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Preliminary hydrogeological interpretation of the Aigion area from the AIG10 borehole data

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Abstract

The AIG10 borehole provided direct access to hydraulic conditions. The first results of two open-hole pumping tests and one artesian production test are presented. From the first pumping test in the conglomerates, a hydraulic conductivity of 10^{-5}–10^{-4} $m\,s^{-1}$ was derived and it was suggested that there is a closed hydraulic system bounded by the Aigion Fault zone and other faults farther north. A second pumping test, in the Olonos–Pindos limestones, showed artesian flow (water pressure of 0.5 MPa and flow of 1.9×10^{-4} $m^3\,s^{-1}$). The transmissivity is about 4×10^{-6} $m^2\,s^{-1}$. Below the fault zone, pressure and flux increased, suggesting karstic water-flow conditions. Water-pressure difference of more than 0.5 MPa between the hangingwall and the footwall provides evidence that the Aigion Fault zone acts as an impervious zone. An artesian production test for the interval 708–1001 m showed a fluid pressure of >1 MPa and natural flow of 1.5×10^{-2} $m^3\,s^{-1}$. A transmissivity of 2–3 $\times 10^{-4}$ $m^2\,s^{-1}$ was determined. A preliminary conceptual hydrogeological model, containing flow parameters and flow paths, is developed, based on data from AIG10 and other wells and springs. ***To cite this article: V. Giurgea et al., C. R. Geoscience 336 (2004).***

Résumé

Interprétation hydrogéologique préliminaire de la zone d'Aigion, basée sur les données obtenues sur le forage AIG10. Le forage AIG10 a permis un accès direct aux conditions hydrogéologiques du flanc sud du graben de Corinthe. Dans ce forage, on a identifié un système aquifère formé par cinq aquifères. Trois d'entre eux sont constitués de graviers et de conglomérats. Un essai de pompage dans ces derniers suggère qu'il s'agisse d'un système hydraulique fermé. Un deuxième essai de pompage, effectué dans les calcaires du compartiment supérieur de la faille d'Aigion, révèle un aquifère artésien et une transmissivité faible. Au-dessous de la zone de la faille, la pression et le débit augmentent, suggérant des conditions d'écoulement karstique. La différence de pression entre les deux compartiments prouve que la faille est presque imperméable. Un essai de production artésienne, réalisé au-dessous de la faille, a mis en évidence une haute pression ainsi qu'un débit naturel haut et constant. À partir des résultats de AIG10, on a pu proposer un modèle hydrogéologique conceptuel, qui prenne également en compte les résultats des mesures hydrologiques et géochimiques d'autres forages et sources. ***Pour citer cet article : V. Giurgea et al., C. R. Geoscience 336 (2004).***

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Mots-clés : hydrogéologie ; Aigion ; zone de faille ; circulation des fluides ; essai de pompage ; modèle hydrogéologique conceptuel

Version française abrégée

Le forage AIG10 a permis un accès direct à la structure profonde ainsi qu'aux conditions hydrogéologiques du flanc sud du graben de Corinthe. On présente, dans cet article, ce projet ainsi que les premiers résultats des essais de pompage effectués dans ce forage. On a réalisé deux pompages à deux profondeurs différentes, ainsi qu'un troisième essai de production artésienne. À partir des résultats de AIG10 et des informations hydrogéologiques obtenues dans des forages voisins, on a identifié un système aquifère formé par au moins cinq aquifères différents, situés à des profondeurs allant jusqu'à 1000 m. Trois de ces aquifères sont formés par des graviers récents et des conglomérats. D'après les résultats du premier essai de pompage, la conductivité hydraulique des conglomérats est d'environ 10^{-5} à 10^{-4} $m\,s^{-1}$. Le rabattement résiduel suggère qu'il s'agisse d'un système hydraulique fermé situé entre la faille d'Aigion et d'autres failles, au nord. Un deuxième essai de pompage, effectué dans les calcaires d'Olonos–Pindos, dans le compartiment supérieur de la faille d'Aigion, révèle un aquifère artésien, avec une pression de 0,5 MPa et un débit naturel de $1{,}9 \times 10^{-4}$ $m^3\,s^{-1}$. La transmissivité des calcaires est faible, d'environ 4×10^{-6} $m^2\,s^{-1}$. Au-dessous de la zone de faille, la pression et le débit augmentent, en suggérant des conditions d'écoulement karstique. La différence de pression de plus de 0,5 MPa enregistrée entre les deux compartiments de la faille prouve que la faille d'Aigion est semi-perméable, ou même presque imperméable. Un essai de production artésienne réalisé au-dessous de la faille pendant trois jours, entre les profondeurs de 708 et 1001 m, a mis en évidence une pression constante de plus de 1 MPa, ainsi qu'un débit naturel de $1{,}5 \times 10^{-2}$ $m^3\,s^{-1}$. Pour cet intervalle de profondeur, on a estimé une transmissivité de 2 à 3×10^{-4} $m^2\,s^{-1}$. À partir des résultats de AIG10, on a pu proposer un modèle hydrogéologique conceptuel. Ce modèle prend également en compte les résultats des mesures hydrologiques et géochimiques d'autres forages et sources.

1. Introduction

The Gulf of Corinth and the northern part of the Peloponnesus/Greece, an area of asymmetric graben structure, step faults and tilted blocks, is one of the most active seismic zones in the world. Six major faults are known to be most responsible for the historic and recent seismic activities in the area of Aigion. To understand seismicity, it is necessary to know the thermal-hydraulic framework of the area. Here we report preliminary results on the hydrogeological conditions around the Aigion Fault, whose trace runs east–west through the harbour of Aigion.

From July until September 2002, the EU Project DGLab-Gulf of Corinth and the International Continental Deep Drilling Project (ICDP) drilled the 1000 m-deep AIG10 borehole with the goal to intersect the Aigion Fault at depth (Figs. 1 and 2). This borehole provided the opportunity for direct access to the geological formations and to an active fault as well as for evaluating through a series of hydraulic tests the in situ hydrogeological conditions. Knowledge about the subsurface hydraulics is the basis to evaluate the mode of subsurface heat transfer, which is a prerequisite for determining and interpreting the terrestrial heat flow. This value, in turn, serves then as an input into models of crustal thermal conditions and the rheology of the crust.

2. Hydrogeological/hydrostratigraphic description

Fig. 2 shows the general lithology and the hydrostratigraphy of the sedimentary succession encountered by the AIG10 borehole down to 1001 m. The first 50 m interval from the top is comprised of weakly consolidated, highly permeable sand and gravel sediments (Meganitas river deposits). The approximate hydraulic conductivity of this first, phreatic aquifer is 10^{-2}–10^{-3} $m\,s^{-1}$. The aquifer is separated from a second conglomeratic aquifer by a 50 m-thick clay. This second aquifer is known from an adjacent borehole Γ_1 at a depth of 112 m, in which artesian flow was observed

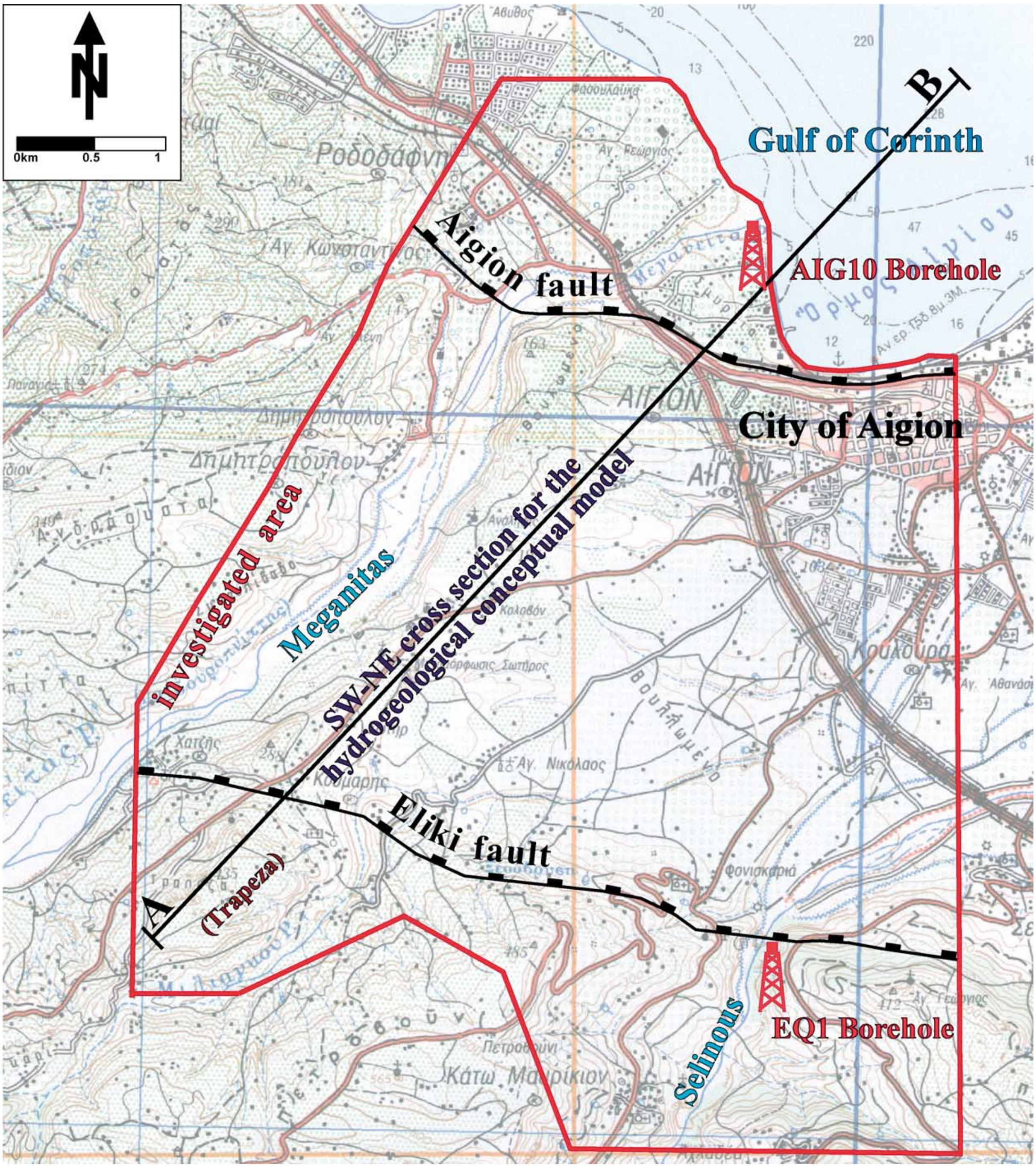

Fig. 1. Location of the AIG10 borehole, Aigion and Eliki Faults as well as of the cross-section chosen for the conceptual hydrogeological model.

Fig. 1. Localisation du forage AIG10, des failles d'Aigion et d'Eliki, ainsi que de la coupe utilisée pour le modèle hydrogéologique conceptuel.

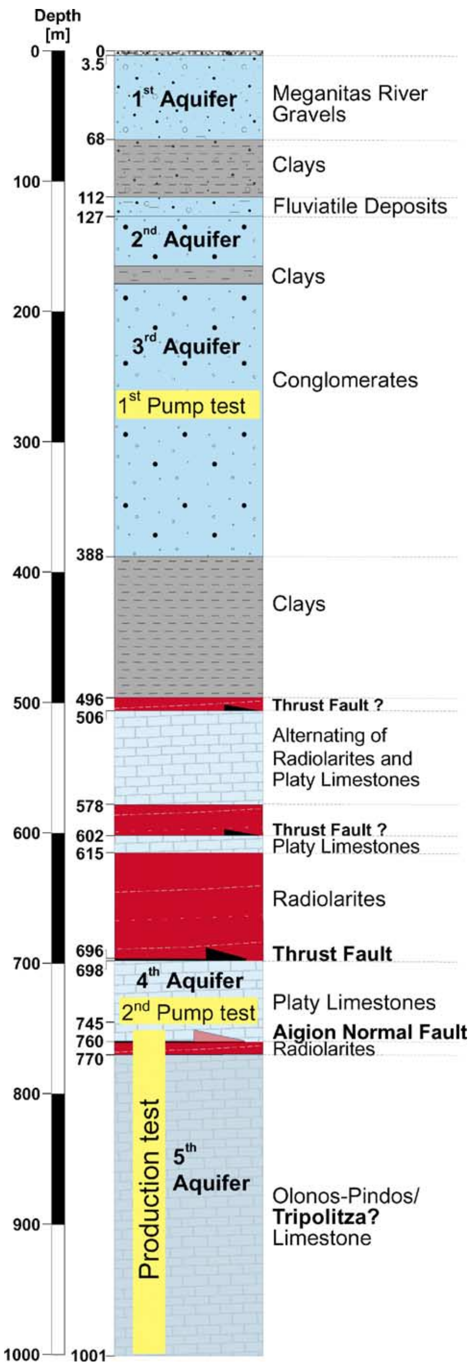

Fig. 2. Schematic litho-log of the AIG10 borehole with hydrostratigraphy and location of pumping tests.

Fig. 2. Litho-log schématique du forage AIG10, avec hydrostratigraphie et situation des tests de pompage.

with flow rates up to 1.4×10^{-3} m^3 s^{-1} (F. Lemeille, pers. comm., 2001). The fact that the thin clay layer at 158–160 m depth within the 250 m-thick conglomerates separates two completely different aquifer systems is supported by hydrochemical analyses. The third and fourth aquifers (Fig. 2) were the subject of the pumping tests performed by AGK in the AIG10 borehole. Furthermore, water-flow rate and pressure were monitored by AGK during a production test performed by IPGP (F. Cornet) in the final open-hole interval of the well (fifth aquifer).

2.1. *Results of hydraulic tests in the conglomerates (1st pumping test)*

The pumping test was made in a $9\frac{5}{8}''$ diameter open-hole interval in the conglomerates between 211 and 256.4 m. A pump was installed at 90 m depth in the cased borehole interval, and a pressure probe for the continuous registration of the drawdown was taped on the water pipe 10 m above the pump. The total duration of the step test was 67 h. The automatic drawdown registration was made every 15 s (Fig. 3).

The hydrochemical analyses of the pumped water (see Fig. 4) showed a very strong domination of the Na and Cl ions. This result, together with the calculated ion-ratios of the major elements and the minor and trace element contents (Br, Sr, Li, etc.), led to the conclusion that the water in the conglomerates is clearly of marine origin, though the concentration of total dissolved solids (conductivity of 56 mS cm^{-1}) is higher than seawater. This aquifer must be well hydraulically isolated from the formations above and beneath it; a hydraulic contact with seawater in the Gulf of Corinth is very probable.

From the several solutions provided by the software Aqtesolv® [2] used in processing the pump-test data, the Moench leakage approach [7] (Fig. 5) provided the best fit and a hydraulic conductivity of approximately 2.7×10^{-5} m s^{-1} for the conglomerates. The Moench leakage approach is based on the Hantush theory of leaky confined aquifers and assumes storage in the aquitards and wellbore skin. It assumes too that an aquitard is overlain by either a constant head boundary (case 1) or a no-flow boundary (case 2) [2,10]. The described first test is corresponding to ‘case 1’ because no water-level changes registered in borehole Γ_1 during pumping. The tested aquifer

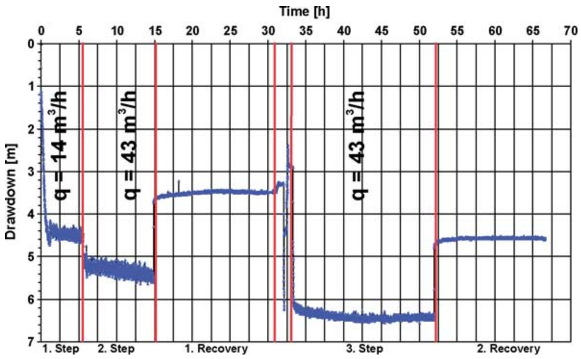

Fig. 3. Time-dependent drawdown, first pumping test. Three pumping steps with the pumping rates and two recovery phases are shown.

Fig. 3. Rabattement en fonction du temps, premier essai. Trois étapes de pompages, avec débits, et deux étapes de remontées sont représentées.

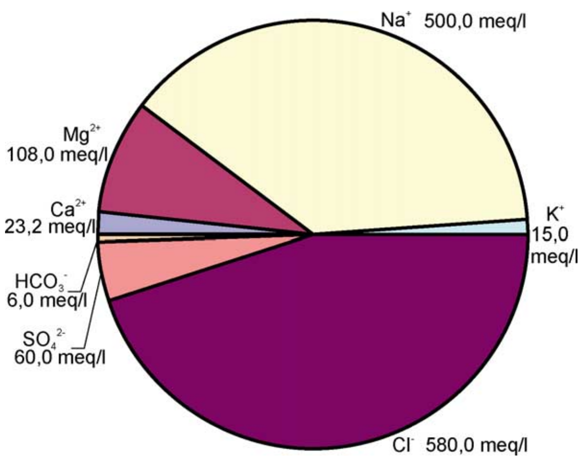

Fig. 4. Hydrochemical results of the first pumping test (in meq l^{-1}).

Fig. 4. Résultats hydrochimiques du premier pompage (en meq l^{-1}).

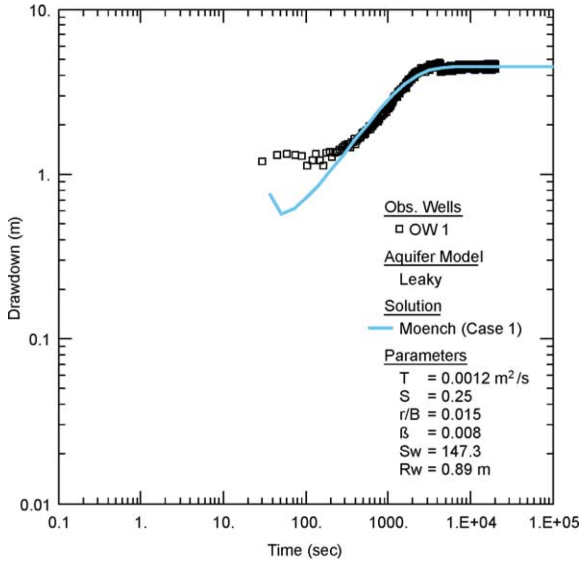

Fig. 5. Processing results of the first pumping test.

Fig. 5. Résultats de la modélisation du premier essai de pompage.

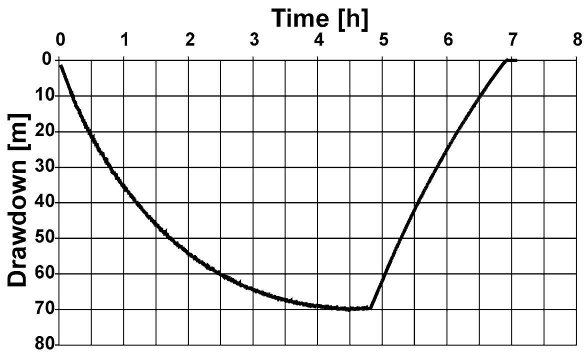

Fig. 6. Time-dependent drawdown, second pumping test.

Fig. 6. Rabattement en fonction du temps, deuxième essai.

is confined and almost artesian (water level only 1 m below annular blow-up preventer). The total residual drawdown of more than 4.5 m (see Fig. 3) could be explained by a semi-isolated lens-shaped conglomeratic aquifer. The semi-isolation is probably due to the presence of an impervious vertical boundary to the south and to the clay layers above and beneath the tested conglomerates. It is likely that such a boundary is due to the Aigion Fault, if the fault acts in this sector as an impermeable barrier. Due to the distant hydraulic contact to the sea, a very slow recovery can be assumed. However, the best curve fitting was obtained by considering leakage through the thin, overlaying clay at 160 m depth or from deeper layers within the conglomerates.

2.2. *Results of hydraulic test (2nd pumping test) in the Olonos–Pindos limestone*

After cementing the casing down to 708 m and coring from 708 to 744.8 m, the second pumping test was performed in the $6\frac{3}{4}''$ open hole in the Olonos–Pindos limestone (Fig. 2, 4th aquifer). The same equipment was used as in the first pumping test. The natural water pressure was 0.5 MPa and

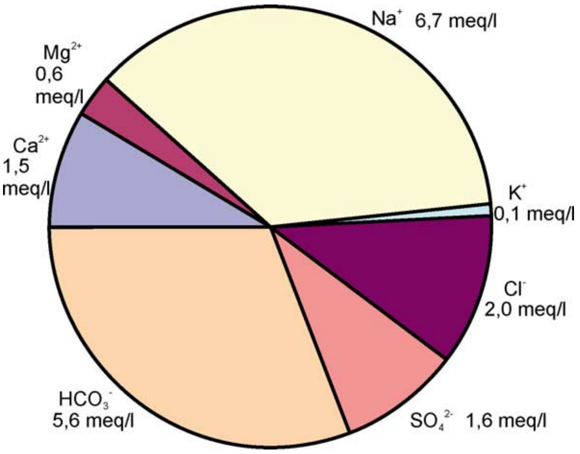

Fig. 7. Hydrochemical results of the second pumping test (in meq l^{-1}).

Fig. 7. Résultats hydrochimiques du 2e pompage (en meq l^{-1}).

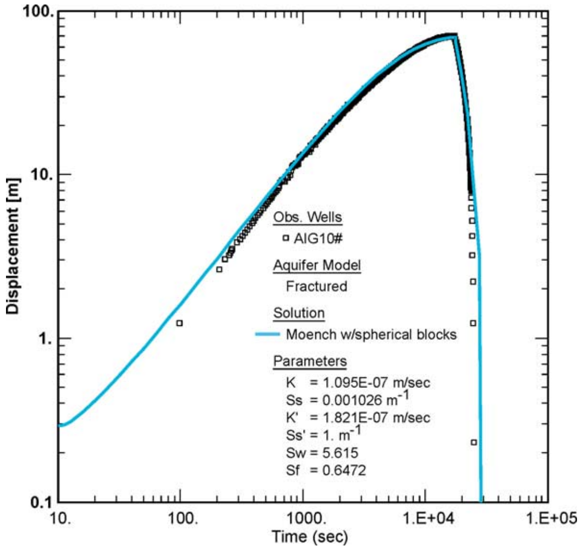

Fig. 8. Processing results of the second pumping test.

Fig. 8. Résultats de la modélisation du deuxième essai de pompage.

the artesian flow rate 1.9×10^{-4} $m^3\,s^{-1}$. Because of the very poor permeability of the limestones, it was necessary to reduce the pumping rate through curbing (closing the valve to increase pressure). After several trials, it was finally possible to perform the test at a flow rate of 3.9×10^{-4} $m^3\,s^{-1}$ (Fig. 6). The hydrochemical analyses (Fig. 7) of the pumped water show a total mineralisation <1 $g\,l^{-1}$ (drinking-water quality), a strong domination of Na ions (similar to the first test in the conglomerates), but a relatively high HCO_3^- concentration (different compared to the first test). This result, together with the calculated ion ratios and the artesian pressure of 0.5 MPa, led to the conclusion that the water in the limestones was recharged in the hinterland of Aigion to the south, where the limestones are outcropping. Very likely reactions with clay minerals (cation exchange) occur to justify the Na enrichment and the observed Ca and Mg removal from solution.

The tested aquifer is hydraulically well isolated from the aquifers above by aquicludes. Any hydraulic contact with seawater can be discarded. The physical water parameters measured during the test at the surface in a bucket (electric conductivity = 780 $\mu S\,cm^{-1}$ and temperature = 23.5 °C) support this theory.

Using Aqtesolv®, the best results of curve fitting (Fig. 8) are obtained by the Moench leakage approach [7] and especially by the Moench approach for fractured aquifers [6]. Data processing resulted in a transmissivity between 1.47×10^{-4} $m^2\,s^{-1}$ (equivalent hydraulic conductivity 4×10^{-6} $m\,s^{-1}$) for the leakage approach and 3.68×10^{-6} $m^2\,s^{-1}$ (equivalent hydraulic conductivity 1×10^{-7} $m\,s^{-1}$) for the fractured aquifer approach.

The following conclusion is drawn: the limestones act primarily as an artesian, confined and fractured aquifer.

2.3. Results from a production test in the Olonos–Pindos limestone (footwall of the Aigion Fault)

After crossing the Aigion Fault by drilling, a sudden increase of pressure and water flux was observed. This observation calls for conditions typical for karstic or densely fractured units, which is supported by the analysis of the drill core obtained at 773–786 m. A three-day production test, under the coordination of F. Cornet (IPGP), covered the depth interval from 708 to 1001 m. The water temperature measured at the surface during the production test varied between 29–31 °C (average 30 °C). The artesian pressure before and after the test was constantly 1 MPa. The head losses during the artesian flow reached 0.12 MPa and were calculated according to the Darcy–Weisbach equation [1,12]. Data processing could not be done ac-

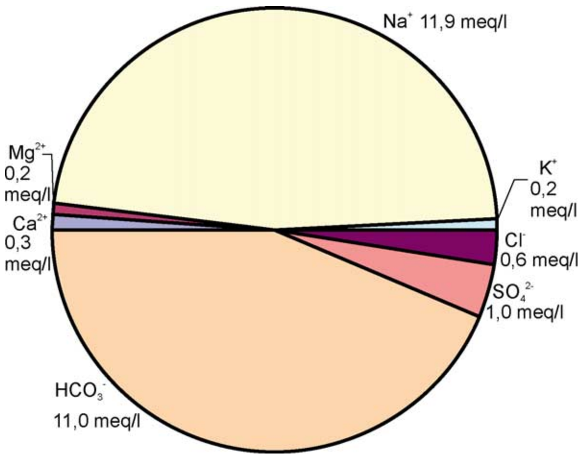

Fig. 9. Hydrochemistry of the 22 September 2002 water production test in limestones below the Aigion Fault (in meq l^{-1}).

Fig. 9. Hydrochimie de l'essai de production du 22 septembre 2003 dans les calcaires au-dessous de la faille d'Aigion (en meq l^{-1}).

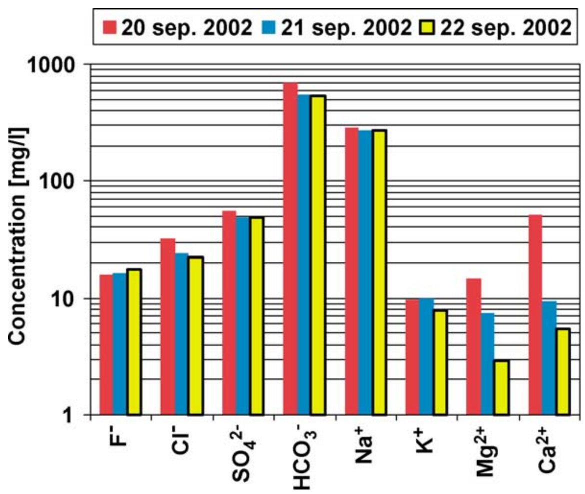

Fig. 10. Change of ion concentrations in water during production test (in $mg\,l^{-1}$).

Fig. 10. Évolution de la concentration des ions dans l'eau pendant l'essai de production (en $mg\,l^{-1}$).

cording to the theory for artesian production tests [4] because during the three days of artesian flow both drawdown (1–0.12 MPa = 0.88 MPa = 88 m water column) and natural flow rate (1.5×10^{-2} $m^3\,s^{-1}$) remained practically constant. Therefore, the processing occurred based on the equation of Dupuit–Thiem [3, 5,13] assuming a constant drawdown at the well radius, equal to 0.88 MPa of artesian pressure and a zero drawdown at a radius of influence R. Considering for this radius R possible values between 250 and 10^4 m, an average transmissivity of $2.1–3.1 \times 10^{-4}$ $m^2\,s^{-1}$ resulted for the 231 m producing interval (770–1001 m in depth). These values would correspond with an average hydraulic conductivity of $0.9–1.1 \times 10^{-6}$ $m\,s^{-1}$. The analysis of the water chemistry (Figs. 9 and 10) shows that the bulk mineralisation is about 1.03 g/l, so that the water practically is of drinking-water quality except for the Na concentration. Similar to the second pumping test, we assume that the high Na concentration originates mainly from cation exchange processes within clay minerals.

The difference in water pressure (pressure step of 0.5 MPa) and in the hydraulic properties of the limestones in the hanging wall and in the foot wall of the Aigion Fault provides evidence that two compartments (aquifers?) exist that communicate hydraulically through a less permeable zone (the Aigion Fault zone plus radiolarites in the footwall).

3. Conceptual hydrogeological model of the Aigion area

The results of borehole experiments reported here, the data from hydraulic tests performed earlier in the limestones of the Selinous valley (transmissivity of $6.9–9.4 \times 10^{-3}$ $m^2\,s^{-1}$, average hydraulic conductivity of the fractures 1.5×10^{-4} $m\,s^{-1}$, well EQ1 in Fig. 1, 90 m deep, completely in Olonos–Pindos platy limestones) [9] and the geological fieldwork focused on the structural pattern at the regional scale in the area south of Aigion [8,11] gave rise to a first conceptual hydrogeological model (Fig. 11) that will serve as a basis for a future numerical thermo-hydraulic model of the Aigion area.

This model is based on a SSW–NNE-oriented, 14 km-long cross-section through the location of the AIG10 borehole, which is in the centre (for location, see Fig. 1). The model area is subdivided into three main blocks:

(1) the area south of the Eliki Fault;
(2) the area between the Eliki and Aigion Faults; and
(3) the area north of the Aigion Fault.

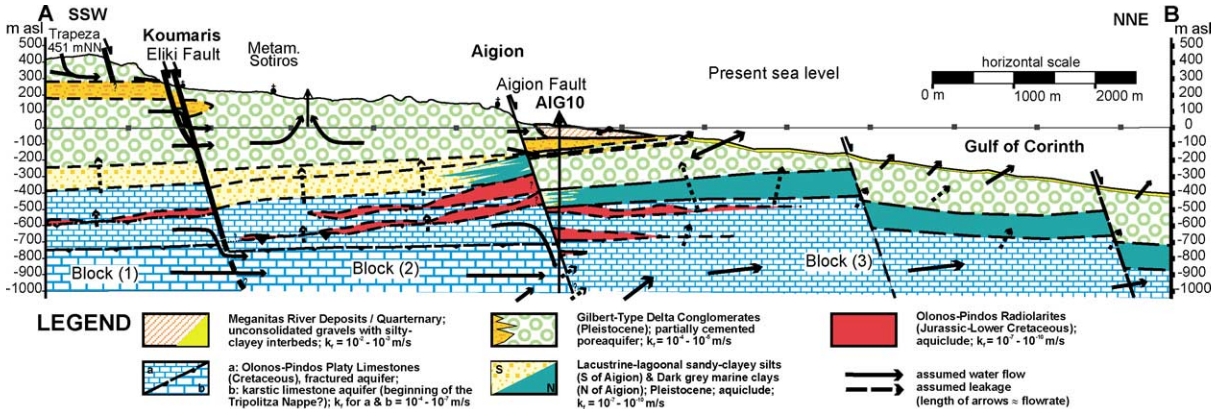

Fig. 11. First conceptual hydrogeological model of the Aigion area with assumed flow paths.

Fig. 11. Premier modèle hydrogéologique conceptuel de la région d'Aigion, avec trajectoires d'infiltration présumées.

While the hydraulic conductivity of the aquifers was determined by the different hydraulic tests, the respective parameter for the aquicludes was approximated. The flow paths were defined on the basis of the water pressures encountered in the AIG10 and Γ_1 boreholes as well as in the water-supply wells of the Selinous valley (EQ1 in Fig. 1).

Thus, the conceptual hydrogeological model integrates all information of the region available at this moment. Model features are the following ones.

- The phreatic water in the uppermost conglomerates of block (1) flows parallel to the clay layer and is emerging in the form of springs.
- The water pressure in the limestones is higher than in the conglomerates in all three blocks; this suggests that an upward-oriented leakage occurs not only through the thick clay sequence at the basis of the Plio-Pleistocene sediments, but also through the thin clay layers in the conglomerates.
- In the conglomerates of block (2), the south–north-oriented flow through the Eliki Fault Zone and upward leakage is additionally stimulated by intensive water withdrawal (shallow boreholes for drinking water and agricultural purposes).
- The hydrochemistry of the groundwater in the conglomerates of block (3) suggests mingling with the Gulf of Corinth water (double arrow).
- The formation water of the Olonos–Pindos Platy Limestone is recharged in the mountains, in the hinterland of Aigion (10 km or more to the south), flows rapidly, and finally is discharged in the Gulf of Corinth (indicated by submarine springs).
- Because the fault zones within the Olonos–Pindos nappe units obviously act as hydraulic barriers, the fluid flow beneath the radiolarites of the footwalls is forced downward along the fault planes. This flow occurs probably until higher-permeability fault zone segments are reached at depth, which allow the flow direction to become sub-horizontal again. After passing this higher permeability fault zone, the flow pattern will be again upward and oriented south–north; this is shown by the short upward arrows at the base of the cross-section. The high hydraulic resistance induced by this assumed complex flow path is supported by the water pressure difference of 0.5 MPa between the limestones in the footwall and those of the hanging wall.

Because the database for the model is relatively poor (only surface observations and few borehole data), it has to be considered as one of several possible models, showing a good fitting with regard to the existing data. Other concepts for the model, e.g. taking into account the lateral extension of the impervious faults in 3D, the existence of a continuous thick impervious clay layer on the ground of the Corinth Gulf resulting in the absence of submarine springs and the rise of freshwater on the northern shore of the Gulf, changing to a south–north-oriented cross-section passing through EQ1 and AIG10, were considered and will be analysed when finalising the model.

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