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Tectonic Evolution and Hydrogeological Characteristics of the Khanaser Valley, Northern Syria, Derived from the Interpretation of Vertical Electrical Soundings

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Abstract—The Khanaser Valley was geoelectrically thoroughly surveyed through a grid which consisted of twelve VES profiles. The tectonically-oriented Pichgin and Habibullaev method was enhanced to be applicable in areas of rugged relief and topography. The enhanced profiles were tectonically interpreted and subsurface structures within the Khanaser Valley were delineated. Accordingly, a tectonic evolutional scenario of the valley was established and its hydrogeological characteristics were derived. An approach for groundwater exploration in areas of prominent relief and topography in dry areas such as the Khanaser Valley was established and its validity was estimated.

Key words: Tectonic evolution, vertical electrical sounding, hydrogeological characteristics, Khanaser Valley, Syria.

1. *Introduction*

The Khanaser Valley is a 4–6 km * 20 km N15° E oriented valley, located at the rims of the Syrian steppe in northern Syria 80 km from Aleppo. It stretches between longitudes (UTM) 357000–378000 and latitudes 3948000–3973000, as a gently undulating plain characterized by a shallow network of wide dry erosion channels. It is confined at 312–333 m elevation above sea level between Shbith Mountain (400 m) to the east and Al Hiss Mountain (450 m) to the west (Figs. 1 and 2), which forms gently rolling plateaus, ending in steep scarps towards the Khanaser Valley. The Khanaser Valley is bounded from the north by Al Jabboul Salt Lake and from the south by Kharaitch depression. The annual rainfall of the area swings between 200 and 250 mm (Soumi, 1991).

The Khanaser Valley was selected by ICARDA (International Centre for Agricultural Research in Dry Areas) for an integrated Project (2001–2005) entitled: “Sustainable Agricultural Development for Marginal Dry Areas, Khanaser Valley Integrated Site in

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Northern Syria" in cooperation with Bonn University (Germany), German Ministry of Economic Cooperation and Development (BMZ), Agency for Technical Cooperation (GTZ, Germany) and the Atomic Energy Commission of Syria, aimed at sustainable management of natural resources of the valley and livelihood improvement of its landusers. ASFAHANI (2007a, b, c) measured in this project an intensive grid of VES profiles covering the valley to evaluate its ground water potential. He defined subsurface structures, fresh water accumulations and paleo buried salt lakes. His new findings triggered a debate on the origin of the valley and its subsurface structures; whether it is a simple elongated topographic low formed principally by erosion, or a distinguished structure.

Accordingly, VES profiles were reinterpreted in this work using the tectonically-oriented interpretative Pichgin-Habibulaev method, which was enhanced by the authors, to construct topographic corrected profiles, in order to:

- Shed light on the origin of this valley and reconstruct its evolutional tectonic history.
- Define the hydrogeological impacts of reconstructing the tectonic evolution of Khanaser Valley, hence interpret the presence of fresh water accumulations and paleo buried salt lakes.
- Establish an approach applicable in similar arid areas, to guide ground water exploration and drilling, and estimate its validity in areas of prominent relief and topography in other dry areas.

2. *Geologic and Tectonic Setting*

Detailed geological and tectonic data on Khanaser Valley specifically, are unavailable. Only a general geologic and tectonic view of a much wider area than Khanaser Valley is provided by DUBERTRET (1953). PONIKAROV (1966) (Fig. 1), and the (GEOLOGICAL MAP OF Syria, 1986) described Aleppo Uplift, in which Khanaser Valley lies, as a structural high in northern Syria separated from Bilaas Block (Northern Palmyrides) by NE trending Turkmaniyeh Othmaniyeh trough. Aleppo uplift is complicated by various folds among which is the NW elongated and gently (3–5°) dipping Khanaser anticline. Rock types outcropped in Aleppo uplift are dominated by Upper Cretaceous marl, marly limestone and limestone, Lower, Middle and Upper Eocene limestone, chalky limestone, marly limestone, marl; and Miocene sandstone, conglomerate and marl. Miocene and Pliocene single vast basalt flow covers considerable parts of Aleppo uplift with a consistent thickness (~ 100 m) (PONIKAROV, 1966). It covers 800 km^2 areas at Jabal Al Hiss, and 160 km^2 area at Jabal Shbith capping Lower and Middle Eocene chalky limestone. The source of lava and its flow directions remained undetermined. PONIKAROV (1966) describes Khanaser Valley as "a 100–150 m low valley separating the mentioned basaltic caps filled by Quaternary deposits."

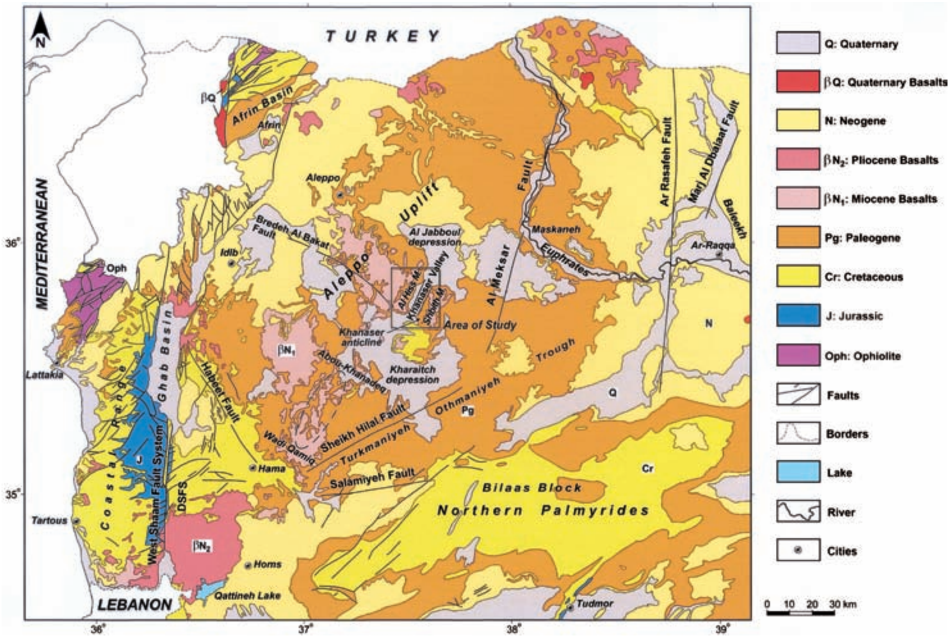


Figure 1
Geological map of the area surrounding the Khanaser Valley, redrawn from PONIKAROV (1966).

Tectonically, Khanaser Valley lies in the middle of Aleppo uplifted paleohigh separating the NNE striking Bilaas Block of the Northern Palmyrides intracontinental basin to the southeast from the NE striking Afrin marginal basin to the northwest. From the west, the paleohigh is bounded by the N-S striking Dead Sea fault system (West Shaam fault system) and from the east by the N-S Ar Rasafeh fault (Fig. 1). Aleppo uplift itself is dissected by NNE faults, e.g., N15°E Al Meksar fault, and by the NE striking Sheikh Hilal fault, the NW striking Habeet fault, the WNW Salamiyeh fault, and by the NW striking Bredeh Al Bakat fault.

DUBERTRET (1953) drew a N25°E fault striking from the Kharaitch depression extending through Khanaser Valley up to the Euphrates River.

Hydrological contributions were provided by different workers (e.g., DE VAUMAS, 1957; WOLFAHRT, 1966, 1967; HOOGEVEEN, and ZÖBISCH, 1999). They all agree that the border between two surface water catchments subdivides Khanaser Valley into two areas. The northern one belongs to the Jabboul catchment with drainage network flowing towards Jabboul Salt Lake. The southern one belongs to the steppe catchment with surface water draining southward to the Kharaitch depression. WOLFAHRT (1966) drew a surface water divide between them near the town of Khanaser, while HOOGEVEEN, and ZÖBISCH (1999) shifted it northward (Fig. 2). The scarcity and the salinity of water resources, which increase from south to north, hinder the development of the valley.

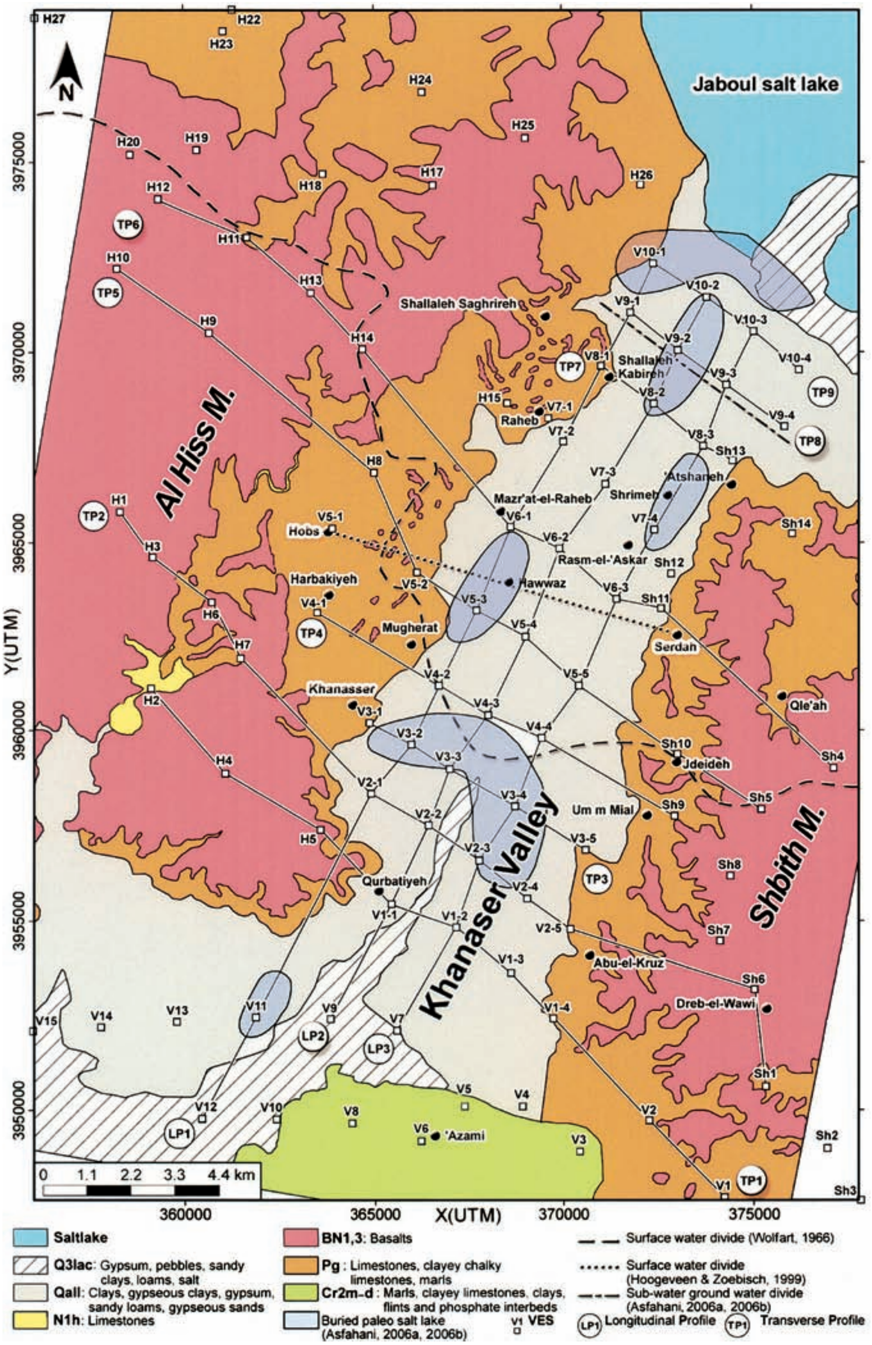


Figure 2

Simplified geological map of the Khanaser Valley shows the measured geoelectrical VES profiles, buried salt lakes and surface and subsurface water divides. Plotted on GEOLOGICAL MAP OF SYRIA (1986), 1:50000 (GEGMR, 1986).

3. *Methodology*

The methodology applied in this research consists of:

1. Conducting a geophysical survey using vertical electrical soundings (VES) covering the entire Khanaser Valley.
2. Enhancing Pichgin and Habibullaev method (PICHGIN and HABIBULLAEV, 1985), which is actually a tectonically-adopted method oriented to interpret VES profiles, principally in flat areas, hence detecting and delineating ~250 m deep subsurface structures. The enhancement of the mentioned method makes it applicable in areas of prominent topographic relief, which is a crucial factor in tectonic interpretation to acquire a reliable subsurface structural image.
3. Interpretation of the enhanced Pichgin and Habibullaev profiles, hence mapping subsurface structures.
4. Reconstructing the tectonic and geologic history and setting a tectonic evolutional scenario of the Khanaser Valley.
5. Concluding hydrogeological characteristics from the establishment of this scenario.

4. *Discussion*

4.1. Geophysical Survey Using Vertical Electrical Soundings (VES)

Electrical resistivity sounding techniques are widely used to determine vertical variations in electrical resistivity. In this research ninety-six Schlumberger configuration electrical resistivity soundings were carried out along nine 10–20 km long geoelectrical profiles (TP1, TP2…., TP9), perpendicular to the valley elongation at a ~1.5 km spacing, and three other 20–25 km long geoelectrical profiles (LP1, LP2, LP3) measured parallel to the valley axis at a spacing of ~1.5 km (Fig. 2).

A maximum current electrode spacing (AB/2 = 500 m) of 500 m was selected for all soundings, allowing a ~250 m penetration depth.

An electrical current is intruded in the VES site by a pair of electrodes (current electrodes, A and B) at varying spacing, expanding symmetrically from a central point. Surface expression of the resulting potential field was measured through the apparent resistance by another pair of electrodes (potential electrodes, M and N) at appropriate spacing. Resistivity ρa, is expressed by the following equation:

$$\rho a = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}} \frac{\Delta V}{I} \tag{1}$$

where I is the current introduced into the earth, and ΔV is the potential difference measured between the potential electrodes.

The instrument used in this research measures directly apparent resistance, and subsequently apparent resistivity "ρa" is computed according to equation (1). Interpretation of resistivity curves is made by a curve-matching technique using master curves (ORELLANA and MOONEY, 1966) for specifying thicknesses and resistivities of corresponding subsurface layers. Approximate models were accurately interpreted using an inverse technique program, until a goodness of fit between a field curve and a theoretical regenerated curve was obtained (ZOHDY, 1989; ZOHDY and BISDORF, 1989).

4.2. Enhancing Pichgin and Habibullaev Method

PICHGIN and HABIBULLAEV (1985) established a method for interpreting vertical electrical soundings (VES), measured along a given profile. This method is considered as one of the best methods developed for distinguishing tectonic fractured zones and dipping contacts. It also permits determination of the direction and inclination of faults under a given profile, hence a subsurface 2-D tectonic image can be obtained.

The principle of the method is based on the fact that when electrical current passes through plane contact between two formations of different resistivities ρ_1 and ρ_2 (Fig. 3a), the boundary conditions of the electrical field on the plane contact are characterized by the following:

A. If the center of vertical electrical sounding configuration is found exactly over a vertical contact between two formations of different resistivities ρ_1, ρ_2 (case a), and the configuration is perpendicular to such a contact, the resulting measured resistivity ρK is given by the following equation:

$$\rho k = \frac{\rho_1 + \rho_2}{2} \tag{2}$$

The measured resistivity is independent from AB and MN lengths.

If there are two vertical electrical soundings VES1, VES2, measured on both sides of a vertical contact (Fig. 3), then all profiling curves for every given AB/2 will be intersected in one point located over this vertical contact. The data of vertical electrical soundings are therefore represented as horizontal multi-depths profiling curves for every given AB/2. The locations of vertical electrical soundings, realized on a given profile, are plotted on abscissa using a linear scale, while the corresponding apparent resistivities (ρK or ρ'K) for each given AB/2 are plotted on the ordinate using a logarithmic scale. This resistivity is also independent from AB and MN lengths.

B. If the configuration is parallel to such a contact, the resulting measured resistivity ρ'K is given by this equation:

$$\rho' K = \frac{2\rho_1\rho_2}{\rho_1 + \rho_2} \tag{3}$$

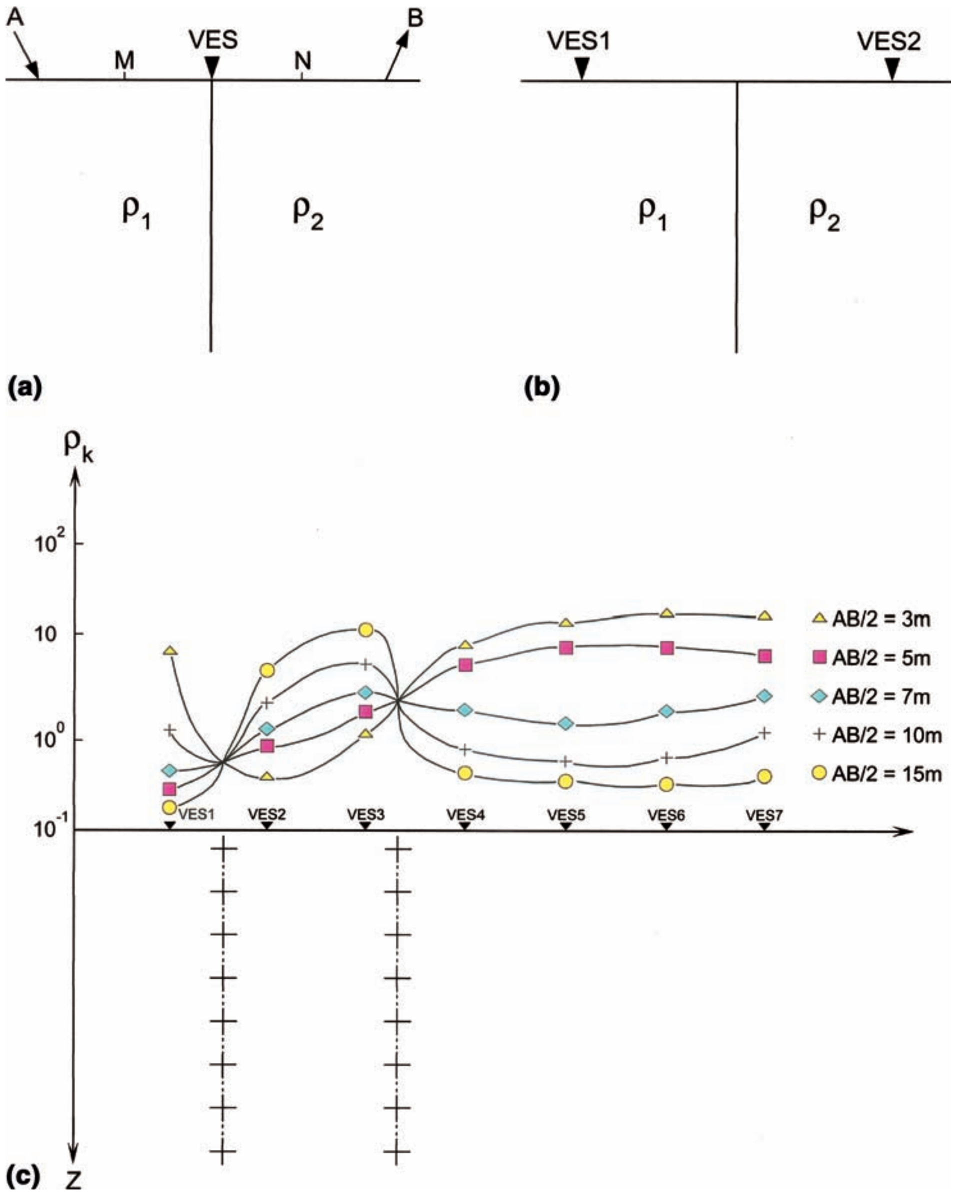


Figure 3
Principle of Pichgin and Habibullaev method.

The intersection points of all horizontal curves, termed "Points of Non-Homogeneity" (PNH) and labeled by "+", are plotted on a 2-D (x, z) geological section. The depth z of each of them can be determined according to the following equation:

$$Z = \frac{(AB/2)_i + (AB/2)_j}{2} \tag{4}$$

where $(AB/2)_I$ and $(AB/2)_j$ are the half separations between the electrodes A and B, for which two horizontal curves are intersected. The tectonic fractured zone is determined by the presence of (PNH) on vertical pseudo-vertical lines as shown in Figure 3.

Geological and tectonic interpretations of such points are based on the following assumptions:

1. When (PNH) are distributed according to oblique lines located at shallow depths, they point to the presence of an inhomogeneous lithologic contact.
2. If (PNH) are arranged along oblique lines dipping down at an angle ≥30°, they represent a tectonic fractured zone.
3. If these points are scattered randomly near the surface, they indicate a homogeneous lithology.
4. If these points are arranged in a certain regular form, they may reflect certain geological structures (syncline, anticline, or simply horizontally layered strata).

Since the Pichgin and Habibullaev method was originally devised for smooth topography (Pichgin and Habibullaev, 1985), it gives inaccurate and sometimes misleading tectonic interpretations in areas of rough topography such as the Khanaser area. To attain a reliable subsurface tectonic interpretation, it was essential to develop and enhance this method, taking into consideration the real absolute elevation of each measured VES point. Numerical values of these elevations were incorporated in the processing software through purposely-developed mathematical formulas as additional crucial factors to achieve enhanced Pichgin and Habibullaev profiles.

The mentioned enhancement and development was performed according to the four following successive phases:

1. Constructing a real topographic profile passing through VES station positions of a given VES profile, hence real absolute elevation of the VES station is considered.
2. For every pair of successive resistivity VESs, of AB/2 spacing along a given profile, all intersections points are localized and projected on a real topographic profile constructed in phase-1. In the Pichgin and Habibullaev method, all intersection points are projected onto a zero reference level, assuming that all VES stations have the same elevation.
3. The intersection points, together with the topographic profile constructed in phase-2, are projected onto the X-Z plane, in order to obtain (PNH), whose depths Z are similarly determined using eqution (4). Localizing (PNH) depth using the enhanced method is more sophisticated and reliable in extrapolating subsurface structures when compared with the Pichgin and Habibullaev original method, since real and true elevation of the intersection points is determined with reasonable accuracy.

4. Procedures of phase-2 are repeated for all AB/2 spacings, in order to localize all possible (PNH) in the X- Z plane.

A computer program was developed through this research to enable performance of the aforesaid 4-phases enhancement through processing the VES resistivity input data, hence acquiring enhanced PICHGIN and HABIBULLAEV VES profiles, which were interpreted according to the conception and rules previously discussed.

Thus the enhanced method became applicable in areas of hard topography and prominent relief, attaining real computer-aided topographic cross sections along VES profiles for imaging subsurface structures over the entire Khanaser Valley.

4.3. Interpretation of Enhanced Pichgin and Habibullaev Measured VES Profiles

Through quantitative interpretation of measured resistivities along nine transerversal (TP1,….. TP9) and three longitudinal profiles (LP1,…..LP3), ASFAHANI (2007a) delineated two distinguished lows of different resistivities developed along the Khanaser Valley elongation. The northern one is (~ 110 m) deep, separated by an elevated structure from the (~ 80 m) deep southern one. Through the interpretation of resistivity isopachs, ASFAHANI (2007b) outlined subsurface structure-bound distribution of saline, brackish and fresh water. He defined the borders of buried subsurface lens-wise paleo salt lakes (paleo sabkhas) with an estimated maximum depth of 50 m. Remarkably, their subsurface planar extensions coincide with the surface spatial distribution of ephemeral saline-water-thriving shrub species (*Prosopis farcta*), whose roots penetrate as deep as 50 m searching for saline water (Oudat, personal communication).

The results of the detailed interpretation of the enhanced PICHGIN and HABIBULLAEV TP1 to TP9 profiles were controlled and calibrated through:

- The measured goelectrical response of different formation surface outcrops in and around Khanaser Valley. The range of resistivitty response of each formation was geostatically processed and to be considered as an electrical signature effective in delineating subsurface extension (Table 1).
- Geological cross sections constructed from the available geological map of the area and matched with the detailed interpretation of the enhanced PICHGIN and HABIBULLAEV profiles to establish the most reliable subsurface structural image.

The enhanced PICHGIN and HABIBULLAEV profiles were first interpreted applying the flat-layer ZOHDY-BISDORF standard on each sounding to define horizontal flatter interfaces corresponding to horizontal layering and match them with the geological data of the area (PONIKAROV *et al.*, 1966) and surface mapping observations carried out by the authors. Thus, the specifications of formations lithology, thickness, lateral facieses changes and resistivities controlled the course of the horizontal lines which link the (PNH). Accordingly, apparently horizontal-aligned PNH must not necessarily be boundaries between different formations. They can simply reflect thin beds or lenses of marl

Table 1

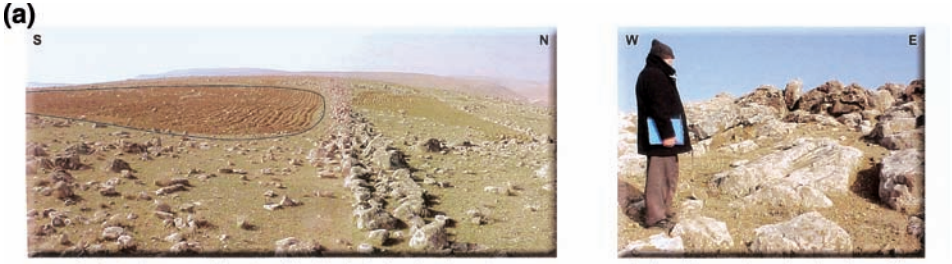
Summerizes the geometry and the electrical characteristics of Quaternary, Eocene, Maestrictean formations, as well as basalt rocks outcropped in the studied area:

Formation	**Minimum**		**Maximum**		**Average**	
	Thickness m	Resistivity Ohm. m	Thickness m	Resistivity Ohm. m	Thickness m	Resistivity Ohm. m
Quaternary	4.5	4.1	99.4	43	38.5	15.3
Basalt	27	100	156	498	60	290
Eocene	54	1.7	283	16	162.4	5.1
Maestrictean	60	16	353.5	113	193.7	49

intervals, chert or pyrite nodules, which are common features within Eocene limestone. Vertical PNH alignments are connected only when reliable surface tectonic and morphologic evidence of faulting was mapped to restrict the most reliable valley subsurface structural and geological solution, without over-connecting PNH in lines of no tectonic and stratigraphic meaning.

The (PICHGIN and HABIBULLAEV) enhanced profiles were thereafter reinterpreted applying the principles of PICHGIN and HABIBULLAEV method which enabled the location of near-vertical faults, revealing the following details:

- A clear concaved shape of the (PNH) was observed along TP1 west of Qurbatiyeh village. The width of the shape attains 7 km and narrows to 4 km along TP2. Clear normal faults, underlying the concaved shape, bound sharply the Khanaser Valley (Fig. 4). A field check confirms the presence of a volcanic crater to the northwest of Qurbatiyeh Village. Flow directions deduced from the layering of the massive, compact-layered basalt observed at the crater's rims are toward the west, northwest and southwest. An ascending lava conduit has been seen in the Qurbatiyeh abandoned quarry. The volcanic crater developed in Quaternary into a maar and accumulated lacustrine sediments which later filled it up. Strikingly, these sediments are mapped by the GEOLOGICAL MAP OF SYRIA (1986), as Q3 sediments accumulated abnormally on a hilltop. (Figs. 5, 6.)
- A remarkable down-narrowing of two normal faults from a depth of 20 m to 350 m observed in TP3 profile was interpreted as subdued northern extensions of Qurbatiyeh lava conduits.
- The normal faults, bounding the valley on the western side, remarkably stepover along TP2 westward. At the surface, this stepover is expressed by a westward retreat of Jabel Al Hiss Eocene chalky limestone cliffs and the capping Miocene basalt, thus widening Khanaser Valley. Strikingly, a 350-m deep normal fault, traced at the valley center on TP4 profile, is considered active, since it penetrates Quaternary alluvial exposed at the valley floor surface.
- Two 350-m deep normal faults were traced on both sides of the valley along TP5.



Cultivated maar sediments of the Qurbatiyeh volcanic crater.

Inclined layered basalt at the rims of the Qurbatiyeh volcanic crater.

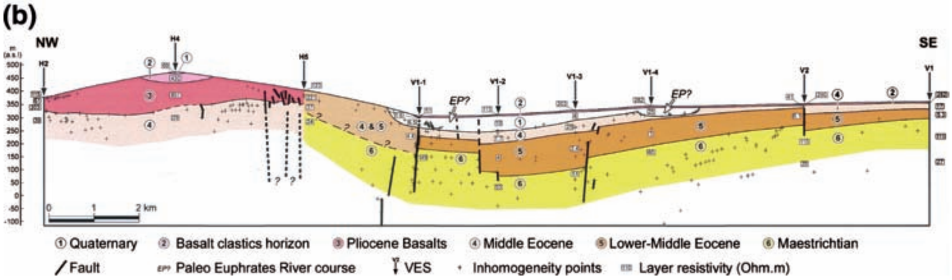


Figure 4

(a) Qurbatiyeh village filled-up maar with their sediments cultivated. (b) Interpretation of the enhanced TP1 profile.

- Two well pronounced normal faults of similar depth could be clearly mapped along TP6 at V6-1 and V6-2. A field check, done by the authors west of the village of Serdah, revealed the presence of a well-preserved complex N15°E elongated volcanic ridge on which four craters aligned in the same direction, were mapped. The area of the ridge and its surrounding is mapped by PONIKAROV (1966) and by GEOLOGICAL MAP OF SYRIA (1986), as valley Quaternary alluvial.
- Two normal faults were mapped along TP7, the first coincides with surface exposure of the northern tips of Jabal Shbith basalt that caps the Eocene chalky limestone, while the second bounds clearly the eastern side of the Khanaser Valley and is characterized by a sharp 200-m downthrow.
- A striking 1500-m wide and <50-m deep horst structure was delineated at the center of the Khanaser Valley along TP8, (Fig. 6). It represents an elevated barrier structure separating a northern low, open to Al Jabboul Salt Lake, from a southern low. These lows coincide with the presence of buried salt lakes separated by a high area, concluded by ASFAHANI (2007a).
- No trace of the mentioned horst is observed on Profile TP9. Instead, a sudden low, confined between two 350-m-deep normal faults, deepens towards the Al Jabboul Depression was delineated.

Remnant water in the center of the southern maar of Serdah multiple-coned volcanic ridge

Maar sediments of one cone of Serdah multiple-coned volcanic ridge

Serdah volcanic ridge

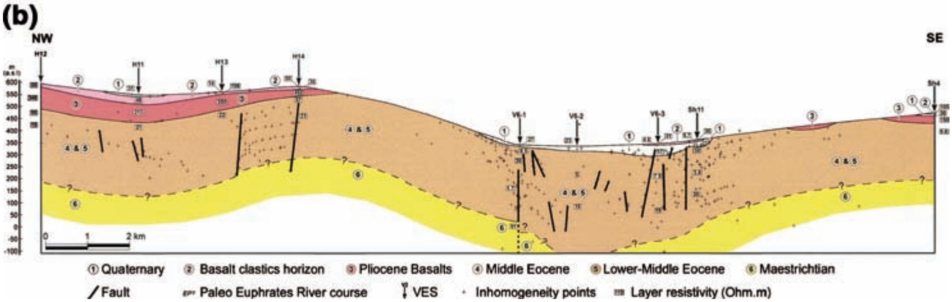


Figure 5

(a) Serdah village volcanic cone and its maar (b) Interpretation of the enhanced Pichgin and Habiballaev TP6 profile

4.4. Reconstructing the Tectonic and Geologic History of Khanaser Valley

Asfahani (2007a, b, c) new findings raised justified questions on the nature, origin, evolution, geometry of the Khanaser Valley subsurface structures and its buried paleo salt lakes, hence this contribution is addressed to answer these issues.

Accordingly, geology and tectonics of the surrounding area as seen on the geological map of the area (Ponikarov, 1966) have been reevaluated in the light of the details derived from the tectonic and lithologic interpretation of the enhanced Pichgin and Habibullaev profiles integrated with the mapped geologic and tectonic field observations. This reevaluation revealed the following remarks (Radwan, 2007):

- A pronounced parallelism of the Khanaser Valley N15°E elongation with that of Al Meksar fault which controls the Euphrates River course from Maskaneh northward, and with the Marj Al Dbaiaat fault which controls Al Khaboor River (Fig. 1).
- A remarkably complete missing of the Upper Miocene basalt in the Khanaser Valley, while it caps Middle Eocene chalky limestone which forms Khanaser Valley shoulders elevated 100–150 meters from the valley floor. Neither basalt flow outcrops, nor basalt-derived clastics could be mapped in the valley proper, (Figs. 1, 2).

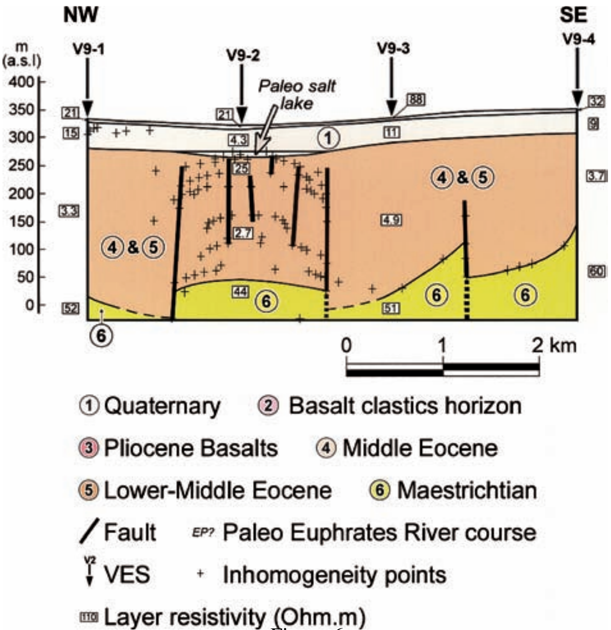


Figure 6

Interpretation of the enhanced Pichgin and Habibullaev TP8 profile showing the horst structure.

- The soil type developed and accumulated in the valley is generally light calcareous or gypsiferous (De Pauw *et al.*, 2006). It is by no means comparable with the typical dark brown-red soils usually developed through weathering processes of basalts, which outcrop very close at the Khanaser Valley shoulders (Fig. 2).
- The pattern of the resistivity isopachs set at different depths by Asfahani (2007a, b, c), and the outlined two lows of variable depth, separated by an elevated barrier and complicated by transverse faulting, point strongly to later tectonics responsible for dissecting the central subsiding part of the graben.

From these mapped details, the following conclusions can be concluded:

- The presence of clear normal faults bounding both sides of the Khanaser Valley is confirmed. These fault marks, indeed a graben structure, never mentioned before in the geological literature, coincides with the Khanaser Valley. Such a structure should have a genetic relationship and interaction with adjacent active structures at the margins of the Arabian plate close to the African and Anatolian plates. The formation of this graben might be attributed to a E15°S extension which prevailed in Northern arabian plate during pre-Helvetian and it seems to be related to the formation of the 40-km distant Al Meksar fault and other parallel faults further east. This extension was responsible initially for the formation of the N15°E deep faulting zone at Khanaser, along which basaltic lava ascended. The faulting zone apparently reactivated later to

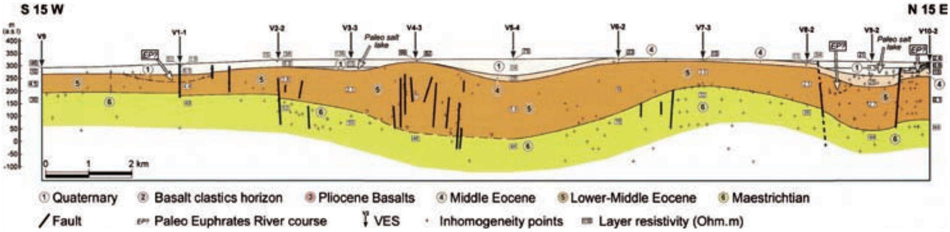


Figure 7
Interpretation of the enhanced Pichgin and Habibullaev LP2 profile showing the northern and southern two low structures along the Khanaser Valley.

form a graben coinciding with the present-day Khanaser valley. In this regard, ZANCHI *et al.* (2002) concluded through their paleo-stress analysis that in an area stretching from Ghab pul-apart to Euphrates graben, a N-S oriented compression (E-W tension) deformed the entire Cretaceous-Helvetian sedimentary succession.

- The presence of narrow faulted zones, traced on some enhanced PICHGIN and HABIBULLAEV profiles across the Khanaser Valley, is a remarkably frequent phenomenon. These zones are interpreted as conduits of reactivated Pliocene-Quaternary ascending basaltic lava, accompanied the formation and development of the Khanaser graben. Characteristic features of such volcanism in the Khanaser Valley are best mapped near Qurbatiyeh at Khanaser Valleys southern parts, where preserved lava conduits and filled-up maar were detected through this research. At Serdah in the center of the valley, a multiple coned volcanic ridge with four filled-up maars, aligned parallel to the valley axis, was detected. The Serdah volcanic ridge may indicate reactivation of volcanism during Late Quaternary.
- The central part of the graben, which coincides with the Khanaser Valley floor, was dissected by a series of W15°N parallel normal faults into differentially-subsiding blocks. This might explain the presence of the buried horst structure which separates the two lows of varied depth and salinity detected by ASFAHANI (2007a, b, c) (Fig. 7).

4.5. Tectonic Evolutional Scenario of the Khanaser Valley

DE VAUMAS (1957), believed that the Khanaser Valley served after the extrusion of Pliocene-Pleistocene basalt as a course of the Paleo-Orontes River. He suggested that it flew from Homs northeastwards to Kharaitch depression, Khanaser Valley and Al Jabboul depression toward the Euphrates River.

PONIKAROV (1966) mentioned outcrops of the Upper Pleistocene alluvial conglomerate consisting of well rounded flint, limestone and basalt pebbles in the Khanaser Valley and in the Abou Ad Duhur vicinity, further west.

Hoogeveen and Zöbisch (1999) reported that Lower Pleistocene (Q1) IV terrace of the Euphrates River is a poorly-cemented conglomerate consisting of white quartz, flint, serpentine, gabbros, basic and medium-extrusive rocks pebbles. This terrace outcrops at the surface to the northeast of the Khanaser Valley and encountered it in the wells drilled in it. The authors found that the outcropped terraces near the Rasm al-Nafl village in Khanaser Valley are actually lacustrine terraces marking the old Jabboul salt lake shoreline. They are 6 m higher than the 312 m current elevation of the Al Jabboul salt lake water table. The authors did not encounter any outcrops of the characteristic Lower Pleistocene (Q1) IV terrace with quartz, serpentine and gabbro, which should be some meters deep beneath the valley floor.

Nevertheless, the widespread erosion in the Khanaser Valley, which completely wiped out the Lower and Middle Eocene chalky limestone and Late Miocene-Pliocene 200–300-m thick basalt cap on both valley shoulders, – the pronounced parallelism of the Khanaser Valley with other faults mentioned before, – the soil type developed in the valley and the presence of the IV terrace deep in the valley point doubtlessly to the effect of a paleo long-lasting and mighty surface running water course. This course ran during Lower Pleistocene at least, through a series of depressions which extended from the Al Meksar fault zone, the Al Jabboul salt lake depression, the Khanaser graben, the Kharaitch depression, the Abou Khanadeq–Qamiq valley and joined Orontes near Hama. This mighty water flow continued westward to Tell Salhab where, it deflected northward into Al Ghab pull-apart probably forming Euphrates paleocourse. The lithological composition of (Q1) IV conglomerate components encountered in the Khanaser Valley (Hoogeveen and Zöbisch, 1999) points to source rocks such as gabbro and serpentinite, neither outcropped to the south, east or west of the Khanaser Valley. The well roundness of the conglomerate components in turn points to a distant source area, which exclusively should be located farther north in Turkey. This evinces the authors' argument that afore mentioned paleo water course run through the Khanaser Valley was a southwestward draining – Euphrates' Paleocourse, not an Orontes Paleo course as De Vaumas (1957) suggested.

The authors believe that the reinterpretation and the previous discussion, confirmed that the Khanaser Valley is actually a graben structure developed along the Al Meksar fault during Neogene and Quaternary time, according to the following scenario (Fig. 7):

I. *Pre-Helvetian*: Due to a prevailing stress regime during Late Miocene, an E15°S oriented tension dominated at least in the Aleppo Uplift, created in Late Miocene N15°E striking deep normal faults such as Al Meksar fault and other parallel faults cut to the east, as well as the Khanaser faults (Fig. 8-I).

II. *Late Miocene-Pliocene*: Due to continuing tension in the same aforesaid direction, Khanaser faults at least were behind the extrusion of widespread basaltic lava extrusion that covered large parts of Jabal Al Hiss and Jabal Shbith in particular. The role of other parallel normal faults in ascending basaltic lava elsewhere in the Aleppo Uplift is not excluded (Fig. 8-II).

III. *Pleistocene-Quaternary*: Due to the reactivation, the same E15°S oriented tension was behind the formation of an approximately 4-km wide 20-km long graben elongated in N15°E (Khanaser Graben) (Fig. 8-III).

IV. *Quaternary*: Due to a change in the direction of the then prevailing tension to N15°E, the central part of the graben was dissected by a series of parallel W15°N normal faults into blocks, which underwent throughout Quaternary time differential subsiding to form irregular complicated horst structures separating two lows in the northern and southern parts of the valley (Fig. 8-IV).

V. *Quaternary*: Paleo-Euphrates water forces its way southwestward from the Al Miksar fault through the Al Jabboul depression, Khanaser graben, Kharaitch depression, Abou Khanadeg-Wadi to Qamiq Valley, eroding completely the excessive Middle Eocene chalky limestone and Late Miocene-Pliocene basalt that outcrops in the Khanaser graben's central subsiding parts. Paleo-Euphrates joined Orontes near Mahrdeh, then deflected westward toward Tell Salhab, where it deflected again northward into the Al Ghab pull-apart (Fig. 8-V).

VI. Reactivation of two deep faults at Serdah was behind a subarial basaltic extrusion that formed the Serdah multipleconed volcanic ridge. This might be associated with a local uplifting which forced Paleo-Euphrates to abandon its mentioned course, deflect eastward and incise a new course toward Maskaneh. Khanaser graben became a greater lake extending between Al Jabboul and Kharaitch depressions. It shrank gradually and finally filled up by Quaternay lacustrine (Fig. 8-VI).

This Tectonic evolutional scenario is an important contribution to the active tectonics of northern Syria, viewed from a regional perspective involving the seismogenicly active Dead Sea fault system to the west, and the important petroferous Euphrates graben to the east.

5. Hydrogeological Characteristics Derived from the Khanaser Valley Tectonic Evolutional Scenario

The understanding of the Khanaser Valley origin and its buried subsurface structures morphology is hydrogeologically important in locating effectively favorable sites for fresh ground water accumulation.

The valley was developed as a differentially subsiding graben during Quaternary and served temporarily as Paleo-Euphrates' course, and later became a greater lake (Fig. 8-VI).

The differential subsidence of the Khanaser graben's blocks formed characteristic structures of sharp rough morphology, smoothed later by the Paleo-Euphrates running water effect.

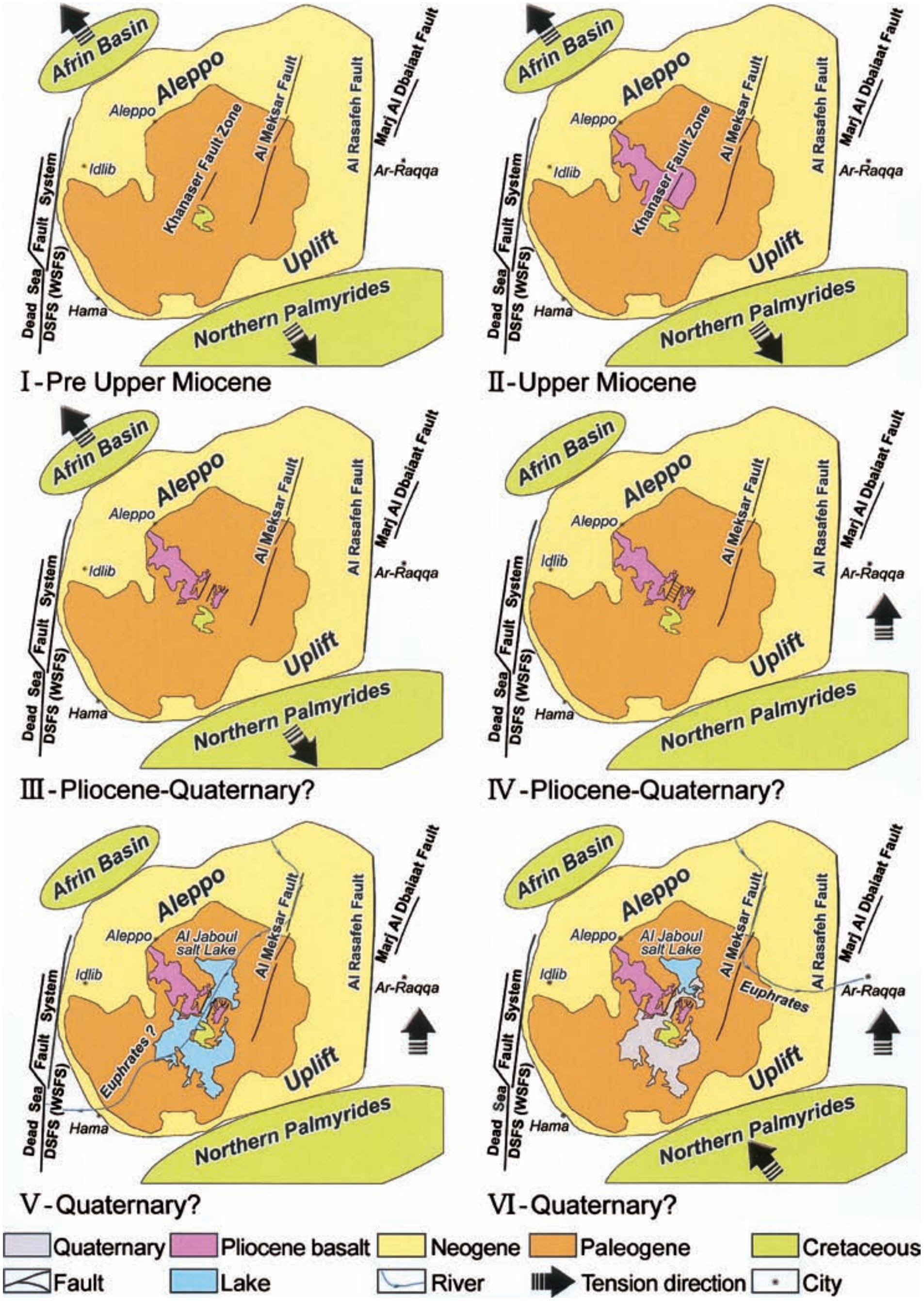


Figure 8
Tectonic evolutional scenario of the Khanaser Valley.

As the Paleo-Euphrates River abandoned its paleo course, deflecting eastward, Khanaser graben became a greater lake extended from Al Jabboul depression to Kharaitch depression. This large paleo lake shrank gradually to its current borders, leaving behind buried paleo salt lakes, whose locations and extensions fit very well with subsurface structures mapped by Asfahani (2007a, b, c) (Fig. 2).

The mapped subsurface horst structure (Figs. 7,8) formed a groundwater divide that separates a northern deeper low structure open to the Al Jabboul salt lake from a shallower southern one. It is close to the surfacewater divide delineated by Hoogveen and Zöbisch (1999) rather than to that suggested by Wolfahrt (1966), to the south near Khanaser town (Figs. 2, 6). From this subsurface divide, ground water flowed NNE toward the Al Jabboul depression and SSW toward the Kharaitch depression Asfahani (2007b).

Annual fluctuation of Al Jabboul salt lake water level (312 m), due to heavy rainfalls, may allow shifting the lake boundaries southward around the (318 m) contour. While, subsurface flows from Al Jabboul salt may run farther south until the buried horst structure, which blocked it either fully or partially. This may explain the relatively high salinity reported by Asfahani (2007a, b, c), in the northern deep structure. Partial percolation of surface run-off may dilute locally the water of, some paleo salt lake remnants scattered as fringed lenses, making their water either brackish or rarely fresh. The role of dense faulting within the Khanaser Valley in mixing saline and fresh water is not excluded. Sulfuric water encountered in some wells drilled in the Khanser Valley may be attributed to partial percolation of rainfall surface run-off, through bituminous chalky limestone Middle Eocene intercalating levels.

The abandoned Paleo-Euphrates River course (Fig. 8) may serve as an available quasi-ready water course to draw Euphrates water to Hama, Homs and even to Damascus, as a less expensive future alternative of the cost-effective sea water desalinization projects proposed to meet the rapidly increasing municipal and industrial water demand and consumption.

6. Establishing a Groundwater Exploration Approach in Dry Areas and Estimating its Validity

The lessons learned from the Khanaser Valley project confirmed well known-basic scientific rules which are often either ignored or underestimated in searching for water in arid areas. The most important one is carefully selecting a suitable site for conducting geophysical surveys, in case it is not preselected. This selection should be based on a profound understanding of the regional and local tectonic setting of the area of concern as a crucial prerequisite to save time, effort and money. Such understanding is still valid and even more needed to guide effectively geophysical survey activities, in an area preselected according to other measures, and groundwater is badly needed to run vital projects.

The authors suggest the following approach to be adopted for groundwater exploration, particularly in dry areas.

- Careful and integrated team-work interpretation and analysis of tectonic and geologic features extracted from available satellite imagery in the light of a solid understanding of the tectonic setting and the geomorphology, stratigraphy and hydrogeology of an already preselected area, otherwise of a wider area, to select adequate areas for subsequent steps.
- Conducting structure-oriented geoelectrical surveys using vertical electrical soundings (VES) covering the entire area of interest. A grid of convenient spacing is much preferred for a 3-D perspective interpretation.
- Interpreting measured VES profiles using the tectonically-adopted Pichgin and Habibullaev method, enhanced through this research, to make it applicable for detecting and delineating, ~250–300-m deep subsurface structures in areas of prominent rugged topographic relief.
- Extracting, compiling and matching the hydrogeological specifications, e.g., aquifers, aquitards, water salinity, ground water flow direction, TDS, etc. derived from the acquired geophysical properties of the penetrated formations.
- Selecting the most suitable sites for drilling fresh water wells.

The advantage of this approach is the diversely-applicable high information yield on reliable subsurface structures in the interested area, the low due costs and the rapidity in applying it. Accordingly, the decision of drilling a well is based on a reliable subsurface image. To check the validity of this approach, an integrated interpretation and analysis of tectonic and geologic features extracted from available satellite imagery and geological maps was performed to predict areas of tectonic, stratigraphic, geomorphologic, and hydrogeologic characteristics similar to those of the Khanaser Valley. An area of striking resemblance is delineated in Abou Khanadeg-Wadi El Qamiq to the NNE of Hama, since it is cut through by N15°E valley along which heavy erosion eradicated the basalt and the underlying Eocene chalky limestone with a similar morphology to that of the Khanaser Valley. This highlights the benefits of applying this approach to guide geophysical surveys, reconstructs its tectonic history and defines adequate subsurface structures convenient to accumulate fresh water.

7. *Conclusions*

Enhanced Pichgin and Habibullaev method, developed and applied in the Khanaser Valley as a representative dry area of prominent relief and topography, proved effectively its validity in detecting fractured and faulted zones and subsurface structures. The tectonic-oriented interpretation of twelve enhanced Pichgin and Habibullaev profiles, elucidates the origin of the Khanaser Valley as N15°E deep normal faults formed by the E-W tension which prevailed in the northernmost parts of the Arabian plate. These deep faults served as basaltic lava conduits before developing into a graben whose central dissected blocks underwent a differential subsiding. The graben served as a course of

Paleo-Euphrates extending from Al Jabboul depression to Hama on Orontes through the Kharaitch depression. Two buried low structures at the valley's northern and southern ends, separated by a horst, were defined. The northern low is deeper and open to Al Jabboul salt lake with more saline water due to a southward subsurface flow. The southern low is shallower with saline, brackish and fresh water, which might be explained by local dilutions caused by a runoff percolation through dense faulting networks.

Reactivation of volcanism in the Khanaser Valley uplifted the area, compelling Paleo-Euphrates to abandon its course and deflect eastwards, leaving behind a great lake covering Al Jabboul and Kharaitch depressions, and shrank gradually to the present day Al Jabboul salt lake. This paleo river course is suggested for use as a natural water course for drawing Euphrates water to major cities in central and southern Syria as a less expensive alternative for the cost-effective sea-water desalinization projects. A reliable, fast, and economical five-steps approach applicable in arid areas of prominent relief and topography in dry areas was established to detect subsurface structures hence locating favorable and promising sites to drill fresh groundwater wells. The application of this approach lead to defining a tectonically, stratigraphically and morphologically similar area to the Khanaser Valley near the NNE of Hama.

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REFERENCES

AL-OUDAT, M. (2004), Personal communication.

ASFAHANI, J. (2007a), *Geoelectrical investigation for charcterizing the hydrogeological conditions in semi-arid region in Khanaser Valley, Syria*. J. Arid Environ. *68*, 31–52.

ASFAHANI, J. (2007b), *Electrical earth resistivity surveying for delineating the characteristics of groundwater in semi-arid region in Khanaser Valley, Northern Syria* (*21*, 1085–1097). Hydrological Processes.

ASFAHANI, J. (2007c), *Geo-electrical investigations*. In (Bruggeman, A. *et al.*, eds.) *Water Resources and Use in the Khanaser Valley, Syria*. ICARDA, Aleppo, Syria (in preparation).

DUBERTRET (1953), *Carte geologique au 200 000e, feuille d' Anitioche avec notice explicicative*, 67 S., 19 Abb., 12 Taf., Damascus.

HOOGEVEEN, R.J.A. and ZÖBISCH, M. (1999), *Decline of groundwater quality in the Khanaser Valley (Syria) due to salt-water intrusion*, Paper presented at the 6th Internat. Conf. on the *Development of Dry Lands*, Cairo, Egypt, 22–27 August.

GEOLOGICAL MAP of SYRIA (1986), scale 1:50000, Sheet Jabboul, General Establishment of Geology and Mineral Resources (GEGMR, 1986).

ORELLANA, E. and MOONEY, H. M. (1966), *Master tables and curves for vertical electrical sounding over layered structures*, Interciencia, Madrid, Spain.

PAUW, DE E., RUYSSCHAERT, G., and MASRI, Z. (2006), *Soils*. In (Bruggeman, A. *et al.*, ed.), *Water Resources and Use in the Khanaser Valley, Syria*, ICARDA, Aleppo, Syria (in preparation).

PICHGIN, N.I. and HABIBULLAEV I.K.H. (1985), *Methodological Recomendations in studying geo- tectonic conditions of vertical electrical soundings data with application of EC computer for solving hydrogeological and geo-engineering problems*, Tashkend (in Russian).

PONIKAROV, V. P., ed., *The Geological Map of Syria*, Scale 1:200000, Sheets I-37-XX (Salamiyeh) (1966).

PONIKAROV, V. P., ed., *Explanatory Notes on the Geological Map of Syria*, Scale 1:200000, Sheets I-37-XX (Salamiyeh) (1966).

RADWAN, Y. (2007), *Brief geology and tectonics of Khanaser Valley*. In (Bruggeman, A. *et al.*, ed.) *Water Resources and Use in the Khanaser Valley, Syria*, ICARDA, Aleppo, Syria (in preparation).

SOUMI, G., *Supplemental irrigation systems of the Syrian Arab Republic* (SAR). p. 497–511, Proc. *workshop on regional consultation on supplemental irrigation*. ICARDA and FAO, 7–9 December 1987, Rabat, Morocco. (Kluwer Academic Publishers, Dordrecht, The Netherlands., 1991).

VAUMAS, E, DE (1957), *Plateaux, plaines et dépressions de la Syrie intérieure septentrionale. Etude morphologique*, Bull. Soc. Géogr. Egypte *30* 97–235.

WOLFAHRT, R. (1966), *Zur Hydrologie von Syrien*, Bundesanstalt füer Bodenforschung und den geologischen Landesämtern der Bundesrepublik Deutschland.

WOLFAHRT, R. (1967), *Geologie von Syrien und Lebanon*, Gebrüder Bornträger, Berlin-Nikola See.

ZANCHI, A., BATTISTA CROSTA, G., and DARKAL, A. N. (2002), *Paleostress analyses in NW Syria: constraints on the Cenozoic evolution of the northwestern margin of the Arabian plate*, *Tectonophys. 357*, 255–278.

ZOHDY, A. A. R. (1989), *A new method for the automatic interpretation of Schlumberger and Wenner sounding curves*, Geophys. *54*, 245–253.

ZOHDY, A. A. R. and BISDORF, R. J. (1989), *Schlumberger sounding data processing and interpretation program*, U. S. Geological Survey, Denver.

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