GeoArabia, Vol. 1, No. 2, 1996
Gulf PetroLink, Bahrain

The Tórtola Fluvial System: An Analogue for the Upper Gharif of the Sultanate of Oman

Fernando P. Silva, António Costa e Silva
PARTEX-CPS
Allard W. Martinius and Koenraad J. Weber
Delft University of Technology

ABSTRACT

The late Oligocene to early Miocene Tórtola Fluvial System of the Loranca Basin, Central Iberian Peninsula is interpreted as an analogue outcrop of the upper member of the Gharif Formation in West Central Oman. The analysis of the depositional environment of the Tórtola and its controlling factors are used to understand the three-dimensional architecture of the Upper Gharif. The distribution of facies and sedimentological variability of the Tórtola is presented in terms of numerical data. Thickness variations from 3 to 16 meters, and average widths of approximately 300 meters, of the Gharif channel sandstones in fields located in West Central Oman, are similar to those of the Tórtola succession. A climatic-controlled model is described and used to explain and predict the occurrence, continuity and evolution of sandstone bodies, both laterally and longitudinally.

INTRODUCTION

The Early Permian Gharif Formation is an important siliciclastic oil reservoir in Oman (Guit, 1995). It consists of fluvial sediments deposited in a broad alluvial plain at the end of the glaciation of Gondwana (Late Carboniferous and Early Permian). Exploitation of this reservoir is difficult due to the rapid lateral variation of facies.

The Gharif is typical of fluvial reservoirs formed at large distances from the sea in intracratonic or foreland basins. These reservoirs are characterized by a low net-to-gross ratio (typically less than 0.4), labyrinthine architecture, poorly or non-connected sandstone bodies and compartmentalization at reservoir scale. This is an important reason for their low-recovery efficiency.

In general, well data from such reservoirs is sparse with respect to the scale of sedimentological variability to be modeled. This is the case for the Gharif reservoir where the data is limited to cores and logs and a limited outcrop region near the basin margin. This data is insufficient to describe its three-dimensional architecture. It is also inadequate to characterize the discrete sandstone bodies internally and to model the reservoir with confidence.

Studies of outcrop analogues are a valid method for resolving sedimentary and architectural uncertainties in strongly heterogeneous reservoirs. The analogue provides insights in the nature and scales of heterogeneities. It enables the construction of three-dimensional stochastic reservoir models and subsequent studies on connectivity and fluid-flow. Many parameters determining fluvial architecture can best be measured on reservoir analogue outcrops.

The use of empirical relationships and correlations derived from outcrop (width to thickness, width to length, etc.), although being complex, frequently results in reasonable estimates for reservoir uncertainties otherwise obtained from adequate well control (Dreyer et al., 1993). The outcrop data, however, must be adequately processed in the model. Also an understanding of the depositional setting, geological framework and sedimentary architecture of the deposits at different scales is required.

The Tertiary Tórtola Fluvial System (Diaz-Molina et al., 1989, 1995; Cuevas Gozalo and Martinius, 1993; Martinius, 1996) forms a suitable outcrop analogue for the upper member of the Gharif Formation. In this paper a detailed comparison between the Tórtola sediments and the Upper Gharif is presented.

TÓRTOLA FLUVIAL SYSTEM

Depositional Setting

The Tórtola Fluvial System developed in the Loranca Basin, a north-south elongated foreland basin (cf. Dickinson, 1974) on continental crust (cf. Bally and Snelson, 1980; Gomez et al., 1996). It originally was part of the intracratonic Tajo Basin, one of the large Tertiary basins of the Iberian Peninsula. The formation of the Loranca Basin in its present configuration was part of the last of three stages which characterizes the structural history of the Celtiberian Range (Alvaro et al., 1977; Arthoud and Matte, 1977; Vegas and Banda, 1982; Sopeña et al., 1988). Its development locally isolated the Loranca Basin from the geographically more important Tajo Basin. At the time of infilling of the basin by the described fluvial system, the tectonic forces responsible for its formation were decreasing in intensity and not powerful.

At the time of activity of the Tórtola Fluvial System, the Loranca Basin was located at a paleolatitude of 30° north of the equator (Smith et al., 1981). Variations of the precession, obliquity and eccentricity cycles of the earth are inferred to have affected the climate by changing the length of seasons and the contrast between summer and winter, and hence of for example rainfall intensity (cf. Berger, 1988; Mattews and Perlmutter, 1994). Mammal assemblages recovered in the study area are indicative of relatively humid and warm climatic conditions becoming increasingly more arid and cold to the top of the sequence. This was confirmed by Díaz-Molina et al. (1989) on the basis of sedimentological data analysis.

During the late Miocene, sea level was 360 km away (Daams et al., 1996), therefore the possible effects of sea level fluctuations moving inland have not affected the Tórtola Fluvial System to such an extent that they are reflected in the stratigraphic record. The presence of the basin margin frontal ramp (the Sierra de Altomira), which acted as a structural barrier or threshold, should have reinforced this relative isolation. No lakes which could significantly influence fluvial deposition were present in the Loranca Basin. Deposition was governed by the activity of two large fluvial systems, the Villalba de la Sierra system in the northern part and the Tórtola system in the southern part of the basin. In addition, minor depositional systems developed on the flanks of anticlinal folds present in the basin (Díaz-Molina et al., 1985, 1989). The Tórtola Fluvial System was about 94 km long, had a maximum lateral extension of 60 km and covered an area of 2,500 square kilometers. It is coalescent with sediments of the Villalba de la Sierra Fluvial System to the north. Local synsedimentary anticlines form part of its southern margin (Figure 1).

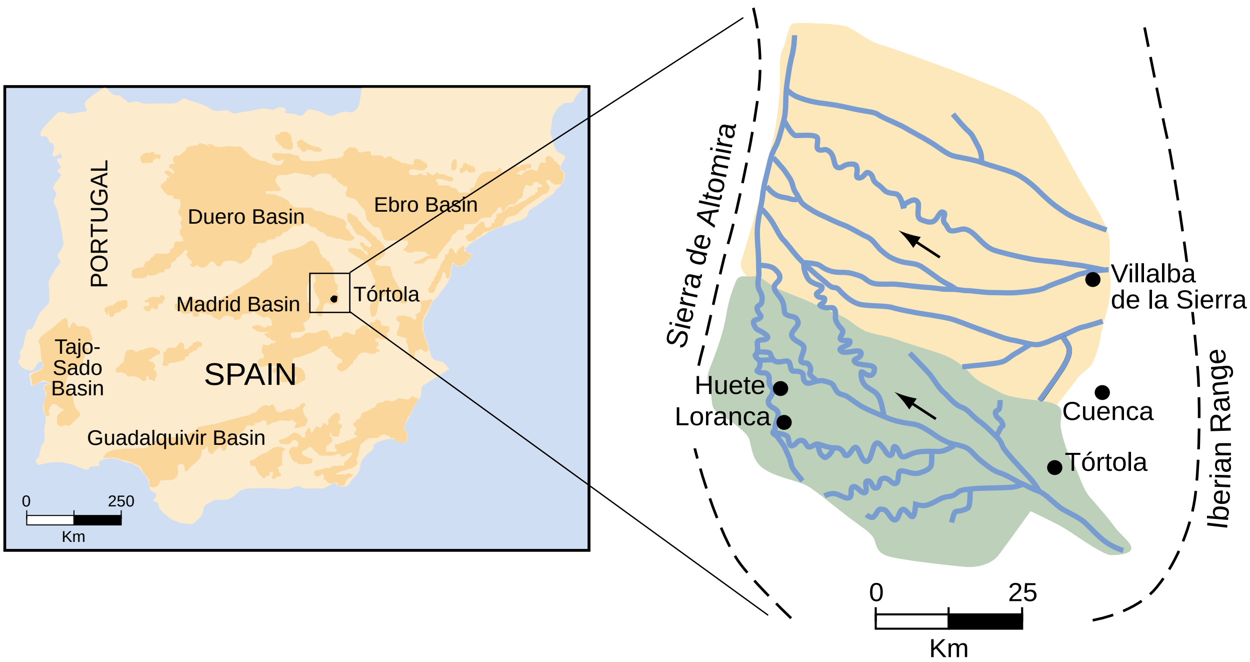

Figure 1: The Loranca Basin and its approximate location within the Tertiary Basins of the Iberian Peninsula (after Diaz-Molina et al., 1989). The Tórtola and Villalba de la Sierra Fluvial Systems are indicated in green and yellow, respectively. Paleoflow direction is indicated by the arrows. Dashed lines represent the outline of the Mesozoic basin.

The Tórtola Fluvial System was dominated by perennial streamflow processes. A general downstream evolution occurred from gravel-rich braided streams, via straight sand-rich stream to mixed-load dominated meandering rivers (Díaz-Molina et al., 1989). Daams et al. (1996) estimated that as much as 43% of the total time is stored in the development of pedogenic calcretes which are part of the distal succession. This implies a mean rate of sediment deposition of 18.7 cm / 1,000 year which suggests a large storage capacity for the basin. Destruction of primary porosity due to compaction was found to be minimal (Hartkamp et al., 1993; Díaz-Molina and Tortosa, 1995). The sands are extremely friable and early cementation of clasts is insignificant (less than 4%). These phenomena indicate a maximum depth of burial not in excess of 300 m (Díaz-Molina et al., 1995).

Depositional Environments, Lithofacies and Heterogeneities

The studied areas belong to what was considered to be the medial and distal zones of the Tórtola Fluvial System (Figure 2). The most proximal parts of the system, predominantly embracing mountain-fed streams, mainly with deposition of coarse-grained sand and gravels, are not described in detail. Down-gradient, streams of the medial area were predominantly straight sand-dominated streams with a braided thalweg pattern around large bedforms and significant discharge variations. The landscape of the distal area was dominated by meandering rivers with meander loops, abandoned meandering channels, small low-sinuous channels, crevasse splays, and flood plain deposits (Díaz-Molina et al., 1989; Martinius, 1996).

Generally, the alluvial deposits consist of two major groups of sediments: floodplain fines and channel-related sandstones and conglomerates (Martinius, 1996). Mudstone deposits of the Tórtola Fluvial System form approximately 70% and 82% of the total volume of the medial and distal area respectively (Figure 3) and are interpreted to have been formed by widespread overbank flooding of interchannel areas during high-discharge periods.

The sandstones occur as distinct, mostly non-connected, channelized or non-channelized, single and multi-storey or composite sandstone bodies embedded in mud- and siltstones. They are classified in seven genetic types based on morphology and lithofacies arrangements: five channelized (multi-storey conglomerate-rich bodies, stacked-bar bodies, giant-bar bodies, ribbon bodies and composite point-bar bodies) and two non-channelized (lobe and sheet bodies). The relative amounts of the various genetic types is shown in Figures 3, 4 and 5; morphological characteristics of the genetic types are summarized in Table I, II, and III.

Sandstone-body heterogeneities occur on five levels and have been classified in a bounding surface (BS) hierarchy following the classification of Miall (Miall, 1988). Figure 6 and Table IV shows the hierarchical grouping and classification of bounding surfaces.

Multi-storey Conglomerate-Rich Bodies

Multi-storey conglomerate-rich bodies occur in the proximal areas of the fluvial system. They have up to 8 storeys, a total thickness varying from 3 to 12 m, an overall tabular geometry, and generally abrupt grain-size changes. The bulk of the body is formed by a stacked sequence of conglomerate-rich storeys, which are overlain by one or several beds of pebbly through-shaped sets of cross-stratified sandstone.

Each storey consists of two parts with a total preserved thickness ranging from 40 to 140 cm. The lower part is formed by 10 to 90 cm thick clast-supported, lensoid conglomerate beds. These beds are poorly to moderately sorted with a maximum grain diameter of 6 cm. The base of the beds is erosive; matrix consists of very poorly sorted, very coarse to fine-grained sand. Infrequently, planar cross-stratification and clast imbrication are found. The upper part is formed by poorly sorted, coarse-grained cross-stratified pebbly sandstone, finning-up to medium sorted sandstone. Occasionally, patches of siltstone are preserved.

Stacked-Bar Sandstone Bodies

Stacked-bar sandstone bodies are found in the medial areas of the fluvial system. They are formed by two to five sequences, each formed by trough-shaped and tabular cross-stratified sandstone, and internally showing a consistent paleoflow direction. Each bar is bounded by a scouring basal surface. One sequence typically is characterized by poorly sorted, moderately to very arkosic sandstone, forming a series of tabular or trough-shaped cosets, dissected by multiple reactivation surfaces.

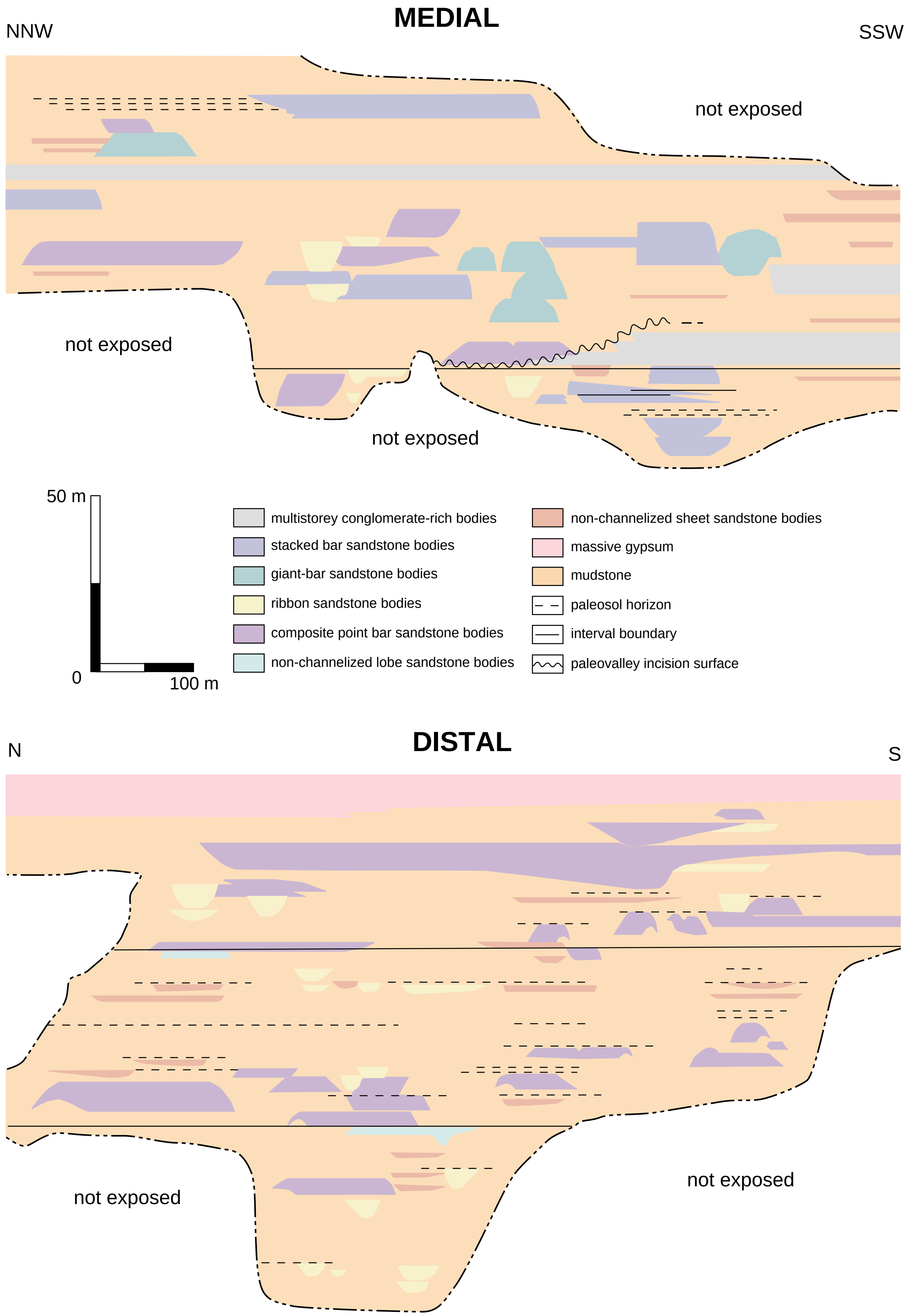

Figure 2: Cross-sectional panels of the fluvial succession of the medial (top) and distal (below) areas (Tórtola System) showing the spatial distribution of the genetic types. The total portion of sandstone in the sections is 29% (medial) and 17% (distal) (after Martinius, 1996).

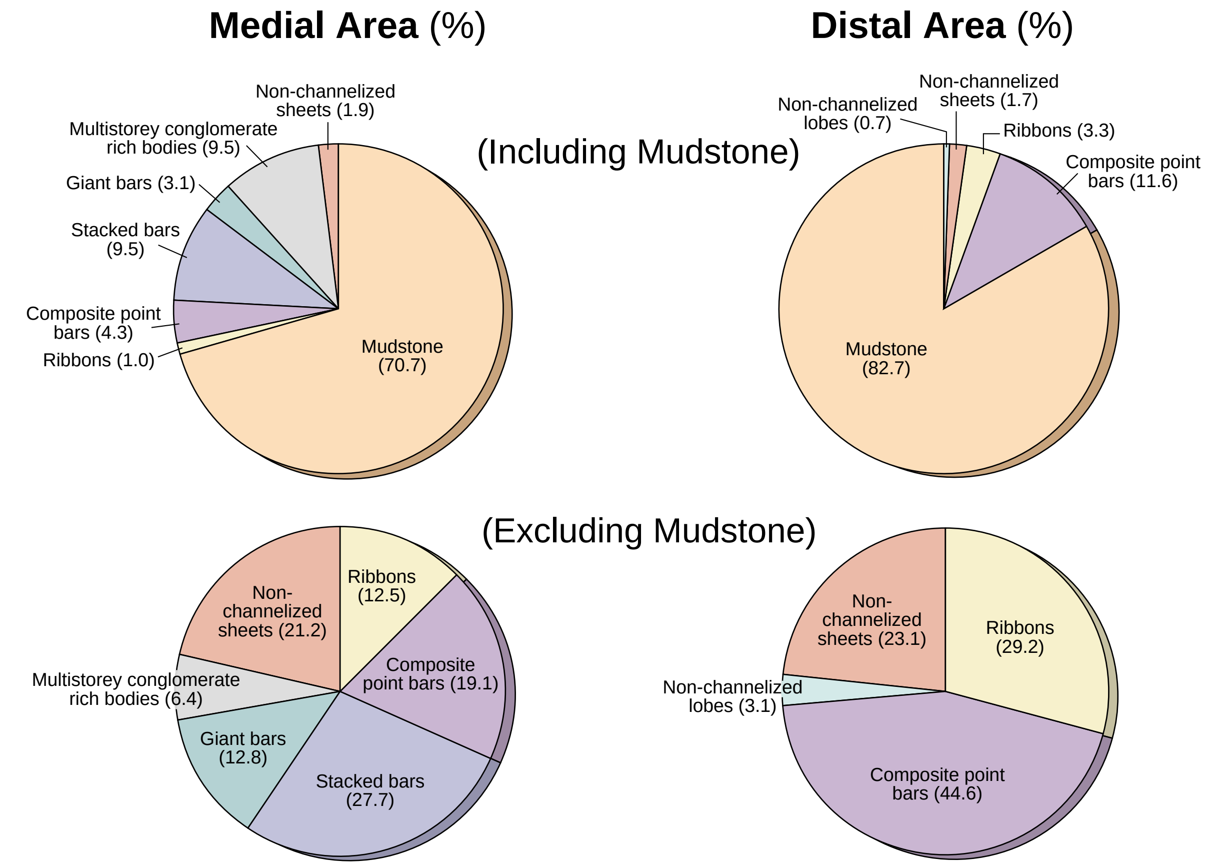

Figure 3: Relative ratios of the fine- and coarse-grained lithofacies and relative ratios of genetic sandbody types from the medial and distal areas of the Tórtola Fluvial System (after Martinius, 1996).

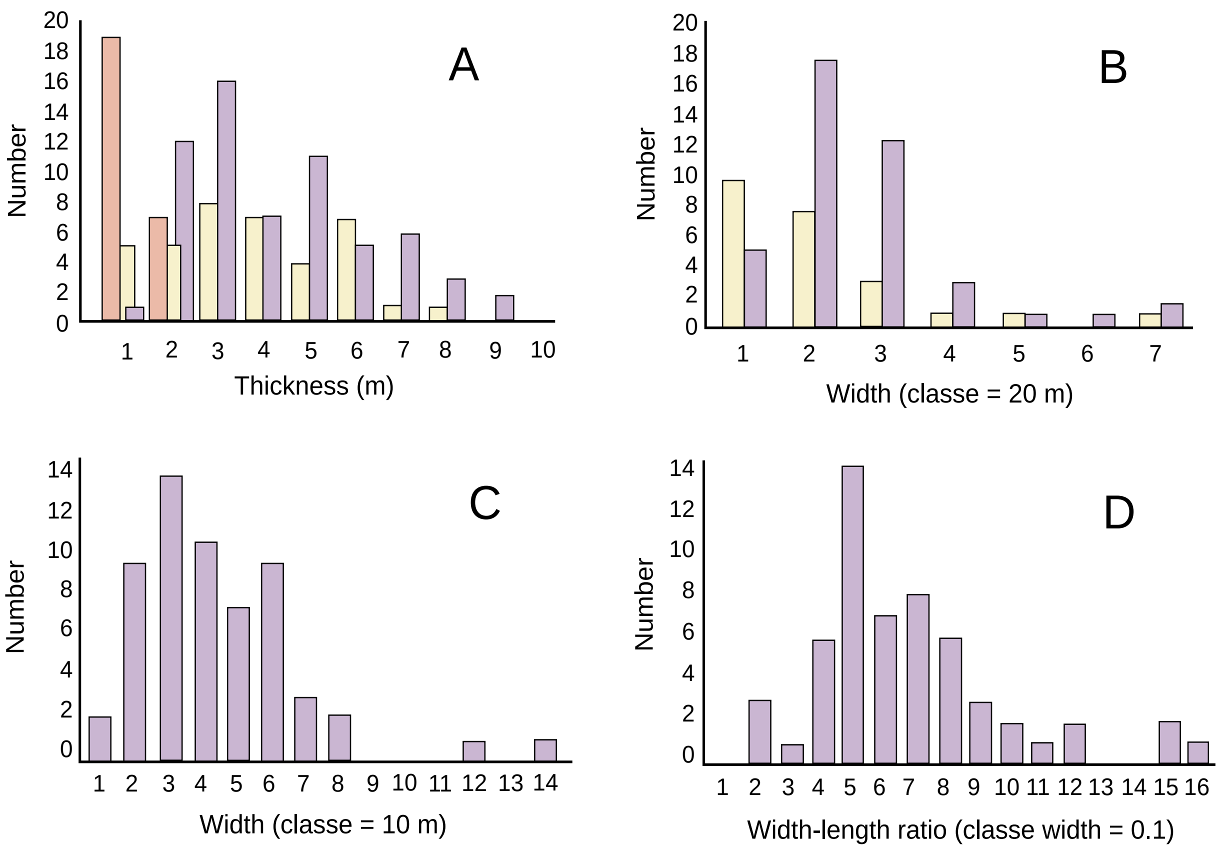

Figure 4: Histograms of sandstone-body morphological data (after Martinius, 1996). Refer to legend of Figure 2 for color code.

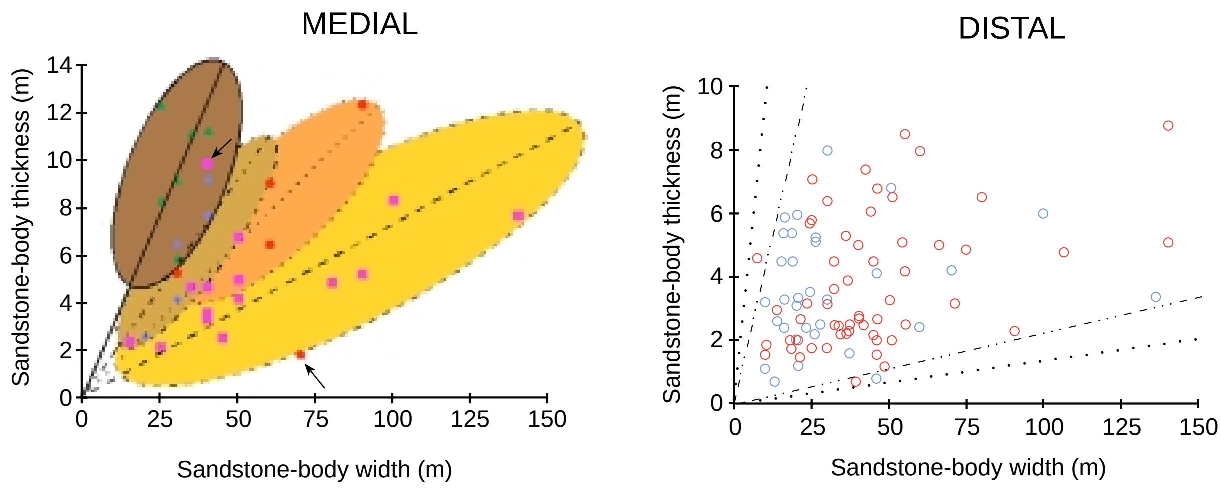

Figure 5: Scatterplot for width (W)/thickness (T) sandstone bodies of the medial area (left). W/T values of each genetic type fall within a distinct zone. Best-fit linear relations suggest that stacked-bar sandstone body width is 14.7 times body thickness, giant-bar sandstone body width is 2.8 times body thickness, ribbon sandstone body width is 5.4 times body thickness and sandstone body width is 7.8 times body thickness. Scatterplot of W/T of ribbon and composite point-bar sandstone bodies of the distal area (right). No relation is found (after Martinius, 1996).

Table I
Morphological Parameters of the Genetic Types for the Tórtola Fluvial System

<table>
<tr><th>Genetic Type</th><th>Medial Area</th><th>Distal Area</th></tr>
<tr><td>Conglomerate-rich multi-storey bodies</td><td>T = 3 - 12 m
L = -
W = 50 - 450 m</td><td></td></tr>
<tr><td>Stacked-bar sandstone bodies</td><td colspan="2">T = 2.1 - 9.8 m
L = -
W = 15 - 145 m</td></tr>
<tr><td>Giant-bar sandstone bodies</td><td colspan="2">T = 2.3 - 8.5 m
L = 35 - 60 m
W = 25 - 40 m</td></tr>
<tr><td>Ribbon sandstone bodies</td><td>T = 2.5 - 9.1 m
L = -
W = 20 - 40 m</td><td>T = 1.1 - 8.0 m
L = -
W = 10 - 100 m</td></tr>
<tr><td>Composite point-bar sandstone bodies</td><td>T = 1.7 - 12.3 m
L = 40 - 120 m
W = 20 - 40 m</td><td>T = 1.6 - 8.8 m
L = 14 - 280 m
W = 10 - 140 m</td></tr>
<tr><td>Non-channelized lobe sandstone bodies</td><td colspan="2">T = 1.5 - 3 m
L = 600 m (maximum)
W = 500 m (maximum)</td></tr>
<tr><td>Non-channelized sheet sandstone bodies</td><td>T = 0.2 - 3.6 m
L = -
W = 30 - 150 m</td><td>T = 0.25 - 2 m
L = -
W = 30 - 150 m</td></tr>
</table>

Note: T represents thickness, L represents length and W represents width.

Table II
Genetic Types, Medial Area
Tórtola Fluvial System

Genetic Type	No.	Minimum	Maximum	Mean	Standard Deviation
Conglomerate-rich multi-storey bodies	3	1,600 m^2	-	-	-
Stacked-bar standstone bodies	15	35 m^2	1,064 m^2	205 m^2	288 m^2
Giant-bar sandstone bodies	6	174 m^2	448 m^2	299 m^2	105 m^2
Ribbon sandstone bodies	5	50 m^2	364 m^2	207 m^2	128 m^2
Composite point-bar sandstone bodies	5	6,240 m^3	132,840 m^3	45,748 m^3	51,047 m^3

Table III
Genetic Types, Distal Area
Tórtola Fluvial System

Genetic Type	No.	Minimum	Maximum	Mean	St. Dev.
Ribbon standstone bodies	32	9 m^2	600 m^2	122 m^2	133 m^2
Composite point-bar sandstone bodies	55	224 m^3	73,267 m^3	14,473 m^3	15,698 m^3
Non-channelized lobe sandstone bodies	3	1,600 m^3	86,250 m^3	30,475 m^3	-

The thickness of tabular sets differs considerably ranging from 0.2 m to more than 1 m. Cosets of climbing ripples are found on top of tabular sets of cross-stratified sandstone. Grain size varies from very coarse sand at the base to medium sand at the top of a single coset. The variation in paleoflow directions between the stacked bars ranges up to 40 degrees. Zeroth- and first-order BS are typified by small grain-size differences on both sides of the BS. The scouring reactivation surfaces dissecting individual bars within the body are classified as third-order BS.

Giant-Bar Sandstone Bodies

Giant-bar sandstone bodies have a flat or slightly concave base, a convex top and a general coarsening-then fining-upward sequence. In almost all cases, the giant bar covers a ribbon-shaped channel-fill (maximum thickness 3.7 m) with a scoured base. The basal part is formed by large avalanching foresets. The top part by small, erosive sets of tabular cross-bedding. A coarsening-up then fining-up transition is observed from medium-grained sand at the base to coarse-grained sand at approximately four-fifth of the section, diminishing to medium-grained sand at the top. The giant bars (large 2-D subaqueous dunes cf. Ashley et al., 1990) occur in the medial parts of the Tórtola fluvial system.

Zeroth- and first-order BS are the most distinct heterogeneities present. They are characterized by small grain-size contrasts between two adjacent foreset laminae formed by grain avalanching. First-order BS are also found at the stoss-side of the bar where they form boundaries between the small tabular cross-stratified sets. Second-order BS are present between the large foreset avalanches and the sets of the upper part of the body. The margin of the body is a fourth-order BS.

Ribbon Sandstone Bodies

Ribbon sandstone bodies are characterized by a scoured, convex-down lower surface, a general fining-upward grain-size sequence and frequent internal erosional surfaces separating distinct scour fills. Grain size varies between pebbly sand and very-fine sand for the thicker channel-fills (up to 7.5 m) and between fine- and very-fine sand for the thinner ones (3 m or less). Trough-cross stratification is the most common

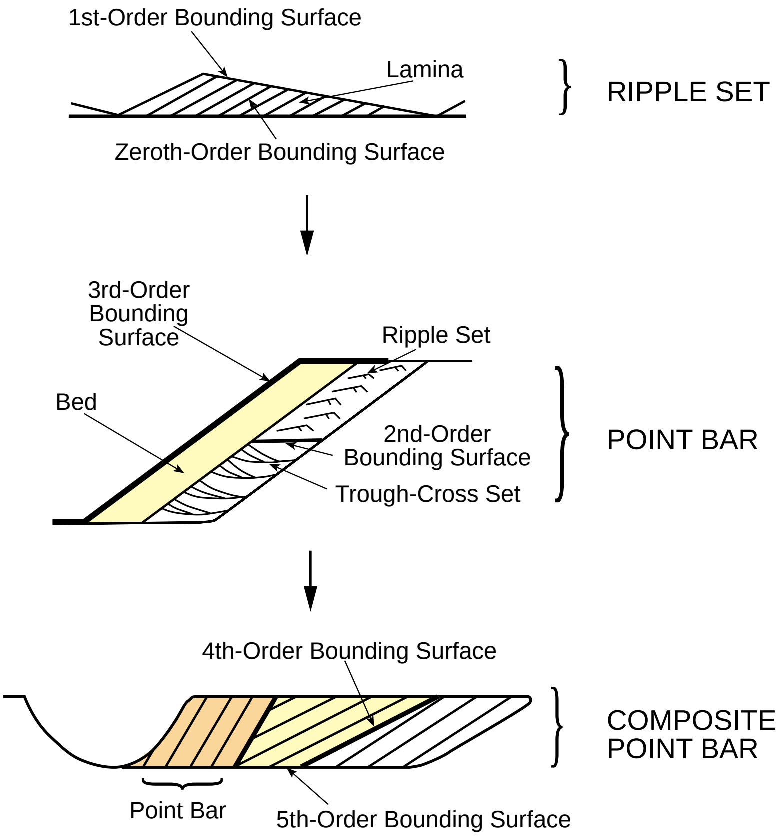

Figure 6: Hierarchical grouping of bounding surfaces and integration of descriptive terms for superimposed sedimentary structures in two-dimensional vertical sections (after Miall, 1988; Bridge, 1993).

Table IV
Classification of Bounding Surfaces (after Miall, 1988)

Order	Type of Bounding Surface
Zeroth-order	Surfaces separating lamina within a sedimentary set.
First-order	Boundaries between individual sets of sedimentary structures.
Second-order	Simple coset bounding structures.
Third-order	Surfaces between composite sets or beds.
Fourth-order	Surfaces separating successive laterally- or vertically-stacked bars.
Fifth-order	Margins of a stacked or composite bar body or the fill of a single channel.

structure. Relative occurrence within the sandstone body in terms of thickness ratio of trough-shaped cross-stratified sets and ripple-laminated sets is 9:1. The value of the width-thickness ratio (w/t) varies between 3 and 25. The upper bound of the w/t value is larger than that of Friend et al. (1979), in accordance with the findings of Alexander (1992) and Nadon (1994). The value of 25 is commonly referred to as the standard for ribbon sandstone bodies.

Completely preserved ribbon sandstone bodies indicate that the thicker the ribbon sandstone body is, the coarser the maximum grain-size and the larger the cross-bedded sets are. It is assumed that the thicker sequences were deposited in larger channels where greater water depth enhanced the formation of larger bedforms, and where higher flow velocities facilitated the transport of coarser grain-sizes. Variations in the size and facies of the channel deposits suggest the coexistence of paleochannels with different discharges.

The number of zeroth- and first-order BS is determined by laminae thickness and the size of the sedimentary structures. Foreset-laminae thickness varies between 0.1 and 1.5 cm. Bottomsets make up

10-30% of trough-cross-stratified sets. Trough-shaped cross-stratified sets and ripple-laminated sets are separated by second-order BS. Third-order BS represent repeated scouring episodes in the channel and can be as long as 30 m in transverse section. Fourth-order BS are absent.

Composite Point-Bar Sandstone Bodies

Composite point-bar sandstone bodies are characterized by an erosive lower surface, a general fining-upward grain-size sequence and the occurrence of lateral accretion surfaces (Díaz-Molina, 1993). They occur predominantly in more distal zones of the fluvial system. An ideal sequence through a composite point bar sandstone body consists from bottom to top of a lag deposit, trough- and tabular-shaped cross-stratified sets and ripple-laminated sandstone on top.

In the medial area, composite point bars have lateral accretion surfaces restricted to the upper one-third or even one-fifth of the body, are on average almost twice as thick, and have a more massive appearance. Lateral accretion surfaces are best visualized in the upper part of the composite point-bar deposits, either by grain-size contrast or by smooth erosive surfaces between inclined cosets of ripple cross-lamination. Changes in the dip direction of the lateral accretion units indicate reactivation surfaces which separate individual point bars (Díaz-Molina, 1993).

The aspects of zeroth- and first-order BS are similar to those of ribbon sandstone bodies. Average preserved size of trough-shaped, cross-stratified sets however is less than those of ribbon sandstone bodies. In longitudinal section, sets at the base are up to 1 m thick and 3 to 4 m wide; average length is approximately 120 cm (50 observations). Third-order BS are reactivation surfaces truncating cosets of trough cross- or ripple lamination in the basal part of the body. They are characterized by sand-sand contacts with similar grain-size and grain-composition below and above the surface. The upper part of composite point-bar sandstone bodies is dominated by large-scale heterogeneities formed by the third-order BS of the laterally-accreted beds. They are repetitive with a relatively regular spacing and consist of a change in grain size. Each lateral accretion unit shows a vertical decrease in average set size and a fining-up from medium sized sand to silt. The thickness of laterally accreted beds, which is equivalent to the spacing between third-order BS, is on average 60 cm. Fourth-order BS separate individual point bars.

Non-channelized Lobe Sandstone Bodies

Non-channelized lobe sandstone bodies form tabular to wedge-shaped bodies in transverse section with a sharp to gradational base. They show a general coarsening-up then fining-up sequence. Maximum body thickness is 3 m and maximum lateral extent 400 m. In transverse section, they are down-lapping and amalgamate in proximal direction. These bodies consist of several, medium- to fine-grained, stacked sandstone beds which are separated by thin (cm- to dm-scale) mudstone layers. Sedimentary structures found include thin sets of through-shaped, cross-stratified sets and more commonly (climbing-) ripple lamination. In all cases, the body is topped by a carbonate paleosol. Bioturbation both by animals and plants is common.

Third-order BS from the most dominant heterogeneity structure. They separate the discrete beds which form the sandstone body. Within these beds, zeroth- and first-order BS are found abundantly, typified by sand to sand contacts and short mean lengths. Second-order BS are found in the central portion of the body. They separate small trough-shaped, cross-stratified sets which fill the feeder channel and overlying ripple-laminated sets. Connectedness of discrete beds is low; bioturbation does not improve the connectivity.

Non-channelized Sheet Sandstone Bodies

Non-channelized sheet sandstone bodies have a relatively large lateral extent (30 to 150 m) and thickness between 0.25 to 2 m. They consist of ripple-laminated medium-grained sand to silt and are predominantly formed by sets of climbing ripples. Occasionally, small sets of cross-stratification are preserved at the base. Their upper part grades into the overlying finer sediments. Commonly, the basal surface is horizontal and gradational with the substratum. Laterally, they either grade into finer sediments or are connected with thicker channel sandstone bodies of which they form the lateral wings (cf. Friend et al., 1986). Poorly cemented carbonate paleosols are a common feature at the top. The characteristics of sheet sandstone bodies are for example similar to the single crevasse-splay sandstones described by Mjøs et al. (1993).

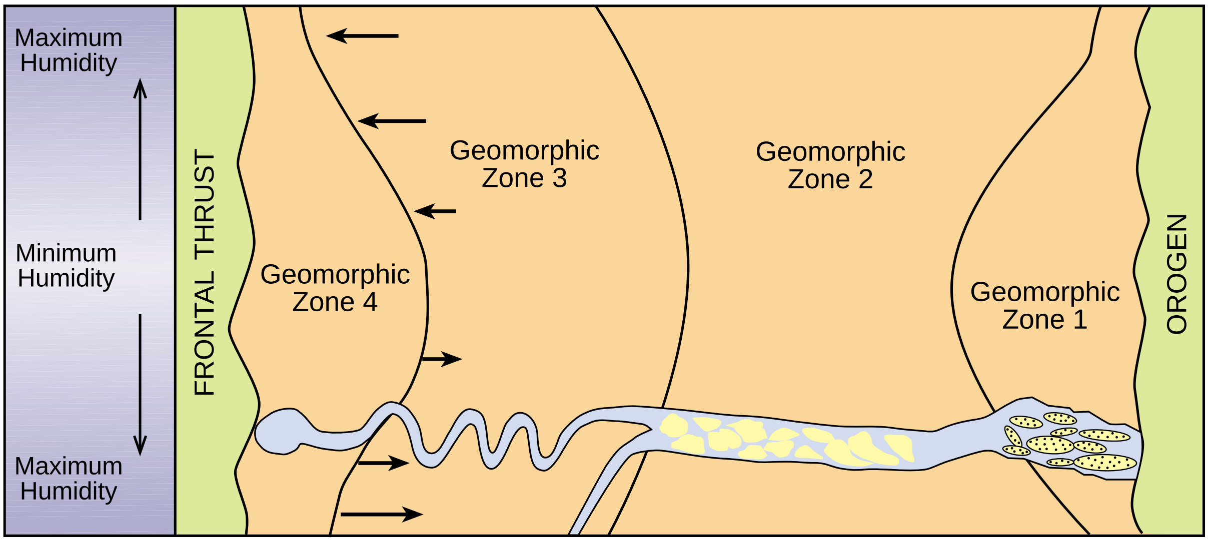

Figure 7: Two-dimensional schematic diagram illustrating the concept of decreasing and increasing activity of the Tórtola Fluvial System in time. Geomorphic zones and relations with changing paleoclimatic conditions indicated. Arrows indicate retrogradation (right pointing) or progradation (left pointing) of geomorphic zone.

Type A non-channelized single-phase sheet sandstone bodies are characterized by zeroth- and first-order BS. Type B sheet sandstone bodies are built-up of very fine sand or coarse silt and lack preserved sedimentary structures. They have a maximum thickness of 30 cm and a restricted lateral extend (30 to 80 m). Frequently they have a bluish colored top as the result of paleosol formation. In the medial area they are, for example, found as a series of stacked layers connected with the cutbank of large composite point-bar sandstone bodies. Type B lacks any type of BS. Both types however show a fining-up in grain size.

Depositional Model and 3-D Fluvial Architecture

Four facies association regions, termed geomorphic zones (Martinius, 1996), have been defined (Figure 7). This definition was based on: (a) the distinctive characteristics of the genetic types as described before; (b) the ensuing interpretation concerning the discharge and sediment yield characteristics of the environment of deposition; and (c) the location of occurrence of the genetic types with respect to the general configuration and average paleoflow direction of the Tórtola Fluvial System.

The Tórtola Fluvial System is a distributary system and the classification in downstream successive geomorphic zones is in accordance with the observation of Díaz-Molina et al. (1989) of downstream change of channel planform style along the stream profile of the system. It is envisaged that the four geomorphic zones were contemporaneous during activity of the Tórtola Fluvial System. The order of the geomorphic zones reflects the decreasing slope and energy conditions in down-stream direction along the distributary system.

Geomorphic zone 1 of the Tórtola Fluvial System was typified by deposition of gravels and sands in bedload-dominated braided streams. Geomorphic zone 2 was typified by straight sand-dominated streams in which large bedforms were present. These streams had a braided and occasionally high-sinuous thalweg pattern and were subject to significant discharge variations. This type of streams produced the stacked- and giant-bar sandstone bodies of the medial area of the Tórtola Fluvial System.

Geomorphic zone 3 was typified by channel belts of mixed-load dominated meandering rivers producing the composite point bars. In the floodplain areas at the toe of the fluvial system (geomorphic zone 4), small low-sinuous channels and lakes were found. Most of the smaller ribbons, the non-channelized lobes, and lacustrine / palustrine limestone beds are characteristic of this geomorphic zone.

Connectivity patterns are governed by a variety of factors, or geomorphic controls (Schumm, 1977). At the scale of the studied successions, one of the factors controlling connectivity is the variation in size and position of geomorphic zones. Since sandstone-body connectivity patterns are a characteristic attribute of a geomorphic zone, variations in position of a geomorphic zone cause stratigraphic differences in sandstone-body connectivity at a specific location in the fluvial system. The relevance of variations in position of geomorphic zones for the production of oil and/or gas becomes evident when decisions have to be made concerning the location of new exploration or infill wells in hydrocarbon fields of fluvial origin. From a sedimentological point of view, the choice for a particular location is primarily determined by optimum connectivity prospects of sandstone bodies. New production wells, therefore, may for example be drilled deviated depending on the recognition of existing connectivity patterns, that is recognition of variations in position of geomorphic zones. Therefore, the conceivable mechanisms of these variations have to be addressed when studying a fluvial reservoir.

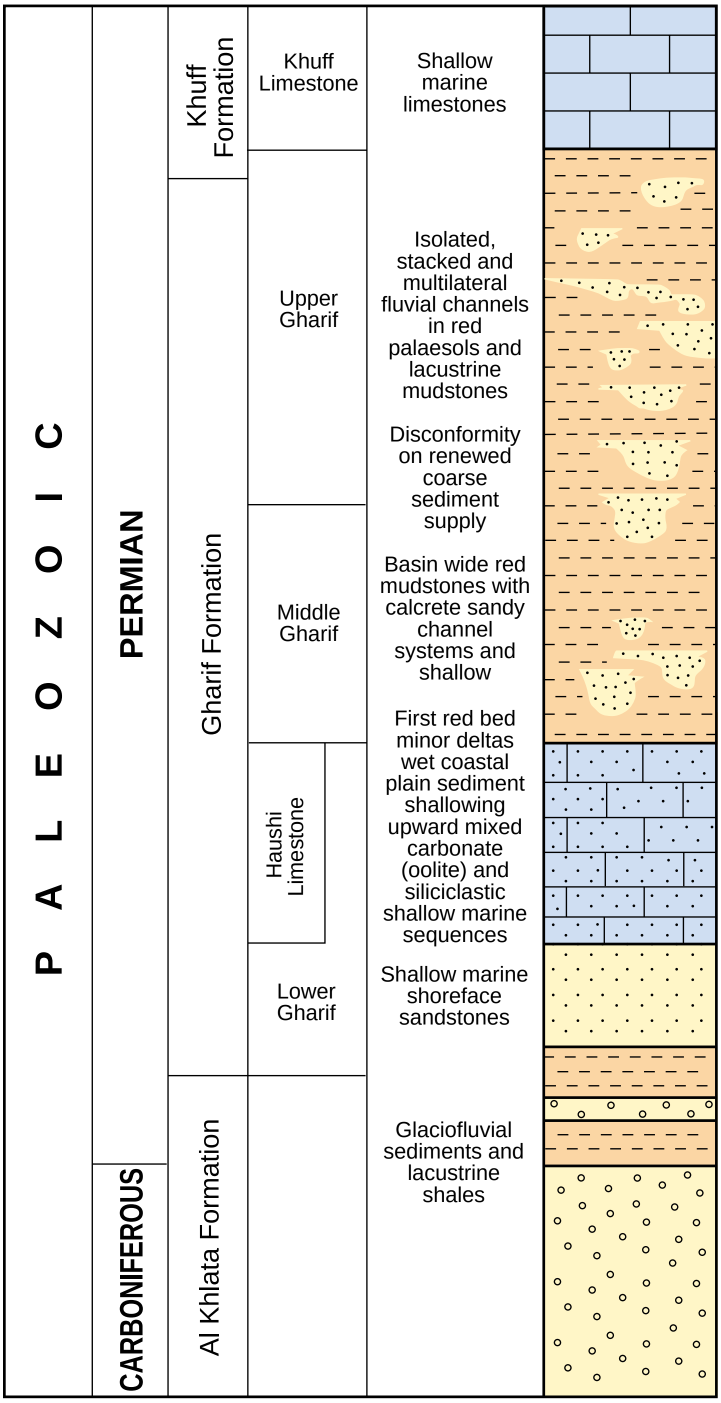

Figure 8: Simplified summary of the stratigraphy and sedimentology of the Gharif Formation in Oman (adapted from Mercadier and Livera, 1993).

THE GHARIF FORMATION OF CENTRAL AND SOUTHERN OMAN

The Gharif Formation, which consists mainly of fluvio-marine sediments, conformably overlies the glacio-lacustrine sediments of the early Permian Al Khlata Formation (Levell et al., 1988). Both formations constitute the Haushi Group which is overlain by the shallow marine carbonates of the Late Permian Khuff Formation, the main regional seal (Figure 8). The Gharif sandstones usually consist of laterally discontinuous, low net-to-gross, poorly interconnected alluvial channels, and are reservoirs in about 75 oil accumulations in central and southern Oman.

The thickness distribution of the Gharif Formation is remarkably constant over large areas which indicates that sedimentation took place over a vast mature depositional surface of low topographic relief, controlled largely by climatically induced sea level changes superimposed on an overall eustatic sea level rise caused by the global Gondwana deglaciation (Figures 9 and 10). Maximum distance from source area to base level was around 350 km and the general paleoflow was towards the northwest. Syn-depositional tectonic activity over the area was minimal but tectonic events, possibly related to the initiation of the Tethyan rifting phase, are known to have occurred in north and eastern Oman (Blendinger, 1990; Ries et al., 1990).

In the subsurface the Gharif Formation is subdivided in three units, the Lower, the Middle and the Upper Gharif. The Lower Gharif consists of a basal unit of cross-bedded quartz sandstones that locally contain crinoid debris and brachiopods. Upwards more marine influences became apparent and a mixed carbonate and siliciclastic shallow marine sequence occur. The Lower Gharif shows the largest lateral facies variation. The contact with the underlying Al Khlata Formation is usually gradational. Above the contact the sequence shows a wide variety of facies going from sandy braidplain channels interbedded with lacustrine and overbank mudstones in the eastern area to lower coastal plain and shallow marine sandstones and mudstones to the north.

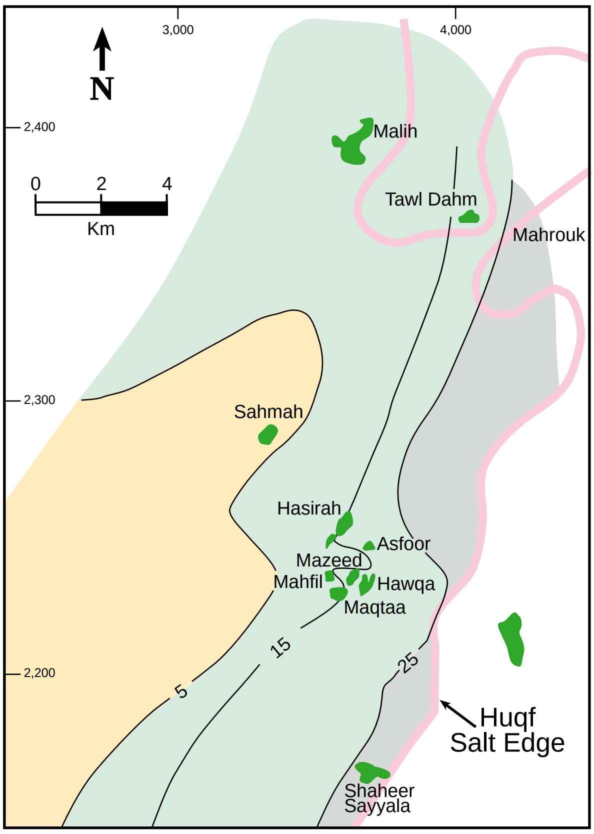

Figure 9: Upper Gharif net sandstone thickness (m) distribution (adapted from Guit et al., 1994).

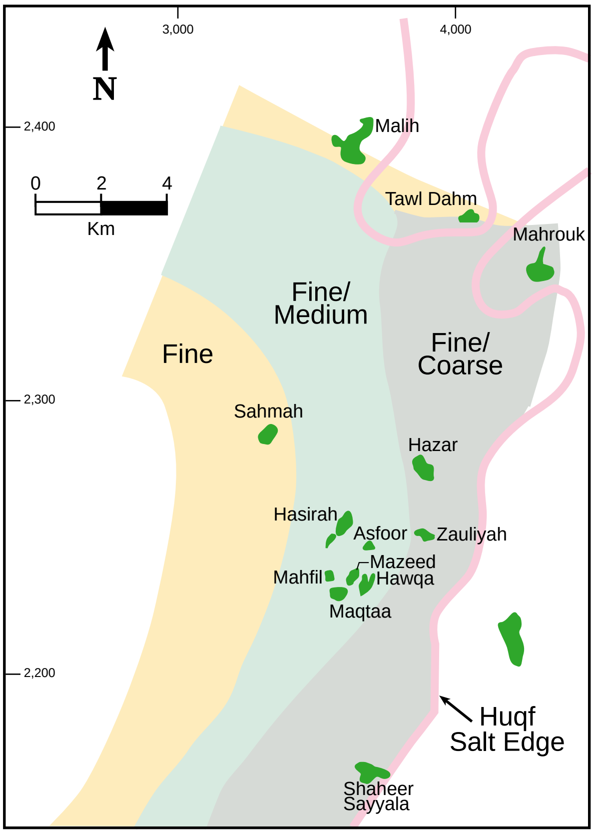

Figure 10: Upper Gharif dominant grain-size distribution (adapted from Guit et al., 1994).

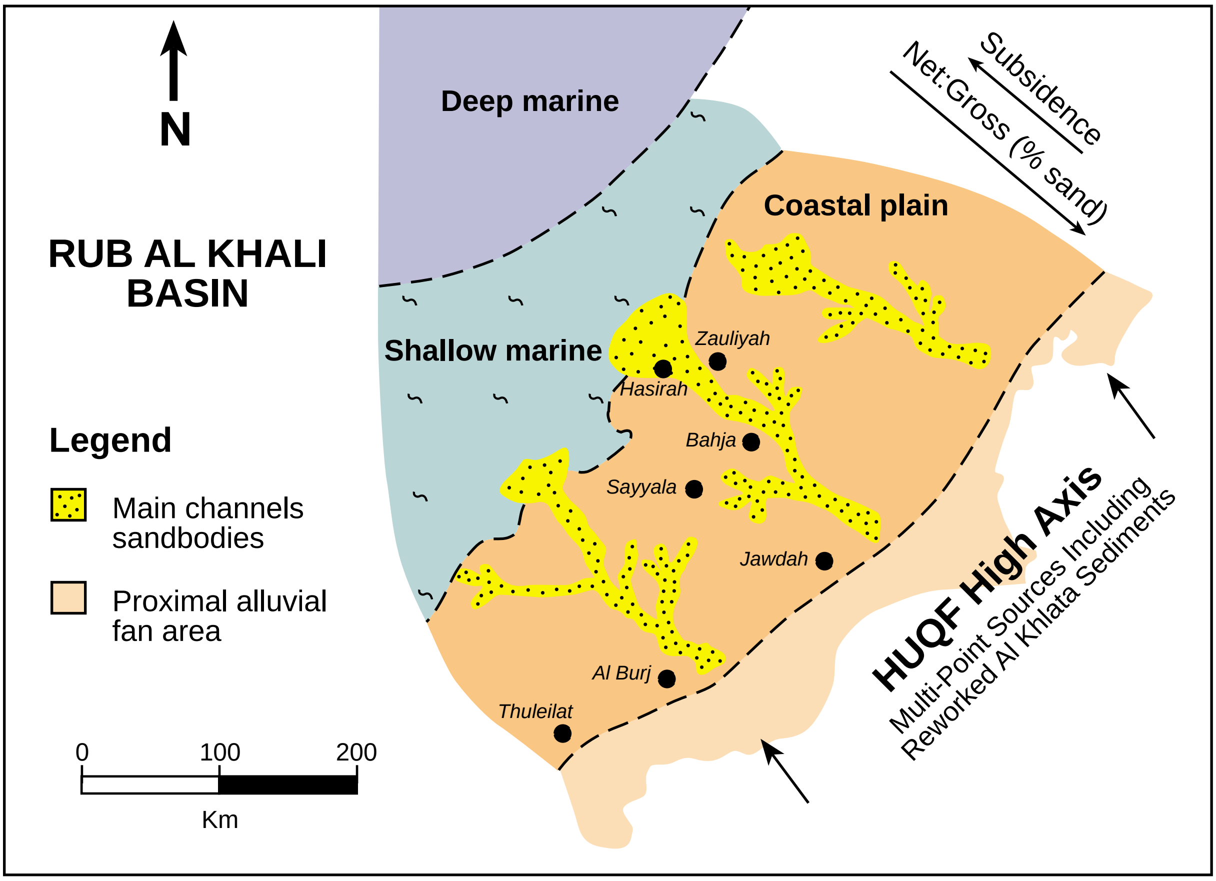

Figure 11: Paleogeographic map of the eastern Arabian Peninsula during the Middle Permian - Top Haushi period (adapted from Mercadier and Livera, 1993).

The fluvial sediments were deposited on a broad alluvial plain as rivers, shed from peripheral highs, flowing north-westwards towards the center of the Arabian Peninsula (Figure 11). The Gharif sandstones are predominantly sub-feldspatic to quartz arenites and included material reworked from the underlying Al Khlata Formation (Mercadier and Livera, 1993). Sandy packages within the Gharif, being composed of stacked sand, silt and claystone successions, rarely exceed 30 m. Individual sandstones, generally reach a thickness of less than 10 m, mostly less than 5 m. Exceptions are the incised valley fills at the Middle to Upper Gharif boundary and some stacked fluvial sandstone packages within the Upper Gharif (Guit et al., 1994).

The Middle and Upper Gharif are two sequences of alluvial plain deposits separated by an areally extensive claystone unit thought to represent an episode of increased aridity. The Middle Gharif consists of trough cross-bedded quartz-feldspar sandstone bodies interbedded with red-brown shales and siltstones of fluvial origin. As whole the Middle Gharif represents a fining-upward alluvial sequence, reflecting a basin-wide decrease of coarse clastic supply, probably related to a change in climate.

The Upper Gharif shows more abundant cross-bedded channel sandstones interbedded with varicoloured shales deposited in an alluvial environment. It marks an episode of re-establishment of the fluvial activity. Incised valley fills at the base of the Upper Gharif are locally a major contributor to production. The remainder of the Upper Gharif has up to four reservoir / seal pairs. Best reservoirs occur in the east, close to the source area, where high net-to-gross ratios are frequent. Further west, distally from sediment source, individual fluvial sandstone are usually thin, of limited lateral extent and poorly connected (Guit et al., 1994), which allows to classify the overall internal architecture of the reservoirs in that area as being of the labyrinthine type.

Labyrinthine architecture (Weber and van Geuns, 1986) is typified by the occurrence of mostly isolated sandstones bodies which have a seemingly erratic spatial distribution. This significantly hampers the production of hydrocarbons from this type of reservoirs and highlights the need to address the influence of sedimentary structures on fluid flow performance as well as the size and spatial distribution of discrete sandstone bodies. Given the frequent insufficiency of the available well data to confidently characterize these highly heterogeneous reservoirs, outcrop studies in reservoir-analogue settings can supply qualitative information and quantitative data sets, important as input data for reservoir modeling.

COMPARISONS: TÓRTOLA FLUVIAL DEPOSITS AND THE UPPER GHARIF MEMBER

The deposits of the Upper Gharif Member show the characteristics of an avulsive channel system similar to the Tórtola Fluvial System. Individual channels from avulsive systems (cf. Richards et al., 1993) can be meandering or braided within slightly meandering banks but the major long-term characteristic of the rivers is that they are avulsion-dominated. Co-occurrence of rivers with different channel pattern reflecting different channel-floodplain relationship is characteristic of avulsive systems, which are also dominated by mudstone.

During the deposition of the Upper Gharif Member in West Central Oman, periods typified by widespread deposition of fines in floodplain areas were succeeded by periods typified by fluvial activity in wide channel belts exhibiting the effects of recurrently changing paleoclimatic conditions from relatively less humid to relatively humid conditions. Laterally extensive mudstone deposits, with occasionally straight-channel sandstones, are inferred to have been formed during relatively dry periods.

The transition to increased channel activity was preceded by significant floodplain incision which resulted in the formation of paleovalleys. Entrenchment of an alluvial plain by channel incision and displacement of the intersection point of a channel to a more distal location is characteristic of relatively less-humid climatic periods (Schumm, 1977; Dun et all., 1987; Wright, 1992). The filling of an incised valley by vertical aggradation, however, is indicative of a significant increase in sediment supply, associated with a change to more humid conditions (Schumm and Ethridge, 1994). The humid optimum is inferred to have been typified by the occurrence of the channel belts which were probably formed by sand-dominated braided trunk channels and by plains-fed meandering channels reworking the alluvial plain (cf. Sinha and Friend, 1994).

Thickness of channel sandstones in fields located in West Central Oman (from 3 m up to 16 m) are similar to those of the Tórtola succession. Similarly, the average width of the Gharif channel belts obtained from horizontal wells intersecting sandstone rich intervals (~ 300 m) resemble to a large extent the Tórtola successions. Furthermore, both paleoenvironmental conditions as well as the sedimentological and architectural characteristics of the Upper Gharif Member are analogous to the ones found during the deposition of the Tórtola system. The successive units in both cases exhibit the effects of recurrently changing paleoclimatic conditions, from less humid to relatively more humid conditions.

CONCLUSION

The deposits of the Tórtola Fluvial System are a suitable outcrop analogue for the upper member of the Gharif Formation in West Central Oman. The analysis of the paleoenvironment of deposition of the Tórtola System and controlling factors are used to analyze and characterize the three-dimensional architecture of the Upper Gharif Member. Use of a climatic-controlled depositional model for long-term development of the fluvial system enhances the current understanding of the occurrences and continuity of sandstone bodies while simultaneously providing means for predicting lateral and longitudinal correlations.

The Gharif Formation is part of a regional sequence of siliciclastic deposits that includes shallow marine to red beds alluvial sediments deposited prior to Late Permian carbonate platform development (Al-Laboun, 1988). Therefore the application of the model may have wider significance. However, more detailed stratigraphic correlation are required to evaluate this possiblity.

ACKNOWLEDGEMENTS

The authors would like to thank Fer Guit, Simon Budd and Paula Wigley, from Petroleum Development Oman and two anonymous reviewers for their helpful comments, suggestions and thoughtful review of a draft version of the manuscript. The authors are also thankful to Gulf PetroLink for its assistance in redrafting the figures.

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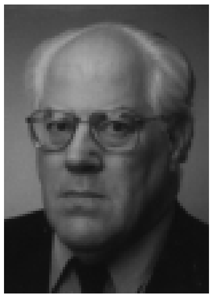
ABOUT THE AUTHORS

Fernando P.T. Silva *graduated in Geology from Lisbon University in 1990. Since then he has been working with PARTEX-CPS as a Reservoir Geologist in several projects in the Middle East and Africa. Parallel to this activity, he also participated in a number of research and development projects related with the application of fractal geometry to the characterization and modeling of naturally fractured reservoirs. Fernando is currently a member of the Portuguese Geologists Association.*

António Costa Silva *obtained his MSc in Petroleum Engineering in 1984 from Imperial College and a PhD in 1993, from the Technical University of Lisbon with a work on mathematical modeling of oil reservoirs. He joined PARTEX-CPS in 1984 and has conducted reservoir studies for several fields in the Middle East and Africa. António also developed a number of research and development projects related to the application of mathematical models for improving the estimation of reservoir properties. He is a member of the Imperial College of Science and Technology, Portuguese Order of Engineers and SPE. He has published about 20 papers on reservoir characterization and modeling.*

Allard W. Martinius *received his MSc in Geology from the University of Utrecht. In 1995, he obtained a PhD in Geology from the University of Technology at Delft, The Netherlands. Allard's PhD research focused on the sedimentology characterization of labyrinthine fluvial sediments as a tool for reservoir modeling. He has published papers on topics related to reservoir characterization, fluvial and shallow-marine sedimentology and paleoecology of marine macro invertebrates.*



Koenraad J. Weber *graduated in 1960 from Delft University of Technology with a MSc in Mining and Petroleum Engineering. He retired in 1993 as Senior Consultant Reservoir Geology from Shell International Petroleum Maatschappij having worked 33 years in Shell research operations in many countries. Since 1985 Koenraad was Professor in Production Geology at the Delft University of Technology and in 1993 he was nominated Associate Professor at the Ecole National Supérieure du Pétrole et des Moteurs. He was a distinguished lecturer for the SPE in 1980 and the AAPG in 1993 and in the same year he received the Distinguished Achievement Award from the AAPG. He is an Honorary Member of the Nigerian Association of Petroleum Explorationists and has published some 40 papers on reservoir characterization topics.*

Paper presented at the 2nd Middle East Geosciences Conference and Exhibition, GEO'96, Bahrain, 15-17 April, 1996

Manuscript Received 18 March, 1996

Revised 5 June, 1996

Accepted 10 June, 1996