Managing clastic reservoir heterogeneity II: Geological modelling and reservoir characterisation of the Minjur Sandstone at the Khashm al Khalta type locality (Central Saudi Arabia)

Benoît Issautier, Yves-Michel Le Nindre, Sophie Viseur
Abdullah Memesh and Saleh Dini

ABSTRACT

The increasing demand on geological reservoirs, whether for developing geothermal energy or for CO₂ geological storage, raises questions on how reservoir heterogeneity might increase or decrease reservoir performance. To address this issue we selected the Minjur Sandstone Formation, a groundwater-bearing formation of Triassic age in Central Saudi Arabia, for complex reservoir modelling, simulation and prediction of the spatial distribution of sand bodies in a fluvio-deltaic system. This paper builds on a previous study that focused on the facies, stratigraphy, and reservoir characterisation of the Minjur Sandstone at the Khashm al Khalta type locality. Its purpose is to construct a deterministic 3-D model for (1) studying the connectivity of the Minjur Sandstone, and (2) illustrating a typical fluvio-deltaic reservoir and its associated heterogeneity. A first model simulates the spatial distribution of the depositional environments, which were further coded into relative proportions of sand, shale, evaporites and carbonates. This leads to a second model that contributes to reservoir applications through estimating the reservoir’s volume and storage capacities. Sequences 1 to 4 of the succession (Upper Jilh Formation—Lower Minjur Member), with a net-to-gross sand/shale ratio (NG) of ca. 8%, consist of poorly connected sandstone reservoir bodies. In contrast, sequences 5 to 9 (Upper Minjur Member), with an average NG of ca. 42%, consist of well-interconnected sandstone reservoir bodies. The NG depends on the tectonic influence and on relative sea-level variations. The best Minjur Sandstone reservoir bodies are at the base of each sequence, where limited available space favours a stack of deposits: interconnected fluvial channels which form wide spreads of coarse sandstone showing little diagenesis. The greatest potential is in the Upper Minjur Member. The effective reservoir volume was isolated using a sand content of > 85%. Rock volume and pore volume for an average porosity of 17% were subsequently calculated from the outcrop model. A representative block of 600 m x 600 m x 144 m was selected in order to simulate a fraction of the reservoir with the same properties as the whole. The block’s CO₂ storage capacity was 57,000 tonne (in the International System, ‘SI’) for an arbitrary CO₂ density of 0.7 (supercritical). This result was then transposed to the aquifer in the Riyadh area where similar conditions are assumed to exist. To obtain a ‘reservoir scale’ estimation, the block dimensions were upscaled to 20 km x 20 km x 80 m (the last figure being the effective thickness given by hydrogeological studies). The inferred storage capacity here was 30.5 Mt (million tonnes, International unit System, ‘SI’), which is an excellent figure when one considers the large-scale projects of Europe (Sleipner: 20 Mt) and Canada (Weyburn: 14 Mt).

INTRODUCTION

The Minjur Sandstone Formation (Bramkamp et al., 1956; Powers et al., 1966; Powers, 1968) is the uppermost formation of the Permian–Triassic Buraydah Group (Vaslet, 1987) which, from the base up, comprises the Khuff Formation (Middle Permian–Early Triassic), the Sudair Shale (Early Triassic), the Jilh Formation (Middle–Late Triassic) and the Minjur Sandstone (latest Triassic). The Minjur Sandstone is an assemblage of sandstone, shale and minor evaporites that Le Nindre (1987)
assigned to a fluvio-deltaic system. It is one of the main aquifers supplying water to the city of Riyadh (Sogreah, 1967, 1968; MacDonald, 1975; Williams, 1982; El-Sharif, 1985; Al-Saleh, 1992; GTZ, 2010) with the best reservoir properties being found in the fluvial sandstone with its 15–25% porosity, and 100 milliDarcy to 10 Darcy permeability (Jones and Hooker, 2010). The type section of the Minjur Sandstone, described by Vaslet (1987), is at Khashm al Khalta where it forms a thick cliff (300 m) overlying the Jilh Formation and capped by the Marrat and Dhruma formations (Figure 1).

Issautier et al. (2012) documented nine depositional sequences at the Khashm al Khalta site of which eight, reflecting eight depositional environments, belong to the Minjur Sandstone, which is split into two members. The Lower Minjur Member is a thick gypsiferous shale assemblage with interlayered calcareous siltstone and scattered sandstone deposits. The Upper Minjur Member is dominated by widespread thick coarse-grained sandstone deposits. Small-scale relative sea-level variations associated with a low clastic influx controlled the deposition of the Lower Minjur Member, whereas tectonic events provided a massive sediment supply as well as accommodation space for the Upper Minjur Member.

The integration of sedimentary heterogeneity in static models is a key process in reservoir analysis. It has been intensely studied in the oil industry where heterogeneity is recognised as a major recovery control parameter (Richardson et al., 1978; Qui, 1984; Lasseter et al., 1986; Thomas et al., 1987; Tyler et al., 1991; Hartkamp-Bakker and Donseelaar, 1993; Robinson and McCabe, 1997; Willis and White, 2000; Li and Caers, 2007; Pranter et al., 2007; Xiangyun et al., 2007; Larue and Hovadik, 2008), and similar studies have been carried out in relation to the geological storage of CO₂ (Flett et al., 2007; Riestenberg et al., 2008; Frykman et al., 2008; Sandoval et al., 2009).

The present study focuses on geomodelling the Minjur Sandstone as an outcrop analogue of the Triassic reservoirs of Western Europe (e.g. Germany, France, UK) and fluvio-deltaic reservoirs in general. It catalogues the heterogeneity encountered in the sedimentary bodies (nature and dimensions) of the fluvio-deltaic reservoirs, as well as a detailed analysis of the connectivity between the reservoir bodies. The final model provides a realistic display of the Minjur reservoir architecture and genetically links the reservoir bodies and their spatial distributions to the sedimentary history of the Minjur Sandstone. An estimate of the Minjur Sandstone’s storage capacity is given in order to compare the Minjur reservoir against other CO₂ geological storage projects.

The abbreviation of units used in the present paper are those of the International System (SI). Consequently, the ‘M’, ‘t’, ‘b’ are the abbreviation of respectively ‘Million’, ‘tonnes’ and ‘billion’.

**WORKFLOW**

The digital terrain model (DTM) used as a base for this study had an original 90 metre resolution (source, SRTM), which is far too large for the purposes of the study and the dimensions of the objects. An intense refinement was carried out using available topographic maps and altitudes and scattered but reliable georeferenced geographic positioning system (GPS) points. The final enhanced DTM has a 10 m resolution, obtained by fitting the grid to the georeferenced points and kriging the data. With this process, the gap between the elevation of the observation points and the initial DTM has been largely reduced.

The starting point for the geological modelling was the sedimentological map of the Minjur Sandstone created using a geographic information system (GIS) on an Ikonos high-resolution (1 m) satellite image (Issautier et al., 2012; Figure 2). The map was originally composed only of polygons containing information on the lithology, depositional environment, etc. For geomodelling purposes, the first step was to convert the polygons into a point set. For this the polygons were crossed with the enhanced DTM so as to build up a 10 m resolution dataset.

The geomodelling was started after the dataset and the DTM were completed. The first step was to complete the structural modelling prior to any property modelling. This consists in designing a 3-D grid whose structure is determined by the outcrop and subsurface geometries. With the present
Figure 1: (a) Location of the Minjur Sandstone study area (Issautier et al., 2012). (b) The geological map of Wadi ar Rayn (Vaslet et al., 1983) shows the location of Khashm al Khalta where the type section was described and where Issautier et al. (2012) characterised the reservoir structure.
study, the Minjur model was originally split into eight units plus the upper Jilh Sequence defined by the sequence boundaries mapped in the field. Each sequence is processed independently and its vertical resolution fixed by the objects to be simulated.

The first model is a depositional environment model. Its purpose is to represent the Minjur Sandstone through 11 sedimentary environments (the twelfth being the gravity deposits but their occurrence as well as dimensions is localised in a limited area so it was neglected) described in Issautier et al. (2012). This model provides a catalogue of the heterogeneities encountered in the fluvio-deltaic reservoirs and describes (1) their nature, (2) their dimensions, and (3) their organisation.

A second model, this time reservoir oriented, is derived from the depositional environment model. The previously built 3-D indicator grid was transformed into a point set whereby each indicator was coded into lithological proportions. As a result, the new conditioning dataset contains four properties (sand, shale, evaporite and carbonate proportions). The lithological property model was built by interpolating the proportions sequence by sequence. The final model gives a fairly good representation of the best porous unit of the Minjur Sandstone.

**GEOMODELLING**

Two main methods can be used to produce 3-D facies models from collected data: interpolation (kriging) and stochastic simulation (pixel-based, object-based and process-based). The choice of method depends partly on the data distribution relative to the facies dimension.

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**Figure 2: Sedimentary map of the Minjur Sandstone at the Khashm al Khalta location. The map illustrates the distribution of the depositional environments and their lateral-vertical evolution. The green, blue and pink colours represent coastal to shallow marine deposits, and the yellow and orange colours represent more proximal deposits (Issautier et al., 2012).**
Stochastic simulation is the recommended method for reproducing small bodies from sparse data and is widely used in the subsurface context since it enables multiple equiprobable solutions. The three main stochastic methods are:

(1) Pixel-based algorithms, which simulate the properties in pixels without any physical notion of a continuous sedimentary body (Journel et al., 1998; Felleti, 2004 for SIS methods; Dubrule, 1989; Koltermann and Gorelick, 1996 for SGS methods; Caers et al., 2001; Levy et al., 2007 and Mariethoz, 2009 for Training image methods).

(2) Object-based methods, which simulate an envelope to enhance the continuity within objects (Viseur, 2004; Deutsch and Tran, 2002) and are often coupled with Gaussian methods for simulating the petrophysical properties. These methods simulate the reservoir architecture without considering the sedimentary law of superposition and erosional depositional processes.

(3) Process-based algorithms, which reproduce the deposition of sedimentary bodies (Lopez, 2003) and attempt a realistic geological representation of the reservoir.

Large sedimentary bodies are fairly well modelled by kriging from scattered field data points. This provides a unique and deterministic model (Matheron, 1963, 1973). External drift or co-kriging can be used to improve the estimation according to defined shapes of sedimentary bodies.

### Indicator Kriging

A classification based on lithology and depositional environment was created for capturing the reservoir units of the Minjur Sandstone. When combined, these two factors affect the quality of the facies for further petrophysical modelling (Table 1). Because the dimensions of the sedimentary bodies in the Minjur Sandstone are fairly constant and in a definite sequence throughout the study area, the kriging method was chosen to model the facies of the different sequences. A lithological property model was obtained at the same time by interpolating the proportions of the lithological components defined in Table 1. This approach provided a quick understanding of the reservoir’s quality.

| CODE_ENV. | ENV. | %SAND | %SHALE | %CARB | %EVAP |
|-----------|------|-------|--------|-------|-------|
| Distal channel | DBAR |   1   |  95    |   5   |  0    |  0    |
| Estuarine bar   | EBAR |   2   |  80    |  20   |  0    |  0    |
| Floodplain      | FPLA |   3   |  20    |  77   |  0    |  3    |
| Fluvial bar      | FBAR |   4   |  95    |   5   |  0    |  0    |
| Fluvial channel  | FCHA |   5   | 100    |   0   |  0    |  0    |
| MF Complex       | MFC  |   6   |  10    |  60   |  30   |  0    |
| Mudflat          | MFLA |   7   |   3    |  80   |  17   |  0    |
| Sabkha           | SABK |   8   |   5    |  75   |  0    |  20   |
| Tidal siltites   | TIDS |   9   |  10    |  85   |   3   |  2    |
| Tidal channel    | TIDC |  10   |  70    |  30   |  0    |  0    |
| Tidal ridge      | TIDR |  11   |  70    |  30   |  0    |  0    |

The modelling (Figure 3) was done sequence-by-sequence so as to (1) account for the specific sedimentological constraints of each depositional system, and (2) keep the best lateral control based on depositional mapping and field measurements. The sequence simulations are “base controlled” (i.e. from the bottom up, and following the lower boundary of each horizon), which ensures that it fits the depositional logic.
The variogram of each depositional environment in the sequence was computed separately on a binary type indicator variable; i.e. where the facies is present, the indicator is set to one (1); where the facies is not present, the indicator is set to zero (0, background) (Koltermann and Gorelick, 1996). The computed experimental variogram gives the sill of the facies (sample variance), and the ranges and azimuth of the structure (maximum correlation distance between pairs of points); i.e. it provides the most probable dimension and orientation of the sedimentary body from the sampled data.

Mapping and data sampling solely from outcrop, however, introduces a strong bias in the calculation since it accounts neither for the whole volume nor for the complete subsurface geometry of the bodies. The ranges and azimuths were therefore adjusted in accordance with the field interpretations of the different depositional systems; an example is given in Table 2. The corrected parameters were subsequently introduced as faithfully as possible into the spherical variograms used for modelling the depositional environments.

### Table 2

| Field-based sedimentological interpretation | Corrections applied to the 3-D variograms |
|--------------------------------------------|------------------------------------------|
| Length = continuous in the area            | Range Y (R1) = ‘infinite’ >> R2          |
| Width = 2,000 m                            | Range X (R2) = Width/2 = 1,000 m         |
| Thickness = 10 m                           | Range Z (R3) = Thickness/2 = 5 m         |
| Azimuth = N090°                            | $\theta = 90^\circ$                      |
Upper Jilh Sequence 1 (40 m thick)

As discussed by Issautier et al. (2012), the contact between the Minjur Sandstone and the Jilh Formation at Khashm al Khalta is marked by the basal black ferruginous sandstone of Sequence 2. The Upper Jilh Sequence 1 consists of a coastal plain (sabkha) drained by small tidal channels and distal fluvial channels. Thus two environments have to be simulated: tidal channels and sabkha. The sabkha being the major facies (i.e. the background), its assignation in the grid occurs at the end of the simulation and fills the empty cells. The dimensions of the sedimentary bodies are displayed in Table 3.

| Environment                  | Range Y (R1) | Range X (R2) | Range Z (R3) | Azimuth |
|------------------------------|--------------|--------------|--------------|---------|
| Distal fluvial channel       | > 1,500 m    | 150 m        | 2 m          | N045°   |
| Tidal channel                | > 1,500 m    | 150 m        | 2 m          | N130°   |

The reservoir bodies being distal fluvial channels and tidal channels, the sequence displays poor connectivity. The sand bodies remain isolated in the floodplain and totally disconnected from one another. This lack of connectivity is associated with a weak sediment supply that did not allow the deposition of sufficient sandstone bodies to initiate connectivity. Larue and Hovadik, (2008) point out that below an NG of 25%, connectivity is very low. As demonstrated in the model, the top of the sequence marked by erosive fluvial channels is not deeply enough incised to create a connection between sequences 1 and 2.

Sequence 2 (40 m thick)

Sequence 2 (coastal plain/estuary) differs from the Upper Jilh Sequence 1 in that the sediment supply was slightly more important. The sequence boundary is marked by low sinuous channel deposits incising the underlying coastal plain. A tidal inlet marking the transgressive stage of the underlying Sequence 1 is overlain by a floodplain and associated river deposits (coastal to meandering) capped by a thick rooted palaeosol.

Five environments are found in this sequence: sabkha, floodplain, distal channel, tidal channel (inlet, called sandwaves in Figure 2) and fluvial channel. The lower fluvial channel does not need to be simulated since property transfer from the map data to the grid is sufficient to reproduce the channelized geometry. The sabkha facies, being the most abundant, is the background. In the end, three environments (distal channel, tidal channel (inlet) and floodplain) were simulated according to the dimensions specified in Table 4.

| Environment                  | Range Y (R1) | Range X (R2) | Range Z (R3) | Azimuth |
|------------------------------|--------------|--------------|--------------|---------|
| Distal channel               | > 1,500 m    | 150 m        | 2 m          | N045°   |
| Tidal channel (inlet)        | > 1,500 m    | 1,500 m      | 4 m          | N000°   |
| Floodplain                   | > 1,500 m    | 1,500 m      | 6 m          | N000°   |

As pointed out in the underlying sequence, clastic influx was still low and consequently the NG of the sequence is very low. Connectivity between the sandstone bodies is almost negligible. Nevertheless, the tidal megripples deposited in the estuary are fairly continuous in the study area, which locally enhances the connectivity between the distal fluvial channels and this tidal floor (Figure 4). The simulated thick floodplain deposited during the relative sea-level high stand ends the sequence and isolates it from the overlying Sequence 3.
Sequence 3 (10 m thick)

Sequence 3, truncated by the overlying sequence boundary, is approximately 10 m thick and mainly shallow marine. It consists of coastal plain deposits with cross-cutting channels grading to a tidal mudflat drained by small interconnected channels (Table 5). The dimensions of the coastal channels are too small to be simulated and, since they are embayed in a floodplain, do not enhance the connectivity; consequently they were not simulated. For the sake of simplicity, the mudflat and floodplain were simulated together as a single unit since they both have low permeability. The only depositional environment to simulate is the tidal channel.
Table 5
Body dimensions in Sequence 3

| Environment       | Range Y (R1) | Range X (R2) | Range Z (R3) | Azimuth |
|-------------------|--------------|--------------|--------------|---------|
| Tidal channel     | > 1,500 m    | 100 m        | 1 m          | N230°   |

The coastal channels at the base of the sequence play no role in the connectivity of Sequence 3 since they are embayed in their floodplain background. However, the sequence’s main reservoir unit is a network of interconnected tidal channels (intra-sequence connectivity). Moreover, the fact that Sequence 4 erodes and truncates this sequence has probably given inter-sequence connectivity, which is important and a key parameter for reservoir purposes; a pathway may exist between the Sequence 3 tidal channels and Sequence 4 braided channels. Despite the thickness and low sand/shale ratio, therefore, this shallow marine sequence is interesting due to the fact that the tidal channels and estuarine bar are connected to the overlying reservoir bodies of Sequence 4.

Sequence 4 (40 m thick)

A sharp change occurs at Sequence 4 with a drastically increased sediment supply compared to the two underlying sequences that are ‘shale’ dominated. The sequence boundary is associated with the establishment of vigorous braided/low-sinuous channel deposits grading to meandering stacked point bars (facies retrogradation due to increased available space). Shallow-marine deposits overlie the continental succession, passing from brackish shaly carbonate deposits to estuarine sand bars. The sequence ends with a thick sabkha.

The kriging of this sequence is complex since it involves simulating seven environments: *fluvial bar*, *fluvial channel*, *tidal channel*, *maximum flooding complex (MFC)*, *floodplain*, *estuarine bar* and *sabkha* (Table 6). To resolve this problem, the simulation was done in two imbricated steps: (1) kriging of the fluvial channel and point bars (the non-simulated cells forming the background), and (2) simulation of the other facies in the previously extracted background. The purpose of this approach is to keep the continuity of the main reservoir bodies and ensure a realistic geometry.

Table 6
Body dimensions in Sequence 4

| Environment             | Range Y (R1) | Range X (R2) | Range Z (R3) | Azimuth |
|-------------------------|--------------|--------------|--------------|---------|
| Tidal channel           | > 1,500 m    | 100 m        | 1 m          | N120°   |
| Fluvial channel         | > 1,500 m    | 800 m        | 4 m          | N045°   |
| Fluvial bar N           | 250 m        | 125 m        | 4 m          | N040°   |
| Fluvial bar S           | 800 m        | 400 m        | 4 m          | N040°   |
| Maximum flooding complex| > 1,500 m    | 600 m        | 1 m          | N000°   |
| Tidal channel           | > 1,500 m    | 80 m         | 1 m          | N120°   |
| Estuarine bar           | > 1,500 m    | 170 m        | 3 m          | N120°   |
| Sabkha                  | > 1,500 m    | 1,500 m      | 2 m          | N000°   |

The complexity and importance of the connectivity in the fluvial reservoir is fully represented in this sequence. A continuous sheet of channel deposits throughout the study area form a base on which were deposited the stacked lateral bars that now form isolated hills. The large reservoir volume is provided by the widespread fluvial channels that form a porous horizon on which the sandstone bars are ‘plugged’ (Figure 5). This connectivity type is primordial; it shows that lowstand systems tract (LST) deposits, because of the limited available space, spread laterally and form wide sheets that have good reservoir properties if the pore is preserved from diagenetic plugging. As accommodation
and available space increase, the facies belt retrogrades and more distal systems, such as meandering point bars, develop. As shown in the model, these form isolated pockets on the fluvial channels which connect them all.

The marine flooding event (TR80) is associated with the development of tidal creeks embedded in the mudflat; these are not a candidate reservoir due to their limited volume. The estuarine bars connected to a tidal channel represent a greater volume than the creeks and could form a large reservoir volume, although so far they are embayed in the calcareous siltstone grading to coastal siltstone.

Sequence 5 (35 m thick)

Sequence 5 marks the base of the Upper Minjur Member. The bottom part of the sequence consists of erosive braided-type interconnected channel deposits with the underlying Sequence 4 having been locally reworked down to the estuarine sand bars. These basal channel deposits are onlapped by a set of three imbricated fluvial bars and an associated floodplain complex (20 m thick). The top part of Sequence 5 consists of a 1-m-thick tidal siltstone reflecting a shallow transgression of the shoreline.

Kriging of Sequence 5 aimed at simulating four depositional environments grading from fluvial channels to fluvial bars with an associated floodplain, and passing up to an infra-inter tidal stage in the uppermost sequence. The fine-grained silty-sandstone of the floodplain forms the background, which reduces the number of environments to simulate (Table 7).
Table 7

Body dimensions in Sequence 5

| Environment          | Range Y (R1) | Range X (R2) | Range Z (R3) | Azimuth |
|----------------------|--------------|--------------|--------------|---------|
| Infra-inter tidal    | > 1,500 m    | 1,500 m      | 1 m          | N000°   |
| Fluvial channel      | > 1,500 m    | 1,500 m      | 4 m          | N040°   |
| Fluvial bar          | 600 m        | 400 m        | 10 m         | N350°   |

The erosive braided channel deposits marking the sequence boundary rework the underlying sequence down to the estuarine sand bars (Figure 6). This feature is well seen to the north of the study area. The model shows that this connection increases the reservoir’s volume. Moreover, the three imbricated bars are ‘connected’ to this basal porous unit, which enhances the reservoir’s capacity. The floodplain and tidal siltstone end the sequence and disconnect the lower connected reservoir volume from the overlying sandstone bodies.

Figure 6: The sequence is characterized by an extremely erosive base marked by braided-type deposits incising the underlying sequence down to the Tr80. Farther north, these deposits could be connected to lateral accretion bars embedded in the floodplain. The final reservoir volume of Sequence 5 is enhanced thanks to its erosive base into Sequence 4.

SEQUENCE 5 MODEL

Sequences 6, 7 and 8 (35, 40 and 30 m thick)

Sequences 6, 7 and 8 display a similar architecture with similar sedimentary body dimensions. The bases of the sequences span the deposition of proximal alluvial fan type deposits. The creation of available space then gave way to a retrogradation of the facies belt resulting in the deposition of a thick floodplain succession grading to tidal deposits in the uppermost part (sequences 6 and 7) with the development of tidal channels and an associated tidal flat.

Kriging used two depositional environment variograms with the floodplain (the third depositional environment, Table 8) forming the background. The three sequences were simulated separately because they do not have the same proportions.
There is no inter-connectivity between these three sequences and so the reservoir capacity relies on the intra-sequence connectivity (Figure 7) of the alluvial fan deposits, which consist of interconnected fluvial channels stacked into a thick widespread reservoir body. These channels in the Minjur Sandstone are of the braided type and known to generate broad sheets in an LST context (Miall, 2006). The thick overlying floodplain isolates the massive sandstone bars.

### Table 8

| Environment         | Range Y (R1) | Range X (R2) | Range Z (R3) | Azimuth |
|---------------------|--------------|--------------|--------------|---------|
| Fluvial channel     | 1,500 m      | 1,500 m      | 5 m          | N000°   |
| Tidal channel       | 1,500 m      | 800 m        | 2 m          | N130°   |

**Figure 7:** The flat sequence boundaries associated with coarse proximal deposits in the model illustrate a change of depositional conditions. The flat-shape is due to a large-scale deposition process partly linked to the progressive infill of the basin which allows lateral migration of the sedimentary systems.

**Sequence 9 (25 m thick)**

Sequence 9 consists only of stacked fluvial channels so that merely one facies has to be considered: fluvial channel. The lateral and vertical stack of the fluvial channels is the main parameter controlling the connectivity of the sequence. The deposits are considered to be braided-type channels deposited during a period of low available space. The reservoir’s volume is controlled only by the sedimentary style and the low available space.

**ESTIMATING RELATIVE LITHOFACIES PROPORTIONS**

The lithological property model aims at simulating the relative component proportions of the lithofacies within the Minjur Sandstone. Using the 3-D property grid built, each depositional environment was transformed into proportions of sand, shale, carbonate and gypsum/anhydrite. This method provides an excellent visualisation of the reservoir’s most porous unit and complements the facies gridding.

The Sandstone distribution model (Figure 8), using an 85% cut-off which means that only the deposits whose sand content exceed 85% are displayed, reveals the quality of the Upper Minjur reservoir. The obtained volume is called the P85. The interconnected stacked deposits of the Upper Minjur Member...
Characterisation of the Minjur Sandstone, Saudi Arabia

Figure 8: Distribution of the > 85% sandstone fraction in the Minjur Sandstone shows that the best reservoir horizons are concentrated mainly within the Upper Minjur Member.

give a high connectivity, whereas the Lower Minjur Member shows only diffuse and isolated sandy deposits. The model also reflects the depositional dynamics of the Minjur Sandstone with small-scale sea-level variations and a weak clastic influx in the lower part and a massive sediment supply combined with subsidence in the upper part. The total rock volume in which the sand content is equal to or greater than 85% is estimated at 52.2 Mm$^3$ (Table 9). It appears that the Upper Minjur Member concentrates 66% of the P85, which confirms its reservoir potential.

Table 9
Minjur Sandstone reservoir volumes containing > 85% sand fraction

| Minjur Sandstone P85 block | Upper Minjur volume of the P85 block | Lower Minjur volume of the P85 block |
|---------------------------|-----------------------------------|-----------------------------------|
| 52.2 Mm$^3$ (Million cubic metres) | 34.9 Mm$^3$ | 17.3 Mm$^3$ |
| 1.8 Bcf (Billion cubic feet) | 1.2 Bcf | 0.6 Bcf |

A ‘representative rock volume’ of 49.6 Mm$^3$ was selected within the Upper Minjur Member. It covers an area of roughly 600 m x 600 m with a thickness of 144 m, and its net-to-gross sandstone to shale ratio (NG) reaches 50.4%. Most of the fine-grained deposits are located in Sequence 5 where a thick floodplain succession was deposited (Figure 9); the floodplain occurrences in the overlying sequence are visible as dark pink-blue colours. Two pore volume estimations were realized on the > 85% sandstone content of the ‘representative rock volume’, which is approximately equivalent to that of the P85 block volume (Table 10):

- The bulk Pore Volume, which is the P85 Block volume corrected by a mean porosity of 17%. This estimation represents the pore volume, which can be filled 100% with CO$_2$ and is optimistic.
- The conservative Pore Volume 2%, which is the P85 block volume corrected by a mean porosity of 17% and a storage coefficient ($S_{st}$) of 2% (EU Geocapacity Report, 2009). The $S_{st}$ factor is a parameter accounting for the compressibility of rocks and fluids through an injection solicitation (overpressure). It is commonly used for the geological storage of CO$_2$ in clastic formations and accounts for ‘semi closed’ or ‘open aquifer’ boundary conditions.
Reservoir volume in the oil industry is often given in barrels, whilst in the CO₂ storage domain, one can represent this volume by its capacity, i.e. the mass of CO₂ (M\text{CO}_2) which can be injected into a given volume of aquifer. This is controlled by the following equation (Bachu et al., 2007):

\[
M_{\text{CO}_2} = A \times h \times NG \times \phi \times P_{\text{CO}_2} \times S_{\text{eff}}
\]

where

- \(A\) is the area of the reservoir,
- \(h\) its thickness,
- \(NG\) its net-to-gross,
- \(\phi\) its porosity,
- \(P_{\text{CO}_2}\) the density of the CO₂ (ca. 700 kg/m³ at 1,200 m depth), and
- \(S_{\text{eff}}\) the storage efficiency, a parameter accounting for the compressibility of rocks and fluids through an injection solicitation (overpressure).

The area of the P85 block volume is approximately 360,000 m², its thickness 144 m, and its NG 50.4%. For an assumed porosity of 17%, a gas density of 700 kg/m³ and a \(S_{\text{eff}}\) of 2%, equation 1 gives this block volume an estimated CO₂ storage capacity of 57,000 t. Upscaling to field scale (which here is roughly 20 km x 20 km x 144 m) in order to keep a control on the lateral facies variations, the inferred storage capacity reaches 55 Mt.

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**Table 10**

| Representative Rock Volume | 85% Block Volume | Bulk Pore Volume | Pore Volume Seff 2% |
|---------------------------|------------------|-----------------|---------------------|
| 49.6 Mm³                  | 25 Mm³           | 4.25 Mm³        | 0.085 Mm³           |
| 1.75 Bcf                  | 0.85 Bcf         | 0.1445 Bcf      | 0.00289 Bcf         |

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Figure 9: The P85 block from within the Upper Minjur Member. It shows a net-to-gross sandstone to shale ration (NG) of 50.4% and has a Pore Volume corrected with a 2% Seff of 0.085 Mm³ (0.00289 Bcf). The Seff factor is a parameter accounting for the compressibility of rocks and fluids through an injection solicitation (overpressure). It is commonly used for the geological storage of CO₂ in clastic formations and accounts for ‘semi closed’ or ‘open aquifer’ boundary conditions.
In the Riyadh area, the uppermost part (80 m thick) of the Minjur Sandstone is a producing aquifer for drinking water. Using the estimations made for the ‘representative rock volume’ of the Upper Minjur Member, the inferred CO₂ storage capacity in the Riyadh area for a reservoir of 20 km x 20 km x 80 m is 30.5 Mt.

One can favourably compare these figures with those of operating industrial projects. For example, Weyburn (Canada) has been injecting CO₂ since 2000 for enhancing oil recovery; 14 Mt had been injected by the end of 2009 and has helped to produce 14,000 more barrels a day. The Sleipner project in the North Sea, which aims to store the CO₂ produced during the extraction of methane in the Utsira Sandstone, contains slightly more than 15 Mt of CO₂.

The shale (Figure 10) and evaporite (Figure 11) distributions in the Minjur Sandstone confirm the coarsening-upward trend noted in the sandstone distribution model. These lithofacies components are predominant in the three lower sequences of the Minjur Sandstone and reflect the low sediment supply. The sedimentation was ‘passive’ with very few fluvial coastal channels draining the coastal plain and providing sediment for the development of tidal channels.

The carbonate distribution (Figure 12) highlights the maximum flooding of the Minjur Sandstone, which has been correlated with the Tr80. This event was responsible for a decreased connectivity between the Lower and Upper Minjur members because it isolated the LST deposits in the lower part of

![Figure 10](image-url)

**Figure 10:** Distribution of the > 50% shale fraction in the Minjur Sandstone shows an upward decrease as a result of the increasing sediment supply responsible for the coarsening-upward trend in the Minjur.

![Figure 11](image-url)

**Figure 11:** Distribution of the > 19% evaporite fraction (or alternatively 19-20% evaporite fraction, content never above 20%) in the Minjur Sandstone displays the sabkha facies (estimated 20% evaporite) which are concentrated mainly in the Lower Minjur Member and dominantly correlated with shale, although sandstone may also be present among the evaporitic facies.
Sequence 3 from the estuarine and tidal deposits in the upper part of Sequence 3. As described through the depositional environment model, a pathway between the estuarine deposits of Sequence 3 and the thick reservoir of Sequence 4 was initiated through erosive contacts. The MFS complex also blocks the connection between the thick Sequence 4 reservoir body and lower Sequence 3 reservoir bodies.

CONCLUSIONS

The present study is the second section of the Minjur Sandstone reservoir characterization. Modelling the formation provides a tool for reservoir prediction through analysis of the connectivity. Two geological models were constructed based on a sedimentological study (Issautier et al., 2012). The first aims at simulating the depositional environments, and the second at simulating the lithological proportions. This double modelling approach provides data on the spatial distribution of the heterogeneity through the depositional environment model and on the reservoir quality and volumes through the lithological model.

The main interest of this work is to develop, for carbon storage applications, a workflow that calculates the reservoir potential of a formation. It involves the whole chain from the field observations (lithology, sedimentology…), their integration in static models to their implication on the reservoir effective porous volume. Obviously, the finality of a geological model is to evaluate uncertainty and quality of a reservoir. In the Carbon Capture Storage context, a geological model should provide: (1) estimates on the storage capacity, and (2) computation grid in which flow simulations will be performed for a better analysis of the reservoir response to gas injection.

The choice of the Minjur Sandstone is a strategic decision. This formation, of Late Triassic age, can be taken as an outcrop analogue of target reservoirs of the same age in Western Europe. Moreover, it is one of the main fresh-water aquifers of Riyadh city. Therefore it can be considered as a key reservoir to study.

The first model, allows a quantitative analysis of the connectivity, defined as two or more reservoir bodies in contact through sedimentological or erosive processes. In this first stage, eleven depositional environments were simulated, grading from infratidal to proximal alluvial fan environments. The model reflects the rapid drift from one sedimentary environment to another. For example, Sequence 4 is composed of two reservoir bodies:

(a) The lower reservoir (20 m thick) is a porous unit of braided tidal channel and meander deposits. The tidal channels are connected to the braided-type deposits that are immediately overlain by lateral accretion bars.

(b) The upper reservoir consists of estuarine, tidal bodies (10 m thick) The erosive deposits of Sequence 4 initiated a connection with the estuarine and tidal deposits of Sequence 3 to form an extensive reservoir body (30 m thick).
Each sedimentary system has its own reservoir characteristics: the braided-type deposits are spread laterally over large distances, the meander deposits are compartmentalized by shale bodies, and the tidal channels are an interconnected system of sand ribbons. It is necessary to consider these rapid environmental variations to determine the connectivity of the reservoir bodies and their capacities and flow dynamics. Yet, at reservoir scale, the lateral variation of facies and sedimentary environment is larger than what can be captured using subsurface data. Consequently, this model stresses the importance of using outcrop analogues in subsurface studies. Analogues illustrate and quantify the depositional environments lateral variation and as a result the connectivity variations. Moreover, they allow a better representation of the reservoir’s architecture and yield to the development of a conceptual model, which can counterbalance the lack of subsurface data.

The lithological model illustrates the geodynamics of the Minjur Sandstone. Thresholds applied on proportions of the lithological constituents reflect clearly the depositional mechanisms and their main drivers:

- sandstone, shale, and evaporites (Upper Jilh Formation, Lower Minjur Member), controlled by sea-level changes,
- shale and carbonate at the maximum flooding interval,
- sandstone and conglomerates, forced by high classic influx related to the opening of the Neo-Tethys Ocean and hinterland uplift at the Triassic/Jurassic boundary.

The low sediment supply associated with small-scale sea-level variations in the lower member gives rise to a passive sedimentation. The rare reservoir bodies are isolated narrow sand ribbons deposited in a fluvial-dominated coastal plain and a tide-dominated intertidal zone. At the opposite, accumulation of thick connected bodies is made possible by strong sediment supply and platform flexuration.

The main purpose of this model is to quantify the ‘quality’ of the Upper Minjur Sandstone by estimating its storage capacity. As a first step, it gives indications of the bulk net-to-gross ratios. Subsequently the use of cut-off values enables a precise estimation of the porous volume; this shows that the Upper Minjur Member consists of widespread thick sandstone bars in which the sand content is about 95%. Using this figure, it was estimated within the modelled area, the storage capacity of the upper part of the Minjur Sandstone (57,000 t). This estimate illustrates the storage capacity of a small block (600 m x 600 m x 144 m). Assuming the properties of this block representative of a broader area, down dip of the outcrop, extended to an aquifer scale similar to the one of Riyadh’s area, the storage capacity would reach 30.1 Mt.

To conclude, the Minjur Sandstone is a thick formation incorporating many depositional environments with varied connectivity and reservoir qualities. The geological models show that the best reservoir units are systematically encountered in the lowermost parts of the sequences representing the LST, with the following transgressive systems tract (TST) being characterised by a well-developed shale unit that isolates the bodies; the Upper Minjur sequences may be connected through erosive relationships. The lithological model indicates the Upper Minjur Member as the best reservoir interval since it consists mainly of clean sand (95%) in thick and wide bars. The estimated storage capacity of the Upper Minjur Member, compared with other reservoirs shows the excellent potential of the Minjur Sandstone.

The next step is to use the information on the Minjur Sandstone to constrain conceptual models with a realistic architecture for estimating the impact of sedimentary heterogeneities and architectures on reservoir performance for the purpose of CO₂ storage.

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**ABOUT THE AUTHORS**

**Benoît Issautier** is a PhD. student at the French Geological survey (BRGM) in collaboration with the University of Provence and the Saudi Geological survey. He is working on the impact of heterogeneities on CO₂ geological storage and his research projects focus on the reservoir characterization of heterogeneous formation and the impact of depositional as well as stacking patterns on the pressure field and reservoir performances during gas injection at industrial scale. Benoît received his Master degree from the University of Nice-Sophia Antipolis in 2008 with a specialty in structural and reservoir geology.

b.issautier@brgm.fr
Yves-Michel Le Nindre has been contributing to Middle East geology since 1979 and has more than 10 years of experience in the geological mapping of the Phanerozoic rocks of Saudi Arabia. He received his Doctorate of Sciences from the University of Paris in 1987 with a dissertation on the sedimentation and geodynamics of Central Arabia from the Permian to the Cretaceous. Yves-Michel was involved in many research and consulting projects in France and abroad (Bolivia, Morocco, Tunisia, Kuwait, Iran, Oman, Saudi Arabia, Ethiopia, India), for sedimentary basin analysis and modelling, especially in hydrogeology, with the Bureau de Recherches Géologiques et Minières until 2000. Since then he has been involved in international projects for CO₂ storage, working with EU state members and CSLF countries (Canada, China, Russia). As a Sedimentologist, Yves-Michel works in France on present-day littoral integrated management. He is a member of the EAGE, ASF and, with BRGM, of the European Network of Excellence for CO₂ geological storage (CO₂GeoNet).

ym.lenindre@brgm.fr

Abdullah M.S. Memesh joined in 2006 the Saudi Geological Survey (SGS), Jeddah, as head of the Phanerozoic rocks mapping and Paleontology Division. He has more than 10 years of experience in the geological mapping of the Phanerozoic rocks. He received his BSc from King Abdul Aziz University, Jeddah, in 1993. From 1993–1999 Abdullah was a geologist with the French Geological Survey (BRGM). From 1999–2006, he was an exploration Geologist for the Saudi Arabian Mining Company (MA’ADEN) phosphate Project. He authored and co-authored 1:250,000-scale geologic maps.

memesh.am@sgs.org.sa

Saleh M. Dini is Head of the Phanerozoic rocks Mapping Unit at the Saudi Geological Survey (SGS), Jeddah. He has about 30 years of experience in the geology of the phosphate exploration, resource evaluation and geological mapping of Phanerozoic rocks particularly of northern Saudi Arabia. Saleh received his BSc from King Abdulaziz University, Jeddah, in 1980. From 1980–1986, Saleh joined Riofinex Limited. He was involved in the discovery of significant phosphate resources in Umm Wu’al area. From 1987–2000 Saleh was a staff geologist in the U.S. Geological Survey (USGS). Saleh has been involved in several research projects in the prefeasibility, resource assessment and feasibility studies of the Al Jalamid, Al Khabra and Umm Wu’al phosphate deposits in northwestern Saudi Arabia. Since 2001 Saleh has been a staff geologist in the Saudi Geological Survey (SGS). He authored and co-authored nine 1:250,000-scale published geologic maps and 14 written reports about Saudi phosphate deposits.

s-dini@hotmail.com

Sophie Viseur is a numerical geologist. She received her Ph.D. from the Nancy School of Geology in 2001. Her primary interests are in geostatistics for channel simulations and their application to hydrocarbon exploration and production. For recent years, she has worked in developing methods for the integration of outcrop data (Lidar) and geological concepts into 3-D carbonate architecture models. Sophie is currently working at GSRC Laboratory, University of Provence, France.

sophie.viseur@univ-provence.fr

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