On the hydrogeology of the Lower Tagus Basin and its Cenozoic geologic evolution

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Abstract

Key-words: Hydrogeology; Lower Tagus Basin; Cenozoic; geological evolution.

The chemical features of the ground water in the Lower Tagus Cenozoic deposits are strongly influenced by lithology, by the velocity and direction of the water movement as well as by the localization of the recharge and discharge zones.

The mineralization varies between 80 and 900 mg/l. It is minimal in the recharge zones and in the Pliocene sand, and maximum in the Miocene carbonated and along the alluvial valley. Mineralization always reflects the time of permanence, the temperature and the pressure.

The natural process of water mineralization is disturbed in agricultural areas because the saline concentration of the infiltration water exceeds that of the infiltrated rainwater.

In the discharge zones, the rise of the more mineralized, sometimes thermal deep waters related to tectonic accidents give rise to anomalies in the distribution of the aquiferous system mineralization model.

The diversity of the hydrochemical facies of the ground water may be related to several factors whose identification is sometimes difficult.

Resumo

Palavras-chave: Hidrogeologia; Bacia do Baixo Tejo; Cenozóico; evolução geológica.

A composição das águas subterrâneas que circulam através dos depósitos cenozóicos da Bacia do Baixo Tejo é fortemente influenciada pela litologia das camadas aquíferas, pelo regime de fluxos e pela localização das zonas de recarga e descarga. A mineralização varia entre 80 e 900 mg/l, sendo mínima nas zonas de recarga e nos depósitos arenosos pliocénicos e máxima nos depósitos carbonatados do Miocénico e ao longo do vale, reflectindo, em cada caso, a permanência no aquífero, a temperatura e a pressão.

Em zonas agrícolas, o processo natural de mineralização das águas sofre perturbações, uma vez que a concentração de sais nas águas de infiltração excede a mineralização da precipitação.

Nos locais de descarga, a subida de águas profundas mais mineralizadas, às vezes termais, relacionadas com acidentes tectónicos de âmbito regional gera anomalias no modelo de distribuição da mineralização pelo sistema aquífero.

A diversidade de fácies hidroquímicas das águas subterrâneas pode relacionar-se com vários factores, às vezes difíceis de identificar.

Introduction

This study concerns the Hydrogeology of the Cenozoic deposits along the Tagus valley between Constância and Setúbal, set by the parallels 6° 30' 00" and 9° 40' 00" W, and by meridians 37° 00' 00" and 40° 46' 00" N (European datum). The concerned area is bound by the Mesozoic at Northwest and North, by the "Maciço Antigo" at North and Northeast; in the South by the Alvalade Basin (Antunes, 1986); and in the West by the Atlantic Ocean (Fig. 1).

Twelve hundred well logs of hydrogeologic surveys with depths between 10 m and 604 m have been studied. The physical and chemical caracteristics of
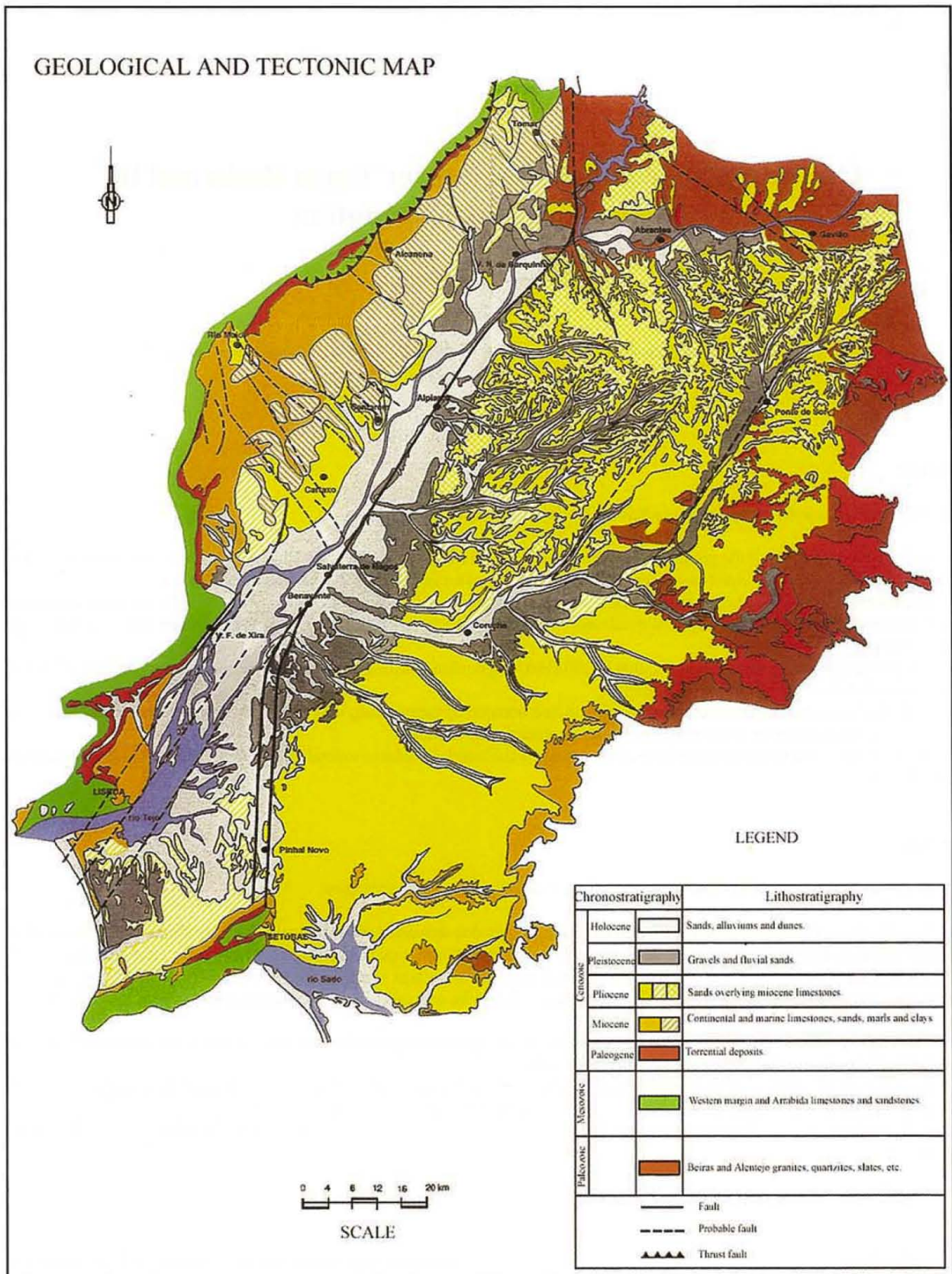
GEOLOGICAL AND TECTONIC MAP

Chronostratigraphy		Lithostratigraphy
Holocene		Sands, alluviums and dunes.
Pleistocene		Gravels and fluvial sands.
Pliocene		Sands overlying miocene limestones.
Miocene		Continental and marine limestones, sands, marls and clays.
Paleogene		Torrential deposits.
		Western margin and Arrábida limestones and sandstones.
		Beiras and Alentejo granites, quartzites, slates, etc.
		Fault
		Probable fault
		Thrust fault

LEGEND

SCALE

Fig. 1 - Lower Tagus basin geology and tectonics.

seven hundred and fifty five samples of ground waters from wells and springs, as water from the river Tagus were recognized

Geologic settings

The Lower Tagus Basin had a tectonic origin in the Eocene after the NE-SW reactivation the hercinic faults. Tectonics, eustatic variations, lithology of the peripheric relief and climate have conditioned the sedimentation. The Basin is filled with materials from the "Maciço Calcário" and from the "Maciço Antigo".

Paleogene

The Paleogene units are formed by reddish, immature sediments: polygenic conglomerates, sandstones, clayey sandstones, claystones, limestones and marls.

In the Lisbon region, there are 425 m thick continental deposits reported to the Paleogene, the "Benfica Complex". These deposits overlie the upper Cretaceous, Lisbon-Mafra Volcanic Formation and are overlain by the mostly marine Miocene infillings of the lower Tagus basin.

The lower subunits of the "Benfica Complex" are especially rich in detrital materials contributed by Paleozoic units, including those from granites that originated quite developped arkose layers. Quartz, quatzite, schist and other clasts are common. Later on, jurassic limestones, sandstones, silex and even basalt clasts prevail. Caliche levels are known, as the "Alfornelos Limestone". The upper part of the "Benfica Complex" may be Oligocene in age.

On the right bank of the Tagus, there are northward outcrops of the "Benfica Complex", upwards north, leaned to the Mesozoic in discontinued lanes. Thickness attains up to 100 m (Aloformação de Monsanto, Barbosa, 1995). This units comprises "Chegranças and Casais Complex" (including the Quinta da Marquesa limestones), the "Abrigada Complex", the "Alcanede Complex" (Monsanto sandstone and Alcanede limestones) and the "Cabos Complex". Sands, clays, arkoses and marls with limestones concretions outcrop at Gavião, Montargil, Ponte de Sor and Mora. The thickness in the oriental part of the Basin is about 50 m (Barbosa, 1995).

In the Setúbal region there are composed by Paleogene reddish sandstones, conglomerates, red marls and white limestones with lacustrine fauna near the top. It contains twinned gypsum crystals (Choffat, 1908). The maximum thickness (200 m to 300 m) is attained west of the Ribeira de Coina (Choffat, *op. cit.*).

At the northern boundary of the Basin, near the Iberian Central Ridge, sandstones whith carbonate caliches and few lydite clasts can be seen on the Paleozoic. Thickness does not exceed 12 m. At Maceira, white quartz clasts predominate over (90%), granite and lydite ones (Barbosa, 1995).

Sediments (mostly sands), were deposited through gravitational flow under a selective and badly defined water regime.

The main drainage, more or less NE-SW paleogene directions (probably three) follow hercinic tectonic accidents (Tagus, Ponte de Sor, Gavião, Nazaré fault, the Zêzere river). They were joined by transversal streams. The main drainage directions can be identified with former rivers related to extant ones: the Tagus downstream of Constância, the Sorraia and Erra rivers.

A preceding river of the Zêzere had its mouth near Nazaré. It drained the southern part of the Iberian Central Ridge, at least during the Eocene. The same river was later captured by the Tagus. The submarine canyon of Nazaré, the most important one of the western Europe, must have been a discharge channel of this river.

The evolution of this region was a complex one because of its location at the end of the Iberian Central Ridge. As a consequence, two main drainages became possible: through Zêzere in the southern part and, in the opposite part, the Douro river, whose northwards migration has occurred (Antunes, 1979; p.163). With this hypothetical river (the drainage regime at the time was torrent like) must be related the Eocene deposits between Nazaré and S. Pedro de Muel, called "Feligueira Grande Complex" (Zbyszewski, 1965).

The forerunners of the Almonda and Nabão rivers drained granites, schists, quartzites and graywackes from Beiras as well as the "Maciço Calcário Estremenho". A pre-Tagus river went along since Gavião, Bemposta and Erra until Setúbal, by through the eastern side of the Serra de São Luís. The Sorraia drained the "Maciço Antigo" to the east, and developped its course southwards; more or less ended at the Águas de Moura channel.

The hydrographic basins and the drainage network of these "rivers" (it might be just be primary directions) where probably poorly ill defined in the Paleogene. These "rivers" allowed connections amongst them, defining a big reception basin, probably due to intensive and long rain events. The deepest and with the largest flow river would be the one along the Tagus valley and maybe the Zêzere valley.

The drainage was ensured by torrents during the rain season, from the "Maciço Calcário Estremenho" and the "Maciço Antigo" to the reception basin. The discharge was through a channel or dejection cone towards the Atlantic Setúbal and Nazaré canyons.

The erosive action is regressive, that is, the erosion at the upstream part of the course constantly makes its origin to step back. Other water lines could have been captured.

Miocene

The Miocene is characterized by alternating continental and marine deposits. A broad alluvial plain and an estuary open to the Ocean between the Sintra and Arrábida mountains developped. Corresponding depositional environments vary from marine, circalittoral to coastal ones to brackish and continental, either fluviatile or lacustrine. The sediments of continental origin may be detritus carried

on by the rivers or results from biological action. Components were carried from the continent into the sea.

Euststatic variation is outstanding and really determinant in the Miocene. These were responsible for the regressions and transgressions (Antunes, 1971), during Miocene and Pliocene times.

The Miocene series thickness differences betweeen the ocean-open part and the center of the Basin may result from factors acting simultaneously or not:

1) the rise of the Setúbal Península after the accumulation of the Miocene deposits in the distal part (estuary) of the river;

2) reactivation of faults along the Tagus valley;

3) the establishment of drainage networks in the Setúbal peninsula, with its origin in the Lisbon and Arrábida hills. The related erosion may explain the lack of Upper Miocene units, while the lower Tortonian exists in the Lisbon region. Upper Miocene is present in the Ribatejo and in the Alvalade Basin.

In Lisbon there is a succession of clays, limestones and sandstones. Cotter (1903/04), based on lithostratigraphic criteria, defined VII divisions.

Marine deposits can also be seen at Alcácer do Sal and Lavre.

Away from the sea, there are fluviatile deposits originated in the "Maciço Calcário Estremenho" to the west, and in the Paleozoic to the north and east. The sediments nature would depend on lithography and river energy. There were also some lakes and lagoons. As a result deposits are much varied there. The continental neogene series is represented by Ota unit (medium to coarse grained sandstone and clays, sometimes with gravel intercalations) and Archino unit (Antunes, 1979), both with oyster levels in their upper part at Vila Nova da Rainha. Over the there are thick oyster banks, more or less coarse sands alternating with marls and clays, sometimes with lignite and oysters. Important vertebrate localities allowed a fine datation from Astaracian-Serravalian to Lower Vallesian-Tortonian (Antunes, 1984). Over the latter there are the Upper Tortonian/Vallesian Cartaxo-Almoster-Santarém limestones (Antunes, 1984), well dated by vertebrates collected at Azambujeira, Freiria, and Asseiceira.

The "Tomar Clays" are part of the Lower "MP Complex" that is also exposed in the Tagus left bank area (see "Carta Geológica de Portugal"). To the north it can be observed in the Asseiceira area near Tomar and in the valley of the Ulme river between Medroa and Abrantes. In the Tagus left riverbank area it appears at Bemposta, Coruche and Mora. To the south, there are outcrops on the rigth riverbank in the Vila Nova da Rainha-Azambuja area and at Lavre, on the left bank. In these area there are outcrops of limestones that are similar to those from Almoster, Upper Miocene. These deposits may be reported to the Vallesian, Upper Miocene (Pais, 1981) even if paleontologic evidence only comprises plant fossils from Quinta das Figueiras, Ulme and Vale de Carros (Pais, 1981).

The concerned deposits are orange/red silty clays with thin sandstone beds. The coarse fraction comprises quartz (more than 75%), feldspars and micas. There are some Fe/Mn concentrations.

The thickness of the same units is under 200m in the left bank area; it does not even attain 10 m on the right bank area.

Pliocene, Pleistocene and Holocene

After the marine transgressions in the Alvalade Basin (Tortonian and late Messinian), corresponding to the Esbarrondadoiro and Santa Maria do Sado units, an important tectonic crisis affects the whole area. Its main effects were the uplift of the Arrábida chain and the leveling of the Setúbal Península. As a consequence, fluvial drainage changes, modifying the former hydrographic network whose profile was then close to a balanced one.

In the Península, rivers that were part of the Lisbon hills drainage, coming from the NW, crossed the Charneca de Caparica, Corroios and Moita areas. Another river would join in from the south, Arrábida, crossing the Cabanas and Coina rivers. A river would drain the western part of the basin (Loures, Ota, Maior, Alviela, Almonda and Nabão) and another its northern area through Santarém and Entroncamento. The drainage headed to the pre-Tagus through the Sorraia channel, and thereafter to its mouth at Setúbal. This situation lasted until the opening of the modern mouth of the Tagus. The tectonic movements in the Tagus valley, caused by the sediments weight, led to changes in the drainage orientation. The Sorraia channel, where the right side rivers would join the main river, reverses its course, after the current Tagus exit rupture. This Tagus rupture was a consequence of the Miocene layers erosion.

From that event on, the main river becomes a stream on the left side of the Tagus the extant main river. Meanwhite, a left E-W tributary of the Zêzere river captures the pre-Tagus waters at Gavião, draining them until Constância and diverting completely the former river course.

The pre-Tagus capture by the Zêzere and the drainage inversion at the Sorraia channel, redirecting the waters to the Mar da Palha left the Setúbal valley.

The sedimentary hiatus during the Upper Miocene in Lisbon can result from intensive erosion caused by the NE - directed drainage network. It stillmay be recognized in the Setúbal Peninsula through the direction of the ground water flows. Hence the Setúbal Peninsula has never been a fluvial discharge area but instead a drained area subject to erosion, transport and some sedimentation.

The retake of preexistent deposits might happen then. This would explain the sedimentary hiatus the Upper Miocene. The transition of the Miocene to the Pliocene might have been marked by an important erosion discontinuity.

These events were followed in the Pliocene by active faulting and Basin subsidence in the extant Tagus area that prevailed until now. Their effects where emphasized

by the Benavente earthquake, in 1990, whose maximum intensity attained the IX level (MM) at Benavente, Samora Correia and Santo Estevão (Moreira, 1984); and X level (MM) at Benavente (Oliveira & Sousa, 1991).

After migrating northwards the Sado river settles near Setúbal in the pre-Tagus abandoned course, assumes the extant profile.

Hydrogeology

Groundwater quality and geological structure

The hydrochemical facies of the ground water that flow through the Tertiary Lower Tagus basin units depend very much of the geological environment. The flow system and the localization of the recharge and discharge areas force the water to follow specific directions pathways which influence the physical and chemical composition. The geology and geomorphology determine the type of circulation and the localization of those areas, while the climate sets the volume of the drained water.

The time between the infiltration and the discharge depends on aquifer depth, the distance and the geological environment. It can take a few hours, days or even years. According to the hydrogeological conditions, it might appear as a local and/or regional flow system, respectively at subsurface or at depth.

The period of the water's contact with the rocks is therefore variable. As a result, some hydrochemical facies can be related to the lithological surroundings, and other ones to the physical and chemical environment and (much less), to the recharge water quality.

All these factors as a whole enable and explain the existence at an underground reservoir of waters with different compositions in extension and depth, even if the aquifer lithologies are not different. These variations are due to the concentration increase of more soluble substances. This can easily be detected because of the increased values of the ions concentration and electrical conductivity, especially in the case of deeper waters and of waters more far apart from the recharge area.

Collateral variation is mainly due to disruptions in the recharge and exploration process, to lithological changes, to the mixture of different waters and to the time of residence, which depends on permeability.

The most frequent cause of the vertical variation is the different permeability of the traversed layers. Consequences depend on the time of stay, which tends to increase with depth, temperature and pressure.

There can be changes on the natural process of mineralization of the ground water in areas of irrigation supplied by deeper waters with larger ion concentration, so that when the water reaches the aquifer surface it is much more mineralized than rainwater. That is due to chemical fertilization and lixiviation of the soils. The repetition of these phenomena lead to increased salinization, which is only hampered by the rainwater infiltration.

The salt concentration depends on the rain regime and the level of re-use. These allow the water to reach the upper aquifer with high levels of salt and nitrogen compounds when the infiltration is weak.

Water physical and chemical composition changes owing to the coming up of sometimes thermal ground waters through major faults. Therefore, water quality differences may result from many factors (sometimes not easily detected) with various levels of activity.

The representation in the Stiff diagram of the ground waters main composition shows several groups that are similar in profile but different in dimension. Each group is similar as far as hydrogeochemical facies are concerned, but differs by mineralization, which is more important as the polygonal areas are larger (Fig. 2).

For each group, the polygonal area increases according to the drainage capacity; it shows its evolution in the salt concentration process. Hence, the mineralization increases from the recharge zones in the eastern and western borders of the basin to the discharge spots along the valley near the course of the main river.

Tectonics, lithology and topography control the discharge spots and how the discharge is carried out, either through concentrated springs with big water flows or in a diffuse way with variable drainage from the deeper layers to the upper aquifer.

The number and characters of the hydrogeochemical groups of the aquifer systems are consequences of: the geology; the local and/or regional flow system; the localization of the recharge areas; the mixing of different ground waters; the influence of the Rio Maior and Pinhal Novo diapirs; the reutilization of ground water in agricultural, alluvium areas; the saline-water encroachement; and (in a lesser scale) contamination.

On the Tagus left riverbank the ground water flows from the eastern border (recharge zone), where water mineralization is lower (80 mg/L). Mineralization values are higher (at least 390 mg/L) towards the central part of the valley.

The E-W water flow (recharge) infiltrates at Abrantes, Ponte de Sor, Chouto and Lavre. It moves to the center of the valley towards smaller gradients. It is forced to come to the surface and deal with the natural barrier formed by the less permeable Miocene deposits. Its course then depends on the active faults of the Tagus valley. Discharge takes place at Ulme, Almeirim, Alpiarça, Salvaterra, Glória do Ribatejo, Benavente and Alcochete; the aquifer variations in these areas are confined (at Almeirim, Alpiarça, Salvaterra, Glória and Benavente) and semiconfined (at Ulme and Alcochete).

Taking in to account the silica levels (60 mg/L) and temperature (27° C) in the discharge zone, one can assume that the ground water flow might reach, especially at Alpiarça, where the impermeable rock substratum is located at a 1495 m depth (by use of the silica geothermometer, Fournier & Truesdell formula, 1974 m, for the cristobalite and considering a geothermic gradient of 33 m and an average year temperature of 16,5° C). This estimate is close to the less than 1400 m sediment's thickness as indicated by a seismic profile (Mendes Victor *et al.*, 1980).
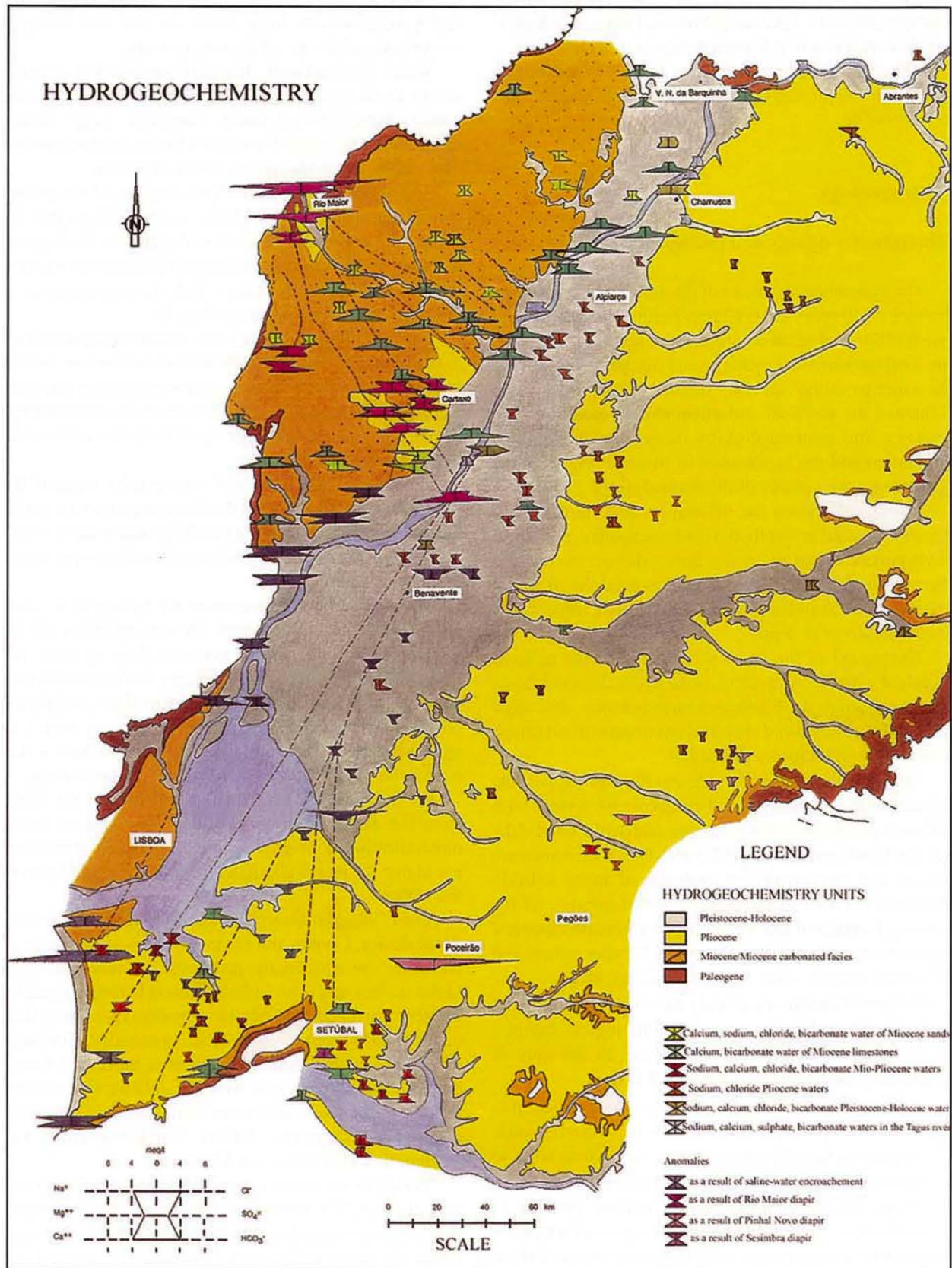
Fig. 2 - Hydrogeochemistry groups in the Cenozoic Lower Tagus Basin.

However, the evolution of the physical and chemical composition of these waters is disrupted by an anomaly related to salt deposits of the Pinhal Novo diapir. In an 8 m deep well at Lagameças (Poceirão), water presented high mineralization values (1244 mg/L) and high levels of chloride (685,7 mg/L), sodium (230 mg/L), sulphate (71,6 mg/L) and magnesium (84,5 mg/L). This only can be explained because Pinhal Novo diapir is very close by.

The deep circulating water that contacts evaporites can surface through the Palmela faults and disperse itself in the Pliocene sands. Mixture with ground water from upper aquifers occurs, although upper aquifers are conditioned by gradients and permeability; the sodium chloride water at Lavre is an example. Supporting this corroborating viewpoint, we observed a higher mineralization in these waters along with a higher silica concentration (23,6 mg/ L) which decreases (16,9 mg/L) with dilution.

In the Setúbal Peninsula, an anomalous situation also results from the mixture of waters from the Pliocene sands and the Miocene limestones with different composition. The small thickness of Pliocene units and their great permeability explain this fact. Taking into account the upper sand levels and the overexploitation of the aquifer, waters of intermediate composition are common in this region.

On the right Tagus riverbank, two aquifers must be taken into account. One lies at subsurface, with transversal W-E flow into the axis basin formed by medium and Upper Miocene limestones at Almoster, Alcobertas, Moçarria, Marmeleira, Santarém, Alenquer, Ota, Alcanena and Torres Novas. It is characterized by calcium bicarbonate waters with mineralization between 400 and 900 mg/ L. Another deeper, N-S aquifer is formed by lower Miocene sandstone deposits between Pernes and Vila Nova da Rainha.

In the Cartaxo region a composition that is not characteristic of the Miocene units occurs. In this region, Miocene units are cut by NW-SE faults that cross Rio Maior. There is a sodium chloride water with chlorid levels that attain 121 mg/L. This phenomenon can not be explained by saline-water encroachment because the sea is too far away. It is due to the mixture of salty waters that flow from Rio Maior.

As far as Pleistocene-Holocene units are concerned, surface waters of wells show abnormally high mineralization levels that exceed those of deeper aquifers in the same area. This occurs in agricultural zones irrigated by ground waters, The systematic re-use of ground waters explains the higher concentration of sulphate, chloride, bicarbonate and calcium.

Above Santarém, connections between river and aquifer have only been recognized at the alluvium level, where waters are similar in sulphate and magnesium contents.

In the Tagus river upstream of the tidel range at Vila Franca de Xira, water composition seems to be constant. This is typical of a river with a big flow. However, the waters mineralization decreases betweeen Vila Franca de Xira and Santarém, as a consequence of the arrival to the river of, less mineralized waters from both riverbanks.

In spite of the association in groups of the Lower Tagus ground waters based on the Stiff diagrams, their ionic classification (according to Pipe) varies little. Sodium bicarbonate and/or calcium waters predominate, except in the detritic zone where mineralization is lower and they can be grouped in the chlorid/sodium branch. Near the Tagus and the Sado estuaries there are hydrochemical structures related to saline-water encroachement; the water is sodium chloride rich in these areas.

The dispersion in the distribution of the dots in the diagram is broad (Fig. 3). This results from the lack of clear borders between the aquifers, of anisotropy, heterogeneity and of mixture of different origin waters.

Waters from the Pliocene vary between the bicarbonate and/or sodium chloride; those from the Miocene are mainly calcium bicarbonate, but there is much variation between sodium bicarbonate and sodium chloride or calcium.

For the Pleistocene-Holocene, chemical water characters are very similar to those from the Miocene. These are mainly calcium biocarbonate waters. That sometimes change into calcium chloride ones.

Conclusions

The study of the ground waters physical and chemical characters confirm the relationships between the hydrogeochemical groups established for the aquifer system and Geology aspects, the flow system, the location of recharge areas, the mixing waters of different qualities and several origins, the proximity of diapirs agricultural regions, saline-waters encroachement in coastal areas, and contamination sources.

The diversity of the hydrogeochemical facies of the ground water is related to different factors whose identification is sometimes difficult.
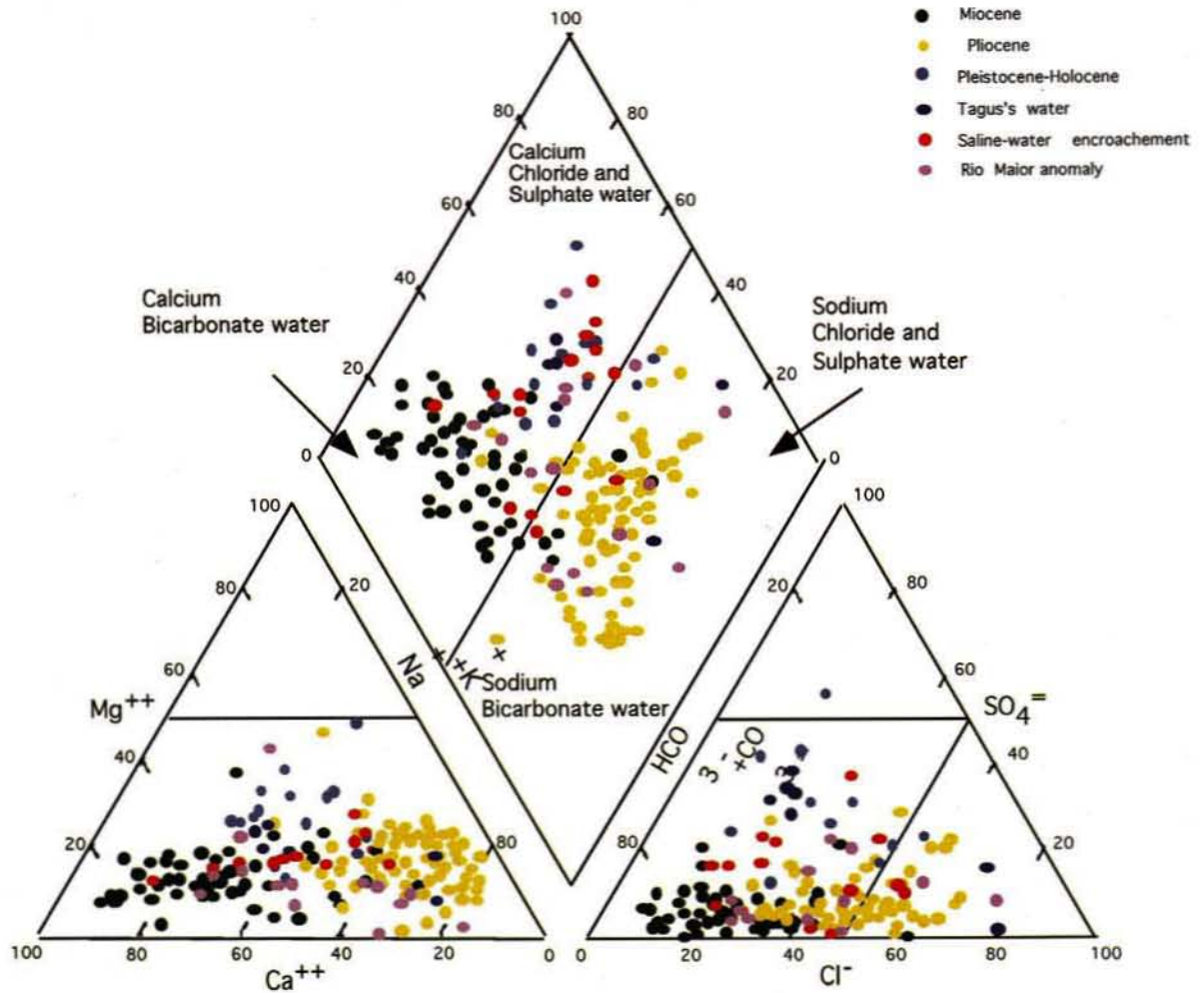
Fig. 3 - Trilinear diagram of water analysis from the aquifer system of the Lower Tagus Basin.

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