How Seismic Can Contribute to Sequence Stratigraphy of Deep Buried Carbonate Banks: The Example of the Late Paleozoic Karachaganak Field (Kazakhstan)*

Fabio Luoni[1] and Ornella Borromeo[1]

Search and Discovery Article #20129 (2012)
Posted February 6, 2012

*Adapted from extended abstract prepared for oral presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2012

[1]eni E&P, Milan, Italy (fabio.luoni@eni.com)

Introduction

The gas-condensate-oil Karachaganak Field is located in the northern part of the Pri-Caspian basin, NW Kazakhstan (Figure 1, left) and consists of Carboniferous-Lower Permian carbonates. It is subdivided into the Main Field, to the east, and in the Western Build-up, to the west, separated by a saddle (Figure 1, right).

At Karachaganak, the presence of three salt diapirs in the overburden makes the carbonate bank reservoir imaging challenging and, as a consequence, the use of pre-stack depth migration seismic has been always mandatory for interpretation.

A good example of using a depth seismic dataset to describe the carbonate bank internal geometry is the 3D full-field seismo-sequence stratigraphy interpretation, carried out for the Lower Carboniferous reservoir, which has become an important piece of work in the most recent eni E&P geological model revision (Borromeo, Luoni, et al., 2010).

Workflow for Interpretation

The seismo-sequence stratigraphy interpretation comprised, first, the recognition of seismic sequence boundaries (SB) and other stratigraphic surfaces (maximum flooding and transgressive surfaces) which have been organized following a hierarchical approach, based on high-, mid-, and low-rank order of cyclicity (Catuneanu O. et al., 2009). This phase of work was carried out by combining seismic volume inspection in a 3D environment with a more traditional line drawing along selected key profiles. Then, the identified surfaces were mapped in detail over the entire field, and the resultant geometrical framework provided valuable indications concerning the evolution of Karachaganak bank. The field-scale consistency between seismic SB and stratigraphic surfaces (unconformities identified on cores or interpreted on logs) was achieved by a systematic well to seismic tie using more than 50 wells with good areal coverage. Seismic zero offset forward modelling was also carried out in a specific sector of the field to further understand if the interpreted seismic SB could be, as alternative interpretation, the seismic response of a diachronous facies boundary associated with a strong acoustic impedance variation. Cross-well seismic profiles were also utilized, providing, in the northern margin of the field, high resolution reservoir architecture images.

Description of the Geometrical Framework within the High-Rank Carboniferous Sequence

The high-rank Carboniferous sequence is bounded at the bottom by the Devonian-Carboniferous unconformity (horizon PV2 – high-rank SB) and at the top by the Carboniferous-Permian unconformity (horizon C1a – high-rank SB).

Within this interval, the high-rank transgressive section (TST - Tournaisian and Early Visean) ends at the top with the Tula regional marker of shale and cherty limestone, which records the maximum sea level (horizon C9 – high-rank maximum flooding surface). The high-rank TST is generally below seismic resolution, and very few stratigraphic features are seismically visible.

The Upper Visean and Serpukhovian high-rank highstand section (HST) records the onset of biohermal deposits and a phase of remarkable vertical growth, characterized by aggrading and prograding internal geometries. In this section, a combination of seismic cube inspection in a 3D environment with a more traditional line drawing, along selected key profiles (Figure 2), allowed identification of two mid-rank seismic SB that, by means of an extensive well to seismic tie, were correlated, respectively, with the Visean–Serpukhovian unconformity (horizon C7, in purple in Figure 2) and with the Intra-Late Serpukhovian unconformity (horizon ILS, in pink in Figure 2), recognized from well data (Figure 3). The Serpukhovian evolution has been mapped over the entire Field and the relevant seismic horizons (Top SERP AGG1, Top SERP AGG2, Top SERP PROG1, Top SERP PROG2, Top SERP PROG3, and Top SERP PROG4) have been interpreted as the seismic response of low-rank SB, developed on top of shallowing-upwards cycles recognized from core and log facies interpretation. The post-ILS transgression is also documented by onlap terminations (horizon LATE SERP transgressive surface) and by a change of the log stacking pattern, with cycles becoming more separated.

To further investigate if the ILS reflector could be interpreted, instead of a seismic SB, as the seismic response of a time-transgressive facies boundary (pseudo-unconformity - Schlager, 2005), zero offset seismic forward modelling was carried out in a specific sector of the field where onlap terminations have been recognized on seismic. Two acoustic impedance models, reflecting the two interpretations, were derived (a) by interpolating the log acoustic impedances inside the 3D seismo-sequence stratigraphy framework (model 1) and (b) by introducing a horizon to mark the diachronous acoustic boundary (model 2). The comparison between the synthetic models (Figure 4, upper) and the actual seismic (Figure 4, lower) would confirm the time correlative nature of the ILS reflector. However, a diachronous acoustic boundary seems to be present in the lowermost interval, correctly crossed by the time-correlative Top SERP AGG1 picking (low-rank SB).

Evolution of Karachagank Bank during the Carboniferous High-Rank Highstand

A detailed interpretation of the Carboniferous high rank highstand finally led to define the evolution of Karachaganak bank. The greatest interpretative effort was dedicated to the Serpukhovian, because the post Tula-Late Visean interval is generally represented by a single peak-trough-peak loop and hence very few stratigraphic details are evident from seismic. Seismic scale mound complexes, with an aggradational to progradational internal geometry, nucleated on top of the Visean–Serpukhovian unconformity (Figure 5).

Aggradation mainly developed during two distinct and seismically interpretable stages that ultimately led to the formation of two seismic-scale mound complexes in the Main Field, the Northern and Southern Mound Complexes, and one in the Western Build-up area (WBU). The two stages were assumed to be synchronous at field scale although no physical correlation between the Main Field and the WBU can be observed from seismic. isopach maps would suggest a shift of the depocentres from south to north and from the Main Field to the WBU evolving from stage 1 to stage 2 of aggradation.

Progradation developed during four distinct and seismically interpretable stages. The lower stages 1 and 2 were interpreted only in the WBU. The upper stages 3 and 4 were interpreted both in the Main Field (east and west from the aggradation regions) and in the WBU, showing evidences of physical correlation between the WBU and the western part of the Main Field. Progradation stages 3 and 4 were supposed to be synchronous over the entire field, with stage 3 representing a significant change in the depositional history (from aggradation to progradation) while stage 4 can be interpreted as down-stepping.

The seismo-sequence stratigraphy framework for the high-rank HST finally comprised two aggradation stages (delimited by Top SERP AGG 1 and Top SERP AGG 2 horizons), and four progradation stages (delimited by Top SERP PROG 1, Top SERP PROG 2, Top SERP PROG 3 and Top SERP PROG 4 horizons), reflecting an overall shallowing-upwards trend of the mid-rank sequence with an ultimate forced regression.

Within this geometrical framework, the facies depositional model sees predominantly microbial bioherm deposits (in situ and reworked) and subordinately bank interior skeletal grainstone and packstone, which occur in the uppermost part of the sequence in the centre of the Main Field.

It has to be pointed out that seismic interpretation in a microbial-dominated context required developing an unconventional approach. Picking was not done horizon by horizon following a predefined scheme, but it was template-based. Starting from an area where moundy geometries were evident, a set of horizons, describing the mound complex growth (basic template), was defined and interpreted at once. The interpretation was then propagated laterally by moving the template that could even be modified (adding or removing horizons), depending on the geometry variations observed on seismic. The template-based interpretation, performed in a true 3D environment, was essential to guarantee that the same correlative event was interpreted at field scale, even in a complex geology, as the microbial mound complexes are.

As a consequence of using this approach, the interpretation scheme was defined only at the end of the work and finally comprised a large number of horizons.

Geometrical Indications from the Cross-Well Seismic across the Northern Margin of Karachaganak

Two cross-well seismic profiles have been acquired in the northern sector of Karachaganak Field, from the bank interior to the bank margin and to the lower slope (the acquisition wells were: E, F and G - Figure 6, upper). In this area the conventional seismic images, the Serpukhovian aggrading units (SERP AGG1 and SERP AGG2), are draped by the ILS in the saddle between two mound complexes (Figure 6, lower). The eastern mound complex shows an intermediate stage of growth (pick in brown in Figure 6, lower) between aggradation stage 1 and stage 2 (pick in red and in yellow in Figure 6, lower), marginally penetrated by well F and not observed in the western mound complex.
The interpretation of the cross-well seismic profiles allowed identifying sequence boundaries on the basis of their reflector geometry relationship. A systematic cross-check between position at wells of the cross-well sequence boundaries and well markers for C7, Top SERP AGG 1, Top SERP AGG2, ILS, allowed us to flag them as high-, mid-, or low-rank sequence boundaries, thus providing the necessary consistency between the two models: the high-resolution seismo-sequence stratigraphy framework (defined along a unique 2D cross-well seismic section) and the low-resolution 3D seismo-sequence stratigraphy model (defined by using the surface seismic as input - Figure 6, lower).

The higher resolution of the cross-well seismic finally provided more detail on the architecture of the bioherms in the saddle between the eastern and western mound complexes (see map on Figure 6 for location of the profile – line in pink). More specifically, in the surface seismic, the aggrading units are imaged as a pair of moundy reflectors; whereas in the cross-well seismic, they are imaged as two packages of moundy reflectors (100 m thick) separated by a package of parallel reflectors (100-150 m), reflecting different facies association as documented by core data. In addition, by imaging the fine-scale geometrical relationships between reflectors, the cross-well seismic would confirm the sequence stratigraphic nature of Top SERP AGG1 and Top SERP AGG2 as low-rank SB developed on top of shallowing-upwards cycles (parasequences recognized from log interpretation).

Conclusions

At Karachaganak, the available depth seismic volume has been recently used for a detailed 3D seismo-sequence stratigraphy interpretation of the Lower Carboniferous reservoir. The most significant result has been achieved within the Serpukhovian interval, part of the high-rank Carboniferous sequence highstand, where seismic-scale mound complexes nucleated on top of the Visean–Serpukhovian unconformity have been recognized and the relevant aggrading, prograding and down-stepping growth phases have been mapped over the entire field.

The vertical growth of the mound complexes (aggradation) shaped a substantial relief which was maintained, though reduced, during the subsequent lateral expansion (progradation) and up to the time of the ILS mid-rank SB, as documented by onlaps identified on seismic and correlated with an unconformity recognized on core.

The geometrical framework inferred from seismic makes Karachaganak an example of a Paleozoic carbonate bank dominated by microbial bioherms, significantly different from the classical flat-topped platform model.

Acknowledgments

We are sincerely grateful to people from eni E&P in Milan who in the last years contributed to this work: Francesco Bigoni, Arrigo Francesconi, Claudio D'Agosto, Cristian Albertini, Davide Camocino (eni E&P) , and C. Cavalli (formerly eni E&P).
We also thank colleagues from KPO and parent companies for the stimulating discussions, and KPO, eni E&P, BG Group, CVX and Lukoil for the permission to publish this article.

References

Borromeo, O., F. Luoni, F. Bigoni, D. Camocino, and A. Francesconi, 2010, Stratigraphic architecture of the Early Carboniferous reservoir in Karachaganak Field, Pri-Caspian Basin (Kazakhstan): SPE-139887-MS, Caspian Carbonate Technology Conference, Atyrau, Kazakhstan.

Catuneanu, O., V. Abreu, J.P. Bhattacharya, M.D. Blum, R.W. Dalrymple, P.G. Eriksson, C.R. Fielding, W.L. Fisher, W.E. Galloway, M.R. Gibling, K.A. Giles, J.M. Holbrook, R. Jordan, C.G.St.C. Kendall, B. Macurda, O.J. Martinsen, A.D. Miall, J.E. Neal, D. Nummedal, L. Pomar, H.W. Posamentier, B.R. Pratt, J.F. Sarg, K.W. Shanley, R.J. Steel, A. Strasser, M.E. Tucker, and C. Winker, 2009, Towards the standardization of sequence stratigraphy. Earth-Science Reviews, v. 92, p. 1–33.

Schlager, W., 2005, Carbonate sedimentology and sequence stratigraphy: Concepts in Sedimentology and Paleontology: SEPM (Society of Sedimentary Geology), Series No. 8, 200 p.

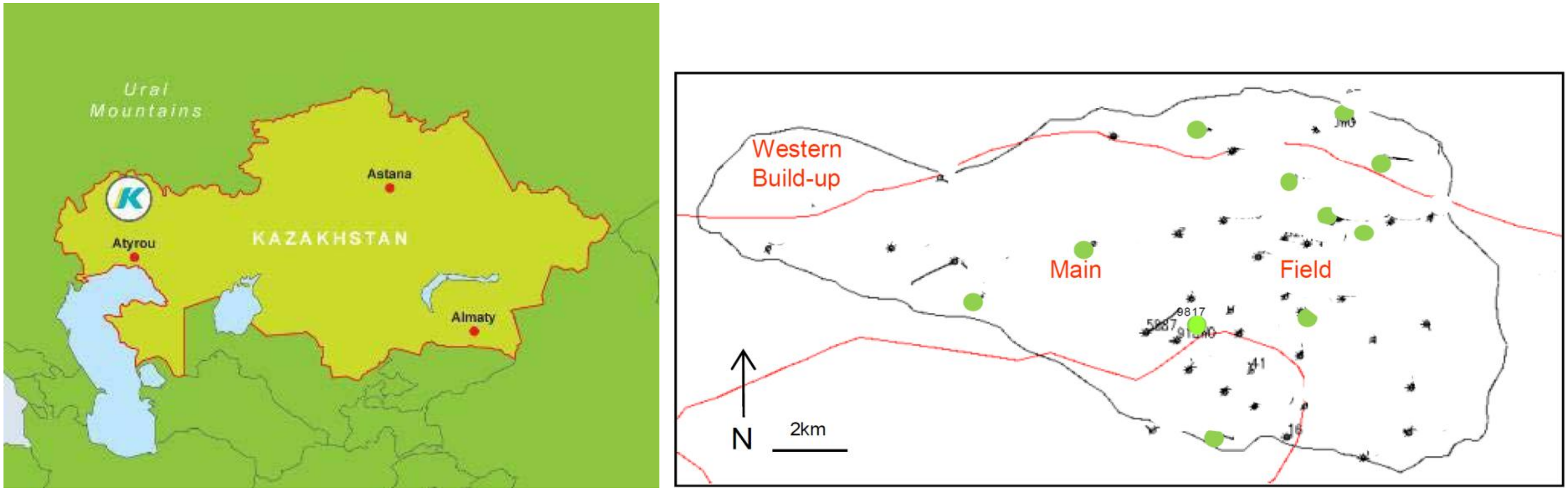

Figure 1: Location map for Karachaganak Field (left); Field outline (black) with the wells used for this study. Diapir outlines are in red; green spots are recent cored wells (right).

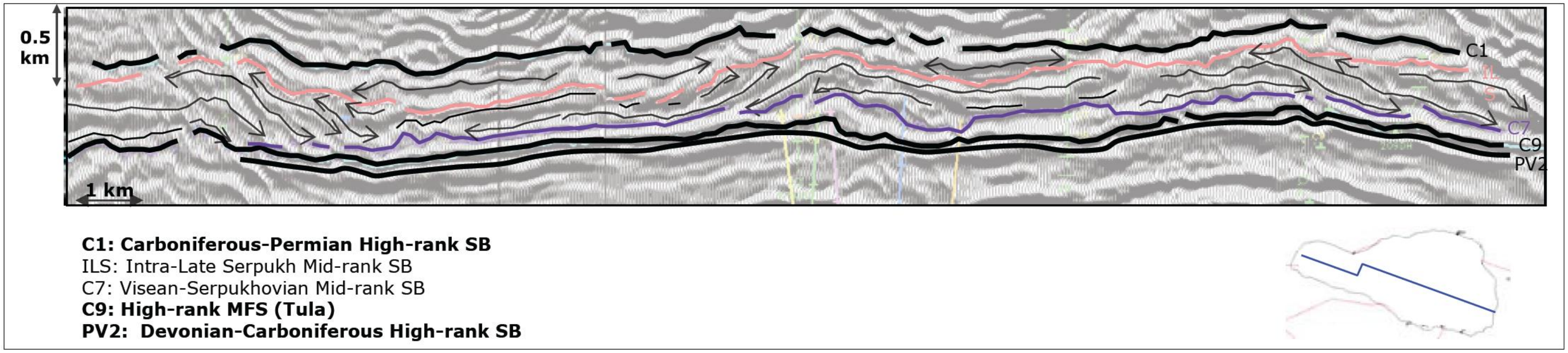

Figure 2: Line drawing along a key profile. The high-rank Carboniferous sequence is bounded by C1 and PV2 horizons and the high-rank MFS is represented by the Tula-C9 horizon (black bold lines). Within the high-rank HST (above C9), two mid-rank SB (C7 and ILS horizons) are in purple and pink. Between C7 and ILS, aggrading and prograding patterns are evident representing the evolution of the bank during the Serpukhovian HST. The post-ILS transgression is documented by onlaps recognized from seismic and from log-stacking pattern.

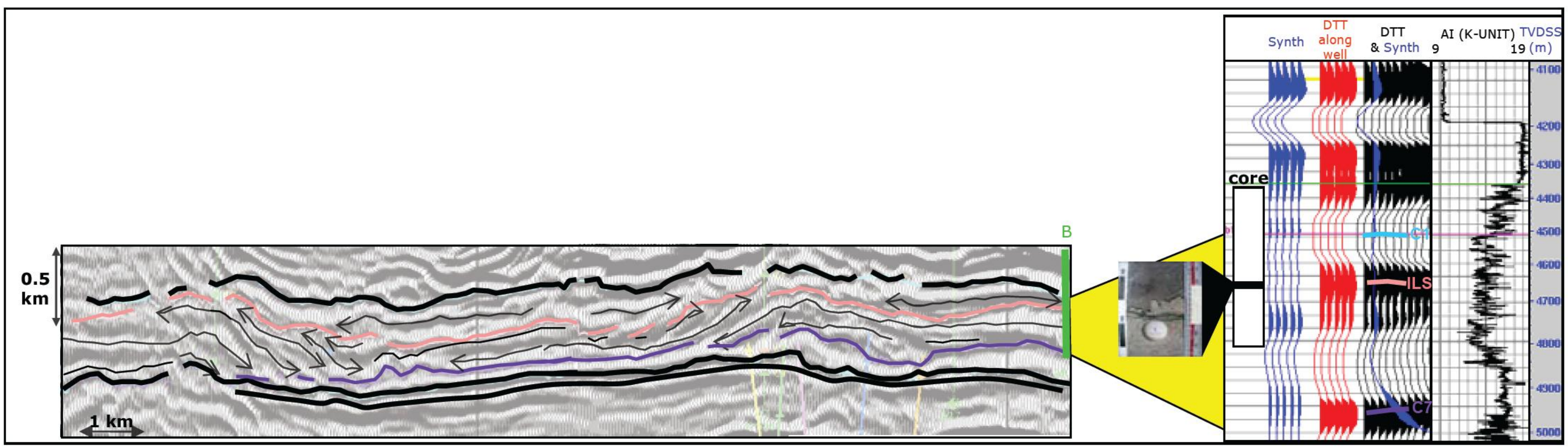

Figure 3: Example of correlation supported by well-to-seismic tie between seismic SB identified on seismic and unconformity recognized in core.

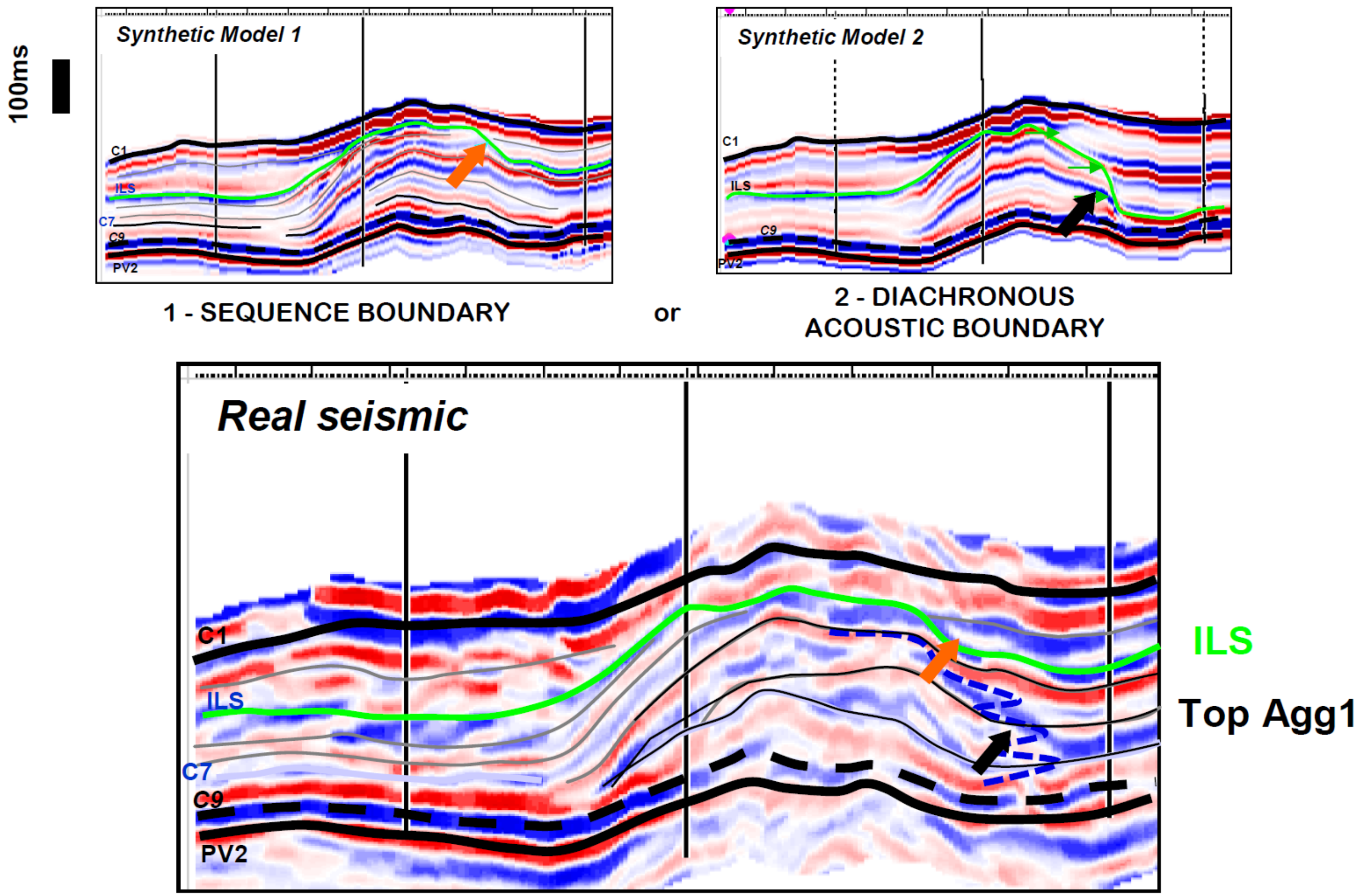

Figure 4: Zero offset forward modeling. The synthetic seismic from acoustic impedance models 1 (top left) and 2 (top right) are compared with the real seismic (bottom). The reflector termination indicated by the orange arrow is not a pseudo-onlap, confirming the time correlative nature of the ILS. In the deepest section, pseudo-onlaps (indicated by the black arrow) occur where a diachronous acoustic boundary has been introduced in the acoustic model (blue dotted line) which correctly is crossed by the Top Agg1 (time correlative SB) picking.

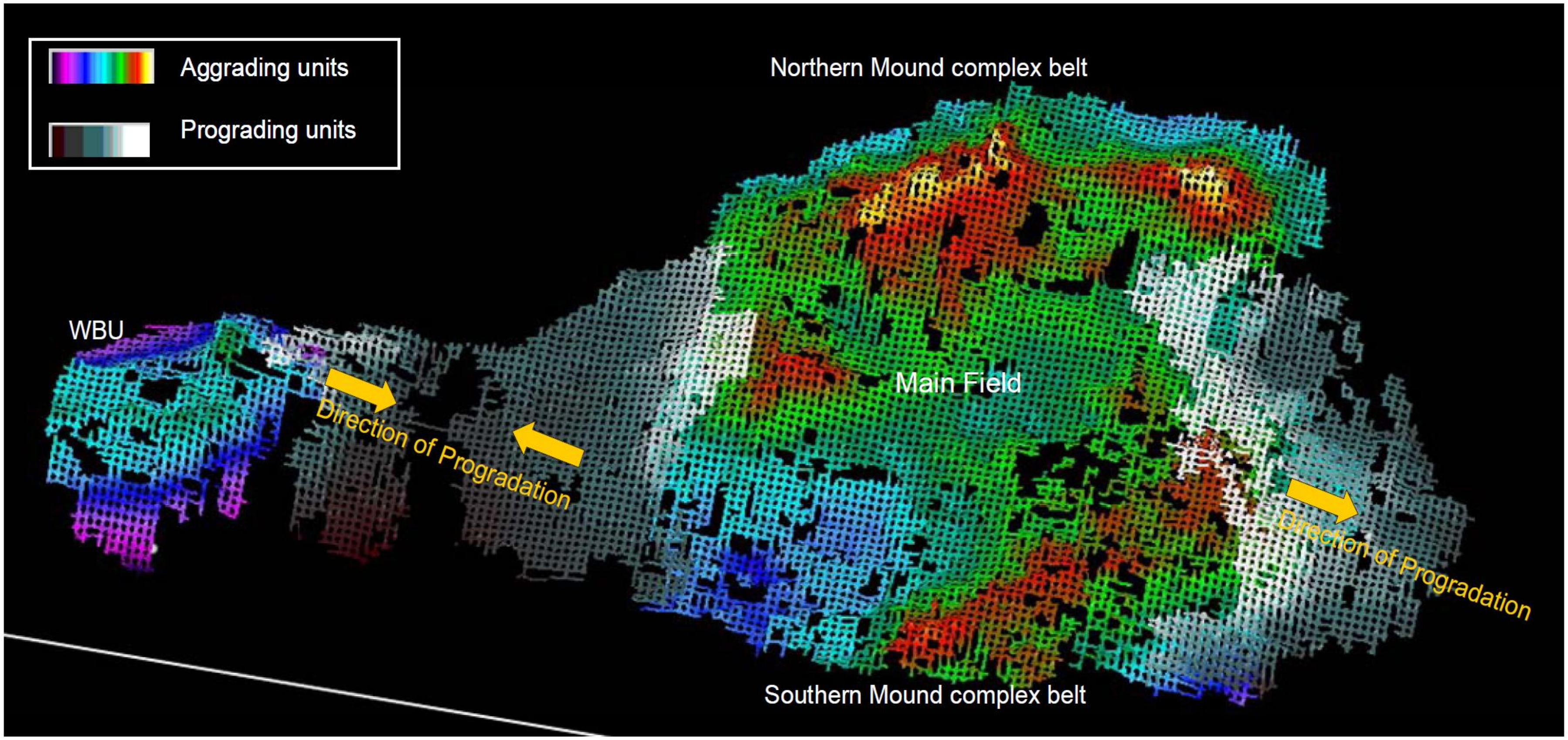

Figure 5: Serpukhovian high-rank HST evolution from aggradation to progradation.

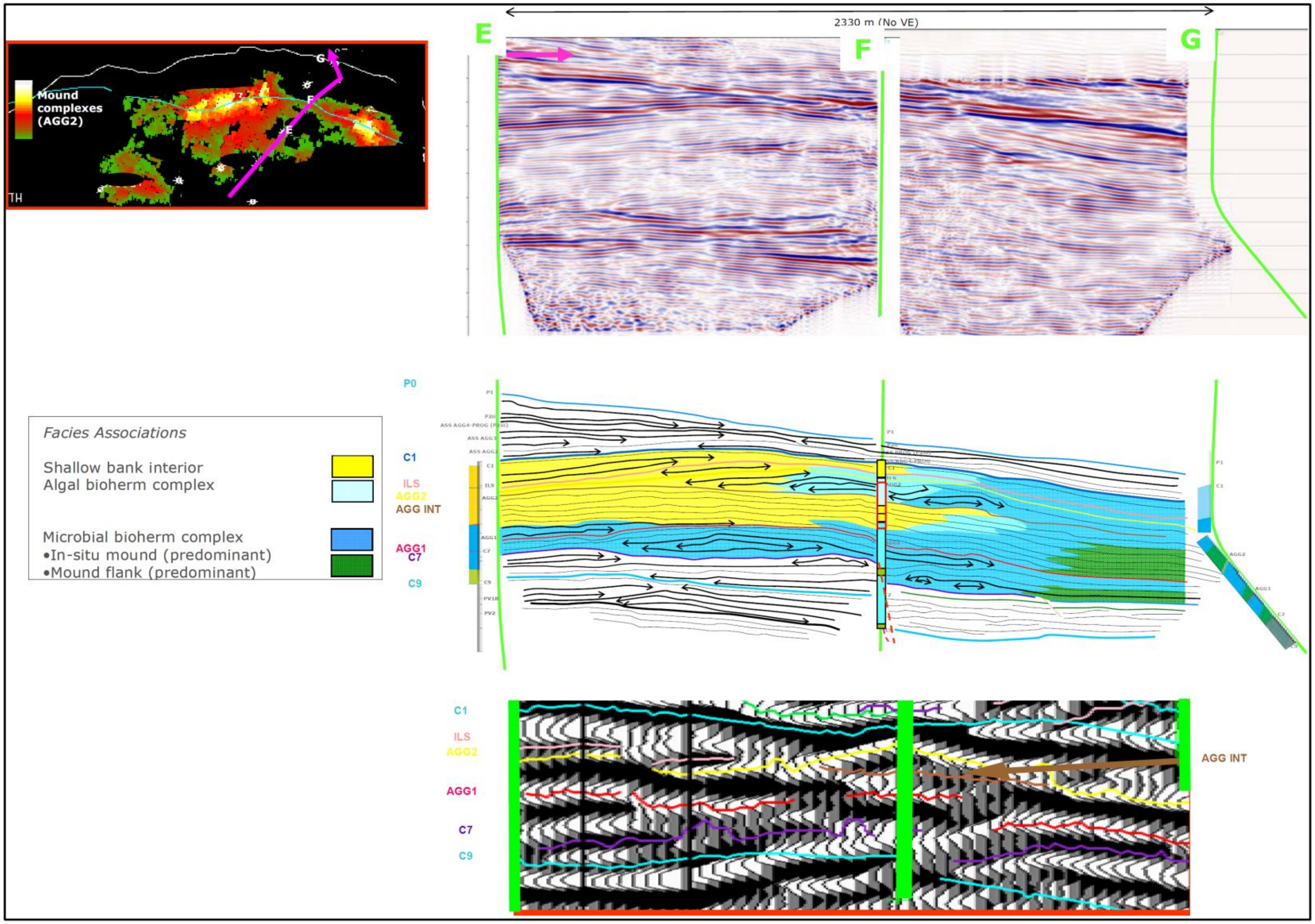

Figure 6: Cross-well seismic profiles (upper), high-resolution seismo-sequence stratigraphy framework with associated facies distribution (middle) and interpreted surface seismic (lower).