Modelling the sedimentary geometry of hydrocarbon reservoirs currently represents one of the most important challenges for the oil industry. Predictions are required for the external and internal geometry of the reservoirs, as well as of the distribution of porosity, permeability, fluid-flow barriers and pay intervals. Such predictions are especially critical for reservoir deposits in environments where the distribution and continuity of the sand bodies can be highly complex (e.g. Barwis et al. 1990). This is the case in meandering stream systems, which form excellent reservoirs but frequently have puzzling three-dimensional distributions of the different parameters. Study of the wealth of information provided by good surface outcrops can assist in understanding subsurface reservoirs. In this article we describe the geology of such an example, the Tertiary meander belts exposed in the Loranca Basin, central Spain.

GEOLOGICAL SETTING

The Loranca Basin (Fig. 1) contains thick Cenozoic continental deposits. The studied meander belt sediments are included in the 'Upper Unit', composed of the Törtola and Villalba de la Sierra coalescent depositional systems (Fig. 1), of Late Oligocene to Early Miocene age (Díaz-Molina et al. 1989). The fluvial fan systems were formed during tectonic deformation, with progressive unconformities on the flanks of growing anticlinal folds. At the top of the Upper Unit, in Early Miocene times, gypsum deposits covered most of the basin.

Based on surface, seismic and drill hole data, the area is known to contain a north-trending, thin-skin thrust belt vergent to the west; Mesozoic and a part of the Tertiary strata are deformed. Regional seismic lines show that Mesozoic and Tertiary strata are detached from Palaeozoic basement and Permo-Triassic tegument at the level of Triassic salt (Keuper). Folding and salt migration into the cores of the anticlinal structures generated primary synclines as well as secondary rim synclines in some areas. These structures, coupled with faulting, controlled the distribution of facies (i.e. fluvial palaeocurrents) as well as the location of depocentres.

Meander belt sediments were studied on the east flank of the Huete ramping anticline, north of the Huete village. For reservoir characterization, a 640 m long by 130 m thick cross-section was studied in detail (Fig. 2). Lithologies include sandstones, mudstones, limestones, gypsiferous silts and gypsum. Two thin, continuous, limestone layers are present. The upper one divides the cross section into two portions. The upper portion is characterized by the presence of gypsum as crystals in mudstone or as cement in sandstones, whilst in the lower portion gypsum is virtually absent.

The studied section has been buried beneath only 200 m of sediments; the overburden was low enough so that sandbody geometries are generally well preserved. Correction of differential compaction between silty clays and sandstones allowed the restoration of syn-sedimentary fluvial architecture.

DEPOSITIONAL ENVIRONMENTS

Floodplain elements

The landscape was often dominated by meandering rivers, with meander loops, abandoned meandering channels, channel-fills, crevasse splays, levees and flood basin deposits. Abandoned meandering channels are filled with a wide variety
developed at the top of abandoned channels and over marginal bodies. Reactivation surfaces separate adjacent point bars as have been interpreted as playa-lake sediments as they contain reservoir sands and form in isolated or connected point bar the most important permeability barriers within a reservoir gypsum crystals (Diaz-Molina basis of their triangular geometry in cross section and/or their channels, probably associated with crevassing. Overbank system. In the upper part of the cross-section the silty clays subordinate lacustrine marls and/or limestones, that represent that may show an erosional base. Levees are recognized on the Channel-fill deposits include sandy fillings in non-meandering most flood basin deposits consist of massive silty clays with channel trends. The methodology followed for the recon­struction of meander belts is explained in Fig. 3. Meander loop portions were identified by facies analysis, assisted by comparison with available geometrical models (Diaz-Molina 1993). Using this, and applying sedimentological concepts, the wave lengths, radii of curvature and amplitude of the meanders were reconstructed on enlarged aerial photographs (scale 1:2140). When enough data were available, the positions of buried or eroded meander loops were predicted. Fitting the sandstone exposures into 18 reconstructed meander belts helped to determine palaeo­channel trends. The methodology followed for the recon­struction of meander loops is explained in Fig. 4. In some of the reconstructed examples measures of meander wave length were obtained, ranging between 195 m and 385 m. The mapping identified 43 meander loops. Using their stratigraphic position and thickness, a three-dimensional reconstruction was made showing the depositional archi­tecture of superimposed meander belts. The geometric forms for each meander loop were idealized, the plan contour of each body was approximated to a polygon and the thickness was supposed constant. Meander loops can be modelled as right prisms with parallel bases, whose volumes are greater than those of the original sandstone bodies. The coordinates of the prisms were compiled in a file of geometrical data which was processed in a CAD computer program allowing 3D views of the potential reservoir sand­bodies (Fig. 5) and the geometrical inspection of the 3D architecture. Sandstones represent less than 17% of total volume. The overlap areas constitute only 15% of the prism basal surfaces.

They are internal unconformities shown by erosion and changes in grain size. They formed by adjustment of the channel shape once the critical curvature threshold was reached (Diaz-Molina 1993). Identification of the reactivation surfaces is indispensable for reconstruction of meander loops and palaeochannel trends. Meander loop width and depth depend on palaeochannel size. The lateral extent of the meander loops was also controlled by meander amplitude and the lateral juxtaposi­tion of point bar bodies. In the studied cross-section (Fig. 2), meander loop width ranges between 495 m and 12.5 m, and their thickness varies between 3.25 m and 9.15 m.

**Point bar facies**

The term point bar is used here to indicate a composite bar formed by a set of conformable lateral accretion units (Diaz-Molina et al. 1989), which correspond with a group of parallel scroll bars in a plan view. Two types of point bar sequences are found in the exposures. The less frequent was generated by helicoidal flow, originating vertical changes in sediment grain size and lateral accretion surfaces. Ripple cross-stratification is the dominant sedimentary structure in 90% of all point bars. Ripples composed ridge bed forms, showing concave or planar erosional surfaces. Ripple structures that migrated upstream or up and down the point bar topography indicate that flow conditions were not helicoidal (Nanson 1980). Spiral vortices could explain the opposing flow directions and could have produced the concave erosional troughs observed inside these deposits (Fig. 3 A and B). Troughs between ridge crests may present lag deposits, consisting of intrabasinal clasts. Composite bars delimited by flat surfaces (Fig. 3 C) would correspond to sections parallel to flow vortices.

**THREE-DIMENSIONAL ARCHITECTURE**

Meander loop portions were identified by facies analysis, assisted by comparison with available geometrical models (Diaz-Molina 1993). Using this, and applying sedimentological concepts, the wave lengths, radii of curvature and amplitude of the meanders were reconstructed on enlarged aerial photographs (scale 1:2140). When enough data were available, the positions of buried or eroded meander loops were predicted. Fitting the sandstone exposures into 18 reconstructed meander belts helped to determine palaeo­channel trends. The methodology followed for the recon­struction of meander belts is explained in Fig. 4. In some of the reconstructed examples measures of meander wave length were obtained, ranging between 195 m and 385 m. The mapping identified 43 meander loops. Using their stratigraphic position and thickness, a three-dimensional reconstruction was made showing the depositional archi­tecture of superimposed meander belts. The geometric forms for each meander loop were idealized, the plan contour of each body was approximated to a polygon and the thickness was supposed constant. Meander loops can be modelled as right prisms with parallel bases, whose volumes are greater than those of the original sandstone bodies. The coordinates of the prisms were compiled in a file of geometrical data which was processed in a CAD computer program allowing 3D views of the potential reservoir sand­bodies (Fig. 5) and the geometrical inspection of the 3D architecture. Sandstones represent less than 17% of total volume. The overlap areas constitute only 15% of the prism basal surfaces.
Fig. 2. Cross-section along the Mayor River Valley. Conditioned by topography, successive meander belts were cut along selected parallel directions displacing to the east.

PETROLOGY AND PETROPHYSICS

The sandstones are lithoarenites mainly composed of moderately to well sorted quartz and sedimentary carbonate rock fragments. Intrabasinal carbonate components are concentrated in channel lags, internal erosional surfaces delimiting ridge structures and in specific foreset laminae. The framework composition suggests a recycling from Mesozoic sedimentary rocks in the Iberian Range. Diagenesis is not intense and consists mainly of calcite and gypsum cementation and compaction. In the lower section, only calcite cement (<10%) appears, while gypsum is the dominant cement type (20 to 30%) in the upper section, completely occluding primary pores. Variation in cement mineralogy up-section is related to the increase in groundwater salinity during deposition (Diaz-Molina et al. 1989). Compaction has deformed the micritic grains so reducing primary porosity. Micritic grains played a decisive role in the porosity reduction of sandstones in the lower section. The total thickness reduction of sandstone bodies caused by compaction has been estimated to be 27% and 15% in the lower and the upper section, respectively.

Porosity varies up to 30%. Primary porosity is represented best in the lower part (5–25%) with intergranular macropores (0.5–0.06 mm). In this part of the section, secondary porosity (<5%) appears mainly as oversized pores generated by dissolution of carbonate grains. In the sandstones the average size of primary pores is directly related to the average size of pore-forming grains (nearly 1/2 smaller than grains), as shown by Hartkamp et al. (1993). These authors also found that sandstone permeability (0.5–20 D), measured in outcrops with a probe permeameter, is mainly a function of pore size. Therefore, given the significance of these petrographical parameters, permeability values can be estimated (Fig. 3). A general decrease in permeability occurs up-sequence. Vertical fluctuations in permeability trends are directly related to sequence type, being more frequent in types A and D (Fig. 3). Thus, fluctuations in grain size may even create vertical fluctuations in permeability.
permeability barriers on a point bar sequence scale. Although the framework lithology has not been considered in permeability estimation, concentration of intrabasinal micritic pebbles between ridge structures and in certain foreset palaeochannel deposits reflects the growth of the Huete ramping anticline. Northwest orientations of palaeochannel trends in the lower portion, change to north-orientated upwards trends, parallel to the Huete fold.

**Fig. 4.** Stages in the reconstruction of a meander belt. (1) Exposure map showing the outcrops of the different lithologies. (2) Facies analysis allowed interpretation of meander loop portions. (3) Meander belt reconstruction. Superposition of reconstructed meander belts allowed mapping of the areas in which successive sandbodies are vertically connected (4).

**Fig. 5.** Three-dimensional reconstruction of fluvial architecture in the studied area. The 3D model shows the complex distribution of potential reservoir sands in this type of environment. Deflection in palaeochannel deposits reflects the growth of the Huete ramping anticline. Northwest orientations of palaeochannel trends in the lower portion, change to north-orientated upwards trends, parallel to the Huete fold.
A Sedimentary structures

![Sedimentary structures diagram](image)

B Grain size distribution

![Grain size distribution diagram](image)

C Permeability (estimated)

![Permeability diagram](image)

Fig. 6. Bed forms, grain size and permeability distribution in a point bar dominated by ridges. (A) Cross-section of point bar where partially preserved ridges exhibiting point bar sequences of the D type are the dominant bed forms; (B) textural logs showing grain size distribution throughout the point bar body; (C) estimated permeability logs obtained from grain size distribution data.

are of proportional size (Leopold & Wolman 1960). For instance, bigger river systems develop larger meander loops, but overlap areas can represent a similarly low percentage of the basal surfaces of the meander loops.

Moreover, the 3D model can be used as a predictor in fluvial successions of Late Oligocene–Early Miocene age, deposited in a similar climate, and where the effects of subsidence, width of the basin, and size of the catchment area can be inferred. In a narrower basin, discharge and channel concentration would produce thicker porous rock bodies and a relatively higher content of interconnected sandstones than that observed in the Loranca Basin.

Heterogeneities representing probable fluid flow barriers occur at different scales. Major discontinuities are caused by the flood basin silty clays which serve to isolate non-amalgamated meander loops. Other discontinuities are represented by the overlap surfaces between stacked meander loop bodies, as well as by the reactivation surfaces separating point bar bodies. At a more detailed scale, other internal heterogeneities are represented by the lateral decrease of grain size between lateral accretion units.

Inside the sandstones, two other sources of heterogeneity affect permeability values. Soft pebbles occur at the base of trough erosional surfaces. Changes in grain size occur between ridge structures, especially when very fine sand to silt at the top of the ridges is preserved from erosion. When ridges are preserved, multiple and amalgamated sand ribbons may occur around the meander bend, which would complicate fluid flow. Such deleterious effects on reservoir quality are not restricted to small channels because flow separation in meander bends is a function of bend tightness and Froude number, which have similar effects in big rivers (Leeder & Bridges 1975).

This research was funded in part by the Commission of the European Communities in the framework of the Joule Programme (1990–1993), Sub-programme: Hydrocarbons.

![Gamma ray readings diagram](image)

Fig. 7. Statistical distribution of gamma ray readings for deposits representative of the different sedimentary environments. Squares and crosses respectively represent maximum and minimum recorded values. Extreme segments of the bars respectively represent the values of the upper and lower standard deviation. Segments in the central portion of the bars are the mean values. N: number of readings; CPS: counts per second.
Fig. 8. Synthesized stratigraphic log, showing lithologies and interpreted environments as well as a gamma ray log obtained from scintillometer readings in the field. Rectangles in the gamma ray log represent the value of the standard deviation corresponding to the gamma ray readings in counts per second (CPS). The gamma ray log was traced by following the mean values of the gamma ray readings for each type of deposit.

REFERENCES