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Title: Forward seismic modeling as a guide to improve detailed interpretation of deltaic systems: Example of the Eocene Sobrarbe Deltaic Complex (South-Pyrenean foreland basin, Spain) as a reference to the analogous Albian-Cenomanian Torok-Nanushuk Delta of the Colville Basin (NPRA, USA)

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Abstract: The analysis of forward seismic models generated from outcrop studies improves seismic interpretation. The Middle Eocene Sobrarbe delta outcrops (South-Pyrenees, Spain) are excellent candidates for forward seismic modeling because of their extraordinary continuity and exposure. A stratigraphic dip-section was built from this detailed outcrop dataset and converted to an acoustic impedance model by attribution of petrophysical properties to 17 selected facies. The transect shows thin sedimentary beds and subtle facies variations that led to simulate seismic models under near-reality conditions. Two stacked and migrated forward seismic models were generated with 30 and 60 Hz Ricker wavelets. A blind seismic sequence interpretation using the seismic-stratigraphy method revealed significant differences with the 4th-order sequences identified in the field by classical sequence stratigraphy. Higher-order sequence boundaries and/or composite reflections caused by interferences near facies-transition zones create incorrect reflexion terminations and pseudo-reflexions that can be misinterpreted as sequence boundaries. We propose a seismic facies analysis from alluvial plain to deep basin environments by descriptions and interpretations of seismic reflexion parameters. This work also presents guidelines to identify the different systems tracts within the 4th-order depositional sequences. The correct interpretation of seismic systems tracts allows to better predict sub-seismic reservoir facies distribution and quality. The most voluminous reservoirs with high net-to-gross ratios are characterized by: (1) a transparent seismic facies due to the low internal reflectivity of thick laterally-stacked delta front deposits in a falling stage systems tracts; (2) discontinuous and strong amplitude reflections of stacked turbidites within a transparent interval in the highstand systems tract clinoforms bottomsets. Finally, close similarities between the seismic model and real seismic lines from the Torok/Nanushuk deltaic system (Colville

Basin, NPRA, USA) allowed the direct analogy and discussion of our results.

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- The forward seismic model was made from a very detailed correlation panel of deltaic outcrops
- The “seismic stratigraphy” methodology is consistent and allows the correct interpretation of most of seismic sequences
- Reflections from rapid lateral facies transitions and higher-order sequence boundaries can lead to seismic interpretation mistakes
- The seismic facies of 7 facies associations observed at outcrops have been described
- The prediction of the reservoir bodies distribution and quality in a deltaic depositional system was highlighted in highstand, transgressive and falling-stage systems tracts
- Most of the attributes and geometries of the forward seismic modeling have been recognized in a real seismic analog

**Forward seismic modeling as a guide to improve detailed interpretation of deltaic systems:
Example of the Eocene Sobrarbe Delta (South-Pyrenean foreland basin, Spain), as a reference to
the analogous Albian-Cenomanian Torok-Nanushuk Delta of the Colville Basin (NPRA, USA)**

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ABSTRACT

The analysis of forward seismic models generated from outcrop studies improves seismic interpretation. The Middle Eocene Sobrarbe delta outcrops (South-Pyrenees, Spain) are excellent candidates for forward seismic modeling because of their extraordinary continuity and exposure. A

1 stratigraphic dip-section was built from this detailed outcrop dataset and converted to an acoustic
2 impedance model by attribution of petrophysical properties to 17 selected facies. The transect shows
3 thin sedimentary beds and subtle facies variations that led to simulate seismic models under near-
4 reality conditions. Two stacked and migrated forward seismic models were generated with 30 and 60
5 Hz Ricker wavelets. A blind seismic sequence interpretation using the seismic-stratigraphy method
6 revealed significant differences with the 4th-order sequences identified in the field by classical
7 sequence stratigraphy. Higher-order sequence boundaries and/or composite reflections caused by
8 interferences near facies-transition zones create incorrect reflection terminations and pseudo-
9 reflections that can be misinterpreted as sequence boundaries. We propose a seismic facies analysis
10 from alluvial plain to deep basin environments by descriptions and interpretations of seismic
11 reflection parameters. This work also presents guidelines to identify the different systems tracts
12 within the 4th-order depositional sequences. The correct interpretation of seismic systems tracts
13 allows to better predict sub-seismic reservoir facies distribution and quality. The most voluminous
14 reservoirs with high net-to-gross ratios are characterized by: (1) a transparent seismic facies due to
15 the low internal reflectivity of thick laterally-stacked delta front deposits in a falling stage systems
16 tract; (2) discontinuous and strong amplitude reflections of stacked turbidites within a transparent
17 interval in the highstand systems tract clinoform bottomsets. Finally, close similarities between the
18 seismic model and real seismic lines from the Torok/Nanushuk deltaic system (Colville Basin, NPRA,
19 USA) allowed the direct analogy and discussion of our results.

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46 *Keywords: Forward seismic modeling, Sobrarbe deltaic complex, Seismic facies, Seismic stratigraphy*

47 48 49 50 51 52 **1. Introduction**

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55 In most provinces of the world, oil and gas reservoirs are experimenting a mature stage of
56 production with remaining reserves located in subtle stratigraphic traps. One of the main challenges
57 in exploration and production is to predict and characterize the thickness and extent of reservoir

bodies that are below or at the limit of seismic resolution. The well data of a few centimeters of vertical resolution (1-D) is too sparse to allow an accurate spatial propagation of facies within a computer model of a petroleum reservoir. By contrast, seismic surveys allow to investigate the 2-D and 3-D stratigraphic architecture of reservoir units for a seismic resolution of 10 to 20 meters. Seismic resolution prevents or impairs the interpretation of high-frequency sequences (higher than third-order). Unfortunately, there is no subsurface tool leading to the acquisition of 2-D or 3-D geological information at the meter-scale, scale used for reservoir modeling in the petroleum industry.

Outcrop studies allow to integrate the whole range of geological observation scales in two or three dimensions: from the thin-section to the stratigraphic and structural regional scale (Nichols, 2015). Therefore, outcrop studies provide geological data which fill the resolution gap between well and seismic data. Integrating the results of these very detailed outcrop studies in reservoir models is not automatic. The integration requires a phase of upscaling, back to the seismic scale, and the identification of guides and subtle criteria to improve the seismic interpretation of high-frequency sequences. This work leads to better predict the distribution and characterization of reservoir bodies within the different systems tracts. Forward seismic modeling, which simulates a theoretical seismic line from a geological transect, is the ideal tool to complete this step (Biddle et al., 1992; Rudolph et al., 1989; Helland-Hansen et al., 1994; Anselmetti et al., 1997; Schwab et al., 2007; Falivene et al., 2010; Bakke et al., 2011; Holgate et al., 2014).

Ancient fluvio-deltaic systems hold an important proportion of global hydrocarbon reserves. The world-class outcrops of the middle Lutetian to Bartonian Sobrarbe deltaic complex (Dreyer et al., 1999) exposed in the South Pyrenean foreland basin are very good analogs for fluvio-deltaic sandstone reservoirs in active tectonic settings. The exceptional outcrop continuity enables to characterize the small-scale geometry and heterogeneity variations of the sedimentary bodies accumulated from the continental domain to the relatively deep basin environment (**Figure 1**). The

1 sedimentary and stratigraphic architecture analysis leads to identify the global and local factors
2 controlling the tectono-sedimentary evolution of the delta. The Sobrarbe Delta has already been
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4 studied on several occasions: stratigraphic and tectono-sedimentary evolution (Wadsworth, 1994;
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6 Dreyer et al., 1999; Moody, 2014; Grasseau, 2016); geometries (Callot et al., 2009; Odonne et al.,
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8 2011); sedimentary facies (Labourdette, 2011; Mateu-Vicens et al., 2012) and diagenesis (Hoareau,
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10 2009). The aim of the present paper is to provide guidance to improve the seismic interpretation of
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12 real subsurface deltaic systems from the forward seismic modeling of the Sobrarbe deltaic complex
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14 outcrops.
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19 Several authors have already published seismic deltaic system analysis using forward seismic
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21 modeling of clinoforms (Helland-Hansen et al., 1994; Zeng and Kerans, 2003; Holgate et al., 2014)
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23 and deep siliciclastic turbidite systems (Bourgeois et al., 2004; Schwab et al., 2007; Falivene et al.,
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25 2010). Other models focused on the interpretation uncertainties of the “seismic-stratigraphy”
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27 methodology (Hodgetts and Howell, 2000; Zeller et al., 2015) or on the seismic interpretation limits
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29 due to seismic resolution (Rudolph et al., 1989; Schlager, 1991; Biddle et al., 1992; Helland-Hansen et
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31 al., 1994; Gartner and Schlager, 1999; Zeng and Kerans, 2003). The Sobrarbe Delta forward seismic
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33 model presented in this paper was built from a field transect measuring 15 km long and 700 m of
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35 average thickness. Entire stratigraphic architecture and lateral facies variations observed in the field
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37 were preserved (**Figure 2a**) to generate a seismic image similar to a real subsurface seismic line. The
38
39 effects of subtle facies variations and lens-shaped bodies showing a thickness or extent below
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41 seismic resolution could be analyzed. The forward seismic model allowed to study the seismic image
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43 of the deltaic system at the scale of: (1) low- and high-frequency sequences (3rd and 4th order), (2)
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45 systems tracts (controlled by the evolution of the Accommodation (A) versus Sedimentation rate (S)
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47 ratio), (3) sediment bodies seen from the alluvial plain to the deep-marine basin, (4) specific
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49 geometries such as submarine slide surfaces which are relatively frequent in a syntectonic settings.
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51 Several synthetic seismic models were generated with different peak-frequencies (20 to 60 Hz) to
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1 discuss the influence of seismic resolution on interpretation uncertainties and to define guides or
2 subtle criteria to minimize them.
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5 The forward seismic models have been compared to the real seismic lines of the the Early-Cretaceous
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7 (Albian) deltaic system located in the National Petroleum Reserve of Alaska (USA) (**Figure 2b**). The
8
9 deltaic system made up by the Nanushuk and Torok Formations (Brookian Sequence) is characterized
10
11 by large-scale clinoforms which filled progressively the Colville foreland basin during the
12
13 development of the Brooks Mountain Range (Molenaar, 1983, 1985, 1988; McMillen, 1991; Bird and
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15 Molenaar, 1992; Houseknecht, 2001; Houseknecht, Bird, et al., 2009; Houseknecht, Burns, et al.,
16
17 2009). The Sobrarbe deltaic complex and the Nanushuk/Torok delta were both accumulated in
18
19 syntectonic compressive settings and display similar geometrical and sedimentological features. The
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21 analogy between the forward and the real seismic lines allows to directly apply the results of this
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23 study on a concrete example and to discuss their validity.
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33 **2. Outcrop transect: the Sobrarbe Delta**

34 **2.1. Geological setting**

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37 The Pyrenean chain is an E-W intracontinental mountain range resulting from the collision between
38
39 the Iberian and European plates from the Late Cretaceous to the Tertiary times. The Pyrenees
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41 constitute a divergent asymmetric orogenic wedge with associated foreland basins to the south and
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43 north (Muñoz, 1992). The studied stratigraphic unit is located in the South-Pyrenean Zone which is
44
45 bordered northward by the axial zone and southward by the non-deformed Ebro foreland basin
46
47 (**Figure 1b**). The South-Pyrenean zone is represented by a piggy-back sequence of southwards-
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49 displaced Mesozoic thrust sheets (Bóixols-Cotiella, Montsec-Peña Montañesa and Gavarnie-Sierras
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51 Exteriores) which developed a series of thrust-top sedimentary basins from the Upper Cretaceous to
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53 the Paleogene (Ori and Friend, 1984). The north-south contraction and shortening is accompanied by
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1 a migration of deformation from east to west due to a counterclockwise rotation of the Iberian plate
2 (Choukroune, 1974, Arthaud and Séguret, 1981; Roest and Srivastava, 1991; Muñoz, 1992).
3
4 Present day North-south trending synsedimentary anticlines and synclines also developed at or near
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6 the lateral/oblique ramps of these thrusts (**Figure 1b**). However, some of them have suffered
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8 important vertical axis rotations during the emplacement of different thrust sheets (Muñoz et al.,
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10 2013).
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14 The south-Pyrenean foreland basin is made up of several sub-basins delimited by major north-south-
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16 trending folds perpendicular to the orogen. The Middle Eocene succession of the Sobrarbe deltaic
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18 complex progressively filled the Ainsa sub-basin located at the top of the Gavarnie-Sierras Exteriores
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20 nappe in the central part of the South-Pyrenean foreland basin (**Figure 1**) (Puigdefàbregas et al.,
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22 1992; Muñoz et al., 1994). The geometry of the Ainsa basin is mainly controlled by the NNW/SSE
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24 trending Buil syncline located between the synsedimentary anticlines of Boltaña (west) and Mediano
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26 (east).
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32 The Sobrarbe deltaic complex corresponds to a syntectonic sedimentary wedge locally thicker than
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34 1000 m. The progradation of this sedimentary system over more than 15 km towards the NNW
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36 (**Figures 1 and 2a**) was controlled by the orientation of the Ainsa sub-basin (Puigdefàbregas, 1975; De
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38 Federico, 1981; Wadsworth, 1994; Dreyer et al., 1999; Grasseau, 2016). The Sobrarbe Delta consists
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40 of a succession of depositional environments characteristic of a fluvio-deltaic sedimentary system
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42 mainly dominated by fluvial currents (Garrido-Megias, 1968; Van Lunsen, 1970; Puigdefàbregas,
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44 1975; De Federico, 1981; Wadsworth, 1994; Dreyer et al., 1999; Moody, 2014; Grasseau, 2016).
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53 **2.2. Transect and depositional environments**

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56 The great lateral continuity of the Buil syncline western exposures have allowed to make a
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58 correlation transect between the villages of Mondot and Santa Maria de Buil which is the input data
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of the forward seismic modeling (**Figure 2a**). This highly detailed proximal (SSE) to distal (NNW) correlation transect was built from 40 field-measured stratigraphic log sections (Scale: 1: 100) physically correlated between them. The fluvio-deltaic system base is defined on the Buil syncline west limb by the black-marl marker level of San Lino (Arbués et al., 2011; Grasseau, 2016). The top of the Sobrarbe deltaic complex is the Olsón stratigraphic discontinuity interpreted as a minimum of accommodation within the Escanilla Formation (Bentham, 1992; Dreyer et al., 1999; Muñoz et al., 2013).

On the Sobrarbe deltaic complex five depositional environments and 16 sub-environments have been differentiated (Grasseau, 2016) (**Figures 1, 2a and Table 1**).

The Prodelta environment is characterized by blue-gray marls incised by fine to coarse sandstones and heterolithic sandstones interpreted as turbidite channels and lobes (**Figure 2a**). These deposits belong to the San Vicente Formation (Van Lunsen, 1970). Two kinds of turbidite system were defined: a type 1 turbidite system characterized by continuous thin deposits extended from the delta front to the prodelta environment, a type 2 turbidite system which is thick and isolated within the prodelta marls in more distal parts of the basin. Type 1 turbidites consist of an alternation of meter-thick fine- to coarse-grained sandstone beds with planar bedding, and heterolithic intervals of several-centimeters-thick fine-grained sandstone beds and marl. Type 2 turbidites consist of stratified fine- to medium-grained sandstone with planar bedding and megaripple cross-bedding. These deposits grade laterally to fine-grained sandstone layers presenting planar and current-ripple bedding, which alternate with laminated silt intervals.

Towards the continent, the deep marine San Vicente Formation grades progressively to the deltaic Sobrarbe Formation characterized by delta-front to delta-plain deposits. Delta front environment is characterized by sandstone deposition on deltaic foreset and topsets. Silts and bioturbated fine- to medium-grained sandstone, locally carbonate-rich (due to a high concentration of nummulites), form the distal to middle delta front deposits deposited on foreset areas (De Federico, 1981; Wadsworth,

1994; Dreyer et al., 1999; Grasseau, 2016). A succession of erosive medium- to coarse-grained sandstone beds with planar bedding and megaripple cross-bedding, interpreted as mouth-bars and terminal distributary channels, form the proximal delta front deposits of the topset where local tidal reworking was recorded by sediments. Submarine gravity slides, more than hundreds of meters wide, locally incise the delta-front and prodelta deposits cutting down more than 100 m of thickness (**Figure 2a**) (Wadsworth, 1994; Dreyer et al., 1999; Callot et al., 2009; Grasseau, 2016). Carbonate shallow marine deposits, accumulated during transgressive episodes, are characterized by (1) localized carbonate platforms made up of reef or peri-reefal facies, or (2) sandy-carbonate shoals rich in nummulites (**Figure 2a**). Towards the proximal part, upper delta front deposits grade to shale-rich lower delta plain deposits, locally incised by fine- to coarse-grained lenticular sandstone bodies with megaripple cross-bedding, corresponding to isolated fluvial distributary channels.

The Escanilla Formation (red facies association in **Figure 2a**) is the alluvial lateral equivalent of the Sobrarbe Formation. It consists of an association of conglomeratic sandstone and fine- to coarse-grained sandstone layers, corresponding to amalgamated fluvial channels incising the alluvial plain reddish shales (Garrido-Megias, 1968).

2.3. General stratigraphic architecture

The Sobrarbe delta complex is a large-scale highly-progradational and moderately aggradational system punctuated by two transgressive episodes resulting in three Transgressive-Regressive composite sequences of hundreds of Kyrs of duration. A more detailed sequence-stratigraphic analysis (Grasseau, 2016) subdivided the succession in nine 4th-order depositional sequences S1 to S9 in **figure 2a**. Most of these sequences are defined from the four-tract model (Hunt and Tucker, 1992) including Lowstand, Transgressive, Highstand and Falling-stage systems tracts. However, in some cases a regressive systems tract has been defined when the differentiation among Lowstand, Falling-stage systems tract and Highstand was not possible. In this last case, sequences are two-tract type (T-R

1 or Transgressive-regressive sequences from Johnson et al., 1985, Embry & Johannessen, 1992; López-
2 Blanco, 1993; López-Blanco 2000). Deltaic sequences S1 and S2 were only deposited on the
3
4 southeastern area of the Bui syncline. Thus the western Bui syncline transect (correlation panel)
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6 shows a detailed architecture of the Sobrarbe deltaic complex including only sequences S3 to S9
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8 **(Figure 2a)**. These 4th order sequences can be subdivided in a series of higher-frequency sequences
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10 or parasequences whose stacking defines the different systems tracts trends.
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14 The variations of the 4th-order depositional sequences stacking pattern form three 3rd-order
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16 depositional sequences SI to SIII equivalent to the transgressive-regressive composite sequences
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18 (Johnson and Murphy, 1984; Embry and Johannessen, 1992). Sequence SI records the progradation
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20 of the deltaic system over more than 12 km towards the NNE and the accumulation of more than 200
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22 m-thick deposits in the distal part. The 300 m-thick Sequence SII is characterized by two regressive
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24 phases separated by a minor transgressive stage. The deltaic system prograded and retrograded over
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26 distances ranging from 5-6 km. Sequence SIII is mainly characterized by 40 m-thick Nummulite-rich
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28 deposits recording a major transgression of the deltaic system over more than 12 km. The
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30 backstepping of the deltaic system is followed by the progradation of facies belts over 15 km and the
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32 accumulation in the distal part of at least 250 m of deposits. The original dip of clinoforms varies
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34 from 0.2° to 5.7° (Grasseau, 2016).
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42 The sedimentary organization of the 3rd-order sequences was clearly influenced by the variations of
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44 the subsidence rate of the Ainsa sub-basin. The development of tectonic structures of more or less
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46 wide amplitude hid locally the effects of subsidence during certain periods. These parameters are
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48 recorded by particular depositional geometries such as wedging towards active tectonic structures,
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50 increase of clinoform dip angles and delta progradation rate, or by an important accumulation of
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52 sediments in the topset of the deltaic system in areas affected by an increase of subsidence
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54 (Grasseau, 2016).
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3. Subsurface analog: the Nanushuk-Torok fluvio-deltaic system

The Albian-Cenomanian Nanushuk-Torok deltaic system was deposited in the Colville foreland basin (National Petroleum Reserve of Alaska, USA). The foreland basin mainly formed during the Cretaceous and Tertiary, by flexural subsidence in response to the simultaneous development of the Brooks Range orogenic belt to the south, of the Herald Arch thrust belt to the west and of the Beaufort rift shoulder to the north (**Figure 3**) (Bird and Molenaar, 1992; Moore et al., 1994).

The Nanushuk-Torok system corresponds to a syntectonic prograding-aggrading fluvio-deltaic complex within a first-order depositional sequence (Molenaar, 1985, 1988; Mull et al., 2003; LePain et al., 2009). The base of this deltaic succession corresponds to the Hue Shale Member, known as the gamma-ray zone (GRZ) or highly radioactive zone (HRZ), a highly organic-rich condensed shale interval deposited in the most distal part of the basin (Carman and Hardwick, 1983; Molenaar, 1983, 1985, 1988; Molenaar et al., 1987; Bird and Molenaar, 1992; Creaney and Passey, 1993). The overlying prodelta deposits correspond to the Torok Formation, mainly made of silty shales, siltstone, mudstone and argillaceous sandstone, incised by turbidite sandstone channels and lobes (Molenaar, 1985, 1988; Bird and Molenaar, 1992; Houseknecht, 2001; Houseknecht and Schenk, 2007; LePain et al., 2009). On seismic lines, the Torok Formation corresponds to the foreset and bottomset parts of well-imaged clinoform reflections (**Figure 2b**). In the topset part of the sigmoid clinoforms, the Torok Formation grades laterally to the Nanushuk Formation, mainly characterized by an alternation of shale and sandstone beds. The sandstone beds are coarsening-up and thickening-up amalgamated delta-front deposits, characterized by storm wave-generated structures. These delta-front deposits grade laterally to a complex facies assemblage of sandstone, mudstone, coal and conglomerates, interpreted as bay-fill, delta-plain and alluvial-plain deposits (Fisher and McGowen, 1969; Ahlbrandt et al., 1979; Huffman et al., 1985, 1988, Molenaar, 1985, 1988; LePain and Kirkham, 2001; Houseknecht, Bird, et al., 2009; LePain et al., 2009). In the studied area, the sediment distribution within the deltaic system appears to have been mainly controlled by fluvial processes. Shoreface

deposits were however clearly reworked by wave action (Ahlbrandt et al., 1979; Huffman et al., 1988; LePain and Kirkham, 2001; LePain et al., 2009).

To the north of the Colville Basin, the total thickness of prograding wedges ranges between 600 and 1000 meters, whereas in the southern part of the basin, the total thickness reaches 1700 to 2500 meters. The average length of clinoform slope is approximately 30 km in the north and 70 km in the south of the Colville Basin. The average clinoform dip varies between 0.6° and 2.5°. In the foresets and bottomsets, sedimentary accumulations resedimented from gravity slides or destabilizations are frequently imaged on seismic lines by low-amplitude contorted reflections truncating underlying reflections (Houseknecht et al., 2009).

The seismic data base used for our research consists of a grid of 27 2D seismic lines acquired in 1981 by the Federal Government of the United States in the northeastern part of the Colville Basin in the National Petroleum Reserve of Alaska (NPRA). The seismic lines have been processed and migrated via modern technics of signal processing, and then made available to the public domain by the USGS (United States Geological Survey). These seismic lines are characterized by a peak frequency of 40 Hz and a vertical seismic resolution of approximately 20 meters in the studied interval (**Figure 2b**).

4. Forward seismic modeling: methodology

The detailed transect of the Sobrarbe delta was drawn in the GXII (ion) software by first tracing the time lines and then reproducing the lateral facies variations observed at outcrop (**Figure 2**). The parts of the correlation transect that were not visible at outcrop were restored by paleogeographic reconstruction (Grasseau, 2016). A homogeneous unit of 600 meters, corresponding to fluvial deposits, has been added above the Sobrarbe fluvio-deltaic succession in order to take into account the effects of burial (overburden) on the synthetic seismic image. 17 facies (over 24) have been selected on the original transect for their recurrence and their reservoir potential. Each facies was

1 assigned a value of density and a value of seismic wave propagation velocity, in order to convert the
2 outcrop transect into an acoustic impedance model (**Figure 4a, Table 1**). Velocity and density values
3 were interpreted from the analysis of well logs intercepting the Torok and Nanushuk Formations in
4 the subsurface analog (NPRA). For that purpose, a comparative analogy was made between the
5 facies of the two deltas (**Table 1**). On the acoustic impedance model, all the beds measuring more
6 than 5 meters in thickness were represented, even if they were thinner than seismic resolution. The
7 model includes a maximum of geological detail in order to simulate a more realistic composite
8 response of the seismic signal passing through a similar geologic setting (Schwab et al., 2007).
9

10 The forward seismic model was generated from the acoustic impedance model by vertical incidence
11 ray-tracing. This method allows to generate the equivalent of post-stack, processed and fully
12 migrated forward seismic sections (**Figures 4b & c**), directly comparable with real processed seismic
13 lines. The synthetic seismic was created using zero phase Ricker wavelets of varying peak frequencies
14 (30 and 60 Hz), a sampling rate of 4 ms and a Source/Geophone spacing of 6.25 m, comparable with
15 the acquisition parameters of industrial 2D or 3D seismic data. A positive standard polarity is used on
16 the synthetic seismic lines, i.e. a positive amplitude (peak reflection, red color) corresponds to a
17 positive reflection coefficient, and a negative amplitude (trough, blue color) corresponds to a
18 negative reflection coefficient. The theoretical vertical resolution of the forward seismic lines is
19 calculated from Rayleigh's criterion of 1/4 of the wavelength. It corresponds to ca. 25 meters for a
20 peak frequency of 30 Hz and ca. 15 meters for a peak frequency of 60 Hz.
21

22 5. Results

23 The synthetic seismic profiles (30 and 60 Hz) are characterized by a succession of oblique and
24 sigmoid clinoform reflections, presenting variable continuity and amplitude due to the variable
25 distribution of acoustic impedance contrasts within the stratigraphic architecture of the Sobrarbe
26 delta (**Figures 4b & c**). Within the topsets of sigmoid clinoforms, the reflections are mainly tabular,
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1 wavy and discontinuous, presenting either strong or weak amplitude. Foreset reflections are
2 characterized by continuous, medium- to low-amplitude dipping reflections, which locally end by
3 erosional truncation. The bottomset part of the clinoforms is mainly characterized by a transparent
4 seismic facies, within which isolated high-amplitude seismic reflections are visible and locally end
5 with onlap terminations towards the proximal part. The reflections on the 30Hz synthetic seismic
6 model are characterized by higher apparent amplitude and continuity than the reflections on the 60
7 Hz seismic model. With a seismic signal of 30 Hz peak-frequency, more interferences between the
8 reflections provide a lower-resolution image of the stratigraphic architecture of the Sobrarbe delta.
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23 **5.1. Seismic stratigraphy**

24 **5.1.1. Blind analysis**

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26 The analysis of reflection terminations and clinoform offlap-break trajectories (seismic stratigraphy)
27 has allowed the blind interpretation of nine 4th-order seismic sequences on the 60 Hz forward seismic
28 model (**Figure 5b**).
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37 The first interpreted seismic sequence is characterized by a succession of low-amplitude negative
38 reflections (trough) organized as oblique clinoforms, which end with toplap terminations below a
39 continuous high-amplitude peak reflection. This high-amplitude reflection has been interpreted as
40 the seismic sequence boundary.
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47 The second interpreted seismic sequence is also characterized by medium- to low-amplitude oblique
48 clinoform reflections, which end with toplap terminations under a rather continuous peak reflection
49 of high-amplitude, interpreted as the seismic sequence boundary.
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55 The third seismic sequence consists of similar oblique clinoform reflections as in sequence 2. The
56 clinoforms seem to end with toplap terminations under a continuous high-amplitude peak reflection,
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dipping towards the proximal area and marked by a « step-like » undulating geometry around the 10th km of the transect. This reflection is characterized by an incised geometry marked by toplap terminations around the 12th and 13th km of the transect. This peak reflection, interpreted as the top of sequence 3, is also the top of sequences 1 and 2 between 10.5 km and 14 km.

The fourth interpreted seismic sequence is mainly characterized by several medium-amplitude sigmoid to oblique clinoform reflections. The offlap break trajectory, upward and toward the distal area, records a phase of progradation-aggradation of the deltaic system. The clinoforms end with onlap terminations on the reflection corresponding to the top of sequence 3, or with toplap terminations under a high- to medium amplitude continuous reflection interpreted as the top of sequence 4.

The fifth interpreted seismic sequence is relatively thin, consisting of a few tabular high- to medium-amplitude reflections, which correspond to the proximal topset part of sigmoid clinoforms. A very-high-amplitude reflection triplet (peak-trough-peak) is particularly visible in the middle part of this sequence (between 5.5 and 9 km). These reflections become discontinuous with a lower and variable amplitude after 9 km (proximal part of the topset). The upper boundary of this seismic sequence is marked by a continuous reflection of high to medium positive amplitude, characterized by erosional truncations below and onlap terminations above.

The sixth interpreted seismic sequence is characterized by peak reflections of medium to high amplitude, locally undulating, corresponding to sigmoid clinoforms that are truncated distally and end with onlap terminations proximally. The trajectory of the clinoform offlap-breaks appears mainly vertical which corresponds to an aggradation. The upper boundary of this seismic sequence is a discontinuous peak reflection of very variable amplitude, marked by erosional truncations and onlap terminations. This sequence boundary is difficult to pick, particularly towards the proximal part.

The seventh interpreted seismic sequence is characterized in its lower part by two high-amplitude reflections corresponding to sigmoid clinoforms, marked by a steep offlap break and a concave-up

1 profile. They end with onlap terminations proximally. The upper part of this seismic sequence is
2 made of high-amplitude, very discontinuous, undulating reflections between the 8th and 14th km.
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4 Between the 3rd and 8th km, these reflections become more continuous, tabular and present a lower
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6 amplitude. They end distally with erosional truncations below a very low-amplitude, concave-up
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8 reflection (slide scar on **Figure 5b**). The upper boundary of this seismic sequence is interpreted on a
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10 continuous reflection of strong negative amplitude (trough), along which several reflections end with
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12 onlap or toplap terminations.
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17 The interpreted seismic sequence 8 is characterized by two reflections of medium to low amplitude,
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19 which geometries resemble sigmoid clinoforms. The top of this seismic sequence is interpreted on a
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21 continuous low-amplitude reflection, marked by onlap terminations.
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25 The ninth interpreted seismic sequence is characterized by low-amplitude concave-up reflections.
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27 They end with toplap terminations below a high-amplitude reflection (between km 0 and 6),
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29 interpreted as the sequence boundary. This reflection grades laterally to a very low-amplitude to
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31 transparent reflection between km 6 and 11, and then becomes discontinuous of medium amplitude
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33 between km 11 and 14.
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41 **5.1.2. Discussion**

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44 A correct interpretation of subsurface data from seismic stratigraphy is necessary to characterize the
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46 general stratigraphic architecture of sedimentary systems. Thus, it allows to limit the uncertainties
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48 linked with the distribution and continuity of reservoir bodies, which are the essential parameters to
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50 predict spatial variations of petrophysical properties and net-to-gross ratio. In theory, the
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52 interpretation of seismic sequences on the synthetic seismic profiles should allow to reconstruct a
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54 sequence architecture identical to the sequence architecture of the geological transect with the
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56 same order of sequences. On the 60 Hz seismic model, the picking of the top of the seismic
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1 sequences 1, 2, 4, 6, 7 and 8 (**Figure 5b**) corresponds directly to the projected position of sequence
2 boundaries described on the geological transect (**Figure 5c**). However, the interpreted seismic
3 sequences 3 and 5 do not correspond to original 4th-order sequences on the geological transect.
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7 The projection of the real geological time lines on the seismic model (**Figure 6d**) shows that the
8 reflection interpreted as the top of seismic sequence 3 is not the seismic image of a unique time line,
9 but the combined image of several very close time lines which appears like a composite reflection,
10 relatively continuous, locally wavy, presenting a step-like geometry. This geometry is particularly
11 visible on the positive high-amplitude reflection presenting a dip towards the proximal area, between
12 kilometers 10 and 11 (**Figures 6b and c**). The seismic imaging, limited by its vertical resolution,
13 generates false reflection terminations and pseudo-discontinuities via tuning effects (interference)
14 when stratigraphic surfaces are too close (Rudolph et al., 1989; Schlager, 1991; Biddle et al., 1992;
15 Helland-Hansen et al., 1994; Gartner and Schlager, 1999; Zeng and Kerans, 2003). Therefore, lateral
16 facies variations can be imaged, at low frequency, by a seismic reflection with a step-like geometry,
17 which resolution increases with the frequency of the seismic profile (Schlager, 1991; Zeng and
18 Kerans, 2003).
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37 A theoretical model of a prograding-aggrading deltaic sequence was drawn on the GXII software, and
38 then converted into a synthetic seismic profile in order to analyze in detail the seismic response of
39 the facies transition between delta-plain and delta-front deposits in the topset of sigmoid clinoforms
40 (**Figure 7**). On the synthetic seismic line generated with a 30 Hz peak frequency (**Figure 7b**), the
41 transition zone between the delta-plain facies and the delta-front facies is characterized by a high-
42 amplitude positive reflection presenting a wavy, step-like geometry, under which pseudo-oblique
43 clinoform reflections terminate with pseudo-toplap terminations. With a 60 Hz peak frequency
44 (**Figure 7c**), the reflections, imaging time lines, can be better followed across the facies transition, but
45 they show a significant amplitude variation in this area. These high-amplitude parts of the reflections
46 can catch the eye of the interpreter and be misinterpreted as a proper reflection (pseudo-
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unconformity, Schlager et al., 1991; Stafleu and Schlager, 1995). This “false reflection”, dipping towards the proximal part, is directly comparable with the composite reflection interpreted as the top of seismic sequence 3 in the synthetic seismic model of the Sobrarbe delta (**Figure 6c**). The theoretical model confirms that the top sequence 3 reflection corresponds to the composite seismic image of a facies variation between delta-plain and delta-front deposits and not to the seismic image of a time line / sequence boundary.

The same type of reflection, but characterized by a negative amplitude, locally wavy and presenting a step-like geometry, associated with pseudo-downlap terminations of the clinoforms, is observed within seismic sequence 2 (arrows on **Figure 6d**). By analogy with previous results and comparison with the geological model, this step-like reflection is interpreted as the seismic image of a facies transition between silt and sandstone delta-front deposits and prodelta marls.

In this kind of deltaic clinoform systems, the main criteria to differentiate between the image of a real time line (true unconformity) and a facies transition (pseudo-unconformity) are: the step-like geometry of the reflection and its dip towards the proximal area, associated with the presence of pseudo-toplap terminations below (or downlap terminations above). Reflections presenting these particular geometries were actually observed in the seismic lines of the Colville Basin analog (**Figure 7e**). In this real seismic line, all the geometrical criteria are visible, but the amplitude of the composite reflection is not as high as in the seismic models. It may be due to a lower contrast of acoustic impedance between the delta-front and the delta-plain facies in the Torok/Nanushuk system. The integration of the forward seismic modeling results allows to clearly improve the interpretation of this seismic line, with potential implications at the reservoir scale.

The top of the seismic sequence 5 on the interpreted forward seismic model is characterized by several erosional truncations and onlap reflection terminations between kilometers 3 and 4 (**Figure 5b**). According to seismic facies analysis (cf. 5.2.4), this reflection can be interpreted as the seismic image of a major submarine slide surface, filled by draping distal delta-front deposits. These slide

1 surfaces are particularly well developed in highly-aggrading to retrograding depositional sequences,
2 imaged by: the presence of a very-high-amplitude reflection (triplet peak-trough-peak) in the distal
3 part of the topset of sigmoid clinoforms; a vertical or proximally migrating offlap-break trajectory.
4 According to the geological transect, the slide surface becomes conformable proximally, only
5 showing a minor downward shift of delta-front facies. This interpreted seismic sequence boundary is
6 therefore not a 4th-order sequence boundary, but a higher order sequence boundary.
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18 **5.2. Seismic Facies**

19 The lithological units corresponding to the different depositional environments of the outcrop
20 geological model are characterized by parameters influencing their seismic image, such as: the
21 geometry, thickness and extent of the beds and the type of acoustic impedance contrasts. The
22 comparative analysis between the synthetic seismic profiles and the outcrop transect allows to
23 associate each lithological formation with a seismic facies, i.e. a group of reflections differentiated by
24 their seismic parameters: configuration, amplitude, continuity and frequency (Mitchum et al., 1977).
25 In hydrocarbon plays, the correct interpretation and the mapping of the different seismic facies,
26 coupled with well data analysis, constrain the distribution of sediment bodies within the different
27 sequences or systems-tracts, and infer the properties of potential reservoir systems.
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43 The seismic facies imaging the alluvial-plain, delta-plain, delta-front, slide-scar fill, type 1 and 2
44 turbidites, isolated carbonate platform and nummulite shoal deposits have been characterized in
45 detail in the 30 Hz and 60 Hz forward seismic models. An analogy with the seismic facies observed on
46 the real seismic lines of the Colville Basin (NPRA) is then proposed (**Figures 8 and 9**).
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57 **5.2.1. Alluvial-plain seismic facies**

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Alluvial-plain deposits are characterized by fluvial channels, laterally and vertically amalgamated within flood-plain red shale (Escanilla Formation). In the synthetic seismic models, this lithological unit is imaged in the topsets of the progradational-aggradational deltaic complex by overall tabular and discontinuous reflections, presenting high but variable amplitudes and an average frequency (Figure 8a). These reflections locally show a concave-up, convex-up or undulating geometry. The concave-up geometry can be interpreted as the seismic expression of the original geometry of a channel-base or as a push-down effect due to a velocity anomaly above. The convex-up geometry is the result of a pull-up effect, due to a reverse velocity anomaly above. These push-down and pull-up effects are generated by high positive or negative velocity contrasts between the lens-shaped channel-fill and the surrounding rocks. In the real seismic lines from the Colville Basin (NPRA), this seismic facies is observed in the proximal part of the topsets, at least 20 km before the offlap break of the clinoforms (Figure 8a).

5.2.2. Lower delta-plain seismic facies

The distributary channels, isolated within delta-plain shales are imaged differently according to the frequency used to generate the seismic models. On the 60 Hz forward seismic section, the seismic facies is characterized by very discontinuous, high-amplitude concave-up reflections, presenting a slightly higher frequency than in the alluvial-plain seismic facies. These reflections are localized within a transparent facies, induced by the lack of lithological contrasts within the shale intervals (Figure 8b). This seismic facies is also located in the topset, between the alluvial-plain facies and the offlap break. On the 30 Hz forward seismic models, the delta-plain seismic facies is characterized by sub-tabular reflections, more continuous than in the alluvial-plain facies and with amplitudes varying between low and medium. On the real seismic lines of the Colville Basin (NPRA), the identical seismic facies has not been observed, but a similar facies characterized by low-amplitude, tabular and

continuous reflections could correspond. This facies is also located in the topset, between the alluvial-plain facies and the offlap break.

5.2.3. Delta-front seismic facies

The massive and relatively thick sandstone units corresponding to the proximal delta-front deposits are poorly imaged on the forward seismic lines. They are characterized by low-amplitude reflections or by an almost transparent facies located under the step-like composite reflection which marks a lateral transition of facies (see paragraph 5.1.2) from delta front to lower delta plain. The distal delta-front sandstone units, organized in thinner layers interbedded with prodelta shale, are imaged by continuous dipping reflections (clinoforms) of medium to low amplitude and average frequency (**Figure 8c**). These sandstone bodies are thinner than seismic resolution and therefore each bed is not imaged by a distinct seismic facies. However, the alternation of sandstone and shale is imaged by a succession of clinoform reflections, resulting from the interference between the image of the top and the base of the sandstone beds (peak-trough couplets). Towards the distal domain, the amplitude of these reflections decreases gradually, highlighting the tuning effect associated with the thinning of the sandstone beds towards the basin. These reflections finally disappear within a transparent facies unit, imaging the low internal reflectivity within the prodelta marls.

On the real seismic lines from the Colville Basin (NPRA), a high-amplitude positive reflection (red peak) is often visible over a few kilometers proximally before and around the offlap break of the clinoforms (**Figure 8c**). The composite blue trough reflection located below could correspond to the image of the proximal delta-front massive sandstone. The foreset of the clinoforms presents either a transparent facies, or a facies characterized by reflections of medium amplitude, marked by a peak-trough couplet which could indicate the presence of distal delta-front sandstone bodies in the upper part of the clinoform slope. The transparent facies would then correspond to the image of more

homogeneous, argillaceous or silty deposits on the slope, which have also been observed at specific stratigraphic levels in the Sobrarbe delta (Sequence S5, **Figure 2**)

5.2.4. Fill of submarine slide-scars seismic facies

Submarine slide surfaces are poorly imaged on the forward seismic models. Where they can be recognized, they are reflections with a concave-up geometry, steeper than the overlying and underlying clinoforms, marked by erosional truncations and onlap terminations. These reflections are discontinuous and difficult to follow towards the distal part, since the slide surface does not act as a reflector anymore when the fill of the depression becomes similar to the substratum. The clinoforms affected by these slide surfaces present an irregular, undulating geometry, marked by an abrupt and locally discontinuous break of slope (offlap break) (**Figure 8d**). The fill of these submarine slide scars by distal delta-front sandstone and prodelta marls is sometimes imaged by a medium-amplitude reflection corresponding to the interference between the base and the top of the sandstone unit.

On the real seismic analog (NPRA), several clinoforms present all the criteria described above: a reflection with an irregular, concave to undulating geometry, marked by an abrupt offlap break, erosional truncations and onlap terminations (**Figures 2b and 8d**). These reflections can thus be interpreted as the image of submarine slide scars on the slope of the delta. Their fill is characterized either by medium-amplitude dipping reflections which can be interpreted as the image of an alternation of distal delta-front sandstone and prodelta marls, or by a transparent facies corresponding to the image of homogeneous pro-delta marls.

5.2.5. Turbidite seismic facies

1 Type 1 turbidites form thin, laterally extensive sandstone bodies, interbedded within sandy-silty
2 distal delta-front deposits and prodelta marls. On the forward seismic models, they are imaged by
3 continuous reflections which can only be differentiated from the distal delta-front seismic facies by
4 slightly higher amplitude and a slightly lower dip between the foreset and the bottomset (**Figure 9b**).
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6 Towards the foreset, these seismic reflections sometimes end with onlap terminations on the
7 reflections of the distal delta-front facies. The reflections from the type 1 turbidites dim out or
8 disappear abruptly within a transparent interval (prodelta marls) towards the distal domain. Their
9 geometric characters, similar to those of the distal delta-front seismic facies, make it difficult to
10 differentiate them at 60 Hz and almost impossible at 30 Hz. On the real seismic lines of the Colville
11 Basin, this seismic facies could correspond to the medium- to low-amplitude, relatively continuous
12 reflections which mark the distal, less dipping part of the clinoforms (**Figure 2b**).
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16 Type 2 turbidites form relatively thick and well-bedded lens-shaped sandstone bodies. On the
17 synthetic seismic models, they are imaged by high-amplitude discontinuous reflections which can
18 locally be undulating or concave-up, within a transparent interval corresponding to homogeneous
19 prodelta marls in the bottomset of the clinoforms (**Figure 9c**). The amplitude is maximum in the
20 center of the reflections and dim out towards their extremities. Dipping reflections from the distal
21 delta-front facies (or from the type 1 turbidite facies) locally end with downlap terminations on this
22 Type 2-turbidite seismic facies. On the real seismic analog, this type of discontinuous,
23 undulating/concave-up, high-amplitude reflections is frequently observed in the bottomsets of the
24 clinoforms (**Figures 2b and 9c**). These reflections can therefore be interpreted as type 2 turbidites.
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52 **5.2.6. Seismic facies of the isolated carbonate platform**

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55 In the Sobrarbe delta, the isolated carbonate platform unit is characterized by a very high acoustic-
56 wave-propagation velocity compared to the surrounding rocks, and by a thickness lower than or at
57 the limit of seismic resolution. This sediment body is thus mainly imaged by only one composite
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1 seismic reflection (peak-trough couplet) of very high amplitude and low frequency, located near the
2 clinoform offlap break, in the distal part of the topset (**Figure 9a**). This reflection ends with a toplap
3 termination towards the proximal area, because its dip is slightly higher than the overlying
4 reflections. Distally, this well-marked reflection ends abruptly around the offlap break and is replaced
5 by steeper reflections (clinoforms), slightly offset vertically, presenting a lower amplitude and a
6 higher frequency. At 60 Hz, all these parameters are well visible, whereas at 30 Hz the high-
7 amplitude reflection interferes with the one above. At 30 Hz, the abrupt termination of the reflection
8 at the offlap break is the only visible criteria, which can however be wrongly interpreted as a fault.
9 This type of facies can be differentiated from the proximal delta-front facies by its position close to
10 the offlap break and by the lack of continuity with the foreset. A slight pull-up effect may be
11 observed below the high-amplitude reflection imaging the carbonate platform, due to the positive
12 velocity anomaly which characterizes this sediment body (**Figure 9a**). The seismic facies of the
13 isolated carbonate platform was locally observed on the real seismic lines of the NPRA analog (**Figure**
14 **9a**). All the criteria could be recognized: high-amplitude and low-frequency reflection located at and
15 before the offlap break, which ends with a toplap termination proximally and ends abruptly at the
16 offlap break. Unfortunately, no well was drilled through this seismic facies and therefore this
17 interpretation could not be tested.

5.2.7. Nummulite shoal seismic facies

47 Nummulite shoal deposits are characterized by relatively thick intervals made up of alternating
48 homogeneous sandy/marly-limestone beds rich in nummulites and silt/marls, presenting small
49 acoustic impedance contrasts. On the 60 Hz synthetic seismic model, this lithological unit is imaged
50 by continuous, very-low amplitude and slightly divergent reflections (**Figure 9d**). Around the offlap
51 break location, these reflections are truncated by another steep reflection, poorly visible, imaging a
52 submarine slide surface. On the 30 Hz forward seismic model, the reflections interfere and the

1 seismic facies is therefore only represented by one low- to average-amplitude reflection which
2 separates into two distally, while their amplitude dims out. On the real seismic lines of the NPRA
3 analog, a similar seismic facies was observed locally, near the distal margin of relatively thick topsets
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7 **(Figure 9d)**. The presence of clinoforms within these topsets indicates a phase of retrogradation of
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9 the sedimentary system, making environmental factors favorable to the development of a more
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11 carbonate-rich system. However, according to the Cretaceous age of the Torok/Nanushuk
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13 Formations, there would be no nummulites associated with this facies in the Colville Basin.
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21 **6. Seismic response of 4 selected systems tracts containing good potential sandstone reservoir** 22 **bodies**

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26 Four examples of different 4th-order systems tracts have been selected and studied in detail because
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28 of their main geometrical characteristics, particular variation of accommodation and sediment supply
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30 recorded by a related stratal stacking pattern, and the potential interest of sandstone reservoir
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32 bodies (extent, thickness and net-to-gross ratio). These are three Regressive systems tracts from
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34 sequences 4, 5 and 6 interpreted as Highstand systems tract (HST) or Falling stage systems tract
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36 (FSST), and a thick Transgressive systems tract (TST) from sequence 6 **(Figure 10)**. The seismic image
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38 of the selected systems tracts comprising good potential reservoir bodies are analyzed, aiming to
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40 highlight some recognition criteria which can be used to interpret analog deltaic systems in the
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42 subsurface, and therefore to enhance the prediction and characterization of the reservoir bodies that
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44 they hold.
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54 **6.1. S4 Regressive systems tract: Highstand and Falling stage systems tracts**

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57 The regressive systems tract of sequence S4 is characterized by a rapid thickening (over a distance of
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59 1 km) of the sedimentary wedge to reach 50 meters-thick near the delta front **(Figure 10a)** where a
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Highstand systems tract (HST) first and a Falling stage systems tract (FSST) later are developed. The thickness stays relatively constant along the slope and towards the deepest part of the basin. The total length of this S4 regressive systems tract is more than 11 kilometers in our SSE-NNW section.

The topset deposits are poorly preserved and overlain in the most proximal area of the HST by an erosional unconformity identified as a sequence boundary. The erosion of the subaerially exposed sediments records : (1) a decrease in the amount of accommodation space due to a synsedimentary local uplift near the southern area of the section (Grasseau, 2016); (2) a high sedimentation rate. The S4 Regressive systems tract is characterized by sigmoid and oblique clinoforms with progressively increasing dip angles (from 1.4° to 5.7°) associated with a downward shift of facies belts. The sands are accumulated mainly in the delta front (foreset) and/or in the turbidite systems of the FSST. The FSST delta-front deposits form a homogeneous sandstone wedge extending laterally over 3 kilometers. The thickness increases towards the basin to reach locally 50 meters. Its net-to-gross ratio ranges between 40 % and 95 % and decreases along a proximal-distal axis, the mean value being 80 %. The type 1 turbidites, interstratified within delta-front and prodelta deposits, consist of heterolithic marl-sandstone units 10 meters thick and 4 kilometers wide, made up of amalgamated channels. These turbidite units are vertically and laterally heterogeneous, with a net-to-gross ratio ranging from 70 % to 95 % (mean = 83 %).

On the synthetic seismic model, the regressive systems tract of sequence S4 is mainly imaged by oblique clinoform reflections, characterized by positive amplitude and a limited lateral extent (**Figure 11**).

At 60 Hz, the first aggrading-prograding deltaic unit, corresponding to a Highstand systems tract, is imaged by two oblique clinoform reflections, two peaks of average to low amplitude (arrow 1, **Figure 11c**). In the proximal direction, these clinoform reflections end with toplap terminations under an undulating positive reflection (red peak) corresponding to the image of a facies transition between delta-plain and proximal delta-front facies. The topset deposits have a thickness that is lower than

1 seismic resolution and are therefore not directly imaged. The amplitude of the clinoform reflections
2 dims out progressively towards the distal part, due to a lower lithological contrast which is marked
3
4 by a reduction of the net-to-gross ratio within delta-front deposits in this direction. A subtle
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6 amplitude dimming (arrow 1, **Figure 11c**) highlights the low inner reflectivity of the delta-front
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8 sandstone located in the foreset of the clinoforms, a criterion for good homogeneity and high net-to
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10 gross ratio in these deposits. In the bottomsets, the clinoform reflections are overlain with onlap
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12 terminations by higher amplitude reflections imaging type 1 turbidites (arrow 2, **Figure 11c**). The
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14 amplitude of the reflections imaging the turbidite deposits dims out toward the distal part, due to a
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16 reduction of the net-to-gross ratio distally. At 30 Hz, the reflection characterizing the type 1
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18 turbidites is difficult to identify among the clinoform reflections (**Figure 11b**).
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24 The second deltaic unit within this systems tract, a Falling-stage systems tract characterized at
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26 outcrop by oblique clinoforms, is imaged at 60 Hz by two oblique clinoform reflections of very low to
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28 medium positive amplitude (arrow 3, **Figure 11c**). Toward the proximal part, these reflections end
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30 with toplap terminations under a peak reflection imaging a sequence boundary. The proximal part of
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32 the foreset is imaged by low-amplitude reflections forming a relatively transparent facies due to the
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34 lack of inner reflectivity within the homogeneous delta-front deposits. These deposits have a high
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36 net-to-gross ratio (**Figure 11d**). The distal part of the foreset is characterized by an increase of
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38 amplitude in the reflections, highlighting a stronger inner reflectivity, due to (1) the presence of type
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40 1 turbidite deposits, (2) a higher heterogeneity in the distal delta-front deposits. The clinoform
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42 reflections end with downlap terminations on an undulating « step-like » trough reflection imaging a
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44 facies transition between delta-front silty-sandstone deposits and prodelta marls (arrow 4, **Figure**
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51 **11c**).
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53 On the real seismic lines from the Colville Basin, similar seismic systems tracts could be differentiated
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55 by the recognition of the same criteria (**Figure 11e**). They are characterized by oblique clinoform
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57 reflections of medium amplitude and small lateral extent (arrow1, **Figure 11e**). By analogy, the best,
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high net-to-gross, reservoir facies should be located within the transparent seismic facies, imaging the low inner reflectivity of the thick delta-front deposits (arrow2, **Figure 11e**).

6.2. S5 Regressive systems tract: well developed Highstand systems tract

The regressive systems tract of sequence S5 (**Figure 10b**) has a typical sigmoid shape highlighted by a series of clinoforms: it is 20 meters thick in the topset part, thickens over 6 km long to reach more than 250 meters in the foreset to finally thin toward the bottomset. The sedimentary wedge presents a prograding-aggrading trend (normal regression) where most of the delta front sands were accumulated preferentially in the topset areas, whereas the foreset and slope are made up by prodelta marls and minor turbidite units. The dip angle of the clinoforms progressively increases (from 0.5° to 2°) during the deposition of the lower part, and decreases (from 2° to 0.5°) in the upper part of the systems tract. The stacking pattern organization and the related convex-up shoreline trajectory are interpreted as a Highstand normal regression recording a change from aggradation to progradation. In the lower part, the delta-front deposits would make poor reservoirs due to a high level of facies heterogeneity. In the upper part, the reservoir properties are better due to the superposition of well-sorted delta-front sandstone beds, extending 2 to 4 km laterally and stacked over up to 35 meters of thickness. The net-to-gross ratio of this delta-front body ranges from 55% to 85%, with a mean of 65%.

A set of type 1 turbidite deposits is present on the slope of the first low-amplitude and low-angle clinoforms. They consist of marly-sandstone bodies, 2 to 3 km wide and less than 5 m thick, characterized by a very heterogeneous net-to-gross ratio (vertically and horizontally) ranging from 40% to 70%, with a mean of 55%. The marly foresets and bottomsets of the overlying higher-angle clinoforms are locally incised by isolated and confined turbidite channels, a few meters thick and a few meters wide.

1 In the distal part of this systems tract crops out a set of type 2 turbidite deposits of 2 to 5 m-thick
2 well-bedded sandstone, alternating with laminated silt intervals of few-meters to few-tens-of-meters
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4 thick. Locally, 10 m-thick massive sandstone interpreted as turbidite channels incise the type2
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6 turbidite deposits. This whole turbidite unit forms a 3 km-wide and up to 25 m-thick turbidite system
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8 (on this 2D transect). Its net-to-gross ratio ranges from 50 to 85%, with a mean of 70%.
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12 On the synthetic seismic model, the regressive systems tract of sequence S5 is mainly imaged by
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14 oblique clinoforms of large lateral extent and medium to low positive amplitude, interfingering
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16 distally within a transparent seismic facies (reflections 1 to 9, **Figure 12**). High-amplitude undulating
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18 reflections characterizing a type 2 turbidite system are also visible within the bottomsets (reflections
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21 6 and 7).
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25 At both 30 and 60 Hz, the clinoform reflections end with toplap terminations under an undulating
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27 « step-like » peak-trough reflection couplet of high amplitude (**Figure 12**). This reflection is the image
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29 of a facies transition between delta-plain and delta-front facies. This delta-front facies is mainly
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31 characterized by sandstone with a high net-to-gross ratio. The clinoform reflections 1 and 2, of
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33 medium to low amplitude, end distally with downlap terminations on the sequence boundary
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35 (arrows 1 and 2, **Figure 12**). These two peak reflections are the image of type 1 turbidite facies
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37 deposits which accumulated along the slope. Such reflections are difficult to differentiate from the
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39 seismic reflections imaging distal front delta deposits (clinoforms 3 to 5, **Figure 12**). At 60 Hz, an area
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41 with a very low amplitude/almost transparent facies is visible within the topset and the foreset
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43 (arrow 8, **Figure 12c**), revealing the low inner reflectivity of the homogeneous, high net-to-gross,
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45 delta-front sandstone bodies. At 30 Hz, this same interval is imaged by the trough part of the peak-
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47 trough reflection couplet imaging the top of the systems tract (arrow 8, **Figure 12b**). This seismic
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49 facies grades distally to high/medium amplitude clinoform reflections (arrow 9, **Figure 12**), parallel
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51 and continuous, imaging a high inner reflectivity due to the progressive intercalation of distal delta-
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53 front deposits within the prodelta marls. The net-to-gross ratio decreases distally. Reflections 6 and
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7, located within a transparent facies in the bottomsets of the clinoforms, typically correspond to the image of type 2 turbidites. A local increase of amplitude associated with a lenticular geometry highlights the presence of a turbidite channel (arrow 7, **Figure 12**). The net-to-gross ratio decreases towards the margins of the turbidite systems, the maximum value corresponding to the central part of the channels.

On the real seismic line from the Colville Basin, the apparent oblique clinoform reflections 3 to 6 (**Figure 12d**) may correspond by analogy to the seismic response of this kind of regressive systems tract. The amplitude of the reflections decreases within a transparent seismic facies in the foreset and in the topset. Undulating high-amplitude reflections in the distal part of this systems tract can be interpreted as type 2 turbidites (reflections 7 and 8, **Figure 12d**).

The best potential reservoirs, with a high net-to-gross ratio, are imaged by either (1) a seismic reflection of medium to low negative amplitude corresponding to the lower part (trough) of the reflection imaging the lateral facies transition between the delta-plain and delta-front deposits, or (2) a transparent or very low amplitude seismic facies highlighting the homogeneity of delta-front deposits, or (3) a seismic facies corresponding to type 2 turbidites.

6.3. S6 Transgressive systems tract

The Transgressive systems tract of Sequence S6 (**Figure 10c**) is characterized by a constant thickness of 20 to 30 meters over more than 7 km and is truncated by a submarine slide surface basinward.

It consists of a retrograding sedimentary succession in which a series of low-angle (0.5°) clinoforms developed. S6 TST deposits are characterized proximally by proximal delta-front sandstone with tidal reworking. These deposits laterally grade towards the distal area to a fining-up succession of distal delta-front sandstone rich in nummulites overlain by prodelta marls. Delta-front sandstone bodies are very extensive, over more than 6 km, and interfinger toward the SSE with the delta-plain

argillaceous deposits. The net-to-gross ratio increases from the distal to the proximal part and decreases from the base to the top of the sedimentary succession. The net-to-gross ratio ranges from 40% to 65% with a mean of 50%.

On the synthetic seismic model, the transgressive systems tract of sequence S6 is imaged by a reflection couplet (peak-trough) of high to very high amplitude, continuous, subhorizontal and slightly undulating, intercalated within the topset seismic facies (white arrows, **Figure 13**). This reflection is bent by several velocity anomalies (pull-up effects) caused by the presence of lenticular sandstone bodies within the shale interval above (**Figures 13b and 13c**). A slight amplitude dimming can be observed in the distal direction. This reflection is better characterized at 60 Hz, because it stands out from the transparent facies imaging the delta-plain shale. Within this transgressive sandstone body, the net-to-gross ratio increases in the proximal direction and decreases upward.

On the real seismic lines from the NPRA, similar high-amplitude, continuous and slightly undulating reflections intercalated within the topset seismic facies (black arrows, **Figure 13d**) have already been interpreted as the image of a transgressive systems tract (Houseknecht et al., 2009). These high-amplitude reflections present the same criteria as described in the forward seismic models.

The whole transgressive systems tract of the S6 sequence corresponds to a potential reservoir body, comprising however an important silty fraction.

6.4. S6 Aggrading to prograding Highstand systems tract

The regressive systems tract of Sequence S6 (**Figure 10c**) has a homogeneous thickness of about 60 m over a distance of a few kilometers in the topset. It thickens abruptly in the foreset due to a complex of submarine gravity slides deposits which reaches up to more than 120 meters in thickness. This systems tract is then completely truncated by a major submarine slide surface which marks the top of the sequence.

1 The systems tract is made up of a succession of tens-of-meters thick aggrading-prograding
2 sedimentary units within which a series of low-angle clinoforms (0.5°) develop. The stacking pattern
3 organization and the convex-up shoreline trajectory were interpreted as a Highstand normal
4 regression recording a rapid change from a well-developed aggrading stage to a very prograding
5 stage. Along the clinoforms, proximal delta-front sandstone reworked by tidal currents grade
6 laterally to coarsening-up or fining-up medium-distal delta-front sandstone rich in Nummulites, an
7 then to prodelta marls. The Highstand systems tract contains meter-thick argillaceous or silty levels,
8 which limit the vertical and lateral connectivity of the delta-front sandstone bodies. The sandstone
9 bodies are 20 to 40 m thick and 4 to 6 km long (on this 2D transect). A succession of gravity
10 instabilities truncated these deposits towards the basin. The resulting depressions were filled in their
11 proximal part by fine-grained distal delta-front deposits (draping the paleotopography), and in their
12 distal part by some turbidite deposits interbedded within prodelta marls. These elements give a very
13 complex and heterogeneous architecture to the Highstand systems tract of Sequence S6. The net-to-
14 gross ratio remains however high, since it ranges from 40% to 85% with a mean of 71%.

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34 On the synthetic seismic model, the aggrading-prograding regressive systems tract of sequence S6 is
35 imaged by a gently dipping and laterally extensive seismic wedge (**Figure 14**). This systems tract is
36 mainly characterized by the seismic facies corresponding to the fill of submarine slide scars in the
37 distal direction.

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44 At 60 Hz, the regressive systems tract of sequence S6 is imaged by clinoform reflections which are
45 rather discontinuous and characterized by high to average positive amplitude (**Figure 14c**). The
46 amplitude dims out in the distal direction, attesting of a lower lithological contrast, partly due to a
47 decrease of the net-to-gross ratio within the delta-front deposits. Although the delta-front deposits
48 appear rather massive and homogeneous at outcrop (**Figure 14d**), they present a high reflectivity due
49 to the occurrence of marl intervals interbedded in the sandstone units and thick-enough to have an
50 impact on the seismic image. These argillaceous levels limit the vertical connection between the
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1 potential sandstone reservoir bodies and decrease the net-to-gross ratio. In the distal direction, the
2 clinoform reflections end with erosional truncations against steeper reflections imaging submarine
3 slide scars. The seismic facies corresponding to the fill of these slide scars is characterized by high-
4 amplitude, undulating reflections which end with onlap terminations on the base of the slide scar
5 reflection (arrow 3, **Figure 14c**). At 30 Hz, the delta-front seismic facies is characterized by
6 discontinuous, almost chaotic positive high- to medium-amplitude reflections, preventing the
7 identification of clinoform geometries and of the interbedded argillaceous beds within the sandstone
8 units (arrow 2, **Figure 14b**). The infill of the submarine slide scars is only imaged by a sharp increase
9 of amplitude along the reflections, creating a discontinuity that might be wrongly interpreted as a
10 fault (arrow 3, **Figure 14b**).
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24 On the real seismic lines from the Colville Basin (**Figure 14e**), this kind of systems tract can be
25 differentiated by analogy with the synthetic seismic model. The overall geometry is a sigmoid
26 clinoform with a relatively thick topset. In the topset, the reflections are continuous, tabular and
27 locally wavy, with a low to medium amplitude (arrow 1). Their amplitude increases around the offlap
28 break, and more distally the reflections become steeper, discontinuous and undulating, with local
29 onlap terminations. This seismic facies probably corresponds to the image of the fill of submarine
30 slide scars (arrows 2 and 3).
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42 The best potential reservoir facies, with the highest net-to-gross ratio, is the delta-front facies,
43 located in the distal part of the topset and around the offlap break, before the erosional truncations
44 induced by the submarine slides.
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50 **7. Conclusion**

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52 The forward seismic modeling of the very detailed outcrop transect of the Sobrarbe delta has
53 allowed (1) to test the seismic stratigraphy methodology and detect possible interpretation mistakes,
54 (2) to illustrate the seismic image of different facies associations characterizing a fluvio-deltaic
55 system, (3) to analyze the seismic image of four fourth-order systems tracts selected for the good
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potential reservoir properties of their sediment bodies. Therefore, subtle recognition criteria such as amplitude variations, specific reflection geometries, artefacts, could be recognized and then applied on real seismic lines from the analog Torok-Nanushuk fluvio-deltaic system of the Colville Basin (NPRA, USA).

- For this type of deltaic system, the “seismic stratigraphy” methodology is consistent and allows the correct interpretation of most of the 4th-order seismic sequences. However, two possible interpretation mistakes have been highlighted: (1) some reflections are imaging lateral facies transitions instead of time lines, especially in low-frequency seismic lines. They can be identified by their wavy, step-like geometry and their dip orientation towards the proximal area (opposite to clinoform dip direction); (2) some higher-order sequence boundaries can be misinterpreted as 4th-order sequence boundaries, due to the presence of large slide-scar surfaces in this syntectonic deltaic system. These surfaces generate erosional geometries (erosional truncations) and infill geometries (onlap terminations) which are usual criteria for the identification of sequence boundaries on seismic lines.

- The seismic facies of 7 facies associations observed at outcrops have been described in this paper. The detailed comparative analysis of the synthetic seismic model with the acoustic impedance model has allowed the recognition of several criteria to differentiate the seismic facies imaging the different lithological units, each corresponding to a particular depositional environment. The application on real seismic lines of the Colville Basin shows that these criteria can be used to predict the extent of facies belts in the subsurface, and thus to limit uncertainties on the geometry and properties of reservoir bodies in subsurface models.

- In order to predict the distribution and quality of reservoir bodies from the interpretation of seismic data in this type of deltaic systems, it is necessary to consider two parameters: (1) The recognition of the type of systems tract, which is not always easy within fourth-order sequences, due

to interferences, composite systems tract boundaries affected by frequent lateral facies variations, etc. (2) The differentiation of the seismic facies corresponding to the potential reservoir bodies within these systems tracts.

In the falling stage systems tracts, the seismic facies of the best reservoirs bodies (high net-to-gross ratio) can be recognized by: (a) a subtle decrease of amplitude imaging the low inner reflectivity of delta-front sandstone within the foreset of the clinoforms, or (b) by a transparent seismic facies, poorly imaged by a composite trough reflection, due to the low inner reflectivity of relatively thick delta-front deposits.

In the highstand systems tracts, the seismic facies of the best reservoir bodies can be recognized by: (a) a delta-front sandstone seismic facies marked by a trough reflection of moderate to low amplitude, corresponding to the lower part (trough) of the composite reflection imaging the lateral facies transition between delta-plain deposits and delta-front deposits, and (b) a type 2 turbidite seismic facies, within which a local increase of amplitude associated with a lens-shape geometry suggests the presence of a turbidite channel.

Transgressive systems tracts are imaged by a continuous very-high to high amplitude reflection (peak-trough-peak triplet), subhorizontal to slightly undulating, interfingering within the topset seismic facies. The net-to-gross ratio increases along a distal-proximal axis and decreases along a vertical (base to top) axis.

The results of this study can now be applied to other subsurface deltaic systems, in order to test these recognition criteria and maybe reduce uncertainties during the reservoir modeling phase. The continuation of this project will consist in studying the effects of different types of reservoir fluids (water/oil/gas) on the seismic image of this deltaic system.

- Most of the seismic attributes and geometries observed in the Sobrarbe delta complex forward seismic model have been also recognized in the seismic lines of the Torok-Nanushuk fluvio-deltaic

1 system. These analogies related to direct outcrop observations have been useful to improve the
2 interpretation of these real seismic lines.
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Figure 1: Geological setting of the Sobrarbe deltaic complex. **(a)** Simplified geological map of the Lutetian-Bartonian deposits of the Sobrarbe deltaic complex (Grasseau, 2016) showing the main facies associations and geological structures. The thick black line corresponds to the location of the

correlation transect used for synthetic seismic modeling (Figures 2a and 4). **(b)** General map of the Pyrenean mountain range with the main geological units and the study area.

Figure 2: Outcrop-based transect and analog seismic profile of prograding deltaic complexes. **(a)** Simplified stratigraphic architecture of the Sobrarbe deltaic deposits along a correlation transect built on the western flank of the Buil syncline (see Figure 1). Three orders of sequential arrangement have been distinguished: fifth-order high-frequency sequences, fourth-order sequences (S3 to S9) and the third-order transgressive-regressive composite sequences (SI to SIII). **(b)** Real seismic profile C-81 (USGS NPRA subsurface data set), imaging the Albian-Cenomanian Nanushuk-Torok fluvial-deltaic system, used as an analog in this study. This prograding-aggrading deltaic system developed in the

Colville foreland basin, within the National Petroleum Reserve of Alaska (NPRA), USA (see Figure 3 for location).

Figure 3: Map of the northern part of the Alaska North Slope, Chukchi Sea and Beaufort Sea, showing the main geologic elements, seismic facies and paleocurrent data from the Lower Cretaceous First-order depositional sequence (modified from Houseknecht et al., 2009). This sequence corresponds to the deltaic system of the Nanushuk Group and Torok Formation, used as subsurface analog for the Eocene Sobrarbe Delta. The proximal domain of the Nanushuk-Torok deltaic system was located to the west, on the Chukchi platform. This deltaic system prograded toward the East and North-East over several hundreds of kilometers, progressively filling in the Colville foreland basin. Foreset dip directions are from Bird and Andrews (1979) and Houseknecht et al. (2009); topset cross-bed directions are from Huijman et al. (1985). The approximate location of line C-81 (Figure 2b) is indicated. Note that the seismic line is not parallel but slightly oblique to the main sediment transport direction.

Figure 4: Steps used to build the synthetic seismic model of the Sobrarbe delta complex. **(a)** Acoustic impedance model used for generating the synthetic seismic model. **(b)** Synthetic seismic model generated with a 30Hz peak frequency. **(c)** Synthetic seismic model generated with a 60Hz peak frequency.

Table 1: Synthetic table presenting the Sobrarbe delta sedimentary facies that have been selected for the forward seismic modeling, and their petrophysical properties. The values of wave propagation velocity and density have been chosen by facies analogy with well data from the Nanushuk-Torok Formations (NPRA, USA).

Depositional environment	Sub-environment	Facies	Model P-waves velocities (m/s)	Model density (g/cm ³)
Upper delta plain	Braided fluvial channel	Conglomerate	2900	2,27
	Meandering fluvial channel	Very coarse to fine cross-bedded sandstone	3100	2,31
	Well-drained floodplain	Red clay	2600	2,21
Lower delta plain	Distributary channel	Coarse to fine cross-bedded sandstone	3200	2,33
	Ponded floodplain	Grey clay	2700	2,23
	Ponded floodplain	Fine silty ripple-laminated sandstone	3100	2,31
Delta front	Proximal mouth bar and tidal sand ridges	Medium to coarse cross-bedded sandstone	3500	2,38
	Distal mouth bar/Lower nearshore	Carbonate silty to medium sandstone	3300	2,35
	Low energy delta front	Argillaceous silt to very fine sandstone	2900	2,27
Prodelta	Slope	Decimetrical conglomerate or sandstone block in silty matrix	3100	2,31
	Turbidite slope channel	Medium to fine cross-bedded sandstone	3400	2,37
	Slope channel levée or turbiditic lobe	Heterolithic fine sandstone	3200	2,33
	-	Marls/shales	3000	2,29
	-	Black marls	2700	2,23
Carbonate shallow marine	Isolated carbonate platform	Oyster, coral and algae-rich wst/pst	4000	2,47
	Nummulite shoal	Nummulite fst/rst	2900	2,27
	Calciturbidite	Nummulite pst/gst	3200	2,33

Figure 5: Synthetic seismic model of the Sobrarbe delta complex sequential interpretation. **(a)** Uninterpreted forward seismic model, 60 Hz. **(b)** Blind interpretation of the forward seismic model using classical seismic stratigraphy. Nine seismic sequences have been identified. **(c)** 60Hz synthetic seismic model with real 4th-order sequence boundaries projected from the geological transect (black lines).

Figure 6: Synthetic seismic image of the facies transition area between the delta-front deposits and the delta plain deposits (topsets) at 60Hz. **(a)** Complete seismic section at 60 Hz. The black box corresponds to the area of interest to observe the seismic response of lateral facies transitions. **(b)** lateral facies transition (black arrows) without interpretation. **(c)** Possible missinterpretation by using classical seismic stratigraphic methodology. **(d)** Projection of the geological model time lines (reflectors) on the synthetic seismic section.

Figure 7: Schematic theoretical seismic model used to analyze in detail the lateral facies transitions at different frequencies. **(a)** Acoustic impedance model. **(b)** Synthetic seismic model generated with 30Hz peak frequency. **(c)** Synthetic seismic model generated with 60Hz peak frequency. **(d)** Zoom on the area of interest on the 60Hz synthetic seismic model of the Sobrarbe delta complex. Arrows indicate the seismic response of lateral facies transition areas.

Figure 8: Seismic facies analysis characterizing the seismic image of each depositional environment, at 30Hz and 60Hz, and comparison with equivalent seismic facies observed on real seismic lines from the NPRA Torok-Nanushuk analog. Reflections of particular interest are highlighted by black arrows. **(a)** Alluvial plain deposits; **(b)** delta plain deposits; **(c)** delta front deposits; **(d)** Fill of slide-scar surfaces.

Figure 9: Seismic facies analysis characterizing the seismic image of each depositional environment, at 30Hz and 60Hz, and comparison with equivalent seismic facies observed on real seismic lines from the NPRA Torok-Nanushuk analog. Reflections of particular interest are highlighted by black arrows.

(a) Isolated carbonate platform deposits; **(b)** Type 1 turbidite system deposits; **(c)** Type 2 turbidite system deposits; **(d)** Nummulite shoal deposits.

Figure 10: Geometries and reservoir properties of four systems tracts, selected within the Sobrarbe deltaic complex for their reservoir potential for further comparison with their seismic response.

Figure 11: Synthetic seismic image of Sequence S4 Regressive Systems Tract (Highstand + Falling stage systems tracts). **(a)** Acoustic impedance model; **(b)** Synthetic seismic model generated at 30Hz; **(c)** Synthetic seismic model generated at 60Hz; **(d)** Real seismic line 33-81a (NPRA). Arrows highlight points of interest detailed in the text.

Figure 12: Synthetic seismic image of Sequence S5 Regressive Systems Tract. **(a)** Acoustic impedance model; **(b)** Synthetic seismic model generated at 30Hz; **(c)** Synthetic seismic model generated at 60Hz; **(d)** Real seismic line 27b-81 (NPRA). Arrows highlight points of interest detailed in the text.

Figure 13: Synthetic seismic image of Sequence S6 Transgressive Systems Tract. **(a)** Acoustic impedance model; **(b)** Synthetic seismic model generated at 30Hz; **(c)** Synthetic seismic model generated at 60Hz; **(d)** Real seismic lines 12p-81, 16p-81, 18p-81 (NPRA). Arrows highlight points of interest detailed in the text.

Figure 14: Synthetic seismic image of Sequence S6 Regressive Systems Tract. **(a)** Acoustic impedance model; **(b)** Synthetic seismic model generated at 30Hz; **(c)** Synthetic seismic model generated at 60Hz; **(d)** Slide scar surfaces at outcrop; **(e)** Real seismic line C-81 (NPRA). Arrows highlight points of interest detailed in the text.

Figure 8
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Table 1

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	Well-drained floodplain	Red clay	2600	2,21
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	Ponded floodplain	Grey clay	2700	2,23
	Ponded floodplain	Fine silty ripple-laminated sandstone	3100	2,31
Delta front	Proximal mouth bar and tidal sand ridges	Medium to coarse cross-bedded sandstone	3500	2,38
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Prodelta	Slope	Decimetrical conglomerate or sandstone block in silty matrix	3100	2,31
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