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GEOCHEMICAL SETTING AND HYDROCHEMICAL EVOLUTION OF THREE MODERN SALING LAKES IN CENTRAL ANATOLIA

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ABSTRACT

In western and middle Anatolia there are a considerable amount of ancient lake deposits and modern saline lakes that developed in graben basins that were initiated in Middle Miocene and afterwards.

Three of these modern lakes; Lake Acìgöl, Lake Bolluk, and Lake Tersakan, are enriched in Na, SO_4, and Cl ions were studied in terms of their geological and hydrochemical evolutions.

All three of the lakes are related with alkaline volcanism of graben systems, atleast in the beginning stages. Eventhough their recharge sources are similar (groundwater, springs, runoff, etc.), the geological and hydrochemical evolutions of each lake is different. HCO_3 + CO_3 and K ratios show similar patterns for all three lakes. SO_4 is depleted in Lake Acìgöl brine with respect to inflow. Since being spring fed, Lake Bolluk shows SO_4 enrichments due to SO_4 concentrated recharges from travertine pinnacles.

INTRODUCTION

In the important rift systems of the world, the distribution of alkaline basaltic volcanism centers occurring close to saline lakes is not an accidental phenomena. These saline lakes, which initially had volcanically originated inflow, have existed by depositing sedimenter and/or volcano-sedimenter materials during their geological stages. Remnants of the ancient counterparts of these lakes are prevalent throughout middle and western Anatolia (Helvacì, 1977, 1978; Inci, 1991). The graben volcanism of the expansion tectonism during the middle Miocene and afterwards, was a precursor to the occurrence of these depositions. The expansion tectonics which started in middle Miocene, have since still been active in Middle Anatolia (Savasçìn 1989; Savasçìn et al., 1990). For this reason, in addition to the fossil evaporite deposits, especially in middle Anatolia, modern saline lakes are still progressing. Some of these modern lakes are yet in the initial volcanic saline lake stage (e.g., Sofular, Mekke Tuzlasì, and Karapìnar Acìgöl, are in the vicinity of Cappadocia) and mantle originated volcanic gas release has been continuing in this region (Nagao et al., 1989). Saline lakes, which are in the various evaporation stages, depositing carbonites, sulfates, and chlorites, are prevalent in middle Anatolia. None of these lakes can be put

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into the same classical evolution chart, because of the mode of origin, tectonic setting, bedrock type and pattern, climate, and past history varies from one lake basin to the other. This is true even for the lakes which are in the same chemical evaporation stages. As a matter of fact, each of the sulfate depositing lakes of middle Anatolia represents different formation stages.

In this study, three lakes which are sulfate depositing and commercially exploited for $NaSO_4.10\ H_2O$ production, were investigated in terms of considering similarities and differences respective to their settings and evolutions. These saline lakes, Denizli Acìgöl, Bolluk and Tersakan, are illustrated in Fig. 1 along with other ancient and modern lake basins in Anatolia.

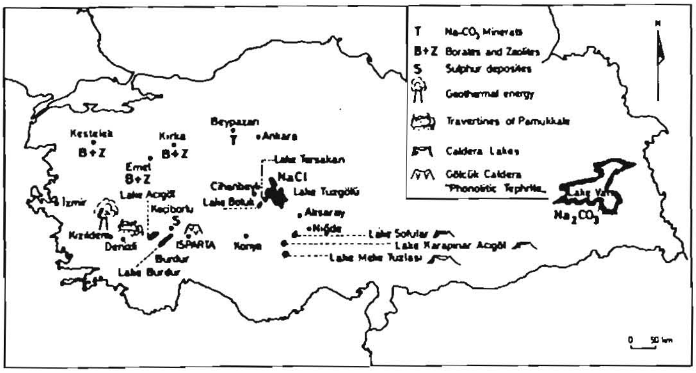

Fig. 1: Location map of some important ancient (Miocene) saline lake deposits and modern saline lakes of Anatolia.

SETTING AND EVOLUTION OF SALINE LAKES

Lake Acìgöl "Denizli"

Lake Acìgöl is situated in a NE-SW directed graben system (Fig. 2). The SE border of the graben is built up of Mesozoic rocks with a steep and high fault zone.

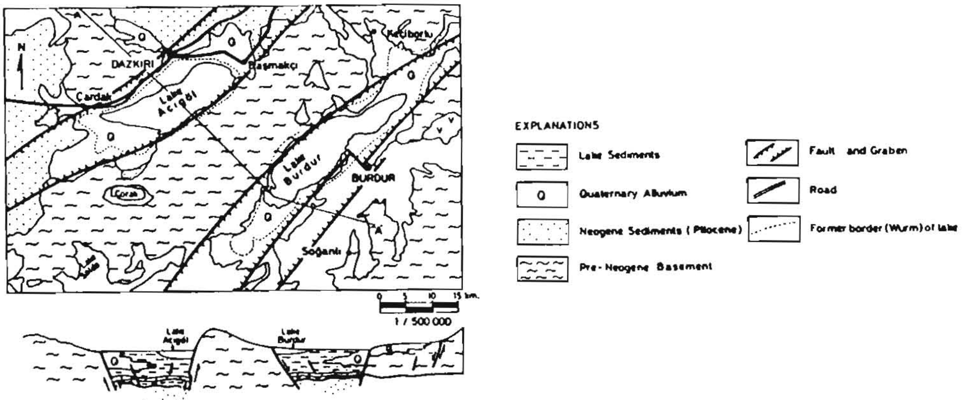

Fig. 2: Geological map of the surrounding area of Lake Acìgöl and Lake Burdur (modified from Koçyiğit, 1984; Erol, 1978; and the geological map of Turkey 1:500,000 M.T.A.).

Twenty drill cores (15-120 m in depth) provided information concerning the presence of sulfide nodules, gypsum crystals, alg depositions, coal intercalated green-gray colored clays, sand, gravel, and carbonate levels in the lake sediments (Içözü, 1991).

Bering (1967) cut a drill core 2 km away from the lake and found from the top to the bottom, 6.5 m mud, 66 m sulfur and gypsum-bearing green colored holocene lake sediments and 25 m thick somatre originated marn. These green colored lake sediments reveal that Lake Acìgöl has been active as a brine for along time. At the lake bottom where the water has been drained for $NaSO_4.10\ H_2O$ production, there are authigenic gypsum crystals and bitum-bearing muds. Sulfate reducing and sulfide oxidizing bacterias are found in these bitume-bearing materials (Içözü, 1991). Lake Burdur, which is located in the SE horsts of the Acìgöl graben (Fig. 2), is only just in the first stage of becoming a brine at least due to the two hot springs (Soganlì and Tümlüce) at the SW border of the lake. Travertine deposits, strambolite layers and authigenic gypsum lamines around Lake Burdur confirms this hypothesis about Lake Burdur.

Extinct hot springs around Lake Acìgöl and also the situation of Lake Burdur, indicates that the hot springs were more active during the geological past than present. There are important indications of these activities even in regions farther away from Lake Acìgöl (e.g., Kìzìldere hydrothermal plant, Keçiborlu hydrothermal sulfur deposits, which were the products of Gölbasì Caldera with phonolitic tephrites near Lake Caldera, Isparta, Fig. 1). The border of Lake Acìgöl during the Wurm glacial period (Erol, 1978) is also illustrated in Fig. 2.

The area of the lake is about 42 km^2 and a maximum of 1 meter deep. About 10 perennial springs carry water into the lake along the fault zone at the SE border (Içözü, 1991). The temperature of some of these springs is about 25-30°C. Some of the hot springs having temperatures of more than 30°C dried up during the last years.

According to meteorological data collected in the past 26 years, the mean annual precipitation is 392.2 mm/yr. The annual evaporation rate is about 754.4 mm/yr. Ephemeral streams, perennial springs, storm runoff, and ground water recharges are the main source of the inflow for Lake Acìgöl.

Lake Acìgöl is a perennial alkaline saline lake (pH=8.2). Hydrochemical data of Acìgöl, including drill wells about 140-150m deep, and artesian spring water have been collected by the SODAS company, who have produced mirabilite ($NaSO_4.10\ H_2O$) since 1970. Data collected by the SODAS company and also collected during this study were utilized to obtain the hydrochemical characteristics of the lake. The composition of the lake water and the inflow waters are compared in Fig. 3. Since Na and Cl ions are not removed during the evaporative processes until the very end (Jones et al., 1977), the Cl concentration can be used as a tracer to find the loss of other ions during the hydrochemical evolution of the lakes. Since Na:Cl ratios are the same for all inflows and lake water. This confirms that the major recharge for the lake is springs, and shallow and deep ground waters. Most of the Ca initially present in the inflow waters have been removed by precipitation of the carbonates. The Na:Cl ratio remains constant until the most consentrated brines (Fig. 3a). The behavior of $HCO_3 + CO_3$ during the brine evolution is shown in Fig. 3b. The loss of $HCO_3 + CO_3$ is because of carbonate precipitation during the evaporation processes. K is originally depleted in respect to Na, in even the

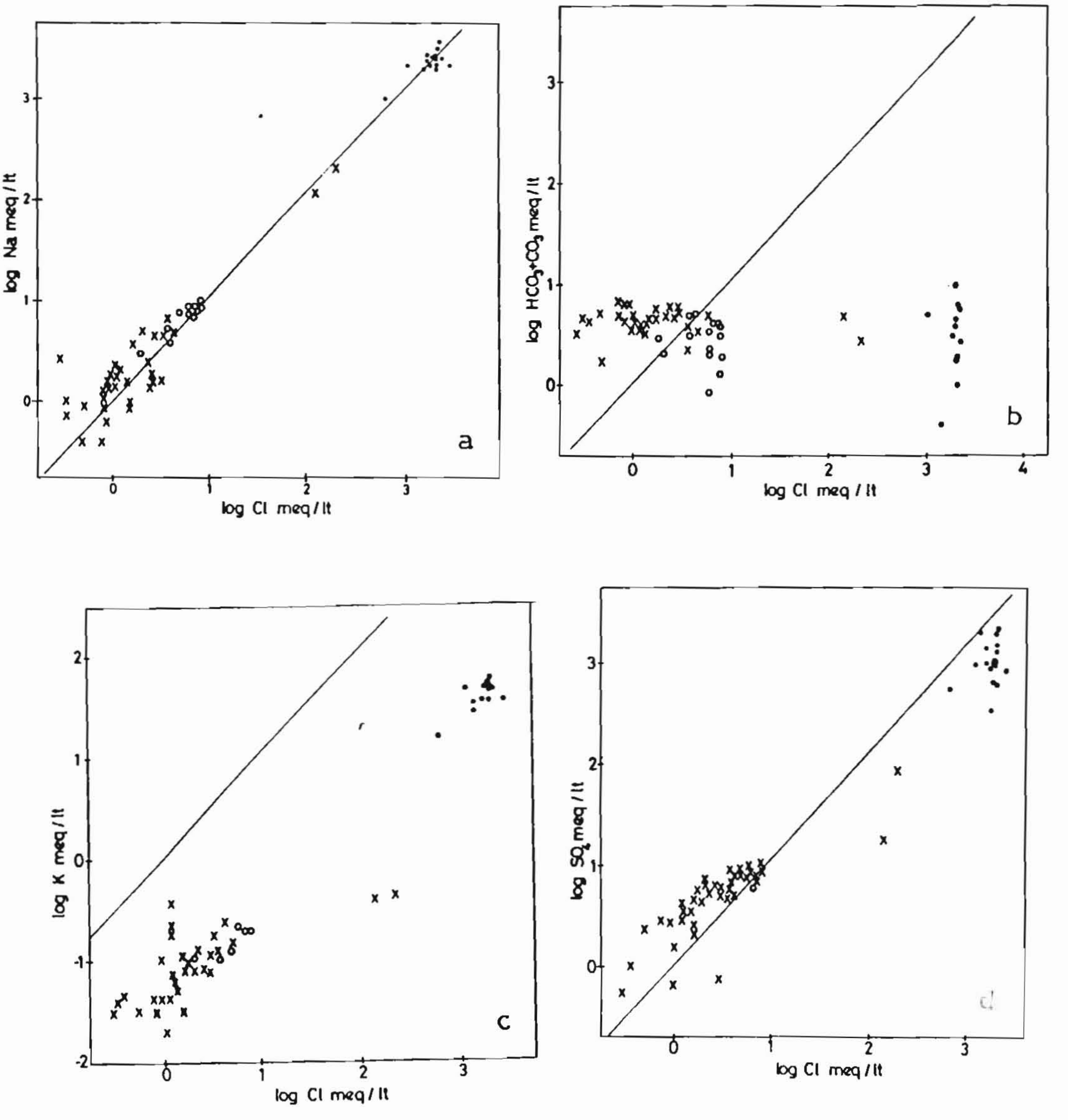

Fig. 3: Na / Cl^- (a); HCO_3^- + CO_3 / Cl (b); K / Cl (c); and SO_4^- / Cl^- (d) of Lake Acìgöl (cross= shallow and deep ground waters; open circles= hot and cold springs; dots= lake water).

inflow waters. This is because K has been attached to some clay minerals. But the K:Cl ratio is constant from inflow to the brine (Fig. 3c). The behavior of SO_4 is shown in Fig. 3d. Lake Acìgöl is deplete of SO_4 with respect to inflow. This is because of $Na_2SO_4.H_2O$ production by SODAS. The chemical composition for representative types of water inflows and lakes are shown in Table 1.

Lake Bolluk and Lake Tersakan

Both of these lakes are located in the paleo-area of the present Lake Tuzgölü (Fig. 1, 4 and 5). From both of these lakes, miriabilite ($NaSO_4.10\ H_2O$) has been exploited commercially for many years and the NaCl enriched remainder has been recharged back into the lakes. The paleo-Tuzgölu basin was disconnected from the widely extended ancient lake basin and had its own evolution.

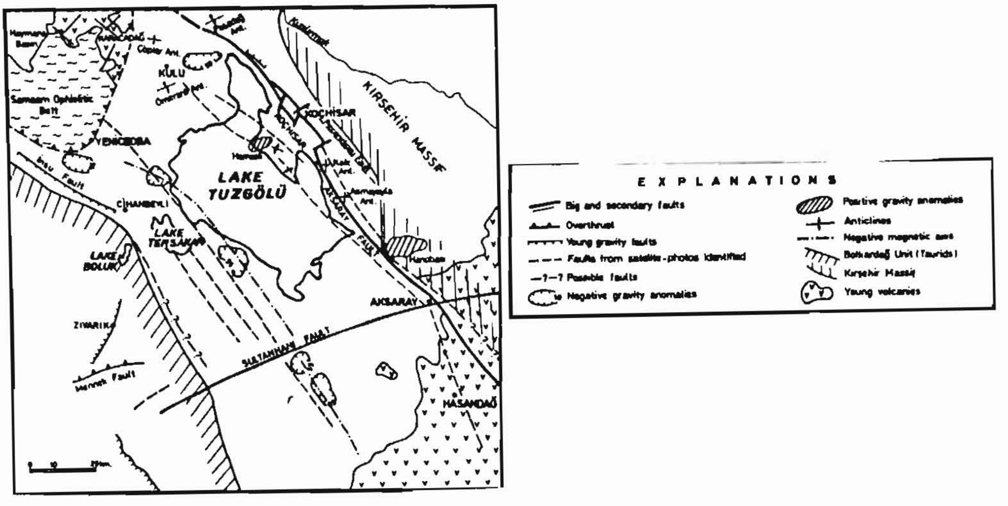

Fig. 4: Important tectonic features of Tuzgölü basin (from Uygun, 1981).

After the Middle Eocene, in which the regression of the sea took place, widely extended graben depositions occurred (Arìkan, 1975). At the same time, Kìrsehir and Bozdag-Sivihisar Massifs became the border of the present Lake Tuzgölu basin (Fig. 4). In the upper Eocene, clastic sediments, gypsum and lignite-bearing Bala Formations and Çankìrì evaporite series developed. Characteristics of the arid periods of the continental close-basin took place during the Oligocene time.

The succession of the terres-trial and marine sedimentation, and the disjoining of the basins from each other by tectonic deformation is very characteristic of this period (Uygun, 1976). The Tuzgölu-paleo-basin is also one of these basins. In the lower Miocene, gypsum-bearing clays are dominant in the Tuzgölu basin. In the Middle Miocene, however, trono deposition occurred at Beypazarì (Inci, 1991; Helvacì, 1989). After the Upper Miocene, the domination of terrestrial units was relevant for the whole of Central Anatolia. It means that extensional tectonic regimes have been continuing in central Anatolia. In Tuzgölü basin, the Cìhanbeyli Formation, with a thickness of 1100 meters, consists of marn and limestone in the south, coarse clastics to the west and

Table 1: Representative and/or mean values of chemical composition of lakes and some of their inflows.

	Mg/lt.							
	Na^{+}	K^{+}	Ca^{++}	Mg^{++}	Cl^{-}	SO_4^{--}	$CO_3^{--}+HCO_3^{-}$	pH
LAKE TERSAKAN	49887	5578	793	11514	11175	35009	892	7.50
LAKE BOLLUK	18000	1350	440	5420	23000	31100	353	8.9
Ground-water	330	27	350	221	1475	2171	280	8
Travertine pinnacles	344	25	483	193	560	2316	342	8.15
Yapalı mineral water	330	23	483	200	565	1939	488	7.75
Yapalı Hamam	335	24	416	193	550	1903	325	7.90
LAKE ACIGÖL	38630	1296	461	3611	48489	29286	320	7.85
Ground-water	5329	101	394	702	8198	4295	198	7.55
Spring	166	5	173	52	192	377	311	7.60
LAKE BURDUR	5835	52	13	920	605	8710	588	9.3
Soğanlı Hot Spring	191	5	33	44	9	102	457	8.12
Tümlace Hot Spring	328	10	41	94	98	333	568	8.31

lacustrine sediment intercalated with volcanic units in the SW are quite common (Uygun, 1976).

Hasandag, Melendiz volcanic centers, and Cappodocia ignimbrite plateau continued their activities from Upper Miocene to historical time. During the last stage of the volcanism, alkaline basaltic graben volcanism, specific to the expansion tectonism, linked up along the fault zones. Karadag, K-rich trachy basalt to the east of Lake Bolluk, is a product of this activity (Fig. 5). Variously sized calderas and maar lakes are still releasing volcanic gas, and this is causing them to become saline lakes (Meke Tuzla, Karapìnar Acìgöl and Sofular, Fig. 1)). The extension of Lake Tuzgölü was wider during the Pleistocene (Erol, 1978). Seismic prospecting around Lake Tuzgölü, showed some negative gravity anomalies and some drill cores pass the NaCl layers at the depth of 700 m. This confirms the presence of NaCl diapir at the bottom of the basin (Uygun, 1976).

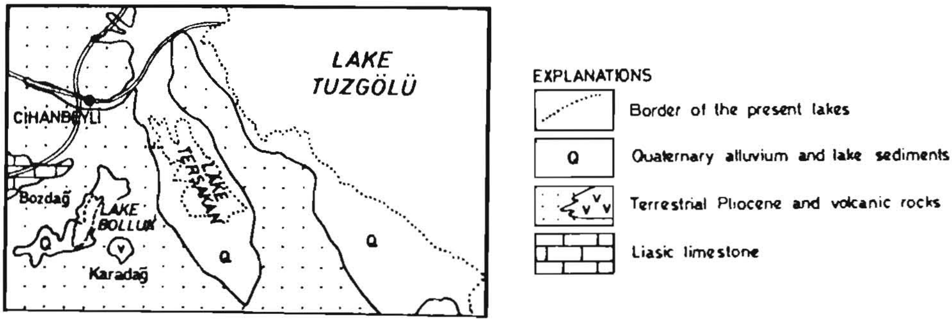

Fig. 5: Geological map of the area surrounding Lake Bolluk and Lake Tersakan (modified from Uygun, 1976).

It is quite apparent that the bottom sediments of Lake Bolluk and Lake Tersakan are the same. Both of these lakes separated from Lake Tuzgölü and initiated their own hydrochemical evolutions. Irion (1970), reported on the basal sediments of Lake Tuzgölü "Except for a small basin section, the water of the Tuz Golü is saturated with NaCl. The SO_4, Mg, and K are particularly high, whereas, the Ca content is relatively low.

The Tuz Gölü sediments consist of more than 75 % of authigenic minerals: magnesite, huntite, dolomite, Mg-calcite, aragonite, gypsum, celestite, and polyhalite.

According to the mineral content and the ion content depending on lake-water concentration, three different sediment types can be found in the Tuz Gölü:

a) Sediments of the central part of the lake:
The pore waters of these sediments dispose of an extraordinarily high ion content. Besides some 50 % of gypsum, the sediment consists of magnesite, huntite, and monomineralic polyhalite layers.

b) Marginal sediments:
With mean ion concentrations of the pore waters, part of the sediments still consists of minerals which are

characteristic of the lake center: magnesite, huntite, and gypsum (< 15 %). It, however, contains a considerable percentage of carbonates being poor in Mg: dolomite, Mg-calcite, and aragonite. The percentage of detrital minerals increases towards the shore, whereas, the marginal sediment hardly contains any authigenic minerals.

c) Sediments of the deepest part of the lake:
At relatively low ion concentrations aragonite, Mg-calcite, and dolomite are formed. At the same time the sediment contains detrital minerals: calcite, feldspars, and clay mineral".

Bottom sediments of Lake Bolluk and Lake Tersakan are observed as carbonate cemented gravels at the marginal and marn and clay in the central area. To the south of Karadag, a drill core cut the following units from top to bottom; 0-25 m carbonate, 30 m clay, 35 m gypsum-bearing marn, 75 m carbonate intercalated clay (Canik, 1988).

In the ancient and the modern extension of Lake Bolluk, Saloman-Calvi and Klinsarge (1939) observed variously sized sixty travertine pinnacles. Erol (1978a), mapped 63 of them and indicated that they are lined up in four different directions. According to Erol (1978a), the heights of these travertine pinnacles range from about 1-30 m from the ground and range from 30m to 500 m in diameter. Canik (1988) explains these phenomena as carbonate precipitations around springs during a span of thousands of years. Some of these pinnacles are still filled up with water and the water levels are different even in neighboring pinnacles. This situation is related with spring discharge characteristics and water outflows along the joints. During the summer seasons, if water is pumped from the man-made wells and artesian wells for the purpose of irrigation, the water levels of all the travertine pinnacles decreases about 4-5 meters.

Joint systems observed in travertine pinnacles confirm that the faults around the lake are still active. Both the so-called Yapalì mineral and Yapalì hamam hot spring waters are located in the same place (in the dry mud flat) of Lake Bolluk. In Tersakan and its surroundings, no travertine pinnacles and/or hot water springs were observed. The occurrence of the travertine pinnacles of Lake Bolluk confirms that Lake Bolluk has been a spring-fed perennial lake. Figure 6 schematically illustrates the cross section of Lake Bolluk and carbonate dissolutions with hot water circulations and formations of the travertine pinnacles.

Each Lake Bolluk (9.5 km^2 of surface area) and Lake Tersakan (38 km^2 of surface area) are about one meter in depth. Yapalì village to the east of Lake Bolluk receives its domestic water from 12 meter deep wells, that have drinkable properties. In the vicinity of the village, at the dry mud flat and in the lake area, there are hot springs (with 35-38°C temperatures and discharges of 1-41 lt/sec) and travertine pinnacles. In the same area, the water of the pumping wells (about 140-150 m deep) have a temperature of 30-35°C and also contain diluted waters.

Both aerobic "oxidizing" (Thiobacillus Thioxidans) and anaerobic "reducing" (Desulfouibrio desulfurucans) bacteria are found in Lake Acìgöl and Lake Bolluk (Dr. F. Ucar, personal communication). In addition, photosynthetic bacteria also are present in this biological cycle.

The Na:Cl ratio, as seen in Lake Acìgöl, remains constant until the end of the evaporation (Fig. 7a). The behavior of HCO_3 +

CO_3 (Fig. 7b) and K (Fig. 7c) during brine evolution also exhibits the same pattern in Lake Acìgöl. However, the SO_4 evolution is different than the Lake Acìgöl SO_4 evolution. The SO_4:Cl ratio remains constant until the most concentrated brine, excluding some ground waters and springs. Since $NaSO_4$. 10 H_2O is present in both lakes, SO_4 depletion is expected for both lakes. However, this is not the case for Lake Bolluk. This is because of the occurrences of SO_4 enrichments of spring waters, which keep the ratio constant up to the very end of the brine evolution (Fig. 7d).

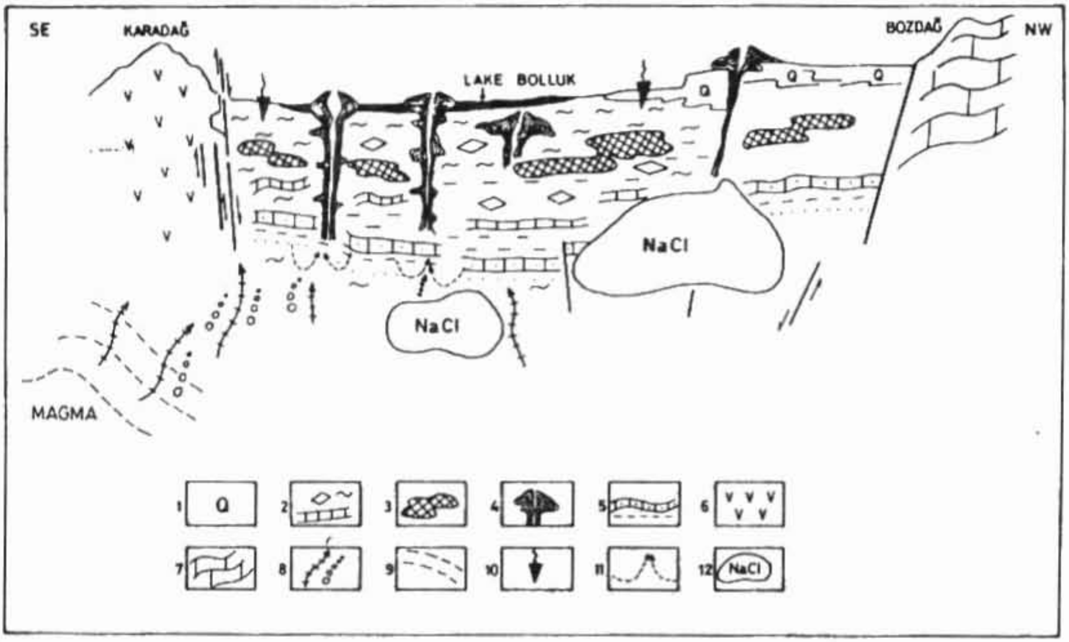

Fig. 6: Schematic cross section of Lake Bolluk:1. Quaternary alluvium intercalated with lake sediments; 2. Lake sediments (mud, gypsum, carbonate, and others); 3. Trapped brines; 4. Travertine pinnacles; 5. Pliocene sediments; 6. K-rich trachy basalt (Plio-quaternary); 7. Jurassic limestone; 8. Magmatic volatiles and hydrothermal transfers; 9. Heat flow; 10. Hot springs; 11. Groundwater circulation; 12. NaCl diapir.

CONCLUSION

Three commercially $NaSO_4$.10 H_2O explioted saline lakes, which take place in graben basins, consisting of different chemical compositions, were examined and an attempt to illustrate their own geological settings and hydrochemical evolutions was undertaken.

In the initial stages for each of the lakes, graben tectonics, wide recharge basins alkaline basaltic volcanism, vola-tile transfers, volcanic gas releases and geothermal waters are common primary occurring features. Modern caldera and maar lakes of central Anatolia, are yet in the first stage of being saline lakes (Meke Tuzlasì, Karapìnar Acìgöl, Sofular, Fig. 1).

Lake Burdur is one example which is in the first stage of becomming a saline lake, having no structural relation with volcanism and [illegible]

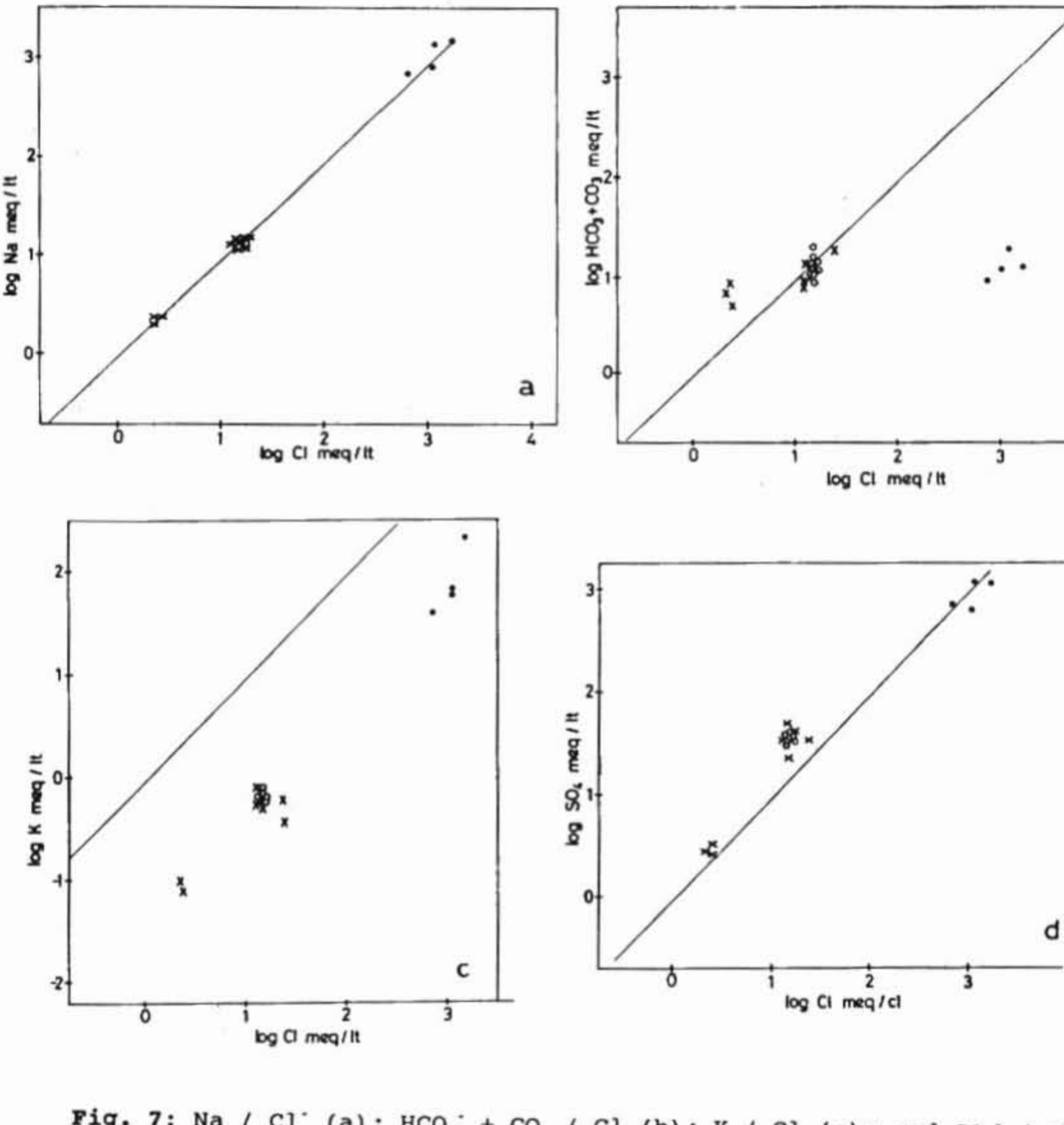

Fig. 7: Na / Cl$^-$ (a); HCO_3^- + CO_3 / Cl (b); K / Cl (c); and SO_4^- / C (d) of Lake Bolluk (cross= shallow and deep ground waters; op circles= hot and cold springs; dots= lake water).

During succeeding stages, the disconnecting of basins by the effect of horst-graben type of deformations, reduction of the lakes in size, the recharging of saline (chlorine) ground waters with the capacity of dissolving gypsum more efficiently, the differences of ground water composition and/or recharge area and movements in step from topographic structure (i.e., Lake Karabogazkan and Lake Caspian models) causes each lake to have its own hydrochemical evolutions and evaporation series. The special evolution of these three lakes can be summarized as follows:

Lake Acigöl "Denizli"

It is a very young graben lake. There is no wide spread salt deposition around it. No underground diapires have been observed underneath the lake basin. The ancient geothermal sources, fumaralitic-sulfataric activities of Gölcük tephrin-phonolite (Özgür, et. al., 1992) and their sulfur deposits (Keçiborlu-Isparta, Fig. 1) were various recharge sources of this lake after Pliocene. Carbonate precipitation is completed (travertines can be seen along the shore). The basement mud of the lake abundantly consists of authigenic gypsum (up to 50-60 %). In this stage Na, SO_4 and Cl ions are concentrated in the lake water.

Lake Bolluk

It is a spring fed perrenial saline lake. It has almost completed its carbonate deposition by the recharging of hot springs. Carbonate precipitation is still continuing in traver-tine pinnacles.

Like in Tüzgölü basin, the deposition of gypsum deceased in Lake Bolluk. However, authigenic gypsum dissolution from Tersier sediments by clorine concentrated groundwater and also by discharging the NaCl enriched and SO_4 depleted water back into the lake by exploitation is a common occurrence. Potasium enrichment of this lake can be explained by being close to the volcanic occurrences. Volcanism of expansion tectonism is characteristic with potasium enrichment (Savasçin, 1989). Since potasium is bounded to clay minerals in the lake sediments, the lake water is enriched for sodium also.

Lake Tersakan

Having developed on the periphery of Lake Tuzgölü as a marginal basin, it shows the properties of a spring fed perennial saline lake and Lake Tuzgölü. However, it has not yet reached the stage of Lake Tuzgölü (NaCI enriched). It is concentrated in Na, SO_4, and Cl and in the basement of the lake, as in Lake Bolluk, gypsum occurrences take place (up to 70-80 %).

The correlation of K, Na, SO_4, CO_3 ions in respect to the Cl ion for each of the three lakes, using ground waters, spring waters, and the porewaters of mud sediments demonstrates them having very good relations.

The Na:Cl ratio does not change in all the inflow waters and the brine, of the lakes. For this reason, when the Na:Cl line is used as a reference, HCO_3 + CO_3 depletion is observed in the brines of all of the lakes. This is related to the carbonate precipitation. K remains constant in all inflows and brines, however, SO_4 depletion is observed because the hot springs of Lake Bolluk are enriched in SO_4 and this makes up the SO_4 loss.

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