INVESTIGATIONS OF LEAD-ZINC DEPOSITS IN NORTHWEST ANATOLIA, TURKEY

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INTRODUCTION

In 1955-56, working in Turkey as an adviser in mineral exploration for the government, and appointed by the United Nations Technical Assistance Administration, I had the opportunity to investigate a number of mineral deposits in the Biga peninsula, located between the Sea of Marmara, the Dardanelles Strait, and the Aegean Sea (Fig. 1). The exploitable deposits comprise lead-zinc ores, iron ores, and lignite beds, and in addition there are showings of gold, copper, molybdenum, wolfram, antimony, manganese, chrome, and sulphur, which, so far, has not proved to be of economic importance. In this paper attention is particularly given to the lead-zinc deposits.

The exploration was carried out under the auspices of the Mineral Research and Exploration Institute (M.T.A.). The assistance in the field as well as in the laboratory by the officials of the Institute is duly acknowledged. In particular, I am indebted to Dr. R. Tolun, former director of the chemical and metallurgical laboratory of the Institute, for a large number of chemical analyses. Since my return to Norway, Professor I. Oftedal of Oslo University kindly carried out a number of spectrochemical analyses of galena and sphalerite samples from my Turkish collection, and Mr. B. Bruun at the Mineralogical-Geological Museum, Oslo, carried out some additional Fe determinations of sphalerite samples.

My work in Turkey was carried out in close co-operation with Mr. T. Eriksson of the Geological Survey of Sweden, and I have profited from many discussions and excursions with him. A great master of identification of opaque minerals, Dr. P. de Wijkerslooth, generously assisted in microscopical investigations, and was in many other ways helpful during my work in Turkey.

GEOLOGICAL SETTING

The geology of the area is rather complicated, since rocks from various periods, but sometimes of similar lithology, have been subjected to intense tectonic movements during the Alpine orogeny, and rocks older than Mesozoicum have been affected by Hercynian and perhaps older orogenies. A recent paper on some parts of the area by G. van der Kaaden (3) clearly demonstrates the intricate geology. Lack of fossils in some older formations is another drawback.

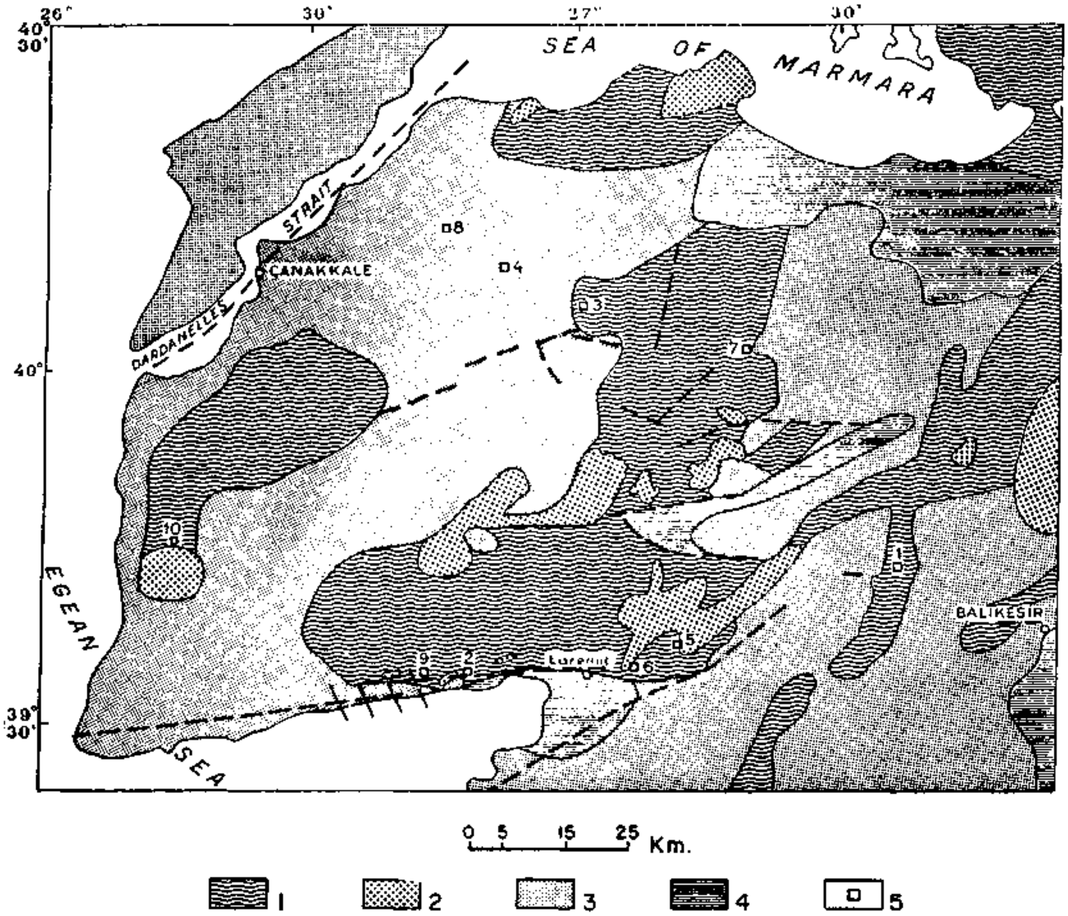

Fig. 1 - Biga Peninsula, Key Map of exploration area

1 - Pre-Alpine metamorphics, etc.; 2 - Granite; 3 - Tertiary volcanics; 4 - Alluvial deposits; 5 - Lead deposits.

Roughly, the geological series of the region can be divided into :

1. Tertiary basins, mostly sediments and tuffs of Miocene age.
2. Tertiary lava flows and pyroclasts.
3. Mesozoic schists, sandstones, limestones and spilites.
4. Schists, quartzites and marbles of varying degree of metamorphism. Furthermore gneisses, amphibolites, and other metabasites.
5. Granites and granodiorites.

The structures of the region are mainly Alpine. The general strike of the bedded and schistoze formations is NE-SW, and even the volcanic formations are sometimes distributed according to this direction. In some older schists, G. van der Kaaden *(loc cit.)* has found a more northerly strike direction which perhaps represents the Hercynian or even older orogenies.

The metamorphic and plutonic rocks (4 and 5 above) occur in the highest mountains, in the region of Kaz Dağı, and its NE continuation, and in two parallel ridges on each side. The volcanic rocks are mainly distributed between these ranges, but cover also faulted parts of the old ranges. The Tertiary sediments are mostly found on the coastal plains, and in some valleys («ovas», in Turkish).

A particular problem is the age of the granites and granodiorites. Wijkerslooth (5) gave good evidence for a late Paleozoic (Hercynian) age, but some authors think they are of Alpine age, like similar plutonic rocks in the Pontides of NE Anatolia. In his recent paper van der Kaaden (3) strongly supports Wijkerslooth's conclusion. This problem is of importance for the discussion of ore genesis, and I shall return to it later.

THE ALPINE OROGENY, VOLCANISM, AND MINERALIZATION OF THE REGION

With the exception of the youngest formations, Pliocene and Quaternary, all formations were folded, in some areas even intensely, during the Alpine orogeny. Thus the strike directions and fold axis are generally the same, NE-SW, in the metamorphic series (Paleozoic or older), in the Mesozoic, and the Tertiary formations. The orogenic stress has not been strong enough to impose lineation of minerals. In the Balya area, there are indications of large-scale thrusts and overfolding (2). The folding, which reached its maximum probably during early Miocene, dwindled and ceased in the region at the end of Miocene. But faulting went on, and the last of the big events, the Aegean faulting, took place during Quaternary time. The main fault directions are NE-SW, E-W, and NW-SE, but several other directions are also represented. The vertical displacements are not well known, but may be considerable in some cases, especially in those of the Aegean period.

The *initial*, Alpine volcanism, in the form of spilite lavas, took place in this region in Cretaceous time (3); just as in the Pontides further east. The ore formation described in this paper is, however, related to the sialic, *subsequent* volcanism, which in the Biga peninsula mainly is of Tertiary age. The attitude of some volcanic strata indicates that they are folded or tilted together with the sedimentary formations. In Çan, H. Wedding (personal communication, 1957), investigating the lignite-bearing Neogene formations, found that an old, kaolinized andesite series underlies the Neogene sediments, which again is covered by an andesite agglomerate, generally unaltered. Van der Kaaden established a similar stratigraphy in his area *(loc. cit.)*. Thus it appears that two main epochs of andesite-dacite extrusion are separated by a time of erosion, weathering, and deposition of Miocene sediments.

For the upward passage of lava and ore-forming fluids, the faulting was most important. The distribution of lava flows indicates that the faults paralleling the strike were the main feeding channels. (The great amount of pyroclastic material is most surprising compared to the scarcity of traces of central volcanoes, such as necks and cauldrons.) The source of the ore fluids was not the lavas themselves, but the underlying magma reservoir. The differentiation of the lavas does not indicate a single series : basic-acid, but rather a rhytmic repetition of andesitic and dacitic lavas (more acid types are rare in the region), with a final basalt extrusion, indicating that true cratogenic conditions were reached.

After emplacement, the lavas have been subjected to different kinds of alterations, some of which are so widespread that they have destroyed the original character of the lavas over large areas. This, I suppose, is caused by weathering before the deposition of the Miocene sediments. Much of the alteration is, however, of an hydrothermal type, and may have occurred before complete solidification of the lava. The most common alteration consists of chloritization of biotite and hornblende, giving the rocks a strong green color. Another alteration: oxidation of iron, colors the lava red. These hydrothermal alterations should not be confused with wall rock alterations caused by the hydrothermal solutions carrying the ore material, but some of them, e.g. kaolinization, may not be easy to distinguish.

DESCRIPTION OF DEPOSITS

Balya Maden (No. 1 in Fig. 1)

This mine, once the largest in Turkey and one of the best lead-silver mines in the Near East (production figures 3.5-4 mill, tons of ore in modern time), was closed and flooded during my visits, and it was not possible to make any systematic sub-surface sampling or surveying. Valuable information on the mineralization was given by V. Kovenko (4) shortly after the mines were closed. T. Aygen (1) mapped the geology in the Balya area, and discussed the stratigraphical and tectonical relationship. The following description is partly based on these two publications, partly on my own investigations, which include the study of a great number of mine maps.

The mineralization mostly occurs at or near the contact of a huge N-S running sill of liparite-dacite, and a strongly folded sedimentary formation. Some of the best mineralizations were found close to apophyses («white dikes») from the sill, where these penetrated limestone beds. The real lava flows which occur to the west of the sill, show no sign of mineralization. The area is strongly tectonized, by shearing, folding, faulting, and perhaps also thrusting. The main volcanic outbreak occurred along a deep, overturned fold. In an earlier paper (2) I have discussed in more detail the structural relationship around the mine. Not much ore cropped out, but it extended downwards for about 300 meters. The mineralization is very irregular, exploration and development expenses must have been high. The longest dimension of the individual ore bodies was generally vertical. Along the strike of the sill, the mineralization was followed about one mile, somewhat intermittently. According to Kovenko (4), the liparite-dacite is cut by post-ore andesite dikes («green dikes»). Some of these could, however, be seen to contain pyrite. It is possible, that the mineralization occurred in stages over a long period, which involved new volcanic outbreaks.

Wall rock alteration is distinct, but" not very striking, and consists of silicification, caibonatization, pyritization, kaolinization, and bleaching (destruction of dark, pyrogenic minerals).

The sulphides found at Balya were according to Kovenko : pyrite, galena, sphalerite, arsenopyrite, tennantite, bismuthinite, chalcopyrite, bournonite, realgar, jamesonite, and auripigment. Of gangue minerals he mentions hematite, quartz, calcite, fluorite, adularia, tremolite and actinolite, garnet, and epidote. Traces of native tellurium are reported too. To the list of ore minerals I can add *geochronite,* the identity of which has been confirmed by X-ray methods. Pyrite was formed first, and was extensively brecciated and replaced by the other sulphides, particularly by galena, which is the main ore mineral. The amount of sphalerite increased downwards. Realgar and auripigment occur in a very limited part of the mineralized area, in veins distinctly younger than the lead formation. Attending them are some minerals not reported by Kovenko : *polybasite-pearceite,* and *cinnabar.*

Of the gangue minerals, quartz and calcite dominate whereas the skarn minerals are rare. The garnet is grossularite.

Other deposits

A great number of small lead-zinc deposits are reported from the region, most of them situated within the volcanic areas, or in other rocks not far from Tertiary volcanics (Fig. 1). They are mostly small veins, a few dm. wide and some meters long, and only in exceptional cases they offer hopes for further prospection. For this study, I have selected deposits occurring in various kinds of wall rocks, and containing gangue minerals of different kinds or proportions. In Table 1 I have concentrated some information which needs a little supplement. In all but a few cases, the main ore minerals and gangue are very coarse-grained and of very similar texture. Pyrite always seems to be the first sulphide to crystallize. It is commonly brecciated, corroded, and replaced by the other sulphides. In some cases a second generation of pyrite is found, which is of only little quantitative importance. Sphalerite and galena, the latter usually dominating, generally show mutual contacts, and their internal age relationship is difficult to determine, mostly they are contemporaneous or sphalerite started to form slightly before galena. Rhythmic deposition of these two sulphides together with gangue is indicated by alternating crustification in some deposits, e. g. Koru Dere (No. 8) and Sofular (No. 7). Chalcopyrite occurs mostly as exsolution blebs in sphalerite, only in exceptional cases in individual grains. In Koca Yayla chalcopyrite is found to be older than tennantite and younger than pyrite and sphalerite. In Hahlar it is younger than pyrite and galena. In Kadılar (quartz vein) tennantite is younger than sphalerite, but older than chalcopyrite. The textures in general indicate that the sulphides of the common base metals crystallized within a short span of time and temperature.

The ore commonly shows epizonal character in textures, such as drusy or otherwise open space mineralization, comb structure of gangue quartz, crustification and vein zoning. Replacement of wall rock has been of subordinate importance. In some cases chalcedony formation, followed by brecciation, antedates the sulphide mineralization. Only the deposit of Bergaz (No. 10) deviates considerably in structural relationship, being of dense, fine-grained character, generally more rich in zinc than in lead, and occurring in skarn zones near Hercynian granite contacts. At the same time, however, Tertiary volcanic rocks occur very close. Since lead and zinc sulphides also formed in connection with the skarn mineralization of the Hercynian granites (e. g. in the Kalabak deposit NE of Edremit) the origin of these fine-grained deposits in the skarn zones is more dubious.

Ordinarily, pyrite, galena and chalcopyrite crystals are free of inclusions. Sphalerite crystals, however, often are crowded with tiny blebs of pyrite or chalcopyrite, crystallographically oriented in sphalerite, indicating exsolution. In some cases also veins and more irregular inclusions of pyrite are present together with remnants of an earlier pyrite. Apparently, the sphalerite crystals, after deposition, were subjected to a drop in temperature and had to shed some of its excess iron and copper. Evidently, the ore solutions which formed these deposits, generally contained very little copper, and chalcopyrite was not formed

Table - 1

No.	*Location*	*Wall rock*	*Structure*	*Sulphides*	*Gangue*
2	**Avcılar**				
	a. Kara Kazan Dere	Marble	Scattered or brecciated contact zones	***gn***, sl, (py)	qtz
	b. Kundacı Dere	»		***sl***, gn, py	qtz, cc, tou
	c. Maden Dere	Sandstone		gn, sl, py	qtz, cc, chl
3	**Koca Yayla**	Andesite, schist, sandstone	Brecciated contact zone SW	***sl***, gn, (cp, py, ten)	qtz, ba
4	**Kadılar Köy**				
	a.	Andesite lava	Shear zone WNW	***gn***, sl, (py)	qtz
	b.	» »	» »	***sl***, ***cp***, gn, (py)	qtz, cc
5	**Halılar Oba**	Schist, arkose	Breccia N	***gn***, ***cp***, ***py***	qtz, chl
6	**Kırcılar**	Granite	Shear zone NNE	***gn***, py	qtz, cc, chl
7	**Sofular Köy**				
	a.	Schist, sandstone, marble	Cross-cutting veins WNW.	gn, sl	cc
	b.			***sl***, (gn)	cc, chl
	c.	Schist	Lens-shaped	***gn***	gross, cc
8	**Koru Dere**				
	a.	Andesite lava and tuff	Cross-cutting veins N	gn, sl	***ba***, qtz
	b.		Fault N	py, cp, (gn, sl)	qtz
9	**Papazlık**	Amphibolite schist	Flat-lying shear zone	***gn***, sl, (py), (cp)	qtz, cc
10	**Bergaz**	Skarn	Steep veins N	sl, gn, (py)	cc, di, tre, (ep)

Mineral index :

gn = galena
sl = sphalerite
py = pyrite
cp = chalcopyrite
ten = tennantite
qtz = quartz
cc = calcite

tou = tourmaline
chl = chlorite
ba = barite
gross = grossular garnet
di = diopside
tre = tremolite
ep = epidote

When underlined, in abundance.
In brackets, sparsely present.

as an independent mineral until the already formed sphalerite was saturated with copper.

Geochemical relationship

The amounts of lead, silver, zinc, gold, and partly of iron in ores or mineral ' concentrates were determined chemically by the chemical laboratory of M.T.A. Semi-quantitative spectrochemical analyses of the trace elements of mineral concentrates were made at the Geological Institute of the University of Oslo, and some additional chemical Fe determinations of sphalerite at the laboratory of the Mineralogical-Geological Museum in Oslo. The mineral concentrates of coarse-grained samples were mostly obtained by crushing and handpicking under the lens, and some low ,Pb-figures show that the procedure sometimes did not succeed too well. In some cases, particularly in fine-grained ore samples, flotation was necessary. The concentrates of sphalerite for Fe-determination were purified by magnetic separation. Great care was taken to obtain pure mineral concentrate for spectroscopic determination. The results of the analyses are reproduced in Table 2.

The spectrochemical method used is semi-quantitative only, giving reproducibility in the order of 50 %. The spectral sensitivity of the metals is :

Ag < 10 p. p. m.
Bi, Sn, In, Ge, Ga : 10 p. p. m.
Sb ~ 10 p. p. m.
Hg 100 p. p. m.
Cd, Te ~ 100 p. p. m.
As ~ 1000 p. p. m.

The results show the usual trace element distribution between galena and sphalerite. The *galena* minerals of the region show the following chemical characteristics :

1. Sn present in only one locality, Balya, in accordance with the supposition of a higher formation temperature for this deposit.
2. Ag always present, notably highest in the «contact» deposits (Balya, Avcılar), distinctly lower in the «skarn» deposits. No significant variation within the other types.
3. No systematic variation of the other elements present.
4. Elements notably rare or absent: Hg (sensitivity poor, however), Ba, As (sensitivity very poor) present in one case only (Balya Maden).

Characteristics of sphalerite

1. Normal amounts of Cd (~ 0.5 percent), no significant variation.
2. Cu in general in the order of 0.0x percent, rarely 0.1 percent, in one «skarn» deposit 0.5 percent.
3. Mn usually about 0.1 percent, in one «skarn» deposit 0.3 percent. In carbonate vein deposits 0.6-1 percent, but perhaps due to contamination of gangue minerals.
4. Co present in carbonate vein deposits only.

Table - 2

	Percent	Galena						Percent		Sphalerite				
				p.p.m.								p.p.m.		
	Pb^k	Ag^k	Au^k	Ag	Bi	Sb	Sn	Zn^k	Fe^k	Cd	Co	Cu	Mn	Sn
Barite veins	80.6	478	tr.	650	—	400	—	n.d.	0.5	5000	—	1000	1000	—
Quartz veins	73.7	115	5	325	25^x	60^x	—	63.7	0.9	10000	—	100	1000	tr.
	66.5	25	0.5	50	10	100	—	63.9	n.d.	10000	—	200	1000	--
Quartz-barite veins	n.d.	n.d.	n.d.	200	150^x	40	—	n.d.	1.—	>5000	—	350	1500	—
Quartz-carbonate veins	70.9^b	563^b	0.3^b	250	5500^x	105^x	—	sl practically absent						
	80.8	260	1	200	—	300	—	n.d.	0.9	>10000	—	500	100	—
Carbonate veins	82.3	261	0.5	200	—	530^x	—	58.3^a	2.3^a	5000	1000	650^x	6000^x	—
	n.d.	n.d.	n.d.	300	3	1000	—	55.8	5.7	1000	—	10000	10000	—
Contact deposits	84.6	2022	1.4	1000	1000	500	30	n.d.	5.2-9.2	n.d.	n.d.	400	1000	—
	80.5	1071	0.5	500	12^x	300^x	—	51.6	9.—	10000^x	—	100	500	—
	63.2^a	8.^{a}	—	800^x	3^x	600^x	—	53.4	7.6	1000	—	1000	>1000	—
	n.d.	n.d.	n.d.	1000	10000	50	—	n.d.	n.d.	n.d.	—	n.d.	n.d.	n.d.
Skarn deposits	81.1^a	93^a	1^a	50	200	100	—	sl absent						
	74.2^a	70^a	2^a	50	200	100	—	42.5^a	10	5000	—	5000	3000	—

Elements market ^{k} are determined by chemical methods, all other ones by spectroscopic methods.
Figures market ^{x} show great variations in the various samples.
Figures market ^{a} represent flotation concentrates.
Figures market ^{b} represent composite samples.
n.d. = not Determined. — = below sensitivity.

5. Elements notably lacking : Sn (trace in one case only), In, Ga, Ge, Sb, Ba, Bi, Hg.

   Thus neither typical high temperature trace elements nor low temperature ones are present in the sphalerite crystals.

Fe in sphalerite

The color of the sphalerite crystals is in the present cases indicative of the Fe content. In the vein deposits, they are honey-colored and contain less than 1 percent Fe, with the exception of those of the carbonate veins, which seem to be intermediate in Fe content.

The «skarn» and «contact» deposits are fairly high in Fe, about 5-10 percent. Within larger deposits, like Balya Maden, there are great variations, even within one sample, as shown by analyses of magnetic concentrates of various intensity. For this reason, and because of the lack of contemporaneous pyrrhotite, the Fe content of the sphalerite cannot be used for determination of the temperature of formation of the deposits. In several cases, typical exsolution blebs of pyrite are found in sphalerite crystals, demonstrating that the saturation point for Fe was reached during the cooling period.

CONCLUSION

The geological relationship, mineral composition and geochemical characteristics of the lead-zinc deposits of the investigated area demonstrate that most of them are closely related, of a subvolcanic type, and are of Tertiary age. A few «skarn» type deposits differ, however, and may be related to Hercynian granites. A few subvolcanic deposits have some mineralogical characteristics of skarn ore, but differ geochemicaliy from the mentioned skarn deposits. Investigation of the isotopic composition of the lead minerals would be of interest to solve the question of whether one or two generations of lead-zinc ore are present in the area.

Manuscript received July 31, 1962

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