractionation calculated from replicate measurements of Pb isotope composition of the NBS SRM-982 standard. External reproducibility of lead isotope ratios of $^{206}Pb/^{204}Pb$=0.1%, $^{207}Pb/^{204}Pb$= 0.15% and $^{208}Pb/^{204}Pb$=

Table 1. Lithological features of the rocks in closed surrounding of Pb-Zn deposits

Formation	Lithologic Features	Age
Siyah Aladağ	limestone; thin, medium and thick bedded; grey-yellow-brown ; shale interbedded	Late Devonian – Late Permian
Harabe	siltstone; cross-bedded; light greenish and grey-brown; dark coloured limestone interbedded	Late Devonian
Nohutluk	limestone with chert; thin bedded; dark grey; tuff interbedded at bottom levels	Early Carboniferous
Köşkdere	limestone with chert; thin bedded, medium and thick bedded; containing plenty of fossils; grey; quartzite interbedded at bottom levels	Carboniferous
Sarıoluk	limestone; medium and thick bedded; light brown and grey; quarzite at upper levels	Early Permian
Arkaçça	limestone with chert nodules; thin and medium bedded; dark grey	Late Permian
Zindandere	limestone and dolomitic limestone, thin and thick bedded; dark grey and black; marl and mudstone interbedded	Late Permian
Küçüksu	partly dolomitic limestone, thin bedded; grey; marl, siltstone and mudstone interbedded	Early – Middle Triassic
Horozkayası	dolomitic limestone and dolomite, thick bedded or massive; dark grey and grey	Middle – Late Triassic
Beyaz Aladağ	dolomite and dolomitic limestone; medium and thick bedded; light grey	Late Triassic – Early Jurassic
Uzunkoltepe	dolomitic limestone, dolomite and chert-interbedded limestone; medium and thick bedded; light grey, brownish and beige	Early Jurassic – Early Cretaceous
Sırçak	massive limestone; yellowish and whitish	Jurassic – Early Cretaceous
Divrikdağı	limestone in thin and medium layered; grey; clay interbedded	Late Jurassic – Early Cretaceous
Zigaderesi	lenticular chert-interbedded limestone, bedded, light grey-beige	Late Cretaceous
Başyayla ophiolitic mélange	serpentinite, serpentinized harzburgite and dunite	Senonian
Zebil	conglomerate, sandstone and mudstone alternation	Miocene
Göynük	basaltic aglomera, tuff and volcanic ash	Late Miocene – Pliocene

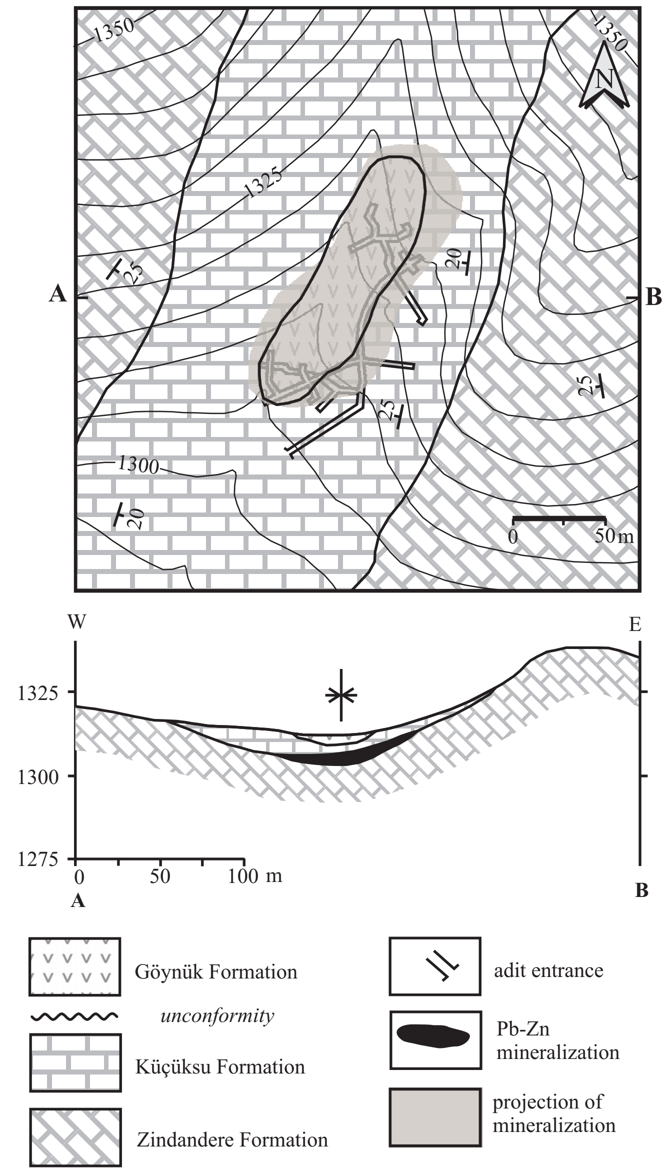

Figure 6. Detailed geological map of the Göynük Pb-Zn deposit.

0.2% (at the 2σ level) has been demonstrated through multiple analyses of standard BCR-1. To minimize the effect of mass fractionation the measurement of the Pb isotope compositions in galena were carried out at constant (and equal to those measured in NIST SRM-982) lead concentrations.

Sulfur Isotope Systematics

A total of 60 galena samples were analyzed and the results are provided in Table 2 and summarized in Figure 8. The $\delta^{34}S$ values are within the range from –0.5 to +0.9‰ (mean= 0.2±0.5, 1σ, n= 14) for Göynük, from +8.4 to +10.9‰ (mean= 9.3±0.8, 1σ, n= 15) for Celaldağı Desandre, from +8.0 to +12.2‰ (mean= 10.7±1.3, 1σ, n= 8) for Demircilik, from +8.9 to +12.4‰ (mean= 10.8±1.3, 1σ, n= 7) for Tekke, from +8.1 to +15.1‰ (mean= 11.5±2.4, 1σ, n= 8) for Havadan and from –3.7 to -4.7‰ (mean= -4.2±0.4, 1σ, n=8) for Suçatı. The $\delta^{34}S$ results allow classification of the deposits into three groups (Figure 6): (i) Celaldağı Desandre (Late Permian host rock), Tekke, Havadan and

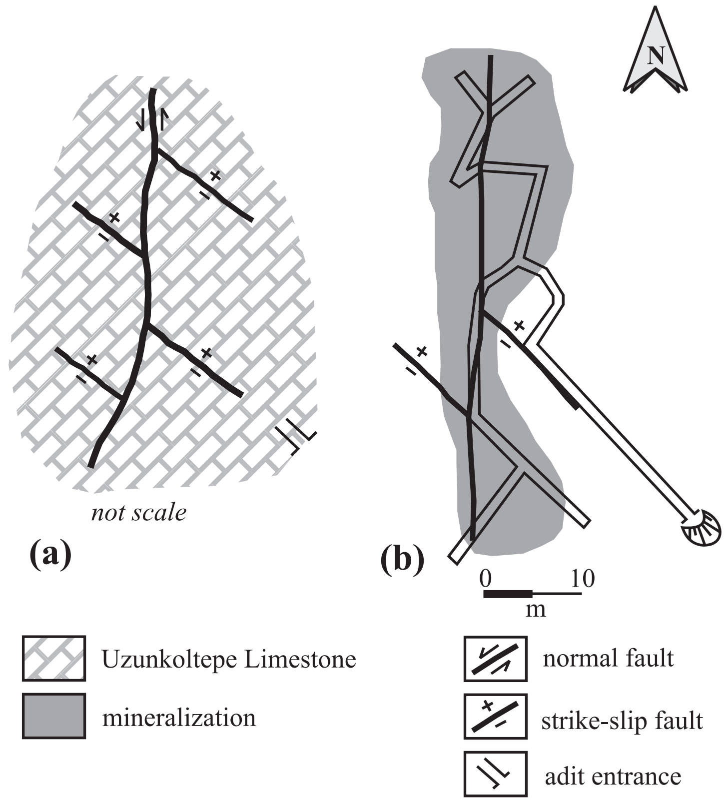

Figure 7. Mineralization and related faulting in the Tekke Pb-Zn deposit, at surface (a) and underground (b).

Demircilik (Lower Jurassic–Lower Cretaceous host rock), (ii) Göynük (Upper Permian–Lower Middle Triassic host rock) and (iii) Suçatı (UpperDevonian–Upper Permian host rock).

The relationship between the mean $\delta^{34}S$ value for each group (except Celaldağı Desandre) and the ages of host rocks of the deposits is noteworthy. Host-rock ages of the fault-related deposits cover a very wide time scale; the host rocks of the Suçatı deposit are Upper Devonian–Upper Permian, whilst those of the Tekke, Havadan, and Demircilik deposits are Lower Jurassic–Lower Cretaceous. Furthermore, the youngest lithologic unit in which ore is absent is Upper Cretaceous. This indicates that the likely emplacement age was Late Cretaceous and contemporary with collapse of the carbonate platform and the onset of nappe development. The relationship between time period and $\delta^{34}S$ values should provide evidence for the geological/geochemical conditions and processes over this long time interval.

Lead Isotope Systematics

Deposits preferred for lead isotope analysis were selected by considering the host rock relations, age of the host rocks, tectonostratigraphic features and geographic distribution, together with the preliminary results of sulfur systematics: the Celaldağı Desandre, Demircilik, Göynük and Suçatı deposits were chosen and a total of 20 galena samples, 5 samples for each deposit, were analyzed. The results of isotopic ratio measurements are provided in Table 2.

Plots of $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ are provided in Figure 9. The isotopic ratios cluster for each deposit, but there is no a linear trend defining enrichment in radiogenic lead. There were no systematic relations between the Pb isotopic ratio values and geographic locations, ages of wall rocks, types of deposit, tectonostratigraphic features or $\delta^{34}S$ values (Table 3).

Lead isotope data of galena from the Yahyalı Pb-Zn deposits are plotted for $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$, and

Table 2. $\delta^{34}S$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values for the studied Pb-Zn deposits (Data encoded with YGC and YDC were obtained from Koptagel *et al.* 2005).

Tectonostratigraphic Units	Deposit Type	Age of Host Rocks	Locality	Deposits	Sample No	$\delta^{34}S$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Siyah Aladağ Nappe	concordant	Late Permian / Early – Middle Triassic	Northwest Göynük Village	Göynük	YGF-1	-0.3			
					YGF-4	0.6			
					YGF-7	0.9			
					YGF-10	0.2			
					YGC-1	-0.1	18.984	15.756	39.105
					YGC-2	0.7			
					YGC-3	0.6			
					YGC-4	-0.1	18.959	15.746	39.049
					YGC-5	-0.3			
					YGC-6	-0.5			
					YGC-7	0.9	18.956	15.729	39.023
					YGC-8	0.4	18.972	15.737	39.103
					YGC-9	0.4	18.971	15.737	39.088
					YGC-10	-0.3			
Beyaz Aladağ Nappe	fault-related	Early Jurassic–Early Cretaceous	Northern Havadan Village	Havadan	YHF-4	11.9			
					YHF-5	8.1			
					YHF-6	12.9			
					YHF-7	11.8			
					YHF-8	15.1			
					YHF-9	10.9			
					YHF-10	13			
					YHF-11	8.1			
				Demircilik	YEF-2	10.4			
					YEF-3	9.8	18.64	15.724	38.855
					YEF-4		18.568	15.708	38.758
					YEF-5	12.2	18.66	15.754	38.953
					YEF-6	11.9	18.65	15.72	38.877
					YEF-7	11			
					YEF-8	8	18.572	15.727	38.815
					YEF-9	10.9			
					YEF-10	11.3			

Table 2. *continued.*

Tectonostratigraphic Units	Deposit Type	Age of Host Rocks	Locality	Deposits	Sample No	$\delta^{34}S$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
					YTF-2	8.9			
Beyaz Aladağ Nappe	fault-related	Early Jurassic –	Northern Havadan		YTF-4	11.1			
		Early Cretaceous	Village		YTF-6	11.5			
				Tekke	YTF-7	9.6			
					YTF-8	10.2			
					YTF-10	12			
					YTF-11	12.4			
					YDF-1	8.8			
					YDF-2	9			
					YDF-4	10.5			
					YDF-5	9.7			
					YDF-8	7.9			
					YDC-1	9	18.697	15.705	38.852
Siyah Aladağ Nappe	concordant	Late Permian	Eastern Denizovası	Celaldağı	YDC-2	9.9	18.684	15.706	38.842
			Village	Desandre	YDC-3	9.2			
					YDC-4	10.9			
					YDC-5	9.7			
					YDC-6	9	18.704	15.709	38.866
					YDC-7	8.9			
					YDC-8	8.4	18.702	15.718	38.901
					YDC-9	8.4	18.722	15.736	38.955
					YDC-10	9.4			
					YSF-3	-3.7			
					YSF-4	-4.7	18.871	15.823	38.324
					YSF-5	-4.4	18.783	15.749	39.13
Siyah Aladağ Nappe	fault-related	Late Devonian –	Southern		YSF-6	-4.6	18.797	15.761	39.173
		Late Permian	Yahyalı Town	Suçatı	YSF-7		18.777	15.652	39.104
					YSF-8	-4.6			
					YSF-9	-3.9			
					YSF-10	-4.2	18.812	15.772	39.186
					YSF-11	-3.8			

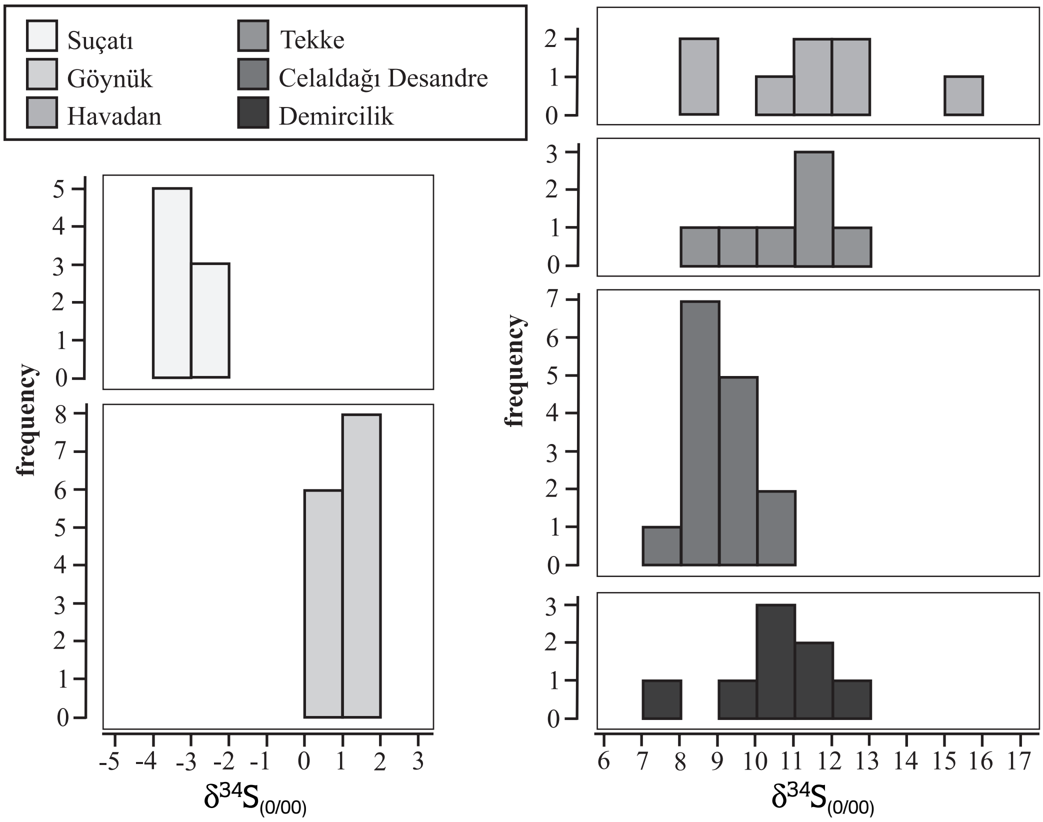

Figure 8. Histogram of $\delta^{34}S$ data for the Pb-Zn deposits.

$^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagrams (Figure 10) on lower and upper crust, and orogen areas, as developed by Zartman & Doe (1981). However, all the lead isotope data from the galena samples plot along upper crust and orogen trends (Figure 11).

Discussion

The $\delta^{34}S$ values of carbonate-hosted Pb-Zn deposits fall into a very wide range explained by the fact that ore genesis originated from sulfur of bacterial or non-bacterial (thermochemical) origins, leached from a variety of rocks, seawater and a mixture of these various ratios (e.g., Ohmoto & Goldhaber 1997). $\delta^{34}S$ values of seawater have fluctuated enormously from the Precambrian to today (Claypool *et al.* 1980), with +35‰ being the maximum for the Precambrian–Cambrian and +11‰ the minimum for the Permo–Triassic. The $\delta^{34}S$ values for the Upper Devonian and Upper Cretaceous in which the ores formed in the Yahyalı region ranged from a maximum of +28‰ to a minimum of +12‰.

Sulfur in galena of the Celaldağı Desandre deposit probably had a seawater origin since its mean $\delta^{34}S$ is +9.3, similar to that of Permian seawater (+11). The mean $\delta^{34}S$ values of the Tekke, Havadan and Demircilik (+10.8, +11.5 and +10.7) are slightly higher than that of Celaldağı Desandre, but probably also formed from a seawater sulfate source. But neither of the mean $\delta^{34}S$ values of +0.2 and –4.2‰ for the Göynük (Upper Permian–upper Middle Triassic) and Suçatı (Upper Devonian–Upper Permian) deposits are similar to the $\delta^{34}S$ values of the related seawater during the period of formation. For Göynük, the $\delta^{34}S$ values exhibit a very narrow range (from -0.5 to +0.9) consistent with the $\delta^{34}S$ value for magmatic sulfur (from –5 to +5), although field observation and ore microscopy provide no evidence of magmatic activity in its formation. Alternatively, this deposit may have formed as the result of bacterial

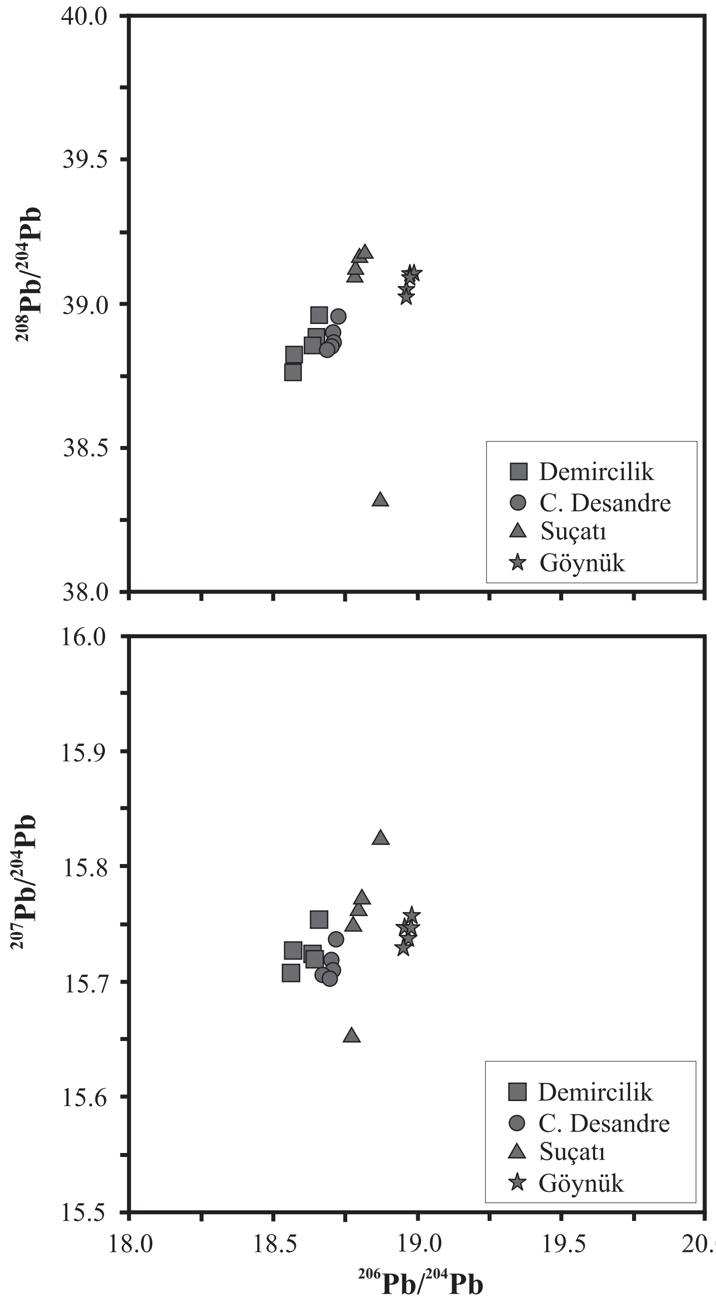

Figure 9. Lead isotope ratios of galena samples from the Yahyalı region.

reduction of seawater sulfate but the narrow range of $\delta^{34}S$ and small isotope shift would be unusual. Perhaps seawater became enriched in the light isotope by sulfur being leached from lithologic units during its circulation, as indicated by Eldridge *et al.* (1993), Sherlock *et al.* (1999) and Roth & Taylor (2000). The influence of the enrichment of light sulfur isotopes was more significant for the Suçatı deposit (range from -4.7 to -3.7‰) than for Göynük. These sulfur systematics of the Suçatı deposit might also be explained by the influence of mixing processes, but the ratio favours bacterial influence or seawater circulation.

Table 3. The comparison of lead isotopic ratio values with the $\delta^{34}S$(‰), tectonostratigraphic units, ages of host rocks and the type of deposits.

Features	Deposits			
	Göynük	Suçatı	Celaldağı Desandre	Demircilik
$^{206}Pb/^{204}Pb$	18.968	18.808	18.702	18.618
$^{207}Pb/^{204}Pb$	15.741	15.751	15.715	15.727
$^{208}Pb/^{204}Pb$	39.074	38.983	38.883	38.852
$\delta^{34}S$(‰)	+0.22	–4.24	+9.25	+10.69
Tectono-stratigraphic units	Siyah Aladağ Nappe	Siyah Aladağ Nappe	Siyah Aladağ Nappe	Beyaz Aladağ Nappe
Age of host rock(s)	Late Permian Early – Middle Triassic	Late Devonian Late Permian	Late Permian	Early Jurassic Early Cretaceous
Deposit type	concordant	fault-related	concordant	fault-related

In conclusion, the sulfur systematics of the studied carbonate-hosted Pb-Zn deposits in the Taurus Mountain Belt in southern Turkey imply that the sulfur originated from seawater in the Demircilik, Tekke, Havadan and Celaldağı Desandre deposits, whilst the Göynük and Suçatı deposits probably have a mixture of sulfur sources.

Lead isotope data of carbonate hosted Pb-Zn deposits are usually plotted as two groups on $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$, and $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagrams. One of these groups shows a linear trend dominated by radiogenic isotopes; the second one is just a group and does not have any trend (Gulson 1986; Nelson *et al.* 1999). Carbonate-hosted Pb-Zn deposits are usually located on the radiogenic lead isotope trend as described by Heyl *et al.* (1974) and Vaasjoki & Gulson (1986). However, Pb isotope data from Pb-Zn deposits in Pine Point (Northwest Territories: Cumming *et al.* 1990), in Southwest Sardinia (Boni *et al.* 1996), in Tennessee in the Appalachian orogen (Kesler 1996; Misra *et al.* 1996), in the Lennard area (Australia: Dörling *et al.* 1996), in Navan (Ireland: Hitzman & Beaty 1996), in Bleiberg (Alpine Austria: Schroll 1996), and in Asturias-Leon (Spain: Tornos *et al.* 1996) do not plot on the radiogenic Pb isotope trend. This situation is interpreted by the above researchers as either reflecting a homogeneous primary source of Pb isotopes, or Pb isotopes which reached homogeneity by interaction between other rocks and ore fluids, which had travelled a long way during ascent.

Researches conducted by Koptagel *et al.* (2001, 2005) in and near to the Yahyalı area show that the evolution of carbonate-hosted Pb-Zn deposits is closely related to rifting of the Eastern Mediterranean, which began in the Early Triassic (Sawkins 1984), or Middle Triassic (Marcoux 1979; Tekeli 1980; Şengör & Yılmaz 1983; Tekeli *et al.* 1984). Koptagel *et al.* (2001, 2005) proposed that Pb-Zn deposits are concentrated from marine waters, which travelled along deep cracks and faults at the beginning of the rifting event. At depth, the marine water heated up and dissolved metals from rocks during its ascent, and when the concentration of metal ions increased sufficiently then deposition occurred. This process and structural features such as faults and cracks, together with wall-rock permeability and reactivity would

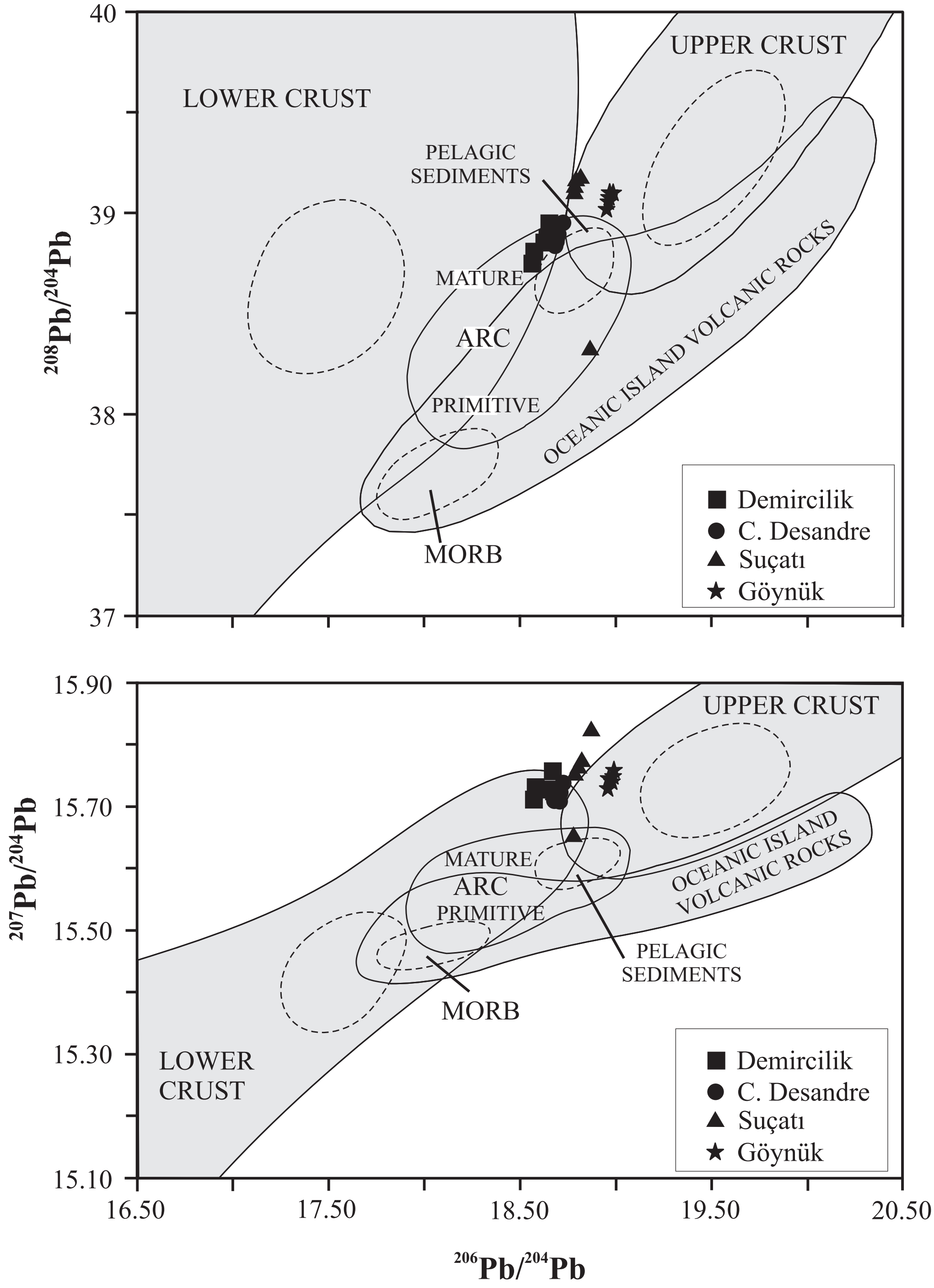

Figure 10. Plot of Pb isotope data from the Yahyalı region on $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$, and $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagrams. Oceanic Island Volcanic Rocks and MORB represent the Mantle area, and Arc and Pelagic Sediments represent the Orogen area. Dotted line indicates each area of greatest concentration (after Zartman & Doe 1981).

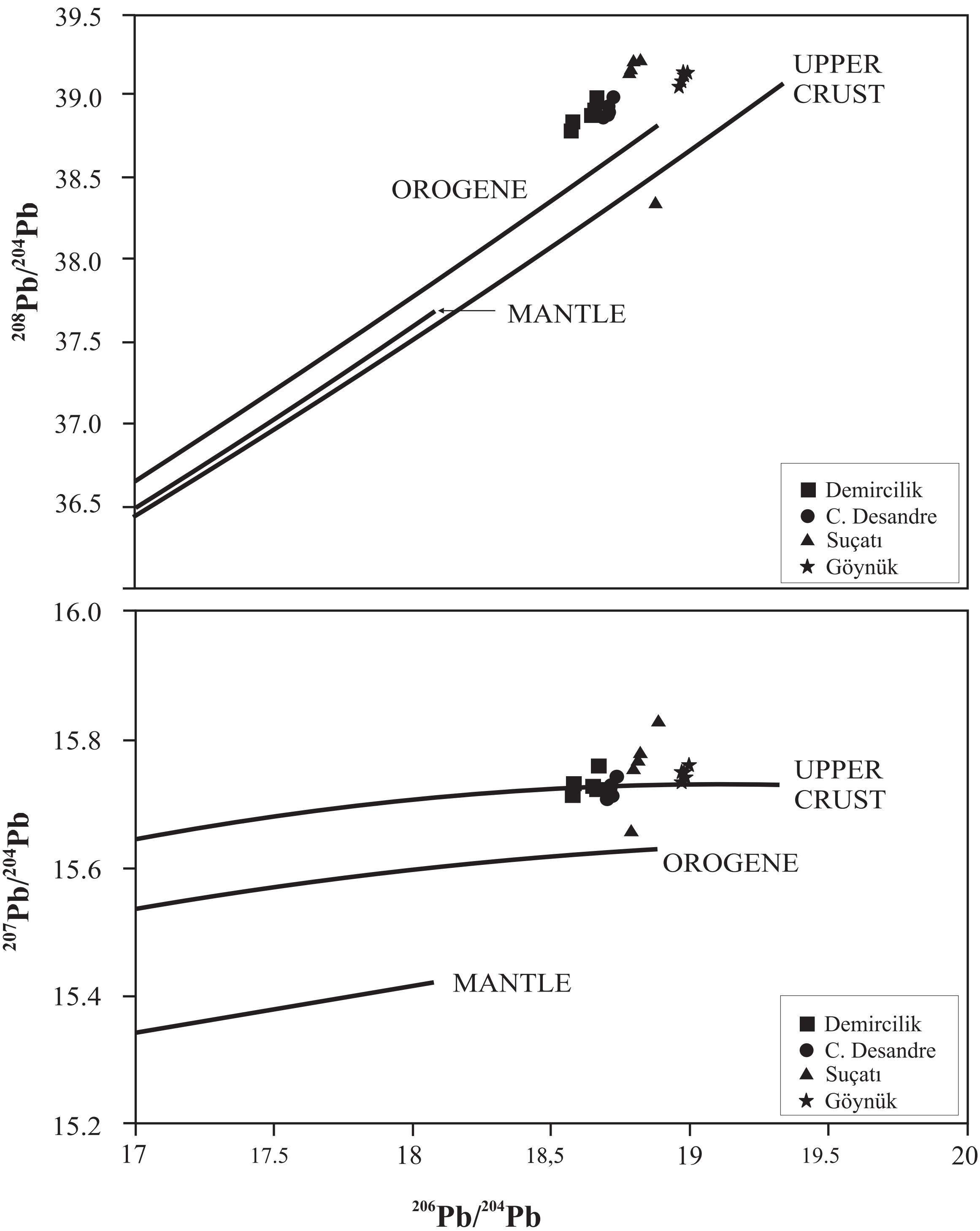

Figure 11. Plot of Pb isotope data of galena samples from the Yahyalı region on Pb isotope evolution diagram. Lower Crust trend is outside the diagram area (after Zartman & Doe 1981).

be the eventual controlling factors of mineralization, geometry of the ore bodies and the alteration. The reason for very significant oxidation of the ores in the Yahyalı region as in the Zamantı Pb-Zn province in general, was the strong effect of the tectonic activities during and after mineralization.

This study showed that Pb isotope data do not show any trend but plot in a small area on isotope ratio diagrams (Figures 10 & 11); i.e. the Pb isotopes are homogenous in composition. This feature is compatible with a formation model for carbonate-hosted Pb-Zn deposits in Yahyalı area, proposed by Koptagel *et al.* (2001, 2005). So, either Pb isotopes in galena are homogeneous in composition at the primary source, or reached their homogenous composition during transport of marine waters. The source of metals in the deposits is either orogenic or concentrated from marine waters, which travelled to depths along the cracks and faults and acquired metals during transport. Isotopic differences in different deposits in the Yahyalı region may be explained by differences in environments of formation for each deposit.

Conclusions

The formations of carbonate-hosted Pb-Zn deposits in the Yahyalı region are grouped in two types: concordant with host rocks and fault-related. Both groups have similar features and no thermochemical alteration/transformation on contact with their host rocks. Based on the sulfur isotope systematics, it is postulated that the origin of the sulfur in Demircilik, Tekke, Havadan and Celaldağı Desandre deposits was seawater sulfate, whilst that in Göynük and Suçatı deposits was related to the mixture of different sources. The ratios of lead isotopes fall into clear clusters, but not in a linear trend defining the inclusion of radiogenic lead.

The aim of this investigation was to make a reconnaissance of lead and sulfur isotope systematics. Further studies, covering fluid inclusions, oxygen isotope systematics, radiometric dating, and trace element geochemistry will provide details on the formation and nature of the mineralization.

Acknowledgements

This study was supported by The Research Fund of Cumhuriyet University (Project no: M-214 grant to O. Koptagel). The authors acknowledge help from the staff of SUERC for sulfur isotope analysis, to Cameron R. Allen (Teck Cominco American Inc.) for constructive contributions in the revision and to P.J. Lechler (University of Nevada Reno, USA) for editing this manuscript. John A. Winchester edited the English of the final text.

References

AKYOL, Z. & PEHLİVANOĞLU, H. 1985. Lead-zinc deposits of Turkey and role of MTA. *Proceedings of the 50th Year of the Mineral Research and Exploration Institute (MTA) of Turkey,* 45–53 [in Turkish with English abstract].

AYHAN, A. 1983. Carbonate bearing zinc-lead deposits of the Aladağ (Yahyalı-Çamardı) region. *Geological Bulletin of Turkey* **26**, 107–116 [in Turkish with English abstract].

AYHAN, A. & LENGERANLI, Y. 1986. Tectonostratigraphical features of Yahyalı-Demirkazık Aladağ region between Yahyalı and Demirkazık. *Jeoloji Mühendisliği* **27**, 31–45 [in Turkish with English abstract].

BLUMENTHAL, M.M. 1952. *Geographical, Stratigraphical and Tectonical Features of the High Aladağ Mountains.* Publications of the Mineral Research and Exploration Institute (MTA) of Turkey D6.

BONI, M., BALASSONE, G. & IANNACE, A. 1996. Base metal ores in the Lower Paleozoic of Southwestern Sardinia. *In*: SANGSTER, D.F. (eds), *Carbonate-Hosted Lead-Zinc Deposits.* Society of Economic Geologist, Michigan, Special Publication **4**, 18–28.

BOZKAYA, G. 2001. *Geology of Koru (Çanakkale) Barite-bearing Lead-Zinc Deposits.* PhD Thesis, Cumhuriyet University, Sivas, Turkey [in Turkish with English abstract, unpublished].

CLAYPOOL, G.E., HOLSER, W.T., KAPLAN, I.R., SAKOU, H. & ZAK, I. 1980. The age curves of sulfur and oxygen isotopes in marine sulfate and their mutual interpretation. *Chemical Geology* **28**, 199–260.

CUMMING, G.L., KYLE, J.R. & SANGSTER, D.F. 1990. Pine Point: A case history of lead isotopic homogeneity in Mississippi Valley-Type district. *Economic Geology* **85**, 133–144.

ÇEVİKBAŞ, A. & ÖZTUNALI, O. 1991. Ore deposits of the Ulukışla-Çamardı basin. *Jeoloji Mühendisliği* **34**, 22–40 [in Turkish with English abstract].

ÇEVRİM, M., ECHLE, W. & FRIEDRICH, G. 1986. Paleocarst related Zn-Pb mineralization of Aladağ mountains. *Geological Bulletin of Turkey* **29**, 27–42 [in Turkish with English abstract].

ÇOPUROĞLU, İ. 1996. Mineralogy and genesis of the Yahyalı Kayseri and Demirkazık Niğde-Çamardı region zinc-lead deposits. *Bulletin of the Mineral Research and Exploration Institute (MTA) of Turkey* **118**, 35–46 [in Turkish with English abstract].

DEMİR, N. & BİNGÖL, E. 2000. Aladağ region oxide-carbonate type Zn-Pb deposits and its relation of structural geology. *In: Earth Sciences and Mining Congress in the 75th Anniversary of the Republic of Turkey,* 573–589 [in Turkish with English abstract].

DÖRLING, S.L., DENTITH, M.C., GROVES, D.I. & VEARNCOMBE, J.R. 1996. Mississippi Valley-Type Deposits of the Southeast Lennard Shelf: an example of the interplay of extensional deformation, sedimentation and mineralization. *In*: SANGSTER, D.F. (eds), *Carbonate-Hosted Lead-Zinc Deposits.* Society of Economic Geologist, Michigan, Special Publication **4**, 96–111.

EFE, A. 1993. *Geology and Genesis of Rahmanlar (Selendi-Manisa) Lead-Zinc Deposits.* PhD Thesis, Cumhuriyet University, Sivas, Turkey [in Turkish with English abstract, unpublished].

ELDRIDGE, C.S., WILLIAMS, N. & WALSHE, J.L. 1993. Sulfur isotope variability in sediment-hosted massive sulfide deposits as determined using the ion microprobe SHRIMP: II. A study of the H.Y.C. deposit at McArthur river, Northern Territory, Australia. *Economic Geology* **88**, 1–26.

ERLER, A. 1979. Study of sulfur isotopes of Karakoca (Simav-Kütahya) lead-zinc deposit. *Jeoloji Mühendisliği* **22**, 117–120 [in Turkish with English abstract].

GÖKÇE, A. & SPIRO, B. 2000. Sulfur isotope characteristics of the volcanogenic Cu-Pb-Zn deposits in the eastern Pontide region, NE Turkey. *International Geology Review* **42**, 565–576.

GULSON, B.L. 1986. *Lead Isotopes in Mineral Exploration.* Developments in Economic Geology 23, Elsevier, Amsterdam, **245 p**.

HALL, A.J., BOYCE, A.J. & FALLICK, A.E. 1987. Iron sulphides in metasediments: Isotopic support for a retrogressive pyrrotite to pyrite reaction. *Chemical Geology (Isotope Geosciences)* **65**, 305–310.

HEYL, A.V., LANDIS, G.P. & ZARTMAN, R.E. 1974. Isotopic evidence for the origin of Mississippi Valley-type mineral deposits: a review. *Economic Geology* **69**, 992–1006.

HITZMAN, M.W. & BEATY, D.W. 1996. The Irish Zn-Pb-(Ba) orefield. *In*: SANGSTER, D.F. (eds), *Carbonate-Hosted Lead-Zinc Deposits.* Society of Economic Geologists, Michigan, Special Publication **4**, 112–143.

HITZMAN, M.W., REYNOLDS, N.A., SANGSTER, D.F., ALLEN, C.R. & CARMAN, C.E. 2003. Classification, genesis, and exploration guides for nonsulfide zinc deposits. *Economic Geology* **98**, 685–714.

İSKİT, M. 1967a. *Aladağ-Yahyalı Pb-Zn Mineralizations and Geological Study of its Near Region.* Mineral Research and Exploration Institute (MTA) of Turkey Report no. 4348 [in Turkish, unpublished].

İSKİT, M. 1967b. *Geological Study of the Denizovası-Süleymanfakılı Between, Zamantı Region.* Mineral Research and Exploration Institute (MTA) of Turkey Report no. 3853 [in Turkish, unpublished].

İSKİT, M. & VOHYZKA, K. 1965. *Geological Study Report of the Yahyalı-Kayseri and Zamantı Region.* Mineral Research and Exploration Institute (MTA) of Turkey Report no. 3798 [in Turkish].

KESLER, S.E. 1996. Appalachian Mississippi Valley-Type deposits: Paleoaquifers and brine provinces. *In*: SANGSTER, D.F. (eds), *Carbonate-Hosted Lead-Zinc Deposits.* Society of Economic Geologists, Michigan, Special Publication **4**, 29–57.

KOPTAGEL, O., EFE, A., ULUSOY, U. & FALLICK, A.E. 1998. Sulfur-isotope study of the Ana Yatak massive sulfide deposit, southeastern Turkey. *International Geology Review* **40**, 363–374.

KOPTAGEL, O., EFE, A. & ULUSOY, U. 2001. *Sulfur Isotope Study of the Göynük and Celaldağı Desandere Pb-Zn Deposits, Eastern Yahyalı, Kayseri.* Cumhuriyet University, Research Project Report no: M–171 [in Turkish with English abstract, unpublished].

KOPTAGEL, O., ULUSOY, U. & EFE, A. 2005. A study of sulfur isotopes in determining the genesis of Göynük and Celaldağı Desandre Pb-Zn deposits, Eastern Yahyalı, Kayseri, Central Turkey. *Journal of Asian Earth Sciences* **25**, 279–289.

LENGERANLI, Y. 1986. *Geology of the Zinc-Lead Bearing Mesozoic Carbonates, Eastern Yahyalı (Kayseri).* Mineral Research and Exploration Institute (MTA) of Turkey Report no. 8026 [in Turkish, unpublished].

LENGERANLI, Y., ÇELTEK, N., BATIK, H., AYAN, A., TÜZÜN, D. & İNAN, A. 1986. *Geology and Report of the Lead-Zinc Mineralization Eastern Yahyalı and South of the Hoşça-Çataloluk Village (Kayseri-Develi).* Mineral Research and Exploration Institute (MTA) of Turkey Report no. 8026 [in Turkish, unpublished].

MARCOUX, J. 1979. General features of Antalya Nappes and their significance in the position of the paleogeography of southern margin of Tethys. *Geological Bulletin of Turkey* **22**, 1–6.

MISRA, K.C., GRATZ, J.F. & LU, C. 1996. Carbonate-hosted Mississippi Valley-Type mineralisation in the Elmwood-Gordonsville deposits, Central Tennessee zinc district: A synthesis. *In*: SANGSTER, D.F. (eds), *Carbonate-Hosted Lead-Zinc Deposits.* Society of Economic Geologists, Michigan, Special Publication **4**, 58–73.

NELSON, J., GABITES, J.E. & PARADIS, S. 1999. *New Galena Lead Isotopic Data From Carbonate Rocks in Northeastern B.C. - Implications for Regional MVT Fluid Migration.* British Columbia Geological Survey Branch, Geological Fieldwork 1998, 81–87.

OHMOTO, H. & GOLDHABER, M.B. 1997. Sulfur and carbon isotopes. *In*: BARNES, H.L. (ed), *Geochemistry of Hydrothermal Ore Deposits.* John Wiley and Sons, 3rd Edition, New York, 992 p.

ÖZGÜL, N. 1976. Some geological aspects of the Taurus orogenic belt. *Geological Bulletin of Turkey* **19**, 65–78 [in Turkish with English abstract].

ROTH, T. & TAYLOR, B.E. 2000. Sulfur isotope and textural zoning of pyrite in mudstone about the polymetallic Eskay Creek Deposit, Northwestern British Columbia, Canada. *Volcanic Environments and Massive Sulfide Deposits International Conference, Hobart, Tasmania, November 2000*, 16–19.

SAWKINS, F.J. 1984. *Metal Deposits to Relation to Plate Tectonics.* Springer Verlag, Berlin.

ŞENGÖR, A.M.C. & YILMAZ, Y. 1983. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics* **75**, 181–241.

SHERLOCK, R.L., ROTH, T., SPOONER, E.T.C. & BRAY, C.J. 1999. Origin of the Eskay Creek precious metal-rich volcanogenic massive sulfide deposit: Fluid inclusion and stable isotope evidence. *Economic Geology* 94, 803–824.

SCHROLL, E. 1996. The Triassic carbonate-hosted Pb-Zn mineralization in the Alps (Europe): The genetic position of Bleiberg Type deposits. *In*: SANGSTER, D.F. (eds), *Carbonate-Hosted Lead-Zinc Deposits.* Society of Economic Geologists, Michigan, Special Publication 4, 182–194.

TEKELİ, O. 1980. Structural evolution of Aladağ Mountains in Taurus Belt. *Geological Bulletin of Turkey* 23, 11–14 [in Turkish with English abstract].

TEKELİ, O., AKSAY, A., ÜRGÜN, B.M. & IŞIK, A. 1984. Geology of the Aladağ Mountains. *In*: TEKELİ, O & GÖNCÜOĞLU, M.C. (eds), *Geology of the Taurus Belt.* Proceedings of International Tauride Symposium. Mineral Research and Exploration Institute (MTA) of Turkey Publications, 143–158.

TORNOS, F., RIBERA, F., ARIAS, D., LOREDO, J. & GALINDO, C. 1996. The Carbonate hosted Zn-Pb deposits of NW Spain: Stratabound and Discordant deposits related to the Variscan Deformation. *In*: SANGSTER, D.F. (eds), *Carbonate-Hosted Lead-Zinc Deposits.* Society of Economic Geologist, Michigan, Special Publication 4, 195–203.

TÜRKÜNAL, S. 1965. *Geology of the Southern and Northern Yahyalı Region and Report of the Galena and Smithsonite Mineralization.* Mineral Research and Exploration Institute (MTA) of Turkey Report no. 3650 [in Turkish, unpublished].

TÜZÜN, D. 1985. *Project of the Pb-Zn Exploration in Zamantı Region:* Mineral Research and Exploration Institute (MTA) of Turkey Report no. 7766 [in Turkish, unpublished].

UEDA, A. & KROUSE, H.R. 1986. Direct conversion of sulphide and sulphate minerals to SO_2 for isotope analyses. *Geochemical Journal* 20, 209–212.

ULAKOĞLU, S. 1983. Geology of the Yahyalı (Kayseri) region in Aladağ Mountains: *Bulletin of Earth Sciences*, *İstanbul University Press* 4, 1–44 [in Turkish with English abstract].

VAASJOKI, M. & GULSON, B.L. 1986. Carbonate-hosted base metal deposits: lead isotopic studies bearing on their genesis and exploration. *Economic Geology* 81, 156–172.

VACHÉ, R. 1964. Die blei-zink-lagerstatte am Bakirdag im Antitaurus (Provinz Kayseri). *Bulletin of the Mineral Research and Exploration Institute (MTA) of Turkey* 62, 91–102 [in Turkish with English abstract].

ZARTMAN, R.E. & DOE, B.R. 1981. Plumbotectonics – The model. *Tectonophysics* 75, 135–162.

Received 06 June 2005; revised typescript received 17 April 2006; accepted 05 July 2006