Transition between Deep-Water Channel-Belt and Overbank Deposits of the Upper Austrian Molasse Basin using 3-D Seismic-Reflection and Core Data*

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Introduction

Mud-rich overbank deposits have not been primary targets of petroleum exploration in the past compared to channel deposits due to their lower sand contents, lithologic heterogeneity, and low-resolution seismic images. Also, well-log data have made it challenging to identify the reservoir quality of out-of-channel deposits. However, as more traditional channelized sandstone reservoirs have become depleted, geoscientists have become increasingly interested in thin-bedded units and thus the processes that are responsible for deposition of overbank sediments.

The present study addresses the depositional processes, architecture, and evolution of sediments in the Puchkirchen Formation of the Atzbach, Schwanenstadt, and Zell-am-Pettenfirst gas fields in the Tertiary Upper Austrian Molasse Basin. The gas-bearing sandstones in these fields were interpreted to be crevasse-splay and overbank deposits to the axial channel within the narrow Molasse Basin (De Ruig and Hubbard, 2006; Hubbard et al., 2009). The present research provides additional details on the depositional setting and documents the spatial variation of main sand bodies and the lithological heterogeneity of these out-of-channel deposits. The evolution of the overbank deposits is documented within the context of the progressively migrating meandering axial channel. The lithology, thickness of beds, and degree of bioturbation are quantitatively described.

Background Geology

The Tertiary Molasse Basin is a part of the North Alpine foreland basin (Figure 1). The Molasse Basin is a classical asymmetric foreland basin that deepens towards the steep tectonically active Alpine thrust front to the south and gradually shallows towards the Bohemian Massif to the north (Andeweg and Cloething, 1998). Alpine thrust complexes comprise the Helvetic zone, the Rhenodanubian flysch, the Northern Calcareous Alps and the imbricated Molasse thrust sheets (Figure 2). The Molasse Basin extends into Bavaria and Switzerland to the west and into the Carpathian foredeep to the east. It is filled with up to 5000 m of predominantly Tertiary clastic sediments in the deepest part. The Molasse Basin was formed in the late Eocene when the European margin was loaded by thrusting of Alpine nappes (Wagner, 1996, Bachmann and Müller, 1991; Andeweg and Cloething, 1998). The intensive imbrication of the European foreland crust in the late Oligocene and Miocene reflects the continued convergence between Africa and Europe and the ongoing Alpine orogeny (Zeigler, 1987). Water depth in the Upper Austrian Molasse Basin reached up to 1000-1500 m based on foraminiferal assemblages (Rögl et al., 1979; Robinson and Zimmer, 1989) during the early Oligocene (Sissingh, 1997; Wagner, 1998).

The Molasse Basin contains Oligocene to early Miocene sediment gravity-flow deposits represented mostly by conglomerates, sandstone, and mudstone that accumulated within approximately 10 m.y. (about 30–20 Ma, Martini, 1971). The deep-water sediments include, from base to top, the Rupelian Sandstone, the Puchkirchen Formation, and the lower part of the Hall Formation. Deposition of 2000 m of sediments occurred within a broad channel belt flowing to the east along the axis of the foredeep. The channel was 3-6 km (Figure 2) wide and more than 100 km long (De Ruig and Hubbard, 2006; Hubbard et al., 2009). Overbank deposits in the Puchkirchen Formation Formation are illustrated in Figure 3.

Previous Work

The Atzbach, Schwanenstadt, and Zell-am-Pettenfirst gas fields in the Austrian Molasse Basin represent overbank and crevasse-splay sediments deposited by flows that spilled north, out of the main axial channel (de Ruig and Hubbard, 2006; Hubbard et al., 2009). Particularly the Atzabach reservoir represents overbank splays stacked on each other and separated by turbiditic mud and silt (de Ruig and Hubbard, 2006). De Ruig and Hubbard observed that the splays grade from thick non-amalgamated sandstone beds deposited by high-density turbidity currents near the channel belt to fine-grained thin sandstone deposits of low-density gravity flows in distal areas to the north. Splay deposition was thought to be associated with the switching of the belt migration from north to the south (Hubbard et al., 2009).

There are a number of studies of overbank and crevasse splay deposits (Piper and Normark 1983; Mutti and Normark, 1987, 1991; Normark et al., 1993; Peakall et al., 2000; Posamentier and Kolla, 2003; Kane et al., 2007, 2010). The process when the muddy top of turbidity current overtops the levee at a sharp channel bend is termed “flow stripping” (Piper and Normark, 1983; Manley et al., 1997). Overbank deposits can be divided into two groups: overbank wedges and channel-related overbank deposits (Mutti and Normark, 1987). The first is represented by thick wedges of fine-grained sediments that reach a maximum thickness near the margin of the basin and pinch out basinward into mudstone and are related to channel overflow causing draping of the slope. These are deposited by flows originating on the slopes surrounding the basin, rather than flows moving down the channel, or flows derived from the channel but which have traveled a long distance away from the point of overbanking so that they no longer reflect local over-spill events or conditions. The second type comprises fine-grained sediments derived directly from the channel that occur within the channel, along its edges or within interchannel areas (Mutti and Normark, 1987). Both types were documented in the Molasse Basin at two scales (Hubbard et al., 2009): 1) Overbank wedges constructed by flows spilling over the banks of the channel belt as a whole and depositing on the basin-margin slopes, 2) sediments deposited within the confines of the basin axial channel belt by flows spilling out of the channel. Hubbard et al. (2009) argues that the narrow configuration of the Molasse Basin resulted in the evolution of atypical levees. They do not resemble gullwing style levees in unconfined submarine fan systems (Flood and Damuth, 1987); they accumulated as overbank wedges on the basin slopes with compacted thickness of over 250 m (Hubbard et al., 2009). The space available for locally developed overbank deposits was controlled by the evolution of the broader overbank wedges. The units studied here are overbank deposits that include levee deposits and associated crevasse and splay units related to overspilling along the northern edge of the axial channel around a large meander bend. Lithologically, these are similar to levees of Amazon fan (Manley et al., 1997) and the Navy fan (Piper and Normark, 1983), which are composed of mud with thin beds of silt and sand.

Methodology

The Atzbach, Schwanenstadt and Zell-am-Pettenfirst gas fields have been extensively drilled (Atzbach ~30 wells, Schwanenstadt - 23 wells and Zell-am-Pettenfirst – 13 wells) and the subsurface imaged with a 3D seismic-reflection data set that covers more than 2000 km^2 of the Upper Austrian Molasse Basin, including recently acquired additional seismic-reflection data of the Atzbach gas field. Thirty-two wells provide core from the stratigraphic interval of interest. Data for most wells includes completion logs, core, and core photographs. The 3D seismic reflection data was used to map the main horizons of the Puchkirchen Formation. Root-mean-square (RMS) seismic-reflection amplitude maps were generated from mapped horizons in order to characterize geometry and distribution of the main sand bodies. The description of core, detailed measurement of sand to mud ratios, and degree of bioturbation were made in 32 wells.

The proportions of burrowed versus intact layers were estimated in order to compare bioturbation abundance in relation to proximity to channels and sandy splays. All cores were measured using a “bioturbation index” on scale from 0% to 100%. The scale is similar to that used by Droser and Botjjer (1989) (Figure 4), where 0 is 0% or no bioturbation, 1 – 25%, 2 – 50%, 3 – 75%, 4 – 100% or complete homogenization. Another quantitative approach included measurement and estimation of sand:mud ratios in all cores in order to plot the abundance and distribution of the sand and predict sand occurrence based on identified systematic trends.

Core-data

A total length of 390 m of core was measured and analyzed from 30 wells in the Atzbach, Zell-am-Pettenfirst and Schwanenstadt gas fields. Multiple fining- and thinning-upward cycles at scale of 10-20 m are present in most wells.

Four main lithofacies were identified in core (Figure 5):

Lithofacies 1 (Lf1). Thick-bedded sandstone. Beds are >50 cm thick and with >80% sandstone. It is present in proximity to channel. Sandstone was deposited by high-density turbidity currents, capable of eroding. Lf1 are observed largely within the channel or in the closest proximity to it. The abundance of pebbles and mud clasts indicates energetic erosive flows. The massive sandstones were deposited by collapsing flows, which lost confinement and were not able to carry their suspended loads.

This facies can be divided into 2 subfacies.

- Lithofacies 1a (Lf1a): Thick-bedded sandstones with pebbles and mud clasts. Pebbles make up >20% of the units. Pebbles are up to 5 cm and average 0.5 cm and observed at the base of sedimentation units. Lf1a is interpreted to be either channel or proximal crevasse splay deposits.
- Lithofacies 1b (Lf1b): Thick-bedded sandstones structureless or showing complete or partial Bouma suites. Lf1b is interpreted to be overbank splays or crevasse splay deposits accumulated in some distance from the levee breach.

Lithofacies 2 (Lf2). Interbedded thin-bedded sandstone and mudstone. It is the most abundant lithofacies in core. Lf2 is composed largely of sandstones indicating deposition of both high- and low-density turbidity currents. The later is more prominent. Complete Bouma suite (Ta-Te) is rare; mostly Tb-Te divisions are present. The sediments were deposited by waning turbulent flows. The overall lack of thick massive divisions indicates that deposition occurred largely within the channel and only diluted top of the flows could reach the overbank areas. Lf2 is interpreted to be levee and distal crevasse or overbank splay deposits.

This facies can be divided into 2 subfacies.

- Lithofacies 2a (Lf2a): It comprises sandstone beds 5-50 cm thick and >20% sandstone.
- Lithofacies 2b (Lf2b): It comprises sandstone beds <5 cm thick and >20% sandstone.

Lithofacies 3 (Lf3). Laminated mudstone with <20% sandstone interbeds. The sediments were deposited by weak flows with little or no sand in it. The sediments are present in the distal outreach of the flows. Lf3 is interpreted to be levee top and distal overbank or crevasse splay deposits.

Lithofacies 4 (Lf4). Slurry-beds, slumps and debris flows. This facies represents a minor part of the deposits and found only within the channel or in the closest proximity to it. Those sediments were deposited by flows that had a high content of mud due to erosion upslope or through the collapse of the levees in crevasses. Lf4 is interpreted to be crevasse splay deposits.

The sand to mud ratios and bioturbation index were calculated for all wells where core is available. The examples of 2 wells that were far from and close to the channel are shown in Figure 6. As expected, the B44 well, which is closer to the channel, shows higher sand content and lower average bioturbation index than the A40 well, which lies in a more distal setting.

Conclusions

Several traceable seismic horizons were mapped through the Upper Puchkirchen Formation, and RMS amplitude maps were generated for each horizon (Figure 7). The narrowness of the Molasse Basin severely restricted the development and distribution of overbank deposits in the Puchkirchen Formation. Those examined in the present study (Figure 7) represent levees, crevasses cut into the levees, and splay deposits, including splays deposited by flows moving through erosional crevasses (crevasse splays) and splays formed by overbanking without significant erosion (overbank splays). Overall, four lithofacies were identified and each corresponds to a specific depositional setting. The presence of mud clasts at the base of the splays is interpreted to represent the development of crevasses through the levees (Hubbard et al., 2009). Mud-rich sandstones and slurry beds within the splays are also signs of levee erosion and crevasse formation. Overbank splays have deposits similar to crevasse splays, but they occupy smaller areas and lack an associated erosional conduit or crevasse through the levee. Both types are common along outer channel bends, where flow momentum increases the probability the flow will overtop or breach the levee (Posamentier and Kolla, 2003). The sand-to-mud ratio decreases away from channel, indicating that the channel was the main source of sediments, and the flows were waning with time and distance.

The degree of bioturbation does not exhibit a clear trend but in some wells is higher in more distal settings. Overall core coverage may be insufficient to document systematic trends in bioturbation.

At the beginning of deposition of the Upper Puchkirchen Formation (Figure 7A), sediments were accumulating in multiple interfingering splays so that the boundaries of individual splays were difficult to trace. The cross-section through the splays shows erosional features at the base of each, suggesting that they may have formed initially as shallow crevasses that were subsequently backfilled as the splays aggraded. The flows depositing these splays were flowing through multiple, separate breaches in the levees although general overbanking without levee erosion may have been more continuous along the levee. The map of the middle of the Upper Puchkirchen Formation (Fig. 7B) shows a single large splay present on the north side of the channel. The top of the Puchkirchen Formation (Figure 7C) shows the presence of a number of channels across the previous splay surfaces. It is not clear yet whether these represent a late stage of overbanking and splay evolution or channels formed by flows that did not originate locally within the main channel.

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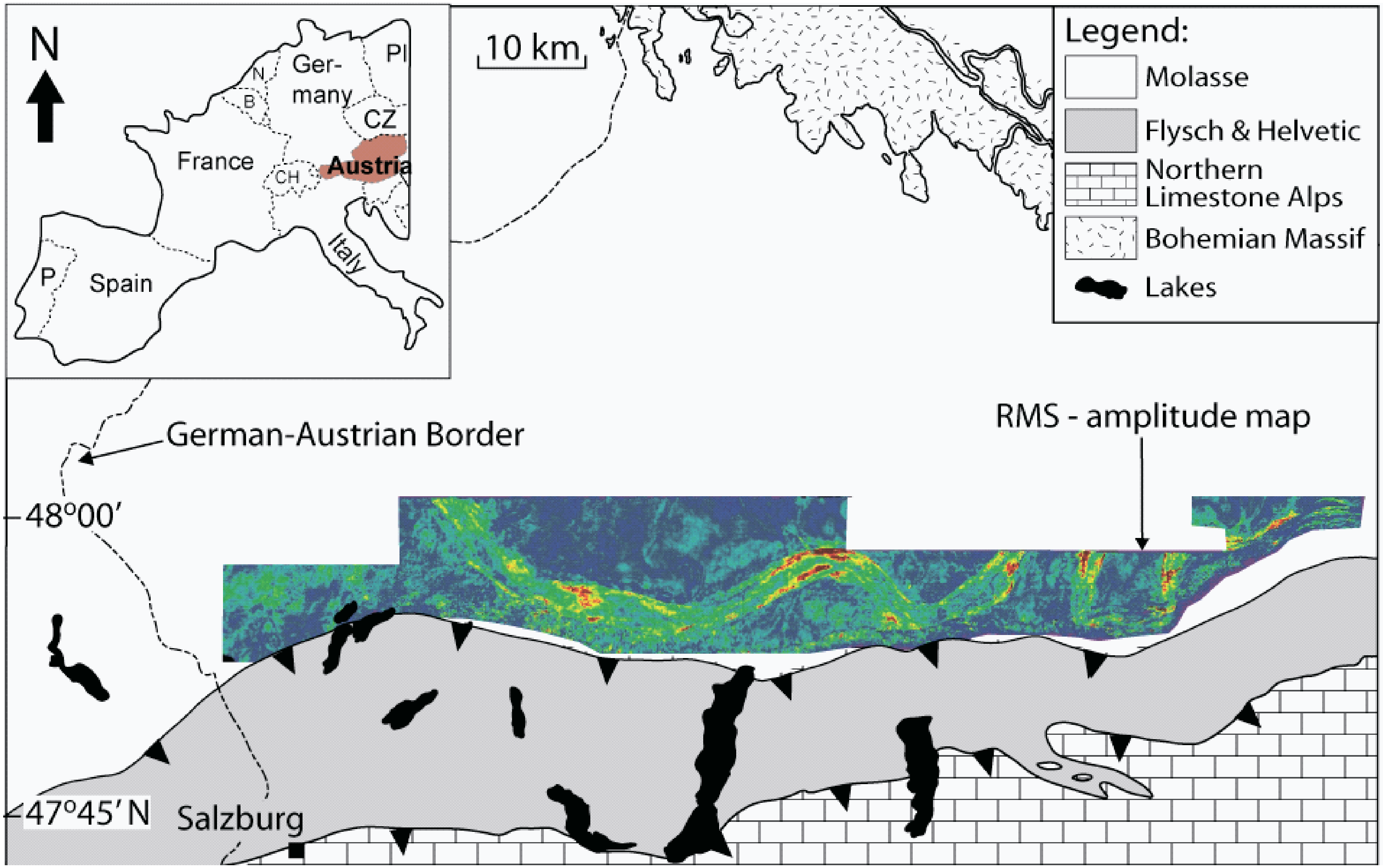

Figure 1. Index map of the Molasse Basin in Upper Austria with RMS-amplitude map of the main channel belt with overbank deposits of the Atzbach (Atz), Zell-am-Pettenfirst (Zapf) and Schwanenstadt (Sch) gas fields present within the study area. Line A-A' shows cross-section in Figure 2 (modified from De Ruig and Hubbard, 2006; Bernhdart, 2011). B-B' cross section is shown in Figure 3.

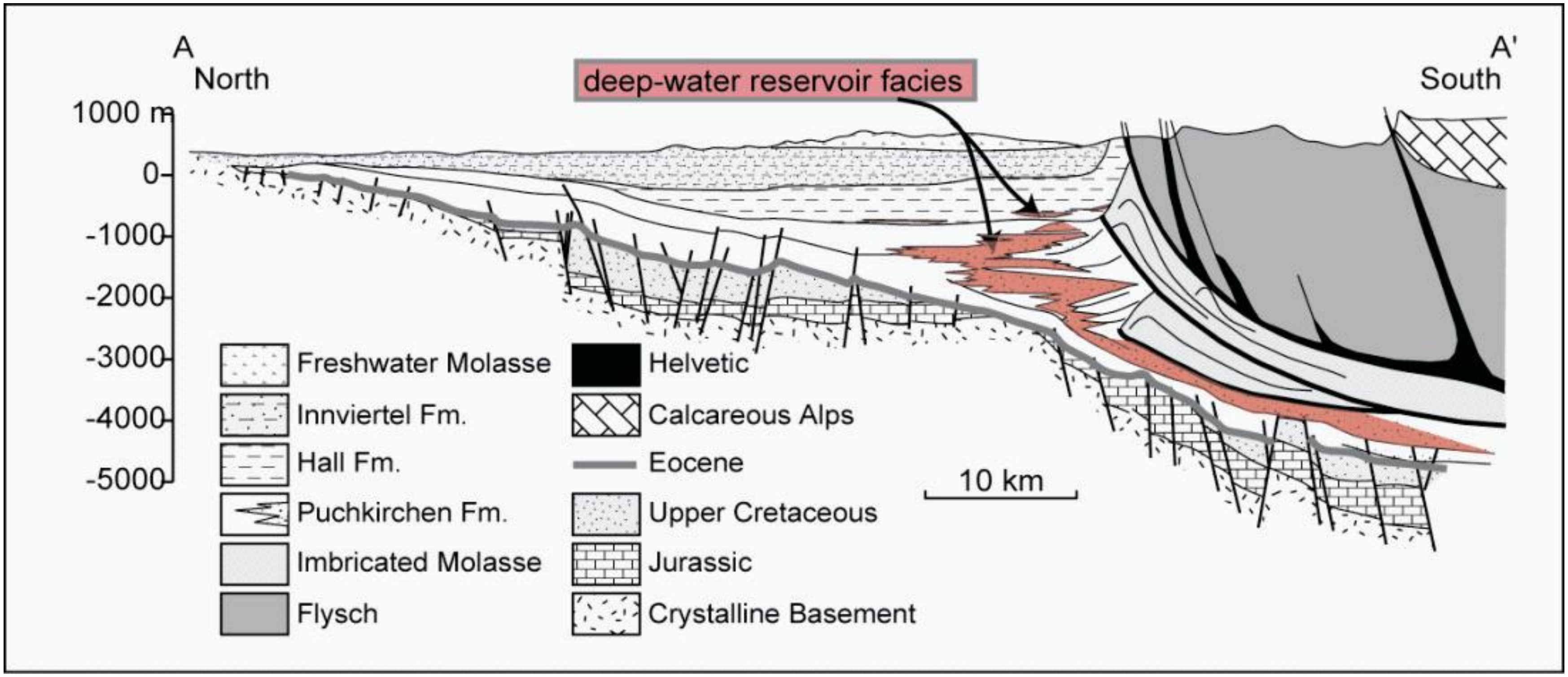

Figure 2. Regional geological cross section of the Upper Austrian Molasse Basin (from de Ruig and Hubbard, 2006; Bernhdart, 2011). See Figure 1 for location.

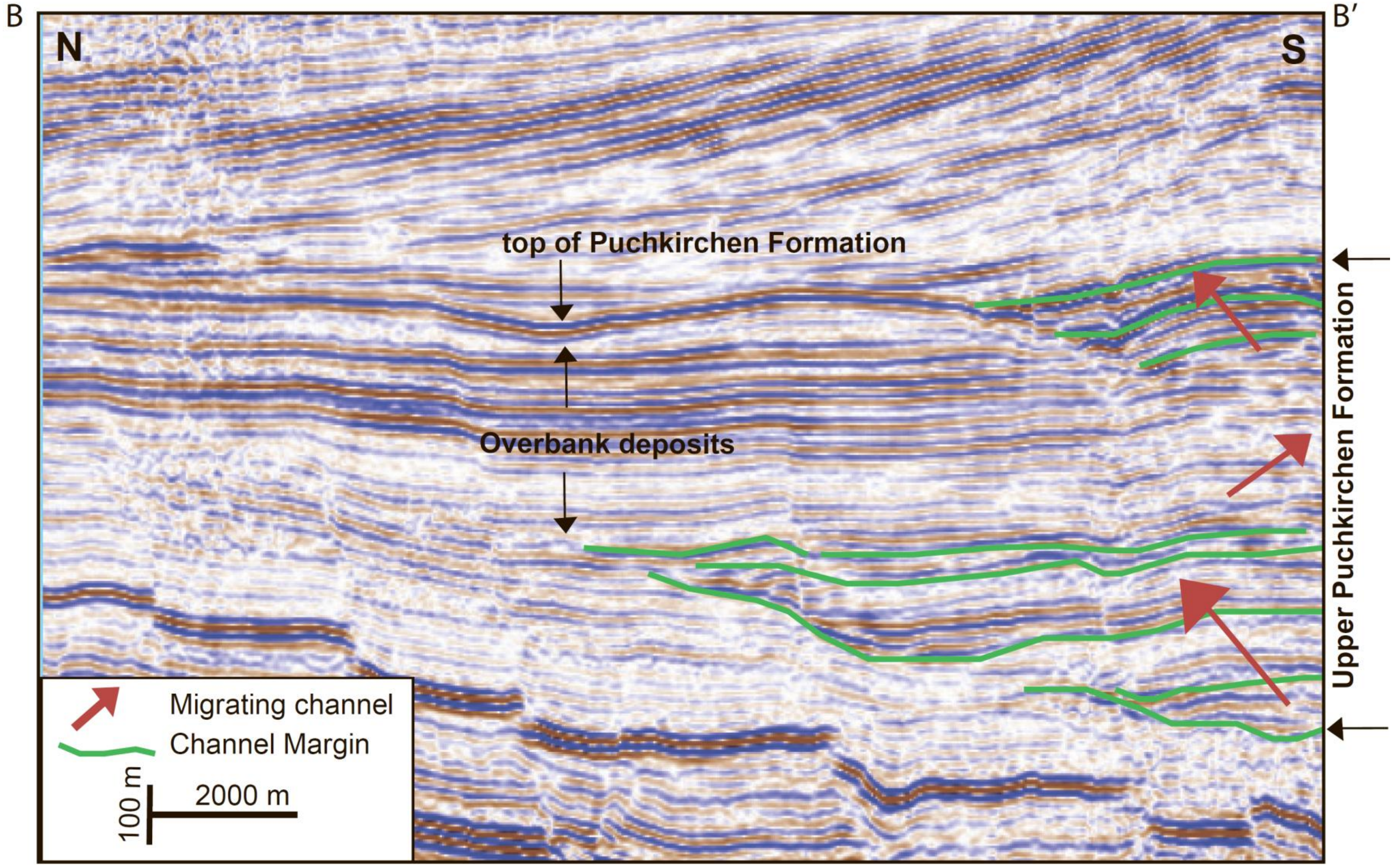

Figure 3. N-S seismic section through the northern edge of the channel belt and adjacent overbank deposits. Note the migration pattern of the channel deposits (green lines), first to the north and then in the middle of the Upper Puchkirchen Formation to the south (channel reflections south of this figure) and then towards the top of the formation again to the north. The overbank deposits were accumulating throughout the evolution of the channel. Line of section is shown in Figure 1.

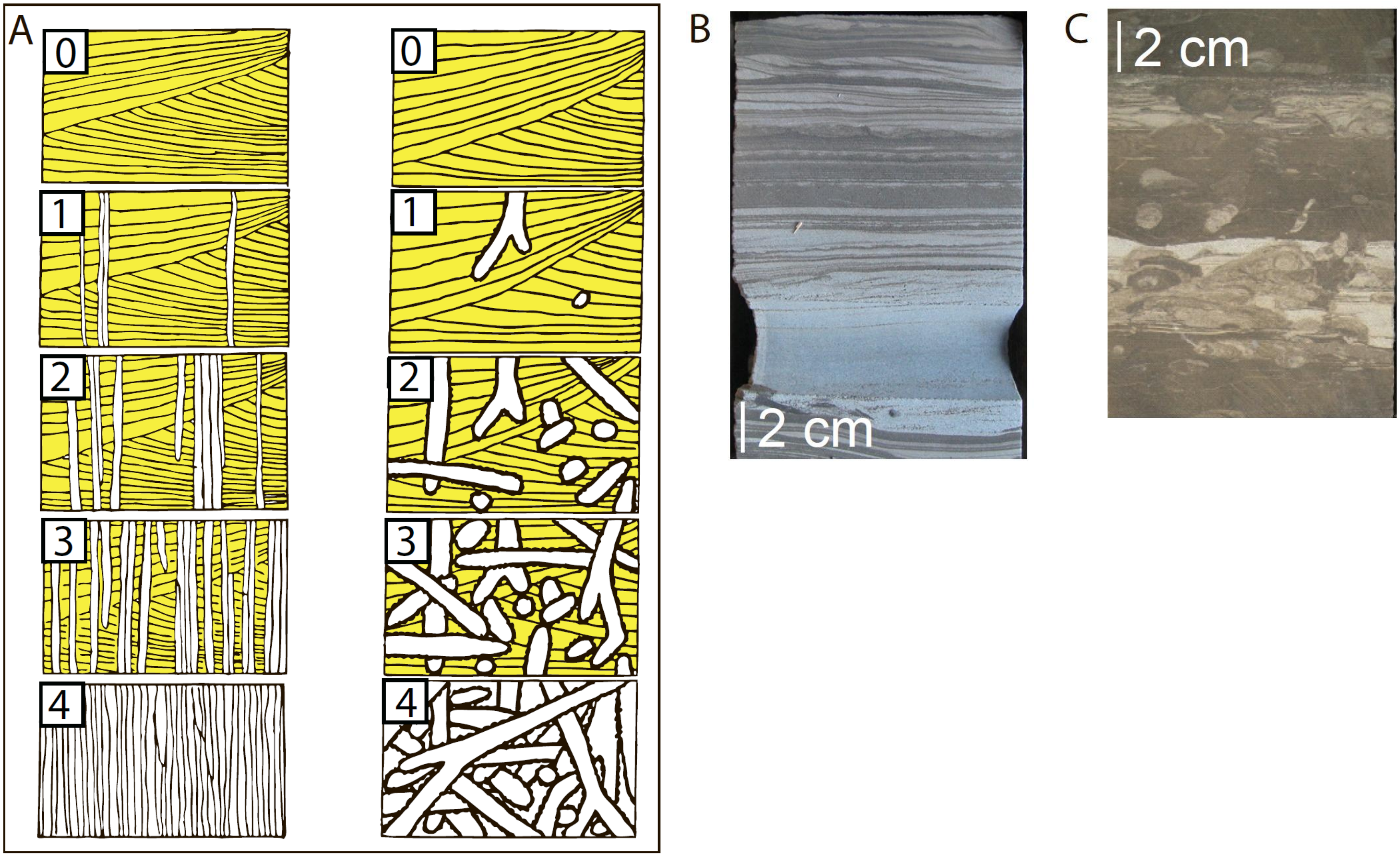

Figure 4. A) Bioturbation index table (modified from Droser and Botjjer,1989). Note that '0' is equivalent to 0% or no bioturbation is observed, '1'-25%, '2'-50%, '3'-75%, '4'-100% or complete homogenization.
B) Example of bioturbation with index 0 or 0%.
C) Examples of bioturbation with index 3.5 or 87%. The unit is disturbed and mixed, no primary sedimentary structure can be identified.

Figure 5. Lithofacies observed in core; they include channel deposits, overbank and crevasse splay deposits. (Scale: box is 1 meter.)

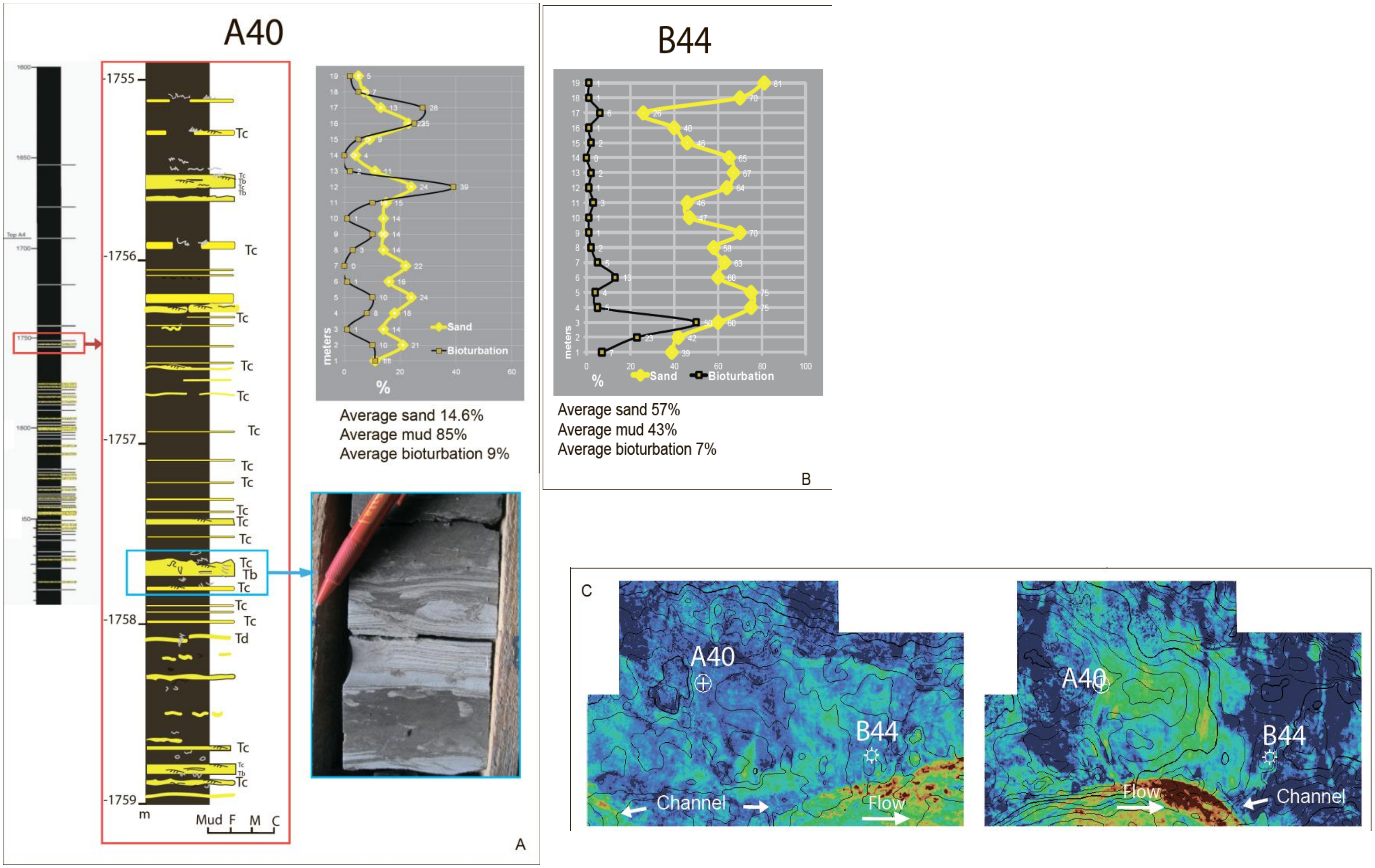

Figure 6. Sand ratios and bioturbation indices for two wells, A40 and B44, which are located far from and close to the channel, respectively.
A) Well A40 with a completion log, measured core interval, core picture, and sand and bioturbation ratios from core.
B) Well B44 with bioturbation and sand ratios from core.
C) Location of the two wells at different times and positions of the migrating main channel (left to right, from older to younger position). Note that the sand influx was changing as the channel shifted and migrated.

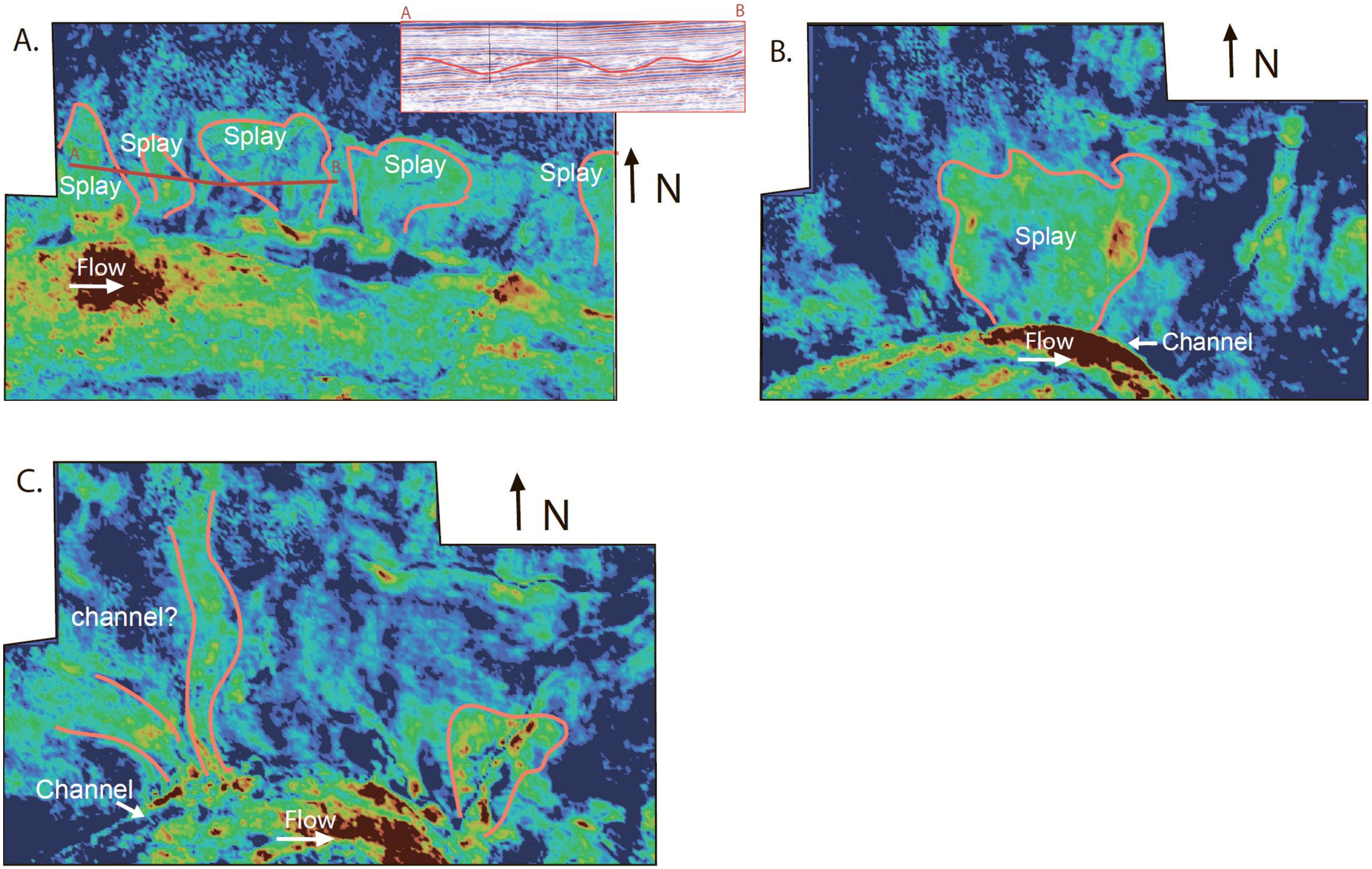

Figure 7. RMS amplitude maps generated for the Upper Puchkirchen Formation. 1) Base of the Upper Puchkirchen Formation. Note multiple splays present north of the channel. These were crevasse splays with continuous overspilling of the sediment from the channel. The cross-section of the splays shows the erosional scours at their bases, suggesting that they formed initially through levee erosion. 2) Middle of the Upper Puchkirchen Formation. A single splay is present north of the channel. 3) Top of the Puchkirchen Formation and base of the Hall Formation. Note the channels widening to the north.