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3D geological modeling of the Kasserine Aquifer System, Central Tunisia: New insights into aquifer-geometry and interconnections for a better assessment of groundwater resources

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SUMMARY

The challenge of this study was to create a 3D geological and structural model of the Kasserine Aquifer System (KAS) in central Tunisia and its natural extension into north-east Algeria. This was achieved using an implicit 3D method, which honors prior geological data for both formation boundaries and faults. A current model is presented which provides defendable predictions for the spatial distribution of geology and water resources in aquifers throughout the model-domain.

This work has allowed validation of regional scale geology and fault networks in the KAS, and has facilitated the first-ever estimations of groundwater resources in this region by a 3D method.

The model enables a preliminary assessment of the hydraulic significance of the major faults by evaluating their influence and role on groundwater flow within and between four compartments of the multi-layered, KAS hydrogeological system. Thus a representative hydrogeological model of the study area is constructed. The possible dual nature of faults in the KAS is discussed in the context that some faults appear to be acting both as barriers to horizontal groundwater flow, and simultaneously as conduits for vertical flow. Also discussed is the possibility that two flow directions occur within the KAS, at a small syncline area of near Feriana.

In summary, this work evaluates the influence of aquifer connectivity and the role of faults and geology in groundwater flow within the KAS aquifer system. The current KAS geological model can now be used to guide groundwater managers on the best placement for drilling to test and further refine the understanding of the groundwater system, including the faults connectivity. As more geological data become available, the current model can be easily edited and re-computed to provide an updated model ready for the next stage of investigation by numerical flow modeling.

1. Introduction

In north African nations such as Tunisia, geological exploration under cover remains the most difficult challenge to success in finding continuing water resources, geothermal energy sources, oil and gas, and mineral resources. Securing these resources nationally means long term commercial self-sufficiency and prosperity. To achieve such goals, understanding the geometry of the subsurface by way of 3D geological modeling is essential. Modeling is also essential for ongoing infrastructure projects such as underground storage and mitigation of natural hazards related to sub-surface geology. 3D geological modeling is a tool increasingly used as a means for synthesising all available data and data types, leading to a better understanding and more realistic representation of a given geological setting. Its usefulness has been demonstrated through many different approaches, and these are widely discussed in the literature (Houlding, 1994; Mallet, 2002; Wijns et al., 2003; Wu et al., 2005; Caumon et al. 2009; Kessler et al. 2009; Fernández et al. 2004; Gjøystdal et al. 1985; Saksa 1995; Groshong, 2006; Mallet 1997, 2002; Calcagno et al. 2008;

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Courrioux et al., 1998, 2001; Martelet et al., 2004; Maxelon and Mancktelow, 2005; McInerney et al., 2005; Gibson et al., 2010, 2011, 2013; Raiber et al., 2012, 2015; Moya et al., 2014).

In central Tunisia, which is characterized by an arid climate, water is a vital and often a limiting factor for adequate livelihood. Groundwater is largely considered as one of the most important current and future natural water sources (Hamzaoui-Azaza et al., 2013; Hassen et al., 2016). In order to preserve this precious resource, and as an aid to better management, the volume of these aquifers needs careful evaluation by assessment of their geometry, structure and connectivity.

The Kasserine Aquifer System (KAS), located in arid zones of central Tunisia, covers an area of about 1300 Km^2 centered on the Kasserine region, and comprises four compartments. From NE to SW they are: the Plain and the Plateau of Kasserine, Oum Ali-Thelepte and Feriana-Skhirat (Fig. 1). The KAS represents a multi-layered system of five hydrogeological units from Cretaceous to Quaternary age, including three main regional reservoirs, namely the Plio-Quaternary, the Middle (Mid-) Miocene sandstone and the Cretaceous limestone.

The KAS is composed of variable thicknesses of varying lithologies comprising marls, sands, sandstones, clays and limestone. The upgradient system comprises an unconfined Mid-Miocene sandstone layer with variable thickness ranging from10 to 300 m, while in the downgradient system, the aquifer is confined. The downgradient system is overlain by marls exceeding 400 m thickness.

Integral to the setting of the KAS is a fault network characterized by discontinuities on seven principal faults. As such, the KAS presents many geological interpretation challenges, due partly to the presence of the faults which have little surface expression, and also to the limited data availability in the large scale of the study area including its extent into the north east of Algeria. To date no application of 3D geological modeling has been attempted in the KAS at a regional scale, and yet many questions and issues have been raised. To resolve the challenges and clarify the characteristics of the geological and hydrogeological systems, 3D geological modeling of the KAS is now applied to: (1) verify the geological mapping in 3D for the study region, (2) assess the geometry and volume of the aquifers, (3) define the possible connections between the Cretaceous limestone, Mid-Miocene sandstone and Plio-Quaternary aquifers, (4) discuss the influence of faults on the connectivity between the four compartments of the KAS, and (5) to construct a conceptual model with a consistent flow scheme of the groundwater, ready for future 3D hydrogeological flow modeling.

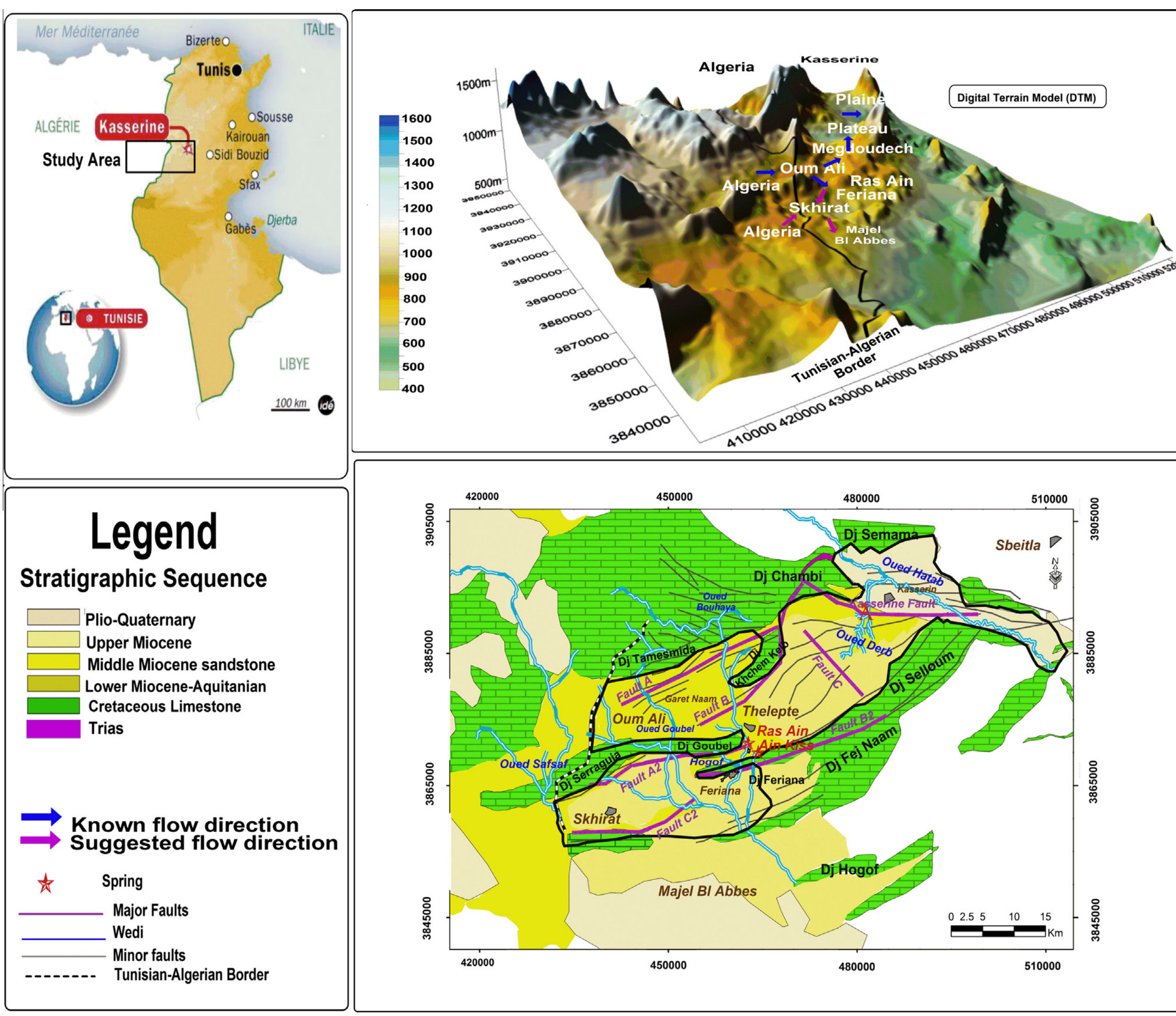

Fig. 1. Study area: Digital Terrain Model and geological map of the KAS.

2. Study area

2.1. Tectonic setting

The investigation area is located in the Central Atlas of Tunisia which is characterized by an emerged zone known as "Kasserine Islet". This zone features a SW-NE syncline developed through major compressive movement (the Atlas Phase) during the Early Pliocene (Degalier, 1952; Dassi et al., 2005). Hydrogeologically, it has been established that the KAS consists of several hydraulically connected strata with different sand, clay, marl and sandstone lithologies. The study area is surrounded by the mountains of Dj Serdj to the north, Dj Chaambi to the north-west, Dj Selloum to the south east, and the Algeria border to the southwest (Fig. 1).

In southern and central Tunisia, the extension–compression regimes of the Atlas Phase led to the formation of folded ranges oriented NE-SW, known as the Atlas Fold Ranges. These are separated by Mio-Plio-Quaternary basins, and together have largely guided the direction of the distributions of the sedimentary deposits since the middle Miocene (Boukadi, 1994; Bedir, 1995; Chekhma, 1996; Zouaghi, 2008; Zouaghi et al., 2011; Yengui et al., 2011).

Also as a result of tectonic events in the Cainozoic, normal SE-NW oriented principal faults were developed in the sedimentary series of the study area, as illustrated in Fig. 1. They are: the Kasserine Fault and Megdoudech Fault (C), located in the Plaine and the Plateau of Kasserine (Khanfir, 1981; Degalier, 1952; Yengui et al., 2011). In Feriana, the relaying of Dj Selloum-Dj Feriana by Dj Goubel leads to the change of the faults direction from NE-SW to E-W (Fig. 1). This torsion may explain the origin of the secondary faults such as Faults A, A2, B, B2 and C2 in the southwest of the study area in Oum Ali-Thelepte and Feriana-Skhirat (Degalier, 1952; Khanfir, 1980, 1981, 1983).

2.2. Geological and hydrogeological setting of the aquifers

The KAS inundates a stratigraphic series which varies from Triassic sandstones and evaporites, through to Quaternary siliceous deposits, as described in Table 1(a) (Burollet, 1956; Hamed et al., 2011, 2014).

The hydrostratigraphic units of the KAS consist of three main aquifers, namely from deepest to shallowest they are: the Upper Cretaceous (Abiod Formation), Mid-Miocene sandstone (OumDouil Formation, Vindobonian), and the Plio-Quaternary aquifer. The hydrogeology here is characterized by sandstone water circulating among the different units constituting these confined and unconfined aquifers. The hydrostratigraphic compartments are namely (ordered from upgradient to downgradient): Oum Ali-Thelepte, Feriana-Skhirat, Plateau and Plaine of Kasserine (Fig. 1).

The three main aquifers are well presented in the Plaine of Kasserine, but in the other compartments (the Plateau, Oum Ali-Thelepte and Feriana-Skhirat), the Plio-Quaternary aquifer is absent, and only the Upper Cretaceous and Mid-Miocene sandstone aquifers are present, together occurring with maximum thickness of 400 m, and comprising coarse to medium-grained sandstone. The Upper Cretaceous and Mid-Miocene sandstone are separated by a thin red clay layer of Hakima Formation from the Aquitanian (Upper Miocene). These reservoirs are made up of clayey sandstone (300 m) and fissured karstic limestone (150 m), respectively (Dassi et al., 2005).

The above descriptions of the aquifers and stratigraphic setting of the KAS were derived from the work of numerous authors in many geological and hydrogeological reports, as well as from borehole lithology logs of drilled water wells in the region (Khanfir, 1980, 1981, 1983; Mbarek, 1981; Zouari et al., 2003; Dassi et al., 2005; Hamed et al., 2011, 2014; Hassen, 2013, 2014, 2016).

3. Methodology

3.1. Introduction

In the last few decades, significant developments have been achieved in the ability to model complex geology and structure by 3D numerical modeling. One code available for this application is GeoModeller software (Calcagno et al., 2008; Guillen et al., 2004).

Developed originally by Bureau de Recherches Géologiques et Minières, France (BGRM) as part of the GeoFrance3D program and more recently by Intrepid Geophysics, GeoModeller is a software tool for constructing 3D models using geostatistics and co-kriging within a potential field method of interpolation (Lajaunie et al., 1997; Chiles et al., 2004; Lane et al., 2007). A potential field method of building 3D geological models considers that a geological boundary or interface is an implicit surface. In mathematics an implicit surface is a surface in Euclidean space defined by an equation. (Euclidean space is determined by three co-ordinates: X, Y, Z.)

Hence a geological boundary (or a fault surface) can be treated mathematically as a particular isosurface of a scalar field defined in a 3D space, called a potential field. As implemented in GeoModeller, interpolation of that field is based on universal co-kriging, and hence solved implicit surfaces honor all of the prior geological data supplied by the user. Prior data must be of two types: contact data points located on the geological (or fault) boundary, and structural vector data (dip-azimuths) located anywhere with the 3D model space. Structural data represent the gradient or derivative of the potential field (Lajaunie et al., 1997). By co-kriging of contact points and structural vector data, GeoModeller will solve each geological boundary in 3D, using an implicit scalar method of interpolation. Fault surfaces are solved in 3D, by the same approach (Lajaunie et al., 1997; Chiles et al., 2004; McInerney et al., 2005).

Based on knowledge from geological prior information such as field data, interpretive maps, cross sections and boreholes, GeoModeller allows the user to add data as model-constraints, and hence test geological hypotheses by solving geological boundary-surfaces, and fault surfaces, together with geology volumes everywhere in the 3D model space.

The modeling approach adopted, as implemented in GeoModeller, also employs rule-based modeling to control the stratigraphic relationships (either 'onlapping' or 'erosional'), and to control fault chronology within the fault network (Chiles et al., 2004).

Thus, rigorous 3D numerical modeling has facilitated construction of a coherent volumetric and structural geological model which honors all available, prior geological information in the KAS.

3.2. Data inputs to the model

Constrained by inputs of prior information (geological or fault control points) from different sources and levels of reliability, GeoModeller was used to build and edita3D model of fairly complex geology and faults in the KAS and north east of Algeria. Prior geological information from many data types such as geological maps and cross sections, borehole logs, and geological outcrop measurements were used to constrain the model. These data were collected from different sources including: The National Office of Mines (ONM), the General Directorate of Water Resources (DGRE) and the Regional Commission of Agricultural Development of Kasserine (CRDA). Different legacy and naming conventions were noted in some of the datasets, such that a degree of interpretation was required to homogenize the data in order to facilitate the creation of a coherent 3D geological model. All data sources used during the model development are listed in Table 2.

Table 1
(a) Lithostrattigraphy of the studied area; (b) modeled units of the KAS with the aquifers resources calculated from GeoModeller 3D geological model.

(a)

Epoch	Age	Stage (Burollet, 1956)		Formation	Lithology
Quaternary		Quaternary			Alluviums,sands, sandstones, gravels, silts and sandy-clays
Tertiary	Neogen	Pliocene			Conglomerate, clay, sandstone
		Miocene	Pontien	Oum Douil	sand and sandstone with intercalated green and grey marl in the shallower sequences
			Vindobonien		
			Burdigalien	Ain Grab	clay, sandstone
			Aquitanien	Hakima	red clay with gypsum
	Paleocene	Oligocene		Fortouna	Hilatus
		Eocene	Priabonian	Souar	
			Upper Lutetian		
			Lower Lutetian	Metlaoui	
			Ypresian		
		Paleocene	Thanetian	El Haria	
			Montian		
			Danian		
Secondary	Creteaceous	Upper Creteaceous	Maastrichtian	Abiod	dolomitic limestone
			Campanian		
			Santonian	Aleg	thick mar, interbeddedwith thin limestone
			Coniacian		
			Turonian	Bahloul	dolomite and claystone
			Cenomanian	Fahdene	dolomite and claystone
		Lower Creteaceous	Albian	Meknassy Group	thin clay and marl interbedded with limestone and dolomite
			Aptian		
			Barremian		
			Hautervian		
	Jurassic	Upper Jurassic	Titonic		Not studied
			Kimmeridgian		
			Sequanian		
			Argovian		
			Callovo-Oxfordian		
		Dogger	Bathonian		
			Bajocian		
		Lias			
	Triassic			Rheouis	clay, laminated gypsum, sandstone, schistose marl and dolomite.

(b)

Mapped and Modelled units	Hydrogeological Carecteristics	Volume (m3)	Percentage of the Total volume (%)	Ressources (m3)
Plio-Quaternary	Aquifer	7.10^{10}	2.19	7.10^{7}-35-10^{7}
Mio-Pliocene	Aquitard	$7.6\ 10^{11}$	11.53	
Middle Miocene sandstone	Aquifer	$1.01\ 10^{12}$	16.04	$11\ 10^{9}$-$55\ 10^{9}$
Lower Miocene	Aquitard	$6.4\ 10^{11}$	2.9	
Creteaceous (Abiod)	Aquifer	$5.87\ 10^{12}$	54.81	
Basement	Basement			

Table 2
Input data using 3D geological model construction.

Data	Source	Note
Elevation	USGS	Digital elevation map is used
Geology	The National Office of Mine Directorate of Trade, engineering and industry, Geological survey of Algeria Khanfir	Geological map of Feriana (1932) (scale 1:200000) Geological map of Tunisia (1958) (Scale 1:500000) Geological map of Algeria (1952) (scale 1:500000) Geological map of Oum Ali-Thelepte (1980) (scale 1:200000)
Well logs	General Management of Water Resources (DGRE) Regional Commission of Agricultural Development of Kasserine (CRDA) Tunisian National Oil Company (ETAP)	173 wells

The fault network, the conceptual model of the different units of the KAS, the geological syntheses and the interpreted regional cross sections were all derived from previous publications (Khanfir, 1980 and Mbarek, 1981). It is thorough to combine data from many different sources, but the challenge which then occurs is that the different resolutions and scales of data must be reconciled. This is the reason why re-scaling and choosing a uniform level of simplification was required when incorporating these data digitally into the modeling workspace.

Besides surface maps, 173 boreholes and wells from oil exploration carried out by the Tunisian Nation Oil Company were used. Also, several boreholes interpreted from electrical prospecting (HYDROAFRICA, 2011) were imported into the modeling workspace in order to help assess the geology of the study area, including at depth. The only available geophysical data in the KAS are derived from electrical prospecting wells used to determine the depth of the water table on agricultural land.

3.3. Building of the 3D geological model

The current 3D geological model was built on a regional scale, centered on the KAS of central Tunisia. It covers an area of 102.8 km $\times$ 76 km, and extends to a depth of 2 km. It includes the geographical areas known as the Plaine and the Plateau of Kasserine, Oum Ali-Thelepte and Feriana-Skhirat aquifer, and the north-east region of Algeria.

The starting point of a 3D modeling process is the interpretation of prior knowledge of the subsurface geology and structures (Lane et al., 2007). The model was developed using the stratigraphic classification defined with in the published geological maps of the study area. The geological structure of the area is fairly complex as shown in Table 1(a). Because of this complexity, detailed mine-scale stratigraphic sub-divisions were not adopted for modeling. The final stratigraphic scheme adopted was sufficiently detailed for representing the reality of geological sequences present, but simplified enough for modeling purposes and adequate speed of computation on a standard desktop computer. The final stratigraphic scheme shown in Table 1(b) can be summarized:

– The Plio-Quaternary,
– The Plio-Miocene called also the Upper Miocene,
– The Middle (Mid-) Miocene sandstone,
– The red clay of the Aquitanian from the Lower Miocene,
– The Cretaceous limestone.

3.4. Geological boundaries

In geological model-building, the shape of geological boundaries in 3D are constrained by both orientation data (dip-azimuths) and known contacts points on formation boundaries. To create these data sets for the KAS study area, and take them from 2D into 3D, it was necessary to digitize 2D geological maps and sections.

First a simplified version of the Geological Map of Feriana (scale 1:200,000) relevant to the KAS and north-east Algeria (Fig. 1) was imported and geo-located into a 3D wireframe of the model (102.8 km $\times$ 76 km $\times$ 2 km). Next, data were directly digitized from the geo-located map into the workspace, immediately creating 3D points/or vector data in the correct 3D location, for contact points and orientations (Fig. 2a and b). This process was repeated with further maps and cross sections.

In order to improve and complete the 3D model in places where geological prior information alone did not provide sufficient information, interpreted model-control points and/or structural data needed to be added. For the KAS geological model, this interpretation process was carried out in the workspace, where 3D validation with all geological data and control points could be tested simultaneously.

The ultimate goal of this work was to ensure the primary geological data were honored by the final interpretation, and hence that the model reproduced all aspects of the outcrop geology (Fig. 2c and d). Several regional scale cross sections from previous literature, as represented in Fig. 3, were also used for digitizing prior information for the KAS region. In areas of fair to good outcrop, the prior information from surface geology, coupled with modest input from an interpreted geology map where sufficient to produce a verifiable geological model. The model verification is also demonstrated on the cross sections presented in Fig. 3 which describe the different compartments of the KAS. They are: Fig. 3-1 Feriana-Skhirat, Fig. 3-2 Oum Ali-Thelepte and Fig. 3-3 representing the small syncline of Feriana to the Plaine of Kasserine. These cross sections which are orthogonal to our surface geology maps reproduced the same geometry of each unit.

3.5. Fault network

Management of faults is critical in constructing a realistic 3D geological model. In the KAS region, seven mains faults were classified. Additionally, the chronological relationships between each fault, and also the geological units affected by (displaced-by) each of the faults were established. Challenges at this stage were the lack of information about the tectonic history of the study area. Only two published cross sections from previous studies were available to indicate the interpreted location and geometry of faults in the KAS. These cross sections as presented in Fig. 3 (1) and Fig. 3 (2) (after Khanfir, 1980), helped to guide fault geometries and build the fault network, but still more information is required.

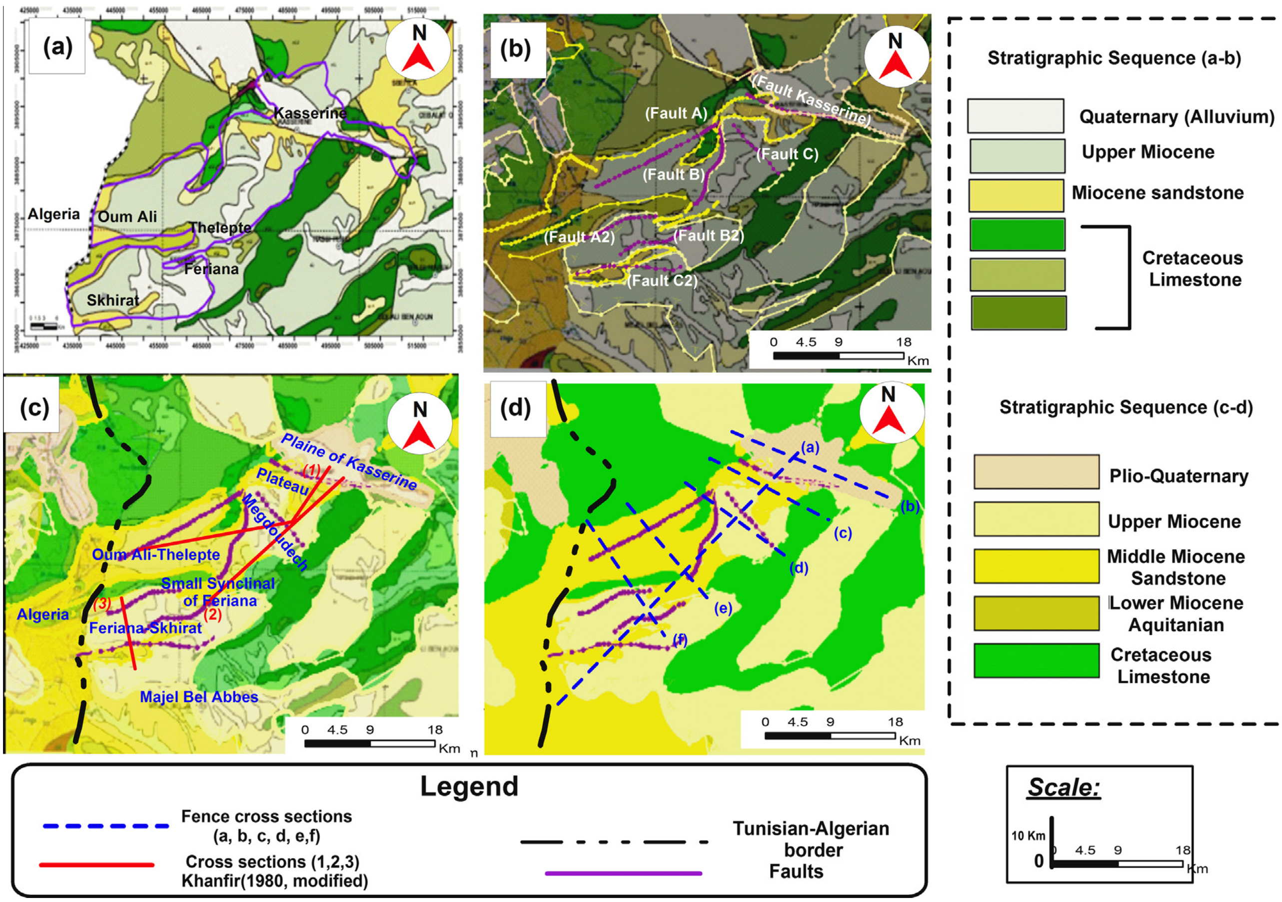

Fig. 2. Constructing of the geological map of the KAS (geological map of Tunisia and Algeria 1:500,000, geological boundaries and 2D geological model).

Hence further interpretation was applied for the modeling effort, including proposing the extensions of faults.

The Kasserine Fault cross-cuts all of the geological formations of the model area from the Plio-Quaternary, to the Cretaceous. Fault C, known as the Megdoudech Fault (separating Megdoudech Basin from the Plateau of Kasserine), also cross-cuts all of the formations from the marl of the Upper Miocene (Plio-Miocene), to the Cretaceous. The same relationship is observed in faults B, B2 and C2, which are located in Feriana-Skhirat region, as shown in Fig. 4 (from a to d). Faults A and A2, located in Oum Ali Thelepte region, cross-cut the formations from Mid-Miocene sandstone, to the Cretaceous.

GeoModeller calculated the final model from the input information constraining aquifer geometry, and the boundaries of all stratigraphic units. The resulting current fault model (Fig. 4a) provides a visual concept for the role of the interpreted fault network in the study area.

3.6. Construction process

McInerney et al. (2005) has described the construction process for building a 3D geological model in GeoModeller. This process can be summarized in four main actions: Inputs, Compute, Plot and Review. After defining the stratigraphic sequence and the faults network for the project, building of the KAS model then became an iterative cycle of reviewing the effects of continuously adding new "input" data. At each iteration, "Computation" of the implicit surfaces of the formation boundaries and faults, together with the volumes, was performed. "Reviewing" the computation each time occurred in 2D or 3Dviewers. Visualization aided geological interpretation and continuous model validation in the workspace.

As expected, comparative 2D and 3D images of the current KAS model illustrates a generally high-level match between the geological map of the study area, and the model computed on the basis of the geological data (Fig. 2D). Similarly, the model satisfactory reproduces the detail of the geology on cross sections in Fig. 3. The model also satisfactorily matches the borehole logs with low misfit values when comparing drill-hole prior information against the model predictions.

Furthermore, we suggest that in model domains located away from firm constraints using prior geological information, the model likely provides defendable predictions and best-possible extrapolations for lithology and structure everywhere throughout the model space.

For the current paper, we refer to the model as the 'current' model, because as more geological data become available(via drilling, further mapping or geophysical survey), thenediting and re-computation can be re-commenced, and thus an updated model can be easily produced.

4. Results

4.1. Geometry and volume of the aquifers

The resulting current KAS geological model was next used to generate multiple outputs such as sections and maps in 2D,3D PDFs, and 3D model-discretizations. These all facilitated in attempts to understand conceptually the geology and geometry of aquifers, as well as the flow behaviors and aquifer-

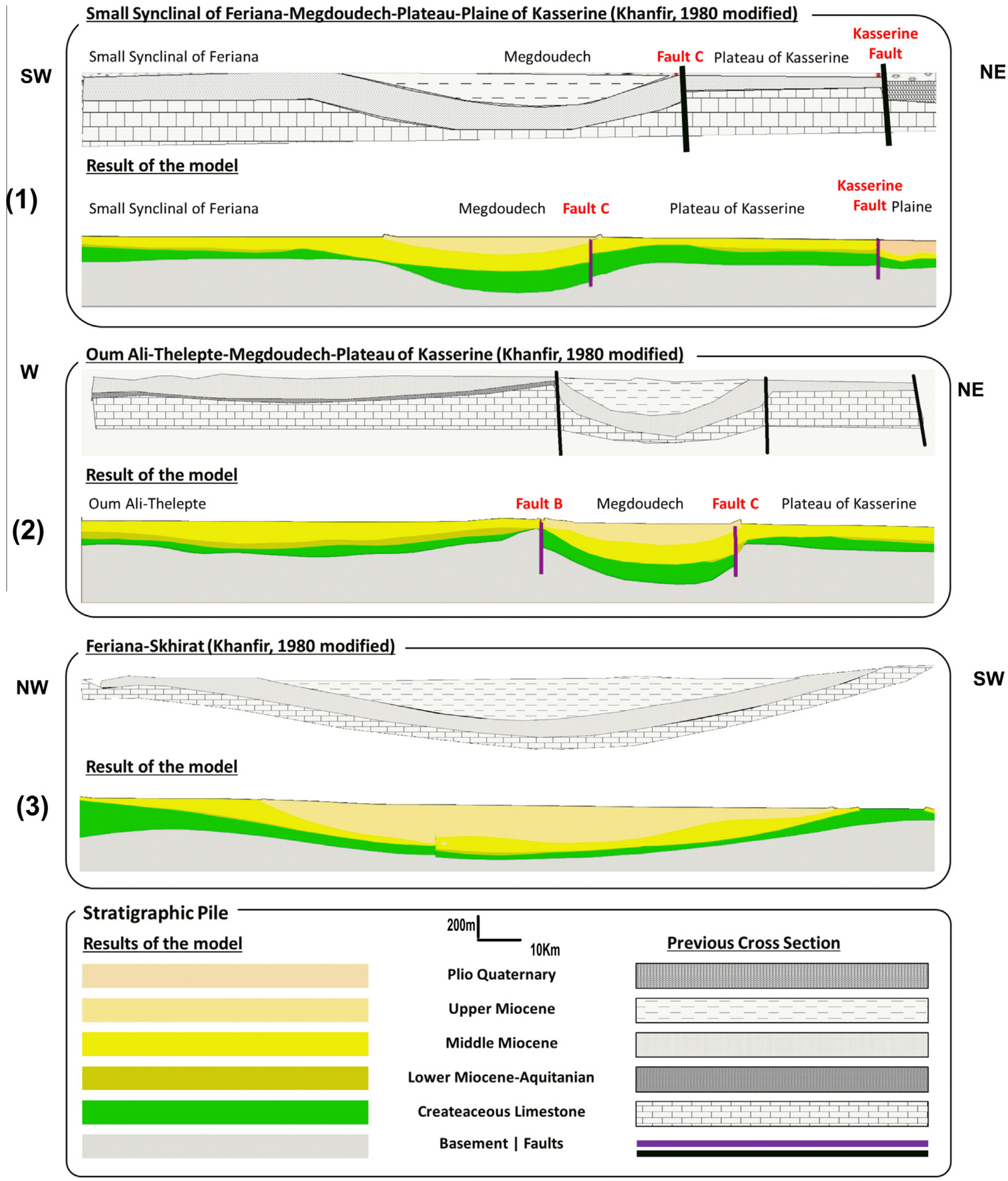

Fig. 3. Reproduced Cross sections from the literature: (1) cross section from Small syncline of Feriana to the Plaine of Kasserine (Khanfir, 1980 reproduced); (2) cross section from Oum Ali-Thelepte to Plateau of Kasserine (Khanfir, 1980 reproduced); (3) cross section of Feriana-Skhirat (Khanfir, 1980 reproduced).

connectivities in the KAS region. Seven cross sections with different views are displayed in Fig. 4a–g. Beginning with the Cretaceous limestone, the cross sections in combination with 3D metadata of the model, enabledestimates to be made about the geometry, thickness and volume of each of the three mainaquifers of the study region.

4.1.1. Cretaceous limestone aquifer

The fence cross sections in Fig. 4 enable different views of the KAS geological model, and hence provide another perspective of the geometry of the deep Cretaceous limestone aquifer (Abiod). Cretaceous geology appears as outcrop in all of the mountains surrounding the model area. The model proposes continuity for the Cretaceous limestone aquifer (Fig. 5b), and a variable thickness of this reservoir from 500 m to 700 m throughout the study area. From Algeria to Kasserine, the Cretaceous limestone is deeper in Feriana-Skhirat with a thickness of about 700 m; while it is thinner in Oum Ali-Thelepte, approximately 500 m.

The volume of this aquifer was also determined by geological modeling. GeoModeller software was used to predict that the Cretaceous limestone represents a volume of $5.87 \cdot 10^{12}$ m^3which is 54.8% of the whole model volume (Table 1b). This was achieved by discretizing the smooth 3D geological model into a regular, orthogonal 3D grid. Each cell of the new grid (at finer resolution is best) was automatically attributed with a given geology formation-identity. After discretization, it is a simple matter for the software to calculate a volume of each geology formation in cubic meters, from the number and size of cells.

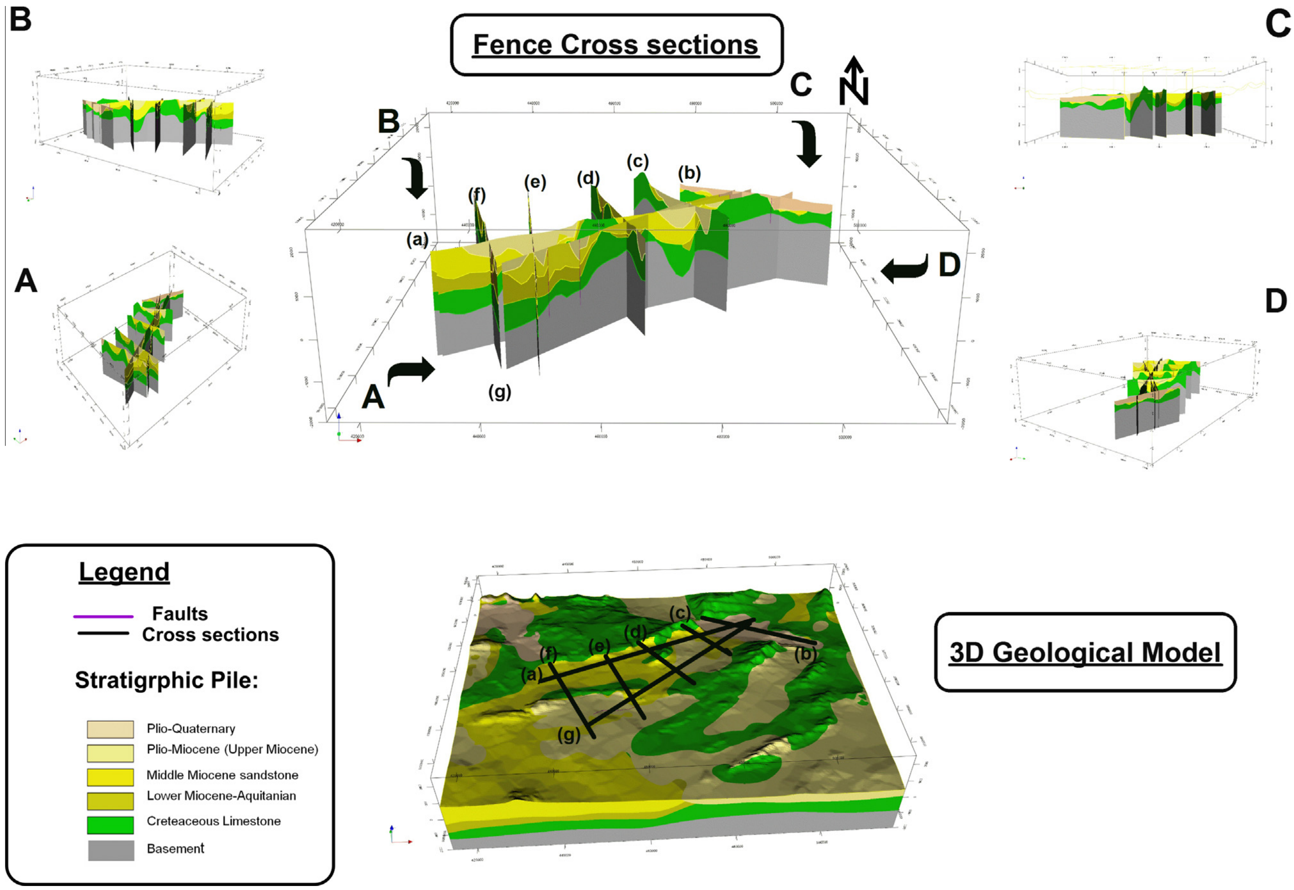

Fig. 4. Fence Cross section discussing the geometry of the KAS (a–g) from different orientations.

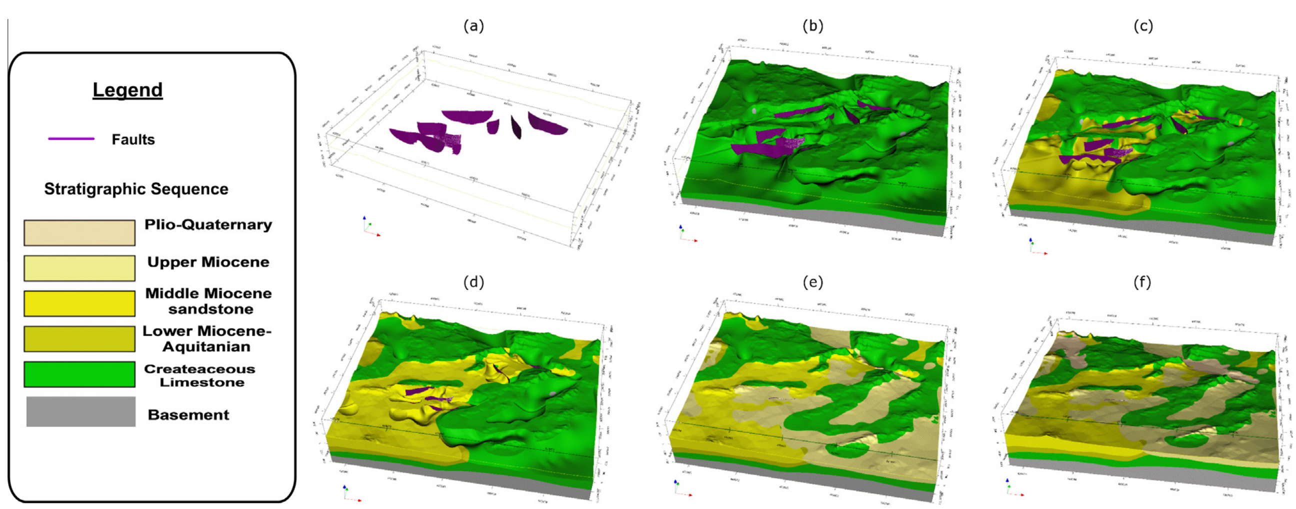

Fig. 5. Relationships between faults and the modeled volumetric geology of the study area, showing different visualisations. (a): fault network alone; (b): faults with Cretaceous limestone; (c): faults with Cretaceous limestone and Middle Miocene sandstone; (d): Faults with Cretaceous limestone and Middle Miocene sandstone and The Upper Miocene; (e): the whole model from the Cretaceous limestone to the Plio-Quaternary.

4.1.2. Middle Miocene sandstone aquifer

The Middle (Mid-) Miocene sandstones hosts the most important groundwater reservoir in central Tunisia. Previous studies have focused particularly on the Mid-Miocene sandstones for more detailed investigations and management of water resources. This study is likewise concerned with the geological extents and geometry of this aquifer, but is additionally concerned with the connections between the Mid-Miocene sandstone and Cretaceous aquifers.

To investigate this topic, different cross sections were extracted from the geological model. Firstly, on a 3D view, as presented in Fig. 5d, the Mid-Miocene sandstone is shown to be widespread throughout the KAS, though everywhere displaying different thicknesses (Fig. 4). The Mid-Miocene sandstone aquifer is also observed in the north-eastern part of Algeria, in the border area. From west to east (from Oum Ali near the Algerian border, to the Plaine of Kasserine), the Mid-Miocene sandstone aquifer has different geometries. In the west it is unconfined in the Algerian border region (maximum thickness of about 450–500 m), until the beginning of the Megdoudech Basin. In Megdoudech, through the fault B zone, the Mid-Miocene sandstone remains thick until the Megdoudech Fault (C), with a thickness of about 450 m. Here it is overlain by an important layer of marl from the Upper Miocene. When encountering the Megdoudech Fault C, the Mid-Miocene sandstone aquifer emerges to outcrop on surface, until the location of the Kasserine Fault. In the upper Plateau of Kasserine, the spring of Oued Derb appears representing the main outlet of groundwater from the Mid-Miocene sandstone aquifer.

On the other side of the study area, in south-west Algeria, several cross sections were also rendered to assess the predicted geological behavior of the Mid-Miocene sandstone aquifer near Feriana-Skhirat, and the small syncline area of Feriana (Fig. 4). The same geometry (as observed in north-west Algeria) is also observed: Near the Algerian border, more to the south of Oum Ali, the Mid-Miocene sandstones are unconfined until reaching the Tunisian-Algerian border. Over this border, the aquifer lies deep, and has a thickness of approximately 330 m up to Feriana. In the small syncline area of Feriana, the Mid-Miocene aquifer emerges to surface, and the two springs of Ras Ain and Ain Kiss are observed from either side of faults A2 and B2, near the Thelepte region. In this area the Mid-Miocene sandstone reaches a thickness of approximately 300 m according to model predictions.

Estimation of the volume of the Mid-Miocene sandstone was calculated in GeoModeller, resulting in a value of $1.1 \cdot 10^{12}$ m^3, equivalent to 16% of the entire model domain (Table 1b).

Knowing the water level in the aquifer, the saturated unit thickness can be calculated. When this value is multiplied by the effective porosity in an unconfined aquifer or the storage coefficient in a confined one, then all multiplied by the extension of the aquifer unit in the study area, the overall available groundwater resources is obtained (De Marsily, 1981, 1986, 2004). Hence we have estimated the available groundwater resource in all the aquifers in KAS by this approach. Consequently, on the basis of Mid-Miocene sandstone porosity between 1×10^{-2} and 5×10^{2} and storage values ranged between 1×10^{-3} and 1×10^{-6} the Mid-Miocene sandstone available groundwater resource may be estimated to be between 11×10^{9} and 55×10^{9} m^3.

4.1.3. Plio-Quaternary aquifer

Different points of view about the Plio-Quaternary aquifer have been presented in previous studies. In some regional maps, such as the 1:200,000 Geological Map of Feriana, and the 1:500,000 geological maps of Tunisia and Algeria, geoscientists consider that the Miocene and Plio-Quaternary are the same unit, called Mio-Plio-Quaternary (Mbarek, 1981). However, on the basis of conceptual models done by Khanfir, 1980, 1981, 1983; Mbarek, 1981; Degalier, 1952, this current study differentiates between the Mid-Miocene sandstone and the Plio-Quaternary aquifers.

The Plio-Quaternary aquifer constitutes essentially the Plaine of Kasserine in central Tunisia and hosts lithologies of sand, marl, gravel and clay. To study this aquifer, a cross section through the entire Plaine of Kasserine was considered (Fig. 4b). It shows that the Plio-Quaternary layer is unconfined throughout the Plaine with an average thickness of 150–200 m. This layer is also observed in a small area in Feriana with a maximum thickness of 50 m. Because of the smaller thickness of this layer, it is not represented in the KAS geological model due to the resolution and scaling choices made. However, the Plio-Quaternary geological volume predicted in this study is approximately 7×10^{10} m^3. Therefore this unit represents just 2.2% of the volumetric model (Table 1b). This further suggests values between 7 and 35×10^{7} m^3 for the available groundwater resource, based on a range of porosities between 5×10^{-3} and 1×10^{-3} (Khanfir, 1980).

4.2. Aquifers interconnection and faults network in the KAS

After identifying the geometry and volume of the main aquifers of the KAS, the possible interconnection existing between these aquifers is presented by discussing the relationships between the geological units which host the aquifers. To establish these relationships, a 3D geological model of each aquifer-hosting unit is presented in Fig. 5.

Firstly, the connection between Cretaceous limestone and Mid-Miocene sandstone was investigated. In Fig. 5b, the Cretaceous limestone (green) is continuous throughout the study area, but it is not usually overlain by the Mid-Miocene sandstone (yellow).

In Fig. 5c and e, the model predicts the existence of an semi-impervious, red clay layer belonging to the Aquitanian (gold) which is separating the Cretaceous limestone from the Mid-Miocene sandstone. This Aquitanian clay has a maximum thickness of 100 m. However, Fig. 5 indicates this layer may be absent in broad areas, such as in the north and east, including parts of the Plateau of Kasserine, Megdoudech Basin and near Feriana. Better geological control, such as achieved by drilling new boreholes, would be required in combination with higher resolution (and smaller scales) of modeling, to confirm or deny this possible finding.

Also note the study area is characterized by an important fault network (Fig. 5a). The current geological model validated the locations of these faults in 3D, and their influence on the geometry of the KAS, together with their role as potential connectivity pathways for groundwater flow.

The presence of these seven principal faults in the KAS leads to a significant level of hydraulic compartmentalization of the aquifers, assuming the faults act as barriers to groundwater flow (Mohamed and Worden, 2006; Moya et al., 2014). Conversely, where one or more fault planes interfere with another, then it is possible (when the physical properties of the fractured rock of the fault-plane support it) that the fault planes may also behave as conduits to regional continuous groundwater flow (Caine et al., 1996; Rawling et al., 2001; Bense and Person, 2006; Bredehoeft et al., 1992; Knott et al., 1996). Thus the intersection of the faults may simultaneously be hosting interconnectivity between several of those separate compartments.

In the region of Oum Ali-Thelepte and Feriana-Skhirat, faults A and B and A2 and C2 are respectively delimiting these two groundwater compartments (Figs. 2c and 6, lower). Meanwhile fault C separates the Megdoudech Basin compartment from the upper Plateau of Kasserine. Similarly, the Kasserine Fault separates the upper Plateau from the Plaine of Kasserine unit.

Where aquifers thin-out or abut against basement highs, this can induce upwelling of groundwater and result in the formation of wetlands or springs at the surface (Raiber et al., 2009). Hence, faults can form important pathways for inter-aquifer, aquifer/aquitard connectivity or for groundwater discharge to surface, which can be marked by the presence of wetlands or springs (Moya et al., 2014).

Further discussion about the behavior of the fault networks in the study area is supported by Fig. 6. In the direction of upgradient, from the Oum Ali region, to the Kasserine region, through the Megdoudech Basin, several fault locations were predicted: The Mid-Miocene sandstone is continuous with no displacement and hence the permeability of rocks is unchanged across fault B, thus the Mid-Miocene sandstone acts as a conduit for continuous horizontal flow. The same fault behavior (little or no displacement) is also

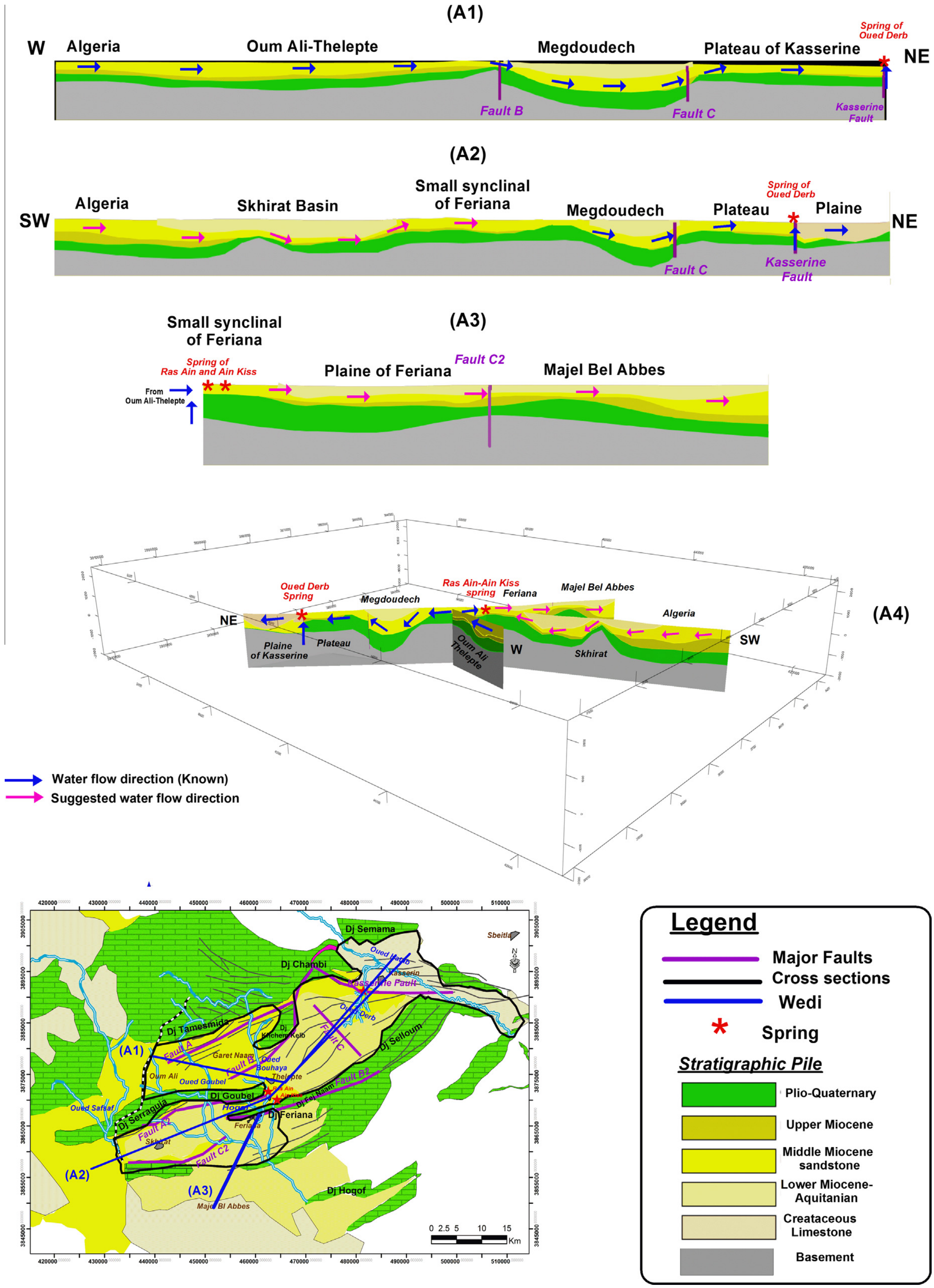

Fig. 6. Cross section showing water flow directions: Section (A1) water flow direction from Algeria-OumAliThelepte-Megdoudech-to Plateau of Kasserine; Section (A2) Water flow from Algeria-Skhirat Basin-Small syncline of Feriana-Megdeoudech-Plateau to Plaine of Kasserine; Section (A3) water flow direction from Small s syncline of Feriana-Plaine of Feriana to Majel Bel Abbes; Section (A4) summary of the different water flow directions in 3D views.

recognized in the Megdoudech Basin across fault C (the Megdoudech Fault). Therefore, this fault is also proposed to support continuous circulation of groundwater through these different units.

However, the Kasserine Fault (known as the Kasserine silt), is proposed to have a different role. Along the Kasserine Fault, the Mid-Miocene sandstone of the Plateau of Kasserine, and the Plio-Quaternary fill of the Plaine of Kasserine are juxtaposed with different permeabilities. Consequently, the Kasserine Fault along these units may act as a barrier to horizontal groundwater flow, but may also form a conduit to vertical flow to surface, leading to groundwater discharge in the Oued Derb Spring.

Similarly, in Feriana-Skhirat, there are some indications that faults A2 and B2 may also behave asconduits to vertical groundwater flow to surface. Such behavior would lead to the formation of the Ras Ain and Ain Kiss Springs. Conversely, we propose fault C2 would act like faults B and C described above: The permeable units of Mid-Miocene sandstone are present on both sides of fault C, and thus would support a conduit for continuous horizontal groundwater flow from Feriana-Skhirat to Majjel bel Abbes.

Regarding the water level information, it also endorses the proposed dual-role of faults. From the Plateau to the Plaine of Kasserine, across the Kasserine Fault, a gap of 40 m may be distinguished. In the Plateau of Kasserine, the piezometric level is higher than 680 m, while in the Plaine it is less than 640 m. As across the faults A, B and C, no significant discontinuity in the groundwater levels is observed. Consequently, these latter faults act as a conduit for horizontal flow. On the other hand, the water level measured from RasAin (in Oum Ali-Thelepte aquifer) and in Feriana-Skhirat is different. There is approximately 100 m of difference observed (Np RasAin = 775 m; Np Feriana-Skhirat <645 m). Such information may reinforce the argument that faults A2 and B2 act as a barrier for horizontal flow, and also as a conduit for vertical flow leading to the formation of the Ras Ain and Ain Kiss Springs.

This paper highlights some possible evidence for the major faults as potential connectivity pathways between aquifers and for groundwater flow to the surface in the KAS. However, structural data for the fault planes are rare in the study area, because expression of the faults in outcrop is rare. For a better understanding of the role of faults in hosting hydraulic connectivity between aquifers, more data are needed such as the width of the fault zone, its mineralogy and permeability. Geophysical survey data and drilling could assist in the future to better understand the fault systems.

5. Discussion

5.1. Overview of conceptual model and flow scheme

The current 3D geological model for the KAS is constrained by borehole log data, surface geology, interpreted cross sections and surface elevation data. The model is used to investigate the geometry of the aquifers, and examine the impact of faulting on the main aquifers and their host geology in the KAS and north-east of Algeria. The main geological structures are mapped in 3D and an assessment is made on how they influence the geometric relationships of the different aquifers, and how they are spatially related to surface hydrological features. The geological model development is part of an ongoing study eventually aiming to prove and quantify the connectivity between the different compartments of the KAS. At this first stage a conceptual hydrostratigraphic model is presented, with several examples of pathways postulated in the study area (Fig. 7).

The conceptual model and flow paths proposed are based on the potentiometric map of the Mid-Miocene sandstone in the KAS which suggests major flow toward the east and southeast from Algeria to Kasserine (Khanfir, 1980; Hassen, 2013, 2014, 2016). However, using the current geological model of the KAS, several

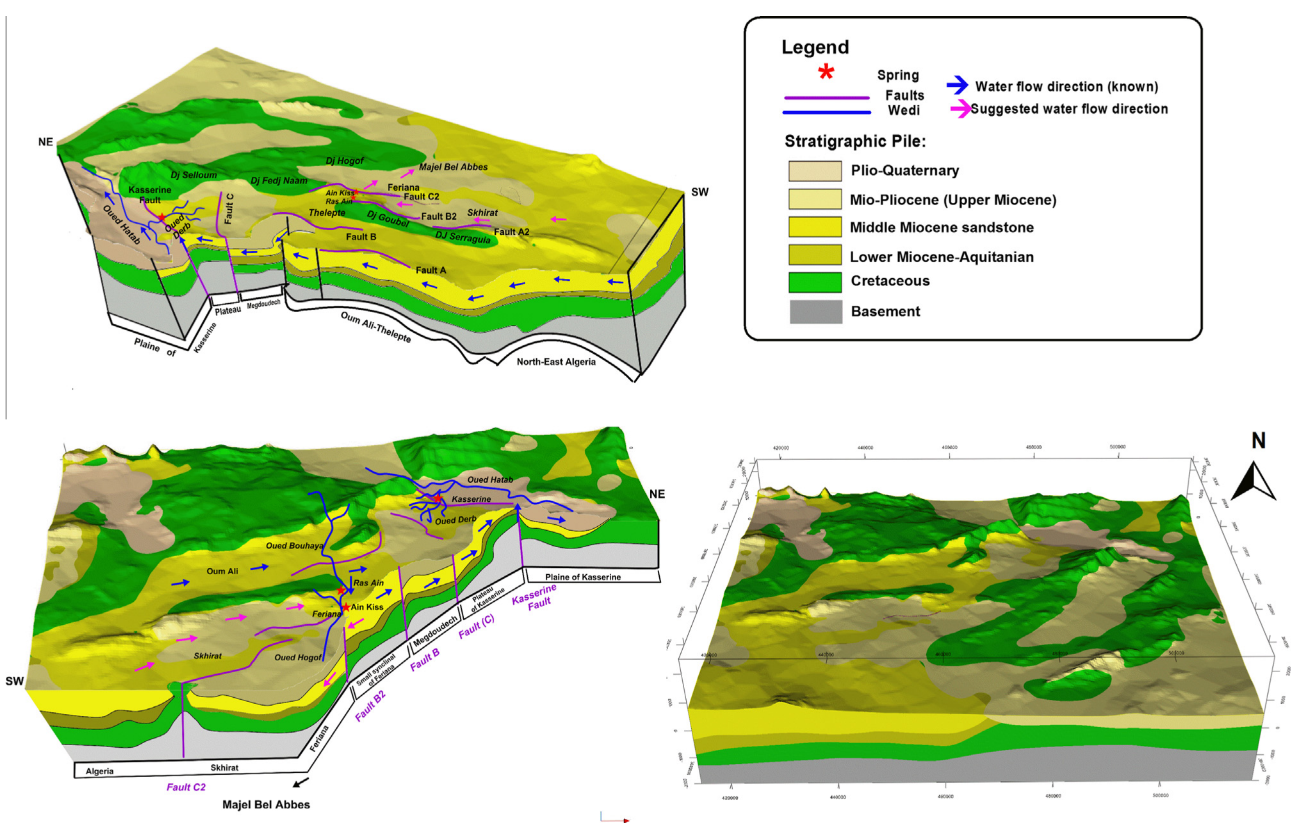

Fig. 7. 3D Conceptual model with different possible flow scheme from different orientations.

new hypotheses for flow schemes and potential connectivity pathways relating to the base of the topography and the structure of the aquifers isdeveloped.

5.2. Aquifer flow regime – Hypothesis 1

The flow paths presented in this section are based on the potentiometric map of the Mid-Miocene sandstone in KAS (Khanfir, 1980). As presented in Fig. 6, Section A1, beginning in the west in the surface recharge zone in Algeria (where the Mid-Miocene sandstone aquifer is unconfined), water infiltrates vertically until it reaches the base of the aquifer-host unit (Mid-Miocene sandstone). It subsequently flows downward along that basal surface depending on gradient, until it reaches fault B. Fault B is proposed as a permeable fault because the adjacent layer beyond it is again the Mid-Miocene sandstone (within the Megdoudech Basin). In this case fault B is considered as a horizontal conduit flow. Next, the flow crosses the Megdoudech Basin until it reaches Fault C. The same phenomenon is observed until flow reaches the Plaine of Kasserine, then crossing before reaching the Kasserine Fault in the north-east. The presence of the spring of OuedDerb on the Kasserine Fault (Fig. 6, Sections A1) as the main outlet of the KAS, confirms this proposed groundwater flow path. Hence the Kasserine Fault is proposed to be acting as a semi-barrier for horizontal flow and simultaneously as a conduit for vertical flow, such that groundwater springs breach surface in this location.

This first hypothesis endorses the fact that the four compartments (Oum Ali-Thelepte, Feriana-Skhirat, Plateau and Plaine of Kasserine) are hydrogeologically interconnected and form a unique regional hydrogeological system. But, because of the total absence of boreholes and piezometry in the small syncline region of Feriana we cannot currently confirm or deny this hypothesis.

5.3. Aquifer flow regime – Hypothesis 2

To describe another groundwater flow regime using the KAS geological model, a second hypothesis describing the Feriana-Skhirat aquifer, is presented. No piezometer data were available for Feriana-Skhirat and no boreholes have been drilled in the small syncline area of Feriana.

This hypothesis is based on knowledge of the surface topography, faults affecting the aquifer-host geology, and the presence of springs indicating the locations of outlets of groundwater flow. Fig. 6, Section A2, and Fig. 7, proposes that groundwater flow commences in the south west of the study area, recharging the unconfined Algerian Mid-Miocene sandstone. It crosses the Plateau of Skhirat where the Mid-Miocene sandstone becomes confined, then joins the small syncline of Feriana, where it becomes unconfined again. In this area two opposite directions of flux are proposed. The first source is proposed to come from Oum-Ali Thelepte to Ras Ain, where the presence of springs is noted at Ras Ain and Ain Kiss (potential evidence for the outlet of Oum Ali-Thelepte aquifer). This direction of flow was verified by piezometry data at Oum Ali-Thelepte aquifer (Khanfir, 1980).

Conversely and simultaneously, another direction of water flow is coming from Skhirat to reach the second part of the small syncline of Feriana. In this area, on the basis of the topography and hydrology, a line of surface water is identified as sharing these two fluxes among Oued Bouhaya and Oued Hogof (Fig. 7). The presence of this line on surface supports the possibility that there is also a line within the sub-surface aquifer, and they share the same scheme of opposite water flux, both above and below the surface. The two opposite flows coming from Skhirat (in the west) and from Oum Ali Thelepte (in the east) join each other at Oued Hogof and Oued Bouhaya, and continue as groundwater flow to Feriana in the south, where they reach Majel Bel Abbes (and possibly also Gafsa, in the south).

This second hypothesis deals with the hydrogeological disconnection of compartments. The KAS may include only the units of Oum Ali Thelepte, and the Plateau and Plaine of Kasserine with a flow direction from the east (north-east of Algeria in Oum Ali) to the Plaine of Kasserine. As for Feriana-Skhirat, the locally very high hydraulic gradient (10% hydraulic gradient across just 10 km) between Ras Ain and the Feriana-Skhirat Basin may enhance the disconnection of this unit from the other three (from Oum Ali-Thelepte to the Plaine of Kasserine). Hence, despite the regional geological connection, locally the Feriana-Skhirat unit may be a part of another hydrogeological system with a south-west Algerian contribution and with an outlet localized more in the south, in Majel Bel Abbes or in the Gafsa Basin.

Until such time when new boreholes are drilled in the small syncline region of Feriana, and piezmoetry data are available from the Feriana-Skhirat Basin, this hypothesis for the true flow direction and the connectivity of these units, can be neither confirmed nor denied.

5.4. Summary

The current KAS geological model, with newly proposed groundwater flow schemes, is presented in Fig. 7 where two different views (a and b) are given. The current model and flow schemes can now be used as to guide by groundwater managers when planning best placement for drilling to discover, test and further refine the understanding of the groundwater system in the KAS, including the faults connectivity.

It is recommended that additional data such as geochemical data, geophysical surveys, and new drilling data are acquired in the small syncline area of Feriana, and elsewhere in the study area for the purpose of updating of the current geological model.

In addition, mineralogical characterization of the fault zones is recommended to further assess the hydraulic characteristics of the faults in the KAS.

6. Conclusions

This study delivers a coherent 3D geological model for the KAS and its extension into north-east Algeria – one which honors the available geological and structural prior information, and offers defendable predictions of lithology and structure throughout the model domain.

Using the model outcomes, the groundwater resources of two main aquifers are quantified. Based on porosity and storage coefficient estimates, groundwater resources of the Plio-Quaternary aquifer range between 7 and 35 $\times$ 10^7 m^3, and resources of the Mid-Miocene sandstone are greater, ranging between 11 and 55 $\times$ 10^9 m^3.

Furthermore, this study evaluates the influence of aquifer connectivity and the role of faults and geology in groundwater flow within the KAS. Two hypotheses are given regarding possible flow regimes throughout the study area, and opposing flow directions are proposed in the region of the small syncline of Feriana. More data acquisition and monitoring are now required to independently confirm or deny the hypotheses. Any additional data which helps further constrain the geological model will also be beneficial to the continual improvement of the current geological model of the KAS.

In conclusion, the 3D geological modeling approach is endorsed as a rigorous method for gaining understanding about the geometry of faults, plus verifying and scenario-testing possible and optimal geological and structural solutions which can fit all available prior information. 3D geological modeling offers strengths, but also comes with limitations. For example modeling complex geological regions with many faults needs many initial 2D interpretations and considerable data density.

Nonetheless, the current model honors available geological constraints satisfactorily, and is deemed sufficient now for initiating 3D numerical flow modeling of the KAS, with the current aquifer geometry and faults serving as input data. As such, the current geological model of the KAS can next be exported as a fully unstructured mesh. In this portable format, it will be available to any future-selected software code that can perform flow simulations.

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