
Large to intermediate-scale aquifer heterogeneity in fine-grain dominated alluvial fans (Cenozoic As Pontes Basin, northwestern Spain): insight based on three-dimensional geostatistical reconstruction

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Abstract Facies reconstructions are used in hydrogeology to improve the interpretation of aquifer permeability distribution. In the absence of sufficient data to define the heterogeneity due to geological processes, uncertainties in the distribution of aquifer hydrofacies and characteristics may appear. Geometric and geostatistical methods are used to understand and model aquifer hydrofacies distribution, providing models to improve comprehension and development of aquifers. However, these models require some input statistical parameters that can be difficult to infer from the study site. A three-dimensional reconstruction of a kilometer scale fine-grain dominated Cenozoic alluvial fan derived from more than 200 continuously cored, closely spaced, and regularly distributed wells is presented. The facies distributions were reconstructed using a genetic stratigraphic subdivision and a deterministic geostatistical algorithm. The reconstruction is only slightly affected by variations in the geostatistical input parameters because of the high-density data set. Analysis of the reconstruction allowed identification in the proximal to medial alluvial fan zones of several laterally extensive sand bodies with relatively higher permeability; these sand bodies were quantified in terms of volume, mean thickness, maximum area, and maximum equivalent diameter. These quantifications provide trends and geological scenarios for input statistical parameters to model aquifer systems in similar alluvial fan depositional settings.

Résumé Les reconstructions de faciès sont utilisées en hydrogéologie pour améliorer l'interprétation de la distribution des perméabilités d'un aquifère. En l'absence de

données suffisantes pour définir l'hétérogénéité originale des processus géologiques, les incertitudes dans la distribution des hydrofaciès et des caractéristiques de l'aquifère peuvent apparaître. Les méthodes géométriques et géostatistiques sont utilisées pour comprendre et modéliser la distribution des hydrofaciès d'un aquifère, mieux comprendre les modèles et mieux gérer les aquifères. Toutefois, ces modèles nécessitent des paramètres statistiques d'entrée qui peuvent être difficiles à calculer à partir du site d'étude. Une reconstruction 3D d'un cône alluvial kilométrique du Cénozoïque dominé par des grains fins, dérivée de plus de 200 sondages continus et distribués de manière resserrée et homogène, est présentée. Les distributions des faciès ont été reconstruites en utilisant des subdivisions stratigraphiques génétiques et un algorithme géostatistique déterministe. La reconstruction est sensiblement affectée par les variations des paramètres géostatistiques rentrés du fait de la forte densité du jeu de données. L'analyse de la reconstruction permet l'identification dans les zones proches et moyennes du cône alluvial de plusieurs formations de sables étendues latéralement et présentant une forte perméabilité; ces formations sableuses sont quantifiées en terme de volume, épaisseur moyenne, surface maximum, et diamètre équivalent maximum. Ces quantifications apportent des tendances et des scénarios géologiques pour les paramètres statistiques d'entrée pour modéliser les systèmes aquifères dans des environnements de dépôts alluviaux similaires.

Resumen En hidrogeología, las reconstrucciones de facies se utilizan para mejorar la interpretación de la distribución de hidrofacies en acuíferos. Cuando la información disponible no permite captar la heterogeneidad generada por los procesos geológicos, puede producirse incertidumbre en el conocimiento de la distribución de las hidrofacies. Los métodos geométricos y geoestadísticos se utilizan para comprender y modelar esta distribución, permitiendo optimizar la explotación de los acuíferos. Habitualmente estos métodos utilizan parámetros estadísticos difíciles de inferir a partir de los datos disponibles. En este trabajo se presenta la reconstrucción tridimensional de un abanico aluvial cenozoico, de escala kilométrica y dominado por sedimentos arcillosos. La reconstrucción de facies se estableció a partir de una base de datos de más de 200

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sondeos a testigo continuo, regularmente distribuidos; y mediante la subdivisión en unidades estratigráficas de carácter genético y un algoritmo geoestadístico determinista. Debido a la alta densidad de datos, las variaciones en los parámetros de entrada del algoritmo geoestadístico apenas afectan la reconstrucción de facies. El análisis de esta reconstrucción permite identificar en las partes proximal y media del abanico aluvial, varios cuerpos de arena extensos que se caracterizan por una permeabilidad relativamente elevada. Se ha cuantificado el volumen, el espesor medio, el área máxima y el diámetro máximo equivalente de estos cuerpos. Estas cuantificaciones proporcionan tendencias y escenarios geológicos útiles para establecer parámetros estadísticos que posteriormente se podrán utilizar en el modelado de acuíferos de dispositivos de abanico aluviales similares al estudiado.

Keywords Fine-grained alluvial fan · Statistical facies modeling · Geostatistics · Heterogeneity · Geometric parameters

Introduction

Sedimentary analogues

The compilation of databases quantifying facies evolutionary trends and geometrical/geostatistical parameters in depositional units is a major research issue (i.e. Falkner and Fielding 1993; Bryant and Flint 1993; Dreyer et al. 1993; Robinson and McCabe 1997; Hornung and Aigner 1999; Tye 2004; de Marsily et al. 2005), and can be achieved in locations where these units are especially accessible, exposed, or sampled. These units are also referred to as analogues (i.e. exceptional outcrop/field exposures, extensively drilled zones, or modern depositional environments). Trends and parameters derived from analogues can be used as scenarios for input statistical parameters (i.e. geometric dimensions or variograms) in studies when the sampling density is not enough to capture the entire spatial variability because of the short-scale variations in sedimentary facies. Nevertheless, realistic models reproducing the spatial variability of facies are necessary to provide control over the uncertainty in facies correlations, and stochastic simulation is applied with either object-based or geostatistical methods (i.e. Haldorsen and Damsleth 1990; Deutsch and Hewet 1996; Koltermann and Gorelick 1996; Webb and Davis 1998; de Marsily et al. 1998, 2005; Kupfersberger and Deutsch 1999; Falivene et al. 2006a, b). In siliciclastic aquifers, the use of realistic facies models to guide the modeling of porosity and permeability improves predictions, because these parameters are commonly correlated with facies (Anderson 1989; Jussel et al. 1994; Ritzi 1995; Fogg et al. 1998; Gómez-Hernández and Deutsch 1999).

Fine-grain dominated alluvial fans

Quantification and modeling of the heterogeneity in Recent to Cenozoic alluvial fan successions constitute significant

aims given their importance in groundwater resources (e.g. Johnson and Dreiss 1989; Johnson 1995; Carle et al. 1998; Weissmann et al. 1999, 2002; Weissmann and Fogg 1999). Most of the descriptions and analyses of alluvial fans have focused on systems characterized by widespread proximal to medial coarse-grain facies, given their ubiquity in many climatic and tectonic settings (Fraser and Suttner 1986; Nemec and Steel 1988; Harvey 1989; Rachocki and Church 1990; Bull 1991; Blair and McPherson 1994; Miall 1996). Oppositely, fine-grain dominated alluvial fans are less widespread and less well documented than coarse-grain dominated fans. Nevertheless, fine-grain dominated alluvial fans are frequently present, and their generation is enhanced in climatic and tectonic settings where rock weathering in the catchments mainly yields mud-sized particles (Bull 1964a, b; Legget et al. 1966; Campbell 1998; Nakayama 1996, 1999; Blair 2003). The trends of hydrofacies distribution in fine-grain dominated alluvial fans have not been extensively described because of exposure limitations and lack of subsurface data (e.g. Bull 1964a, b; Legget et al. 1966; Campbell 1998; Nakayama 1999).

Purpose and scope

This paper deals with a large to intermediate-scale reconstruction of the hydrofacies distribution within a kilometer scale fine-grain-dominated alluvial fan in the Cenozoic As Pontes Basin (northwestern Spain). The purpose of this paper is to document the three-dimensional geostatistical deterministic reconstruction of this alluvial fan, departing from closely spaced wells. The analysis of the reconstruction, combined with surface observations, enabled better understanding and characterization of the heterogeneity related to sand hydrofacies, and provides trends and quantitative parameters describing the laterally extensive sand bodies, which can be potentially used to derive geological scenarios for the stochastic modelling of less-constrained similar or analogue alluvial fan systems.

Geological setting

General basin features

The Tertiary As Pontes Basin (northwestern Spain) is a small non-marine basin (12 km²) associated with an Oligocene–Early Miocene strike-slip fault system, which relates to the western onshore end of the Pyrenean belt, as shown in Fig. 1a and b. The basin basement and ancient catchment zones are made up mainly by major slates and schists, and minor quartzites and gneisses of Precambrian and Paleozoic age, which were intensely deformed during the Variscan orogeny (Manera et al. 1979; Santanach et al. 1988, 2005; Bacelar et al. 1988; Barsó et al. 2003; Fig. 1b). The basin evolution started as a compressive underlapping step over, with the development of two isolated subbasins bounded by E–W oriented thrusts and N–S normal faults. Both subbasins merged into a single depositional area during the subsequent generation of a double retraining bend (Ferrús 1998; Santanach et al. 2005). Figure 1c

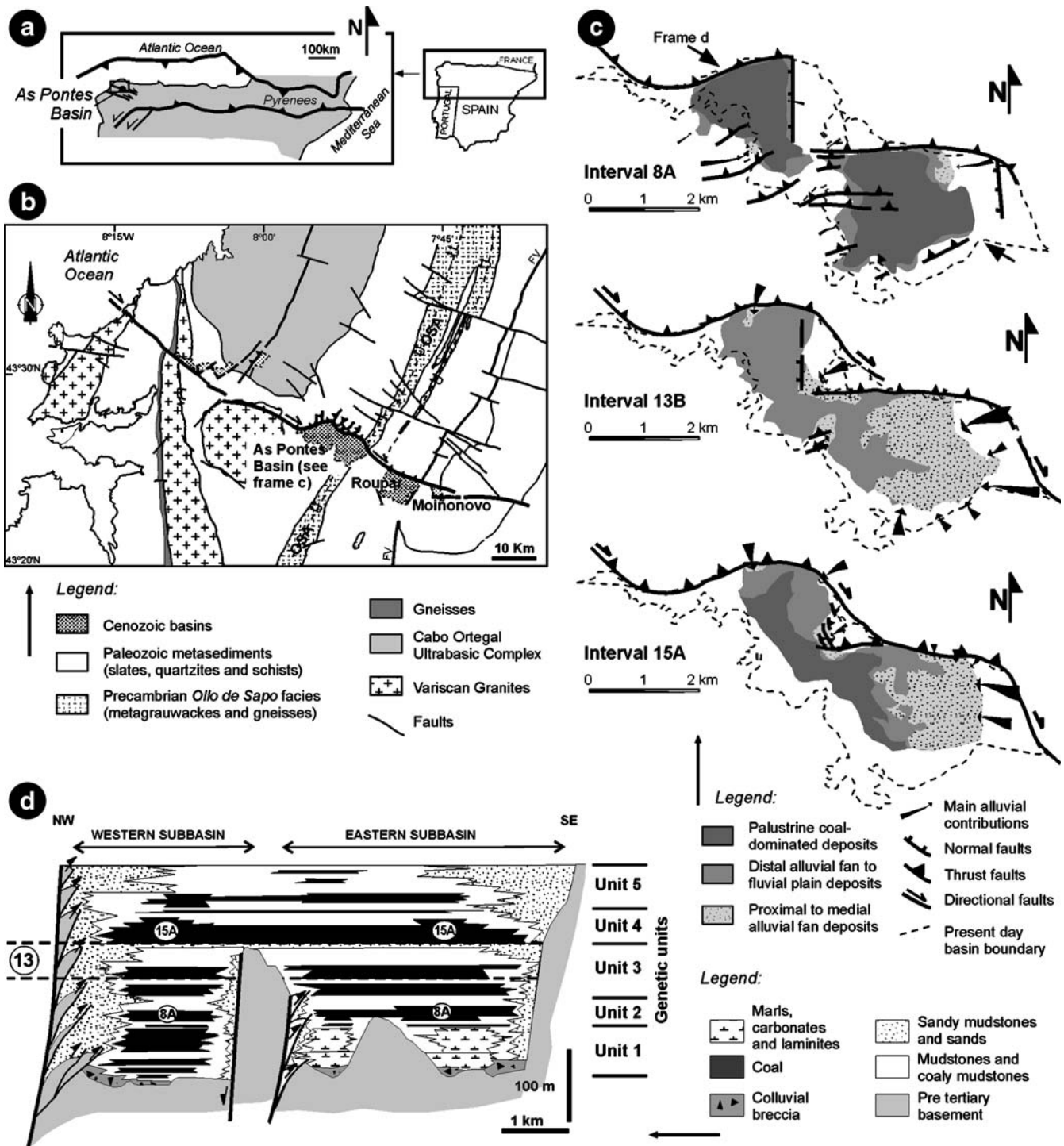


Fig. 1 **a** Location of the As Pontes Basin. **b** Regional geological setting (see location on frame **a**); from Santanach et al. (2005). **c** Paleogeographical sketches of the basin during deposition of intervals 8A, 13B, and 15A, see location in frame **b**. Note the progressive replacement of the active structures from the step over stage (8A); to the double restraining bend stage (15A); by means of a transition stage (13B). Note the contrast between type A intervals, characterized by significant coal deposition in the central basin

zones (8A and 15A); and type B intervals, characterized by progradation of the alluvial fans (13B). Note also the development of the axial alluvial fan in the eastern subbasin from 8A onwards. Structural features from Santanach et al. (2005). **d** Longitudinal sketch of the basin showing the main stratigraphic units, sedimentary facies, and basement structures (see arrows for location on frame **c**), note the position of sequence 13, interval 8A and 15A

shows sketches of three significant basin evolution episodes displaying their main tectonic structures and the associated depositional environments.

The general paleoclimatic conditions during the development of the basin fill have been inferred from paleobiological and sedimentological data (Médus 1965a, b; Menéndez Amor 1975; Baltuille et al. 1992; Cabrera et al. 1994, 1995; Sáez and Cabrera 2002; Cavagnetto 2002). The paleoclimate was subtropical, warmer than in the present and with dry and rainy seasons. High frequency humid-subhumid cycles characterized the basin evolution (Sáez and Cabrera 2002).

Stratigraphy and depositional systems of the basin fill

The sedimentary basin fill was syntectonic and resulted from the interaction of sedimentation in alluvial fans and lacustrine to marsh-swamp systems (Fig. 1c; Cabrera et al. 1995, 1996). Consequently, the basin infill consists of major siliciclastic alluvial facies assemblages together with significant brown coal deposits, as displayed in the longitudinal sketch of the basin in Fig. 1d (Bacelar et al. 1988; Cabrera et al. 1995, 1996; Ferrús 1998; Falivene et al. 2007a). Because of its economic interest as a coal basin, the basin infill has been extensively drilled; Fig. 2a shows well locations in the studied intervals.

The basin infill has been split into five major genetic stratigraphic units (Fig. 1d). Genetic units 2 to 5 are formed by several composite sequences, which have been defined based on sequence stratigraphic concepts applied to continental deposits, and are bounded by isochronous or near-isochronous bottom and top surfaces related to the settling and spreading of the major coal seams (Ferrús 1998; Sáez and Cabrera 2002; Sáez et al. 2003; Fig. 1d). Each sequence consists of two intervals: (1) a lower, areally restricted alluvial-fan interval (labeled interval A), where the siliciclastic successions interfinger with marsh-swamp coals and coaly mudstones; and (2) an upper, areally spread alluvial-fan interval (labeled interval B), composed exclusively of siliciclastics.

Mudstone, sand, and very minor fine-grained conglomerate make up most of the As Pontes Basin alluvial-fan successions. The widespread predominance of mudstone and sandy mudstone facies show that fine-grained sediments fed these systems predominantly. The rock composition of the basin catchment (major slates and schists and minor quartzites and gneisses; Fig. 1b; Barsó et al. 2003; Sáez et al. 2003), and the warm and humid-subhumid paleoclimatic conditions (Médus 1965a, b; Menéndez Amor 1975; Baltuille et al. 1992; Cabrera et al. 1994; Cavagnetto 2002) account for this predominance.

The low-frequency alternation of areally restricted versus areally spread alluvial-fan intervals, which characterizes most of the basin fill, was mainly tectonic in origin, because of variations on subsidence and sediment input rates. Episodes of more intense tectonic activity in the basin were characterized by high subsidence rates, and resulted in the alluvial fans retrogradation and restriction to the basin margin zones. Oppositely, episodes of relative

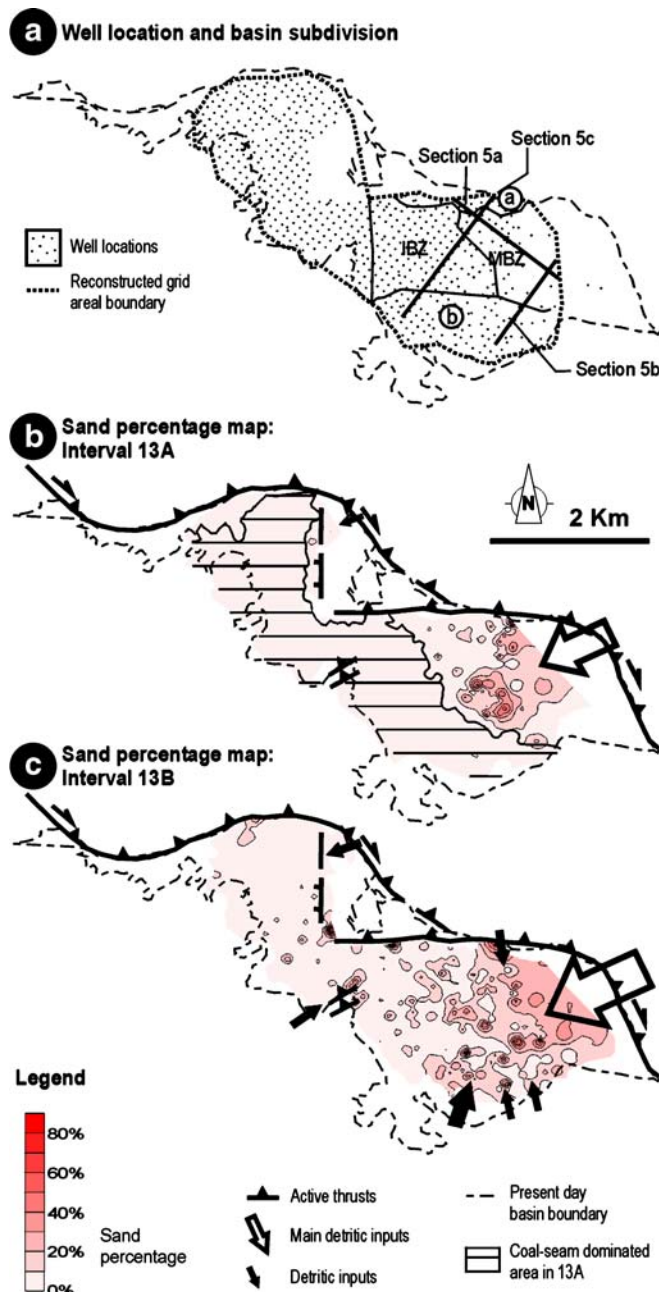


Fig. 2 a Well location in sequence 13 (note regular spacing), and subdivision of the eastern subbasin area according to sand deposition patterns: a) alluvial fans attached to the northern, tectonically active margin; b) alluvial fans fed from the southern inactive margin; (MBZ) marginal basin zone; (IBZ) inner basin zone. Position of sections in Figs. 5 and 8a is also shown. b, c Sand percentage maps for the intervals 13A and 13B. Arrows show the main alluvial feeding points of coarse-grained facies, with the largest ones corresponding to the axial alluvial fan. Active structures during sedimentation of the sequence 13 are based on Ferrús (1998) and Santanach et al. (2005). The coal-seam dominated area in interval 13A is also shown; the boundary encloses the area where coal percentage exceeds 60%. See location of the basin in Fig. 1b

tectonic quiescence gave rise to low subsidence rates that coupled in some cases with larger detritic inputs, and resulted in basinward progradation of the alluvial fan deposits (Ferrús 1998; Santanach et al. 2005).

Alluvial fan facies in sequence 13

The upper part of unit 3 is made up by sequence 13. This sequence was chosen for hydrofacies geostatistical reconstruction because it records one of the largest expansions of alluvial fan deposits during the basin evolution (Fig. 1d). Such a large alluvial fan expansion was triggered both by a long-term drainage back spreading in the basin catchment (Sáez and Cabrera 2002; Barsó et al. 2003), and by minimal subsidence rates probably related to the transition from the step over structural stage to the double restraining bend stage (Ferrús 1998; Santanach et al. 2005; 13B in Fig. 1c).

The deposits of sequence 13 commonly range between 15 and 30 m in thickness, whereas these deposits attain their maximum thicknesses (around 60 m) in the eastern subbasin. Figure 2b shows a map of the lower interval (13A), which is characterized by the accumulation of up to 16-m-thick coal seam in the inner basin zones. This seam interfingers with the alluvial fan deposits, which were mainly restricted to the eastern marginal zone of the basin. Figure 2c shows a map of the upper interval (13B), which overlies interval 13A. During the 13B interval, the coarser-grained facies impinged into the inner basin zones, causing the consequent coal facies disappearance (Cabrera et al. 1996; Ferrús 1998).

In the eastern basin area, four zones can be defined based on the overall distribution of the sand and sandy facies in sequence 13 (Fig. 2b and c). The northern and southern marginal zones (a and b, respectively, in Fig. 2a) were affected by minor transverse alluvial fan systems. The marginal eastern (MBZ; marginal basin zone) and inner central basin zones (IBZ; inner basin zone; Fig. 2a) were affected by the deposition of a larger axially spread alluvial fan (up to 2.5 km in length and 1.3 km in width, Fig. 2b and c). The major, laterally extensive sand bodies of this axial alluvial fan that accumulated in the MBZ and IBZ are the main objective of this study.

Data sets of the axial alluvial fan successions studied

More than 675 wells, amounting to approximately 10,000 m of core description, were available for the study of sequence 13. Of these wells, 151 are located in IBZ and 56 in MBZ. Wells were placed along a nearly regular square grid spaced at about 105 m (Fig. 2a). The available core descriptions resolve beds thicker than 0.15 m.

Facies description and interpretation

More than 30 individual facies were differentiated in the original descriptions according to their lithological (textural) and sedimentological characteristics. These individual facies were assembled herein into five major facies: (1) sand (including muddy sands and very minor sandy fine-grained gravels), (2) sandy mudstone, (3) mudstone, (4) coaly mudstone, and (5) coal. Each major facies has a significant occurrence in the studied sequence, and assembles those

individual facies that were deposited in closely related paleoenvironments and share similar sedimentological and petrophysical properties. Apart from the core descriptions, the open pit mining trenches in the basin fill yielded additional evidence of the main geometric and depositional characteristics of these five major facies, as shown in Fig. 3.

Sand facies

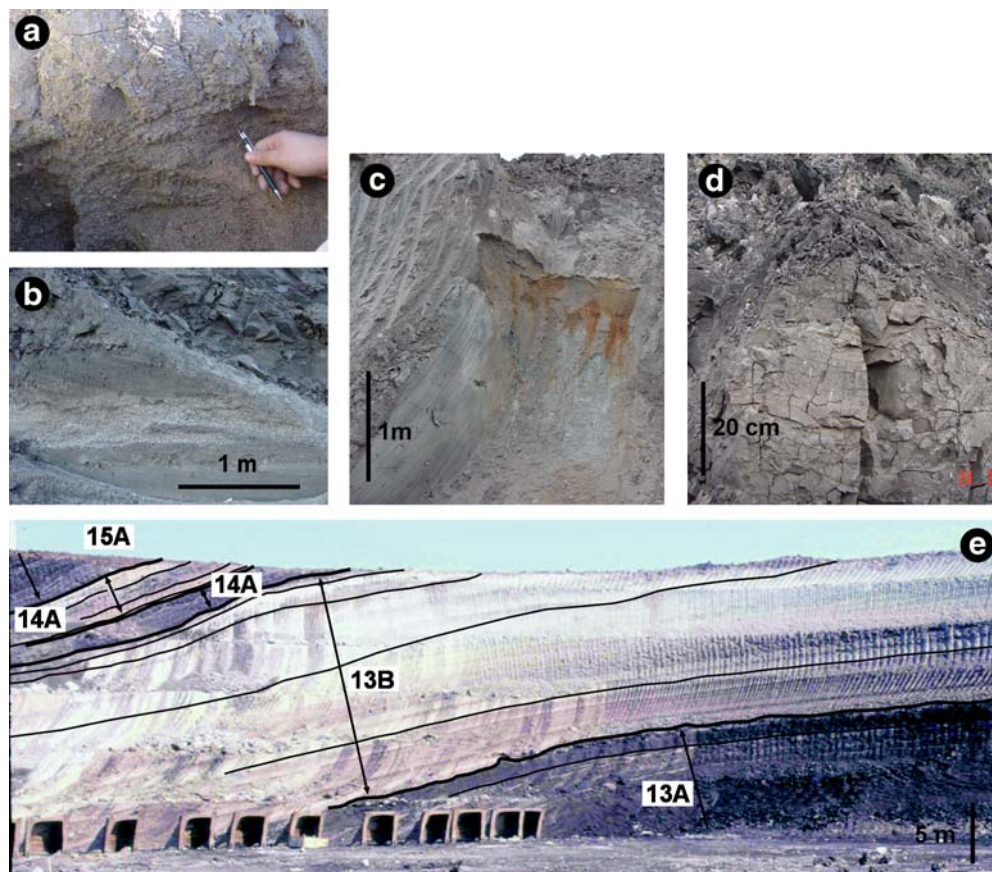
Sand facies are mainly composed of quartzarenites with minor feldspar grains, and range from light colored whitish-greenish to gray. Clay minerals in the matrix are mainly kaolinite, aluminous smectite and minor illite (Sáez et al. 2003). The deposits of this facies are organized according to two major geometries, with changing sedimentological characteristics (Ferrús 1998): (1) laterally extensive sand bodies, and (2) lenticular ribbon sand bodies.

1. The laterally extensive (several hundred meters) sand bodies may be single or multi-episodic and range from a few decimeters up to several meters in thickness. These sand bodies include poorly sorted (even muddy) coarse, massive sand beds; however, well-sorted, medium to fine and massive to cross-stratified-laminated sands also are present (Fig. 3a). Their changing depositional characteristics indicate that these sand bodies resulted from diverse depositional processes. The widespread coarser, poorly mature in texture sands can be interpreted as relatively proximal sheet flow deposits. The finer, more mature sands would be either the results of sheet flow deposits or flashy channel to overbank deposits formed in braided fluvial fringes, which would have developed mainly in the medial to medial-distal alluvial fan zones. These laterally extensive sand bodies accumulated from relatively proximal to medial alluvial fan zones, attaining only a minor development in the distal zones. As a consequence, these sand bodies are especially widespread in the MBZ and attain lesser development in the IBZ.
2. The lenticular ribbon sand bodies (Friend 1983; Miall 1996) consist of moderately to well-sorted coarse to fine-grained, cross-stratified to laminated sands (Fig. 3b). These bodies can also be single to multi-episodic, range from a few decimeters up to a few meters in thickness, and are very continuous along the paleocurrent trends (at least several hundred meters); however, they show a very limited lateral extension across their transverse section (few tens of meters), as observed in the open pit mining trenches (Fig. 3b). Most of these ribbon sands were deposited in terminal distributive fluvial plains developed ahead from the narrow braided-channel fringes characteristic of the medial alluvial fan zones. Thus, they are especially widespread in the IBZ and scarcer in the MBZ.

Sandy mudstone facies

The sandy mudstone facies is light colored (green, gray) and make up mostly massive beds. Sand grains are made

Fig. 3 Facies examples from the open-pit mining trenches in the basin. **a** Poorly sorted, massive to cross-laminated sands, corresponding to a laterally extensive sand body in the medial part of the axial alluvial fan. **b** Well-sorted ribbon sand lens embedded within brown coal facies in the inner basin zones, and accumulated by the distributive fluvial network. **c** Mudstones. **d** Dark brown coal facies. **e** Example of an open-pit mining trench showing sequence 13 in the inner basin zone



up mainly of quartz and minor feldspar, whereas clay minerals (kaolinite, aluminous smectite, and illite) occur in the mud grade (Sáez et al. 2003). This facies makes up laterally extensive, thick and multiepisodic bodies that were mostly deposited on the proximal to medial alluvial fan zones of the MBZ, where the core data show its close vertical and lateral relations with the sand facies. Thinner sandy mudstone bodies often overly and interfinger with the mudstone facies in the IBZ successions, recording the progradational alluvial fan stages (13B). The textural and sedimentological characteristics of the sandy mudstone facies indicate that this facies was deposited mainly by sheet flows spreading from the proximal to the medial alluvial fan zones. In the distal medial to distal alluvial fan successions, this facies is also laterally related with channelized braided sand facies and would record poorly sorted overbank, flash-flood deposits.

Mudstone facies

The siliciclastic mudstone facies range from light-colored (green, gray) to light brown and is mainly massive (Fig. 3c). It is composed mainly by clay minerals (kaolinite, aluminous smectite, and illite) and minor quartz and feldspars (Sáez et al. 2003). Siderite-bearing mudstone beds have been observed in the lower part of

sequence 13, in the transition from the underlying coal seam. This facies is dominant in the IBZ successions that record the progradational alluvial fan stages (13B), and was deposited on distal-marginal mud flats, which graded from the medial-distal alluvial fan zones and surrounded the marsh-swamp environments.

Coaly mudstone facies

Coaly mudstone is massive and characterized by dark grayish to brown colors and high terrestrial organic matter content. The mudstone is made up mainly by clay minerals (early diagenetic kaolinite and subordinated illite; Sáez et al. 2003). This facies is widespread in the IBZ successions recording the retrogradational alluvial fan stage (13A) and developed in transitional environments between distal mud flats and the outer margins of the marsh swamp, peat-forming zones.

Coal facies

The coal facies includes a variety of huminite dominated dark brown coal (Fig. 3d), liptinite-rich pale-brown coal derived from the accumulation of highly degraded aquatic and marsh plant remains, and xyloid brown coal recording the accumulation of wood remnants. These organic rich

facies have been described elsewhere (Cabrera et al. 1992, 1995; Hagemann et al. 1997; Huerta et al. 1997a; Huerta 1998, 2001; Falivene et al. 2007a), and were deposited in marsh-swamp zones where a variety of terrestrial and aquatic plant communities developed (Cavagnetto 2002; Martín-Closas 2003). These environments developed in the IBZ, at the foot of the terminal alluvial fan zones, and during the retrogradational alluvial fan stage.

Sedimentological-paleoenvironmental general interpretation

The sedimentological features of the alluvial fan facies, and their relations with the organic rich facies observed in the core descriptions and the open-pit mining trenches (Ferrús 1998; Sáez et al. 2003), indicate depositional zonation from proximal-medial to distal alluvial fan facies, and then to the marsh-swamp, organic-rich facies (the latter only well developed in the 13A interval). Highly sediment concentrated sheet flows and mud flows were probably the main depositional processes on the proximal alluvial fan zones neighboring the fan apex, although the available well data set does not entirely cover these zones. Diluted sheet flows and braided fluvial floods, which gave rise to water-laid laterally extensive to lenticular sand deposits, were more significant in the medial to distal zones, where terminal distributive channel-fringes and mud-flat deposition was dominated by fine and very fine-grained silicilastics. In summary, the axial alluvial fan in sequence 13 can be described as a mud flow and sheet flow, fine-grain dominated fan (Stanistreet and McCarthy 1993; Blair and McPherson 1994; Miall 1996).

The aquifer system

Alluvial fan sand-related aquifers in the sequence 13 are multiple-aquifer systems made up of discontinuous sand and very minor gravel bodies embedded in a major matrix of low-permeability facies. Aquitard hydrofacies make up very laterally continuous units (from 200–300 m up to 1–3 km), with thicknesses ranging from a few centimeters up to 5–10 m, and very low permeabilities (from 0.04 to 0.3 mD; millidarcy). This hydrofacies is composed of coal, coaly mudstone, mudstone, and sandy mudstone facies; the latter being the most common aquitard facies. Aquifer hydrofacies is made up by sand facies, is not so laterally persistent, and is characterized by higher permeability values (from 3 to 80 mD). Ribbon sand bodies would show the highest permeability values in the aquifer hydrofacies, whereas the laterally extensive sand bodies would have lower permeability values.

Geostatistical reconstruction of the laterally extensive sand bodies

The large amount and high density of core data allowed the application of a deterministic geostatistical approach for the reconstruction of the three-dimensional distribution of

facies in the sequence 13 (Johnson and Dreiss 1989; Ritzi 1995; Falivene et al. 2007b). The analysis of the axial alluvial fan unit in the mid-distal and distal zones also benefited from direct observations of the open-pit mining trenches (Fig. 3e). The combination of both subsurface and outcrop data enabled a more accurate characterization of the major features of the depositional facies assemblages. Core descriptions are the basis for the geostatistical reconstruction of IBZ and MBZ, with especial focus on the laterally extensive sand bodies developed in the proximal and mid-distal axial alluvial fan successions. The most apical-proximal part of the fan was not included in the model, given the absence of well data (Fig. 2a).

Grid construction

The successions gently dip in sequence 13, which was deposited during a relatively quiescent tectonic stage and is affected only by very minor thrusting in the northern basin margin (Fig. 1c), causing no significant perturbation to the axial alluvial fan (Fig. 2b and c; Ferrús 1998). Therefore, and for simplicity, no faults were considered in the model.

Three surfaces were reconstructed from the triangulation of correlated well data, i.e. the base of interval 13A, the boundary between intervals 13A and 13B, and the top of interval 13B. In order to perform the facies reconstruction, a three-dimensional stratigraphic grid was assigned to sequence 13. Two sub-grids, constrained by the reconstructed surfaces, were defined inside the main grid to reconstruct facies in both intervals independently.

Paleomagnetic studies confirm that the reconstructed surfaces are isochronous or nearly isochronous (Huerta et al. 1997b), and, therefore, correspond to paleodepositional surfaces. To provide a reasonable framework for maximum lateral continuity surfaces, a proportional grid correlation style was used (Jones 1988; Falivene et al. 2007b), with the separation between the layers being proportional to the separation between the top and bottom surfaces for each interval, as depicted in Fig. 4. Twenty-eight and 76 layers were used for intervals 13A and 13B, respectively; hence, the mean cell thickness was 0.25 m (ranging from 0 to approximately 0.7 m). Horizontal grid

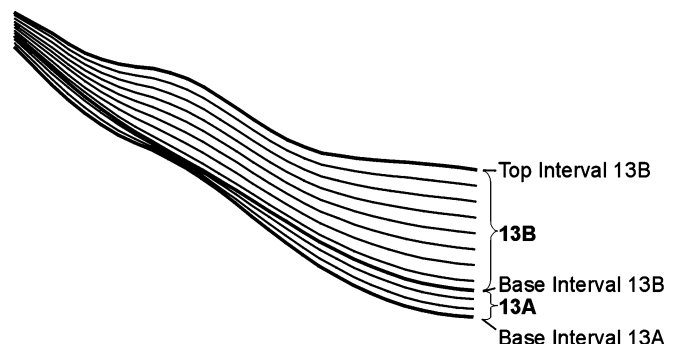
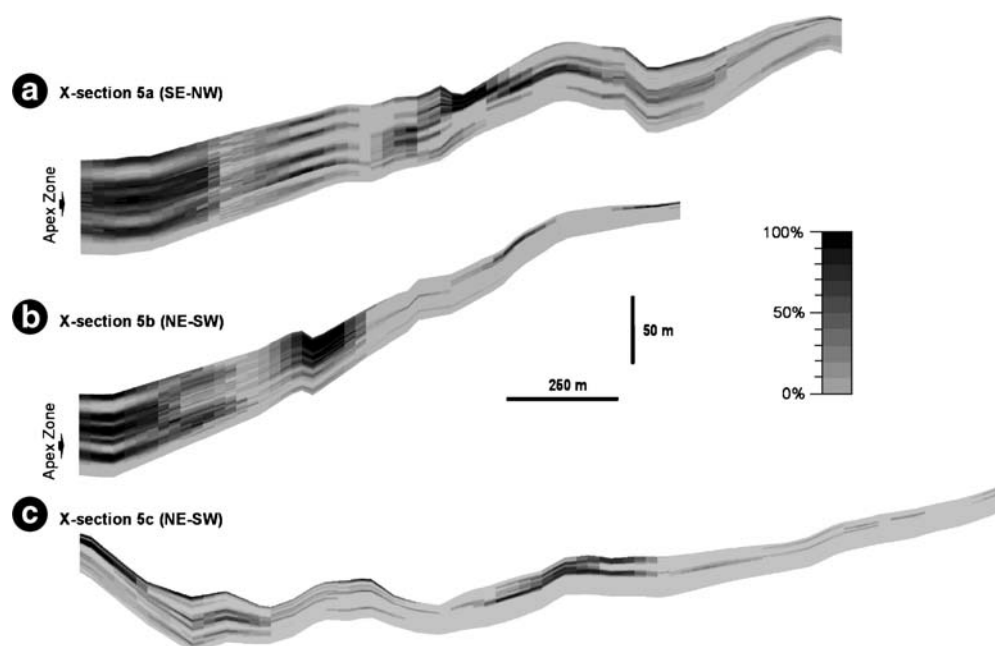


Fig. 4 Detail of a vertical section showing the proportional grid layering style in the two reconstructed sub-grids. Note that only one-tenth of the grid layers are shown

Fig. 5 a–c Sections across the axial alluvial fan deposits showing probability of sand facies occurrence resulting from the interpolation of the indicator variable. See location of these sections in Fig. 2a and compare to the facies model in Fig. 8a, where the same sections are shown. Vertical exaggeration is $\times 3$



spacing was 25 m. The grid spacing enabled to capture in detail most of the sedimentary bodies recognized in the wells. The total number of cells within IBZ and MBZ was on the order of 500,000.

The facies logs were up-scaled to the size of grid cells by assigning the most abundant logged facies to each cell (Falivene et al. 2007b). In total, over 5,300 cells for interval 13A and approximately 14,000 for 13B were intersected by wells in IBZ and MBZ.

Interpolation algorithm

Facies reconstruction was carried out using a deterministic geostatistical algorithm. The Markov analysis (e.g. Gingerich 1969) was used as a quantitative tool to determine whether facies transitions should be treated either continuously or categorically. The results obtained suggested that a categorical approach was the most suitable, and, therefore, indicator kriging (IK) was chosen as the interpolation algorithm (Journel 1983; Deutsch and Journel 1992;

Falivene et al. 2007b). This deterministic algorithm does not impose any order relations on the facies. IK for categorical variables is based on the decomposition of the categories into several binary variables, one for each category (Deutsch and Journel 1992). In this case, each category corresponds to a different facies. Each binary variable is set to one if the related facies occurs, and to zero if it does not. Subsequently, interpolation using ordinary kriging (Matheron 1963; Cressie 1990) is carried out for all the new variables. The results for every category range from 1 (full probability) to 0 (null probability); Fig. 5 shows the probability of sand facies occurrence in three sections across the axial alluvial fan. At the end, the category with the highest probability is assigned to each cell.

Variogram estimation

Indicator kriging (IK) requires estimation of variograms for each category. Starting with the up-scaled facies logs, experimental variogram estimation, theoretical model fitting,

Table 1 Horizontal and vertical variogram ranges computed for the axial alluvial fan in intervals 13A and 13B. Theoretical variogram models were fitted assuming spherical models

		Variogram ranges			
		Horizontal		Vertical ^a	
		13A interval (m)	13B interval (m)	13A interval (m)	13B interval (m)
Aquiclude facies	Coal	>150 ^b	– ^c	>0.35>(2.5–6.3)	– ^c
	Coaly mudstone	150	150	0.15 (1.1–2.7)	0.11 (2.1–5.9)
	Mudstone	180	>200 ^b	0.18 (1.3–3.2)	>0.2>(3.8–11)
	Sandy mudstone	320	>200 ^b	0.3 (2.1–5.4)	>0.14>(2.7–7.6)
Aquifer facies	Sand	400	180	0.28 (2.0–5.0)	0.14 (2.7–7.6)

^a Due to the use of a grid with proportional layering, the vertical ranges are expressed as fractions of the grid thickness. As grid thickness varies between different locations, the real vertical range also varies. Values in parentheses are the approximate average and maximum real vertical ranges.

^b Ranges for coal facies in 13A, and mudstone and sandy mudstone facies in 13B are underestimated (see text for a detailed explanation).

^c Horizontal and vertical range for coal facies in 13B are not presented because coals are very scarce in this term (less than 0.5%).

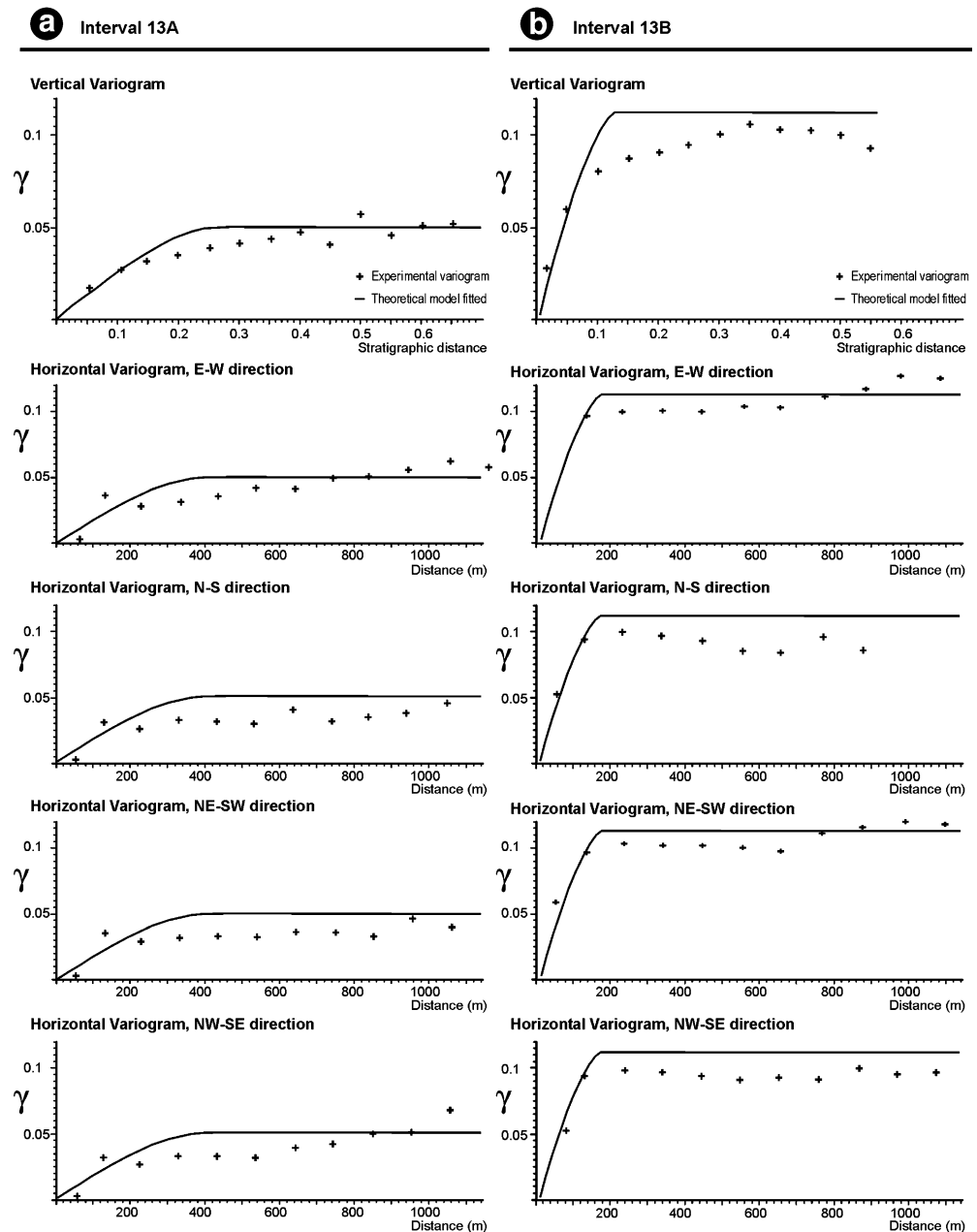
and facies interpolation were undertaken using gOcad (by Earth Decision, Mallet 1992). A new coordinate system was defined with the z-dimension transformed into a parametric dimension using the grid cell indices. In this new system, the horizontal planes represent the best approximation to the paleodepositional surfaces (i.e. where the sedimentary bodies should display most lateral continuity).

Variogram analysis was carried out only for well data located in IBZ and MBZ (Fig. 2a), where the reconstruction was focused. This analysis led to the definition of horizontal and vertical ranges for each facies. Variogram parameters and variogram curves for sand facies are presented in Table 1 and Fig. 6, respectively. As expected, continuity in the paleodepositional plane is larger than in the perpendicular direction. Indicator horizontal variograms

for sand facies both anisotropic (major axis elongated along the paleocurrent direction) and isotropic have been described in other alluvial fans (i.e. Johnson 1995). In the alluvial fan successions examined herein, differences in horizontal experimental variograms along different azimuths are not significant (Fig. 6), and, thus, the theoretical variogram models were fitted with horizontal isotropic ranges.

Some facies (coal in interval 13A, and mudstone and sandy mudstone in interval 13B) show zonal anisotropy in the experimental variograms related to very strong trends in their spatial distribution (Table 1; Gringarten and Deutsch 2001). This effect was not modeled when fitting the theoretical variogram models, yielding an underestimation of the corresponding ranges. However, such relatively small underestimations do not have any marked

Fig. 6 Indicator variograms for sand facies in the axial alluvial fan for intervals 13A and 13B. Experimental variograms were computed using the logs up-scaled to the size of grid cells. Horizontal experimental variograms were computed by considering pairs of points belonging to the same grid layer, and with a tolerance angle of 45° and a bandwidth of 300m for each direction. Vertical variograms were computed by considering only pairs of points in the same well. Theoretical variogram models were fitted assuming spherical models (see ranges in Table 1). Because a proportional grid was used, with variable vertical spacing, vertical variogram distances are expressed in fractions of grid thickness



effect on the resultant body dimensions when applying IK to regularly distributed and high-density data.

Suitability of data to describe the sand bodies

Indicator kriging (IK) was used as a tool to achieve a three-dimensional correlation and interpolation of facies described in a large number of wells. Nevertheless, geostatistical interpolation techniques for automatic facies reconstruction should be applied with caution. For bodies with lateral dimensions smaller than well spacing, interpolation would yield unrealistically extensive bodies with no geological sense. In the alluvial fan successions of sequence 13, various lines of evidence suggest that at least some of the sand bodies can be confidently correlated between adjacent wells:

1. As stated above (see section [Facies description and interpretation](#)), the sedimentological analysis of the information from the open-pit mining trenches confirms the presence of some laterally extensive sand bodies, whose lengths exceed 105 m (the well spacing).
2. The continuity shown by the horizontal experimental variograms for sand facies at small lags (Fig. 6) and the resulting ranges (Table 1) suggest that at least some sand bodies would exhibit lengths exceeding 105 m. It is important to note herein that sand facies groups bodies with two types of depositional geometries (see section [Facies description and interpretation](#)): the laterally extensive sand bodies, which are responsible for the continuity shown by experimental variograms; and the lenticular ribbon sand bodies, which tend to inflate variogram values and obscure any evidence of correlation due to their small size compared to well spacing. Ritzi (2000) and Guardiola-Albert and Gómez-Hernández (2001) report a quantitative relation among variogram range, proportions, and mean body lengths. Based on this relation, the obtained ranges would lead to mean body lengths of approximately 280 m for sand bodies in interval 13A, and 140 m for sand bodies in interval 13B, when using sequential indicator simulation (SIS, i.e. the simulation form of IK; Deutsch and Journel 1992). These mean lengths range between one and two well spacings, and, therefore, the sand bodies are defined, on average, by 1–3 data points in each of the two horizontal directions.
3. Mean sizes of sand bodies (i.e. volumes) obtained using conditioned SIS varying variogram ranges, were compared with those from the IK facies reconstruction, in order to test the hypothesis that the data spacing is sufficiently small to allow deterministic correlation of the wells. In theory, when the variogram range increases, and the proportions are kept constant, the mean dimensions of sand bodies should also increase (Carle and Fogg 1996; Ritzi 2000; Guardiola-Albert and Gómez-Hernández 2001). Figure 7 shows the mean size of sand bodies derived from SIS with several horizontal ranges, and the mean size of sand bodies from the IK reconstruction with the experimentally

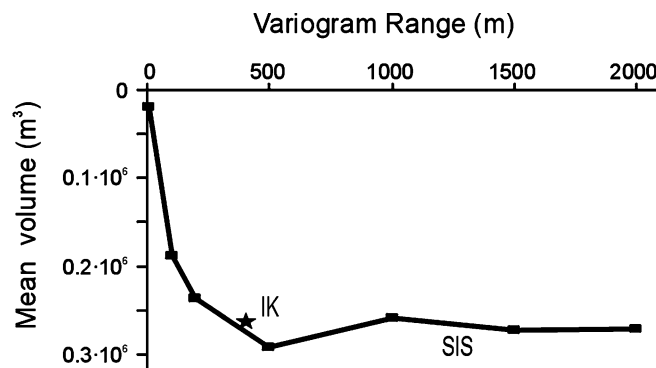


Fig. 7 Test comparing the mean sand body volume obtained from IK using the fitted variogram (*star*), and SIS varying horizontal variogram ranges (*line*) for the axial alluvial fan in interval 13A. Mean sand body volumes from 10 realizations were averaged to obtain each SIS mean volume in order to average ergodic fluctuations (fluctuations of results from diverse simulations built on the same initial parameters). Vertical variogram ranges and proportions in SIS were kept constant, equal to those used for IK. Only bodies with volumes exceeding $11,300\text{ m}^3$ were averaged, because smaller bodies will correspond in most cases to ribbons

fitted ranges (Fig. 6). As the horizontal range increases, the mean sizes from SIS tend to stabilize at a value because of the control exerted by the densely spaced conditioning well data (i.e. the high-density data do not allow simulating larger sand bodies). Moreover, the mean size at which the sand bodies derived from SIS stabilize is close to the one resulting from IK, and the stabilization is practically achieved for ranges comparable to the ones deduced from the available core data. This result suggests that well data can be deterministically correlated, and are sufficient to reconstruct at least the laterally extensive sand bodies accumulated in the studied sequence.

Results and discussion: characterization of the sand bodies

General facies distribution

Figure 8 shows the three-dimensional reconstruction of the laterally extensive sand bodies in the axial alluvial fan successions located within MBZ and IBZ, as provided by the interpolation results derived using IK (see section [Geostatistical reconstruction of the laterally extensive sand bodies](#)).

During interval 13A, sedimentation was dominated by coal accumulation in most of IBZ, and the coarser grained facies of the proximal and middle alluvial fan environments remained very restricted to MBZ (Fig. 2b; Table 2). On the other hand, during the subsequent progradational evolutionary stage (interval 13B), sandy mudstones and sands dominated in MBZ, whereas mudstones and sandy mudstones spread in IBZ (Fig. 2c; Table 2). This evolution was paralleled by the thicker accumulation and concentration of sand facies in MBZ and with their significant, albeit lower, proportions in the IBZ during both intervals.

the perspective view in the *lower left map*). Each disconnected body is depicted with a different color. Position of the fan apex zone is shown for reference. Note the changing perspective and point of view between *frame a* and *frames b and c*. Horizontal scales are approximate because of changes due to the perspective view, vertical exaggeration is $\times 3$

Table 2 Total volume, sand volume, and sand percentage measured from the facies reconstruction, reported for the marginal and the inner basin zones (MBZ and IBZ, respectively) and for intervals 13A and 13B

		Interval 13A	Interval 13B
MBZ	Total volume	$14.5 \cdot 10^6 \text{ m}^3$	$39.8 \cdot 10^6 \text{ m}^3$
	Sand volume	$2.0 \cdot 10^6 \text{ m}^3$	$10.7 \cdot 10^6 \text{ m}^3$
	Sand percent	13%	27%
IBZ	Total volume	$10.6 \cdot 10^6 \text{ m}^3$	$31.1 \cdot 10^6 \text{ m}^3$
	Sand volume	$0.1 \cdot 10^6 \text{ m}^3$	$2.1 \cdot 10^6 \text{ m}^3$
	Sand percent	1%	7%

Inferred shape and dimensions of the sand bodies

Laterally extensive sand bodies within IBZ and MBZ were individualized using face connection between grid cells (following the thinking of Deutsch 1998), as shown in Fig. 8b and c. These bodies were characterized by means of summary statistics on their dimensions, presented in Figs. 9 and 10: (1) volume (Fig. 9), (2) mean thickness

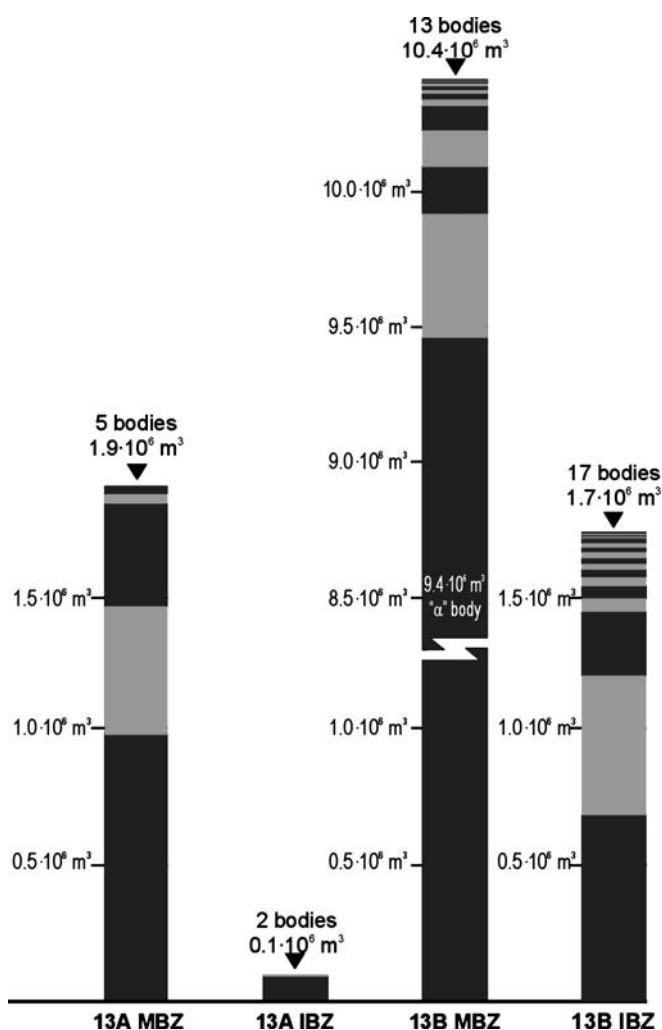


Fig. 9 Volumes for the laterally extensive sand bodies analyzed in MBZ and IBZ, for intervals 13A and 13B. Note that the bar length for the largest body in 13B MBZ (the so-called “α” body) is not shown in its entirety. Black and gray shadings are used only to differentiate the volume of each sand body

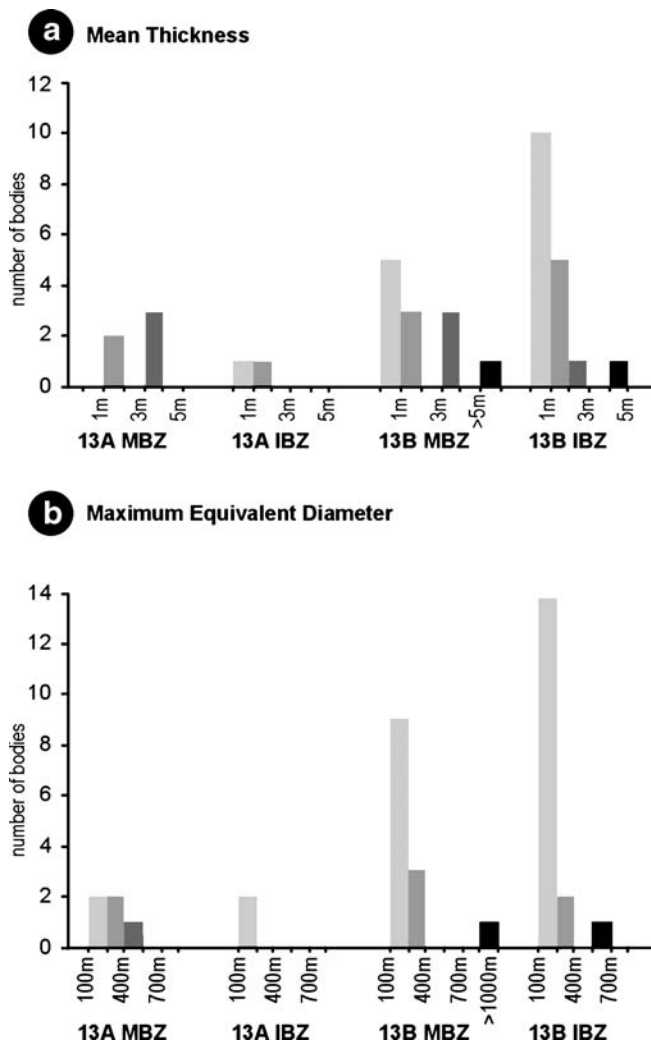


Fig. 10 a, b Histograms for the mean thickness and maximum equivalent diameter of the laterally extensive sand bodies analyzed in MBZ and IBZ, for intervals 13A and 13B

(Fig. 10a), and (3) maximum equivalent diameter (Fig. 10b). Maximum equivalent diameter corresponds to the diameter of a circle with the same maximum area of the selected sand body; this simplification provides us with an approximation to their maximum length, parallel, and perpendicular to the paleocurrent. Only the results for the 37 laterally extensive sand bodies intercepted by at least two wells are presented herein, and a number of characteristics from these bodies must be summarized:

1. These laterally extensive sand bodies include more than 95% of the sand present in the reconstructed axial alluvial fan.
2. Most of these sand bodies show irregular boundaries, and although some of them appear in the reconstruction as elliptical, this apparent simplicity is because the data are not sufficiently dense to capture shapes that are more detailed.
3. Most of the laterally extensive sand bodies show relatively small mean thicknesses (up to 2 m), and

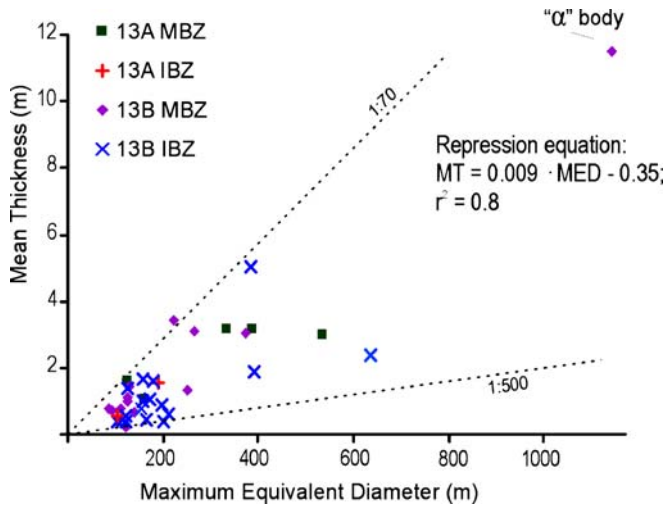


Fig. 11 Aspect ratio for the laterally extensive sand bodies analyzed in MBZ and IBZ for intervals 13A and 13B. See location of the “ α ” body in Fig. 8a and c. The regression equation between mean thickness (MT) and maximum equivalent diameter (MED) is also shown

small maximum equivalent diameters (from 100 to 300 m). Some bodies are thicker (from 3 to 5 m, and rarely up to 11 m), and larger (maximum equivalent diameter ranging from 300 to 800–1,000 m), because of intense stacking and amalgamation. As shown in Fig. 11, thickening is usually paralleled by an increase in the maximum equivalent diameter.

4. The most significant accumulations of sand facies are recorded in MBZ, both in intervals 13A and 13B. The largest sand bodies tend to concentrate there, although some exceptions occur in IBZ during interval 13B (Figs. 9 and 10). In MBZ, most of the sand volume corresponds to a few, very large, multiepisodic bodies. In the more proximal parts of the axial alluvial fan (eastern part of MBZ), laterally and vertically stacked sand deposits were dominant during interval 13B because of the increasing proportion of sand. The largest sand body (“ α ” body) occurs there, characterized by a maximum equivalent diameter of more than 1,000 m, a mean thickness around 11 m, and accounting for approximately 65% of the sand deposited in the axial alluvial fan during sequence 13 (Figs. 8a and c, 9, and 11).
5. In contrast to item 4 above, the sand facies volume accumulated in IBZ is significantly smaller, especially during interval 13A, and during interval 13B, corresponds to a larger number of smaller bodies (Fig. 9).

Other sand bodies, which account for the remaining sand volumes deposited in the alluvial fan, also occur in IBZ and MBZ. These correspond to ribbon paleochannel sands which cannot be mapped with the available data because of their reduced transverse section (see section [Facies description and interpretation](#)). These bodies are mainly expressed in the reconstruction as isolated pods; therefore, their dimensions are not presented herein.

Generation of single to multi-episodic laterally extensive sand bodies

Both field and well observations, coupled with the results of the three-dimensional reconstruction, enabled the precise description of general depositional features of the alluvial fan facies, and provided a better comprehension of the generation and distribution of the laterally extensive sand bodies. The occurrence in fine-grain alluvial fans of single to multi-episodic, laterally extensive sand bodies depends on the more or less repeated development of water laid and/or winnowed deposits (Galloway and Hobday 1996; Miall 1996). In the MBZ, these deposits were associated with the frequent depositional action of sheet floods, which would have resulted in sheet sands. Moreover, in some cases, subsequent braided stream deposition and/or reworking results in the generation of laterally extensive sand bodies (Galloway and Hobday 1996; Miall 1996; Blair and McPherson 1994; Blair 2003). Some of the laterally extensive sand bodies that developed in the medial to medial-distal alluvial fan zones of the MBZ might have resulted also from cycles of trench generation, backfilling, and dispersion of shallow braided channel systems (Schumm et al. 1987; DeCelles et al. 1991).

Implications for aquifer modeling and exploitation

As already discussed (see section [Suitability of data to describe the sand bodies](#)), the sampling well grid captures the laterally extensive sand bodies, allowing their satisfactory and reliable reconstruction. Given the densely spaced conditioning data, it would be of little value either to introduce trends in the proportions (see examples in Journel and Rossi 1989; Falivene et al. 2007a) or use different variograms (i.e. varying ranges or anisotropy directions), for each zone of the axial alluvial fan reconstructed herein. However, variation in facies proportions and variograms along the different alluvial fan zones should be considered when modeling a similar alluvial fan utilizing a stochastic modelling technique with a less closely spaced data set.

The occurrence of unconfined depositional processes, which are typical of the proximal parts of the alluvial fan, and the lateral stacking of sand deposits, would partially overcome the typical elongation tendency of sand bodies along the paleocurrent direction that has been observed in other alluvial fans. These observations (together with uncontrolled small topographic variations or undulations, the presence of non-correlatable lenticular ribbon sand bodies, and curvilinear trends) may also account for the resulting isotropy of the horizontal variogram ranges for sand facies.

The reported parameters (Figs. 9, 10 and 11) can be used to define geological scenarios for modeling similar alluvial fan aquifers. These parameters relate to the laterally extensive sand bodies, which account for the majority of sand facies, and, therefore, porosity in fine-grain dominated alluvial fans. For a more complete modeling of similar depositional systems, the lenticular ribbon sand bodies, which are resolved as isolated pods in

the provided reconstruction (Figs. 2 and 8), should be also included and realistically reproduced. These bodies are mainly related to the development of fluvial water laid deposits, and often occur in the medial to distal basin zones where a distributive fluvial drainage developed (see section [Facies description and interpretation](#)). It was not possible to provide a reliable reconstruction and quantification of these bodies because the well grid does not capture them. However, outcrop observations indicate that lenticular ribbon sand bodies can extend considerably along paleocurrent direction and have the potential to connect several extensive sheet sand bodies. In addition, ribbon sand bodies are typically made up of well-sorted and very permeable material and, thus, may act as preferential pathways for fluid transport.

Concluding remarks

The aquifers residing in fine-grained dominated alluvial fans are characterized by a clear predominance of the aquitard over the aquifer hydrofacies. Thus, aquifer hydrofacies may present a more sparse and unpredictable distribution. The use of indicator kriging applied to a high-density data set enabled reconstruction and interpretation of the hydrofacies structure of a fine-grain dominated alluvial fan. When there is sufficient data density to capture the geological heterogeneity, this method can provide reliable reconstructions of the aquifer-aquitard hydrofacies distribution. A further insight into the heterogeneity of the alluvial system and its origin was obtained through field observation and comparison of the results with the findings of previously described depositional models.

The facies reconstruction enabled us to quantify trends, volumes, mean thickness, maximum area, and maximum equivalent diameter of the laterally more extensive sand bodies. The reconstruction of these bodies resulted in a wide range of dimensions as a function of their changing single or multi-episodic character. This resulted from the frequency and distribution of dominant depositional processes in the diverse alluvial fan and basin zones. Both frequency and distribution varied during the overall progradational evolution of the alluvial system. The successive retractive and expansive situations of the alluvial fan system were contrasted in accordance with the quantified characteristics of the sand bodies. In the retracted alluvial fan interval (13A), fewer laterally extensive sand bodies occur and these were deposited mainly in the eastern marginal basin zone. During the alluvial fan expansive interval (13B), the number of laterally extensive sand bodies increased in the marginal and the inner basin zones. Nevertheless, sand grade concentrated in the marginal basin zones in a few bodies that resulted from intense amalgamation; the largest body amounting to 65% of the sand deposited in the axial alluvial fan during the entire sequence.

The hydrofacies distribution trends and dimensions of the laterally extensive sand bodies can be used as scenarios for input statistical parameters when modeling

aquifer/aquitard hydrofacies in similar fine-grained dominated alluvial fans, or when evaluating poorly known alluvial fans, considering different geological scenarios. These compilations may help to evaluate and reduce uncertainty in the statistical parameters used for building facies models. Thus, in the facies models themselves, which will provide better predictions of hydraulic parameter distributions, and, therefore, improve overall alluvial fan aquifer comprehension and exploitation. However, it should be pointed out that the estimated absolute dimensions and sand fractions could change as a function of geological and climatic constraints despite similar overall trends and processes. The manner in which these parameters can be extrapolated to bigger alluvial fans is still a matter of debate and further quantifications of different alluvial fans are warranted.

The characterization of the occurrence probability, geometry, and distribution of the laterally extensive sand deposits provides also a more accurate geological framework in which to carry out further numerical models of groundwater flow and solute transport.

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