International Journal of Coal Geology 130 (2014) 8–26

Contents lists available at ScienceDirect

International Journal of Coal Geology

journal homepage: www.elsevier.com/locate/ijcoalgeo

Forecasting coal resources and reserves in heterogeneous coal zones using 3D facies models (As Pontes Basin, NW Spain)

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ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form 4 May 2014
Accepted 4 May 2014
Available online 14 May 2014

Keywords:
Resources
Reserves
Splitting
3D facies modelling
Interpolation
Simulation

ABSTRACT

Forecasting coal resources and reserves is critical for coal mine development. Thickness maps are commonly used for assessing coal resources and reserves; however they are limited for capturing coal splitting effects in thick and heterogeneous coal zones. As an alternative, three-dimensional geostatistical methods are used to populate facies distribution within a densely drilled heterogeneous coal zone in the As Pontes Basin (NW Spain). Coal distribution in this zone is mainly characterized by coal-dominated areas in the central parts of the basin interfingering with terrigenous-dominated alluvial fan zones at the margins. The three-dimensional models obtained are applied to forecast coal resources and reserves. Predictions using subsets of the entire dataset are also generated to understand the performance of methods under limited data constraints.

Three-dimensional facies interpolation methods tend to overestimate coal resources and reserves due to interpolation smoothing. Facies simulation methods yield similar resource predictions than conventional thickness map approximations. Reserves predicted by facies simulation methods are mainly influenced by: a) the specific coal proportion threshold used to determine if a block can be recovered or not, and b) the capability of the modelling strategy to reproduce areal trends in coal proportions and splitting between coal-dominated and terrigenous-dominated areas of the basin. Reserves predictions differ between the simulation methods, even with dense conditioning datasets. Simulation methods can be ranked according to the correlation of their outputs with predictions from the directly interpolated coal proportion maps: a) with low-density datasets sequential indicator simulation with trends yields the best correlation, b) with high-density datasets sequential indicator simulation with post-processing yields the best correlation, because the areal trends are provided implicitly by the dense conditioning data.

1. Introduction

1.1. Coal resources, reserves and 3D facies models

Forecasting coal resources and reserves is critical for assessing the feasibility and the optimal development of a coal mine. Resources comprise the estimated amount of coal in the subsurface. Typically, thickness maps have been used for assessing resources, either obtained by: a) interpolation (Starks et al., 1982; Schuenemeyer and Power, 2000; Tercan and Karayigit, 2001; Watson et al., 2001; Heriawan and Koike, 2008a,b; Saikia and Sarkar, 2013; Tercan et al., 2013;), or b) geostatistical simulation methods (Costa et al., 2000; Hohn and McDowell, 2001a,b; de Souza et al., 2004; Olea et al., 2011; Olea and Luppens, 2012; Cornah et al., 2013; Hohn and Britton, 2013; Pardo-Iguzquiza et al., 2013). Interpolation methods applied in this context are appropriate when the goal is to provide a unique composite global estimate for resources. On the other hand, simulations are more useful to capture short-scale fluctuations and local variability in predictions accounting for uncertainty (Goovaerts, 1999; de Souza et al., 2004; Olea et al., 2011; Srivastava, 2013).

Reserves comprise resources that are economically minable at the time of determination (Wood et al., 1983). Some authors have used minimum thickness thresholds to estimate reserves from thickness maps (Schuenemeyer and Power, 2000; Hohn and McDowell, 2001a; Pardo-Iguzquiza et al., 2013;). Heterogeneous coal zones are characterized by frequent coal splitting and rejoining due to interfingering with terrigenous sediments. These result from the variability of sedimentary environments in which coal is generated and accumulated (Hacquebard, 1993; Hower et al., 1994; Thomas, 2003). In these settings reserves can be significantly reduced (compared to resources) because thin coal beds cannot be economically mined (Heriawan and Koike, 2008b). The three-dimensional effects of multiple coal splitting in

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http://dx.doi.org/10.1016/j.coal.2014.05.001

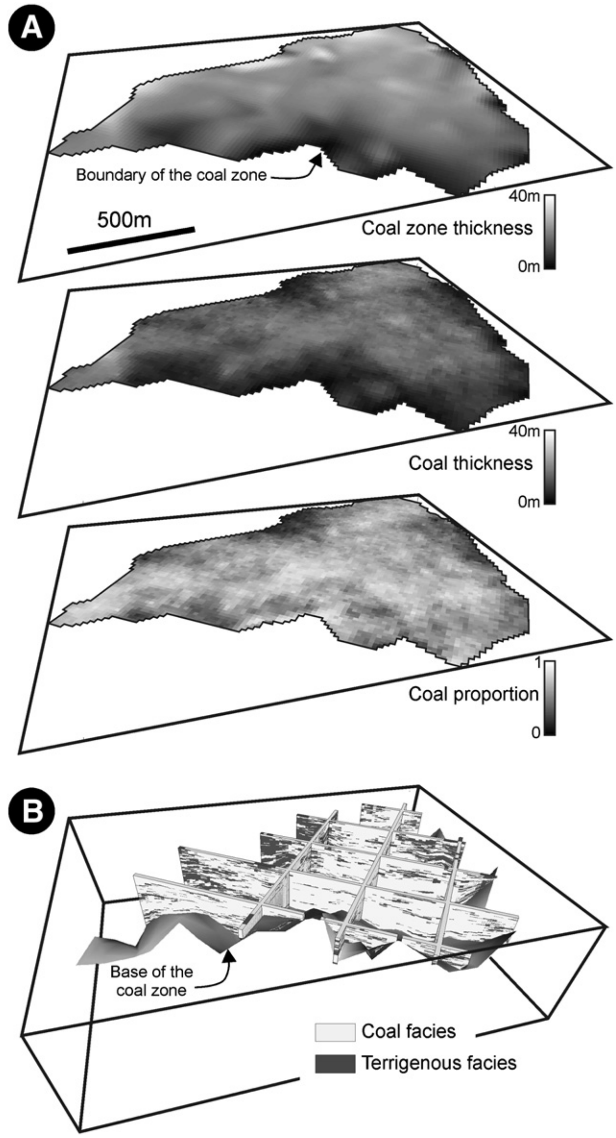

Fig. 1. A) Summary maps characterizing coal versus terrigenous facies distribution in a heterogeneous coal zone. B) Three-dimensional model for coal distribution for the same coal zone viewed by means of a fence diagram. Vertical exaggeration 10×. Note preferential coal splitting due to interfingering with terrigenous sediments in the basin margins.

heterogeneous coal zones are difficult to properly capture and quantify using maps (Fig. 1A).

3D facies models (Haldorsen and Damsleth, 1990, Fig. 1B) provide an alternative to capture coal intercalations and splitting, and improve reserve forecasts for heterogeneous coal zones (Whateley, 2002). Several modelling strategies exist, for example structure-imitating methods aim to reproduce the spatial patterns and distribution of heterogeneities within the deposits without explicitly considering sedimentary processes (Koltermann and Gorelick, 1996). Structure-imitating methods have been widely used to reconstruct or simulate facies distributions in the subsurface, mostly in relation to hydrocarbon reservoirs or aquifers (e.g. Johnson and Dreiss, 1989; Langlais and Doyle, 1993; Gotway and Rutherford, 1994; Lee et al., 2007; de Marsily et al., 1998, 2005). Even in a few cases, the performance of several facies modelling strategies has been compared for reservoirs or aquifers made up of fluvial (Langlais and Doyle, 1993; Journel et al., 1998; Seifert and Jensen, 2000), alluvial fan (Lee et al., 2007) or shallow marine deposits (Jian et al., 2002). However, examples of the application of three-dimensional facies models to coal zones are very limited (Falivene et al., 2007b; Heriawan and Koike, 2008b; Deutsch and Wilde, 2013).

1.2. Aims

This paper focuses on analysing and comparing 3D structure-imitating methods to populate facies distribution within the 6AW heterogeneous coal zone in the As Pontes Basin (NW Spain). Facies distribution in this coal zone resulted from the coeval evolution of different peat-forming wetland environments in a continental basin bordered by alluvial systems, and is mainly characterized by interfingering and intercalations between coal-dominated areas in the centre of the basin grading to terrigenous-dominated areas at its margins.

This type of heterogeneity distribution is difficult to capture with 2D approaches and challenges accurate predictions of coal resources and reserves. Instead, 3D models of facies distributions are tested herein to estimate coal resources and reserves (accounting for coal splitting and assuming exploitation with a bucket wheel excavator). To highlight the effects of the different facies modelling methods, the external geometry (i.e. the total volume) of the coal zone is considered as fixed, and coal quality parameter variations are not explicitly considered. In addition to its complex internal heterogeneity pattern, the 6AW coal zone was chosen because of its significant average thickness (30 m) which might be comparable to other currently exploited coal seams elsewhere; and also because of the existence of an exceptional dataset with 174 continuously-cored wells over an area of 2.05 km^2, resultant from intense coal exploration and production in the basin between 1976 and 2007. Predictions by using decimated subsets of the entire dataset are also obtained to understand the performance of the methods with limited data, such as in studies to determine economics of future mines.

The paper is structured into five parts dealing with: a) the studied dataset and general setup for the models, b) the application of traditional map-based interpolation methods for estimating resources, c) the application of 3D facies interpolation and simulation methods to obtain facies distributions, d) the resultant coal resources and reserves predicted by each method, and e) a discussion and concluding remarks.

2. Studied dataset and general setup

2.1. The 6AW coal zone

The As Pontes Basin (Oligocene–Early Miocene, NW Spain) is a small continental basin (12 km^2) developed in relation to a strike–slip fault system (Santanach et al., 1988, 2005; Fig. 2A).

The basin fill developed into two sub-basins and can be subdivided into 5 major genetic stratigraphic units (Ferrús, 1998; Sáez and Cabrera, 2002; Sáez et al., 2003), with the 6AW zone sitting on the upper part of Unit 1 in the Western subbasin, and bounded by isochronous surfaces (Huerta et al., 1997; Ferrús, 1998; Fig. 2B). This zone accumulated during the early evolutionary stages of the fault system. During its deposition the northern margin of the Western subbasin was affected by thrusting involving mainly basement units, and the eastern margin was bounded by coeval active normal faults limiting the extension of the sedimentation area. Meanwhile, the south-western passive margin recorded onlap and progressive expansion of the sedimentary basin areas, reaching 2.5 km^2 during its late depositional stages (Fig. 2B and C, Ferrús, 1998; Santanach et al., 2005). Coal deposition in the 6AW zone took place in well-developed marshes and swamps where tropical terrestrial and aquatic plant communities (Cavagnetto, 2002; Martín-Closas, 2003) were bordered by short radius fine-grained alluvial fans (Bacelar et al., 1988; Cabrera et al., 1995, 1996; Ferrús, 1998; Sáez and Cabrera, 2002; Sáez et al., 2003; Falivene et al., 2007b). The deposits of the 6AW zone are affected by post-depositional tilting towards the