Integrated Characterization of Intra-Slope Reservoirs: Transferring Facies and Log Imaging Data to Seismic Inversion Constrained by Outcrop Analogues (Marulk Field, Offshore Norway)*

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Abstract

The Marulk Field in Block 6507/2 (PL122) is located on the Dønna Terrace, Norwegian Sea. A Cretaceous dome structure above a Jurassic horst block defines the trap. The main reservoir (Lysing Formation,Turonian-Coniacian) consists of a confined turbidite system fed from east and north-east; sandstone lobes onlap the crest of the tilted block.

The base of Lysing Formation represents a discontinuity generated by the reactivation of the Marulk synsedimentary high; it also corresponds to a sequence boundary related to a regional basin-modification phase responsible for the increase of sand flux toward the basin.

The integration of facies, stratigraphic, high-resolution image logs and seismic inversion analyses permitted the identification of the external shape of the system, the component depositional elements, and their relationships with the syndepositional high. Elastic seismic attributes proved reliable in lithology and fluids definition and permitted visualization of the 3-D distribution of depositional elements. Paleocurrents from ripple cross laminations were measured using the image logs.

Along the eastern flank of the structure, two types of marine onlap are recognized: frontal onlap and lateral onlap. The high-angle (frontal) and the low-angle (lateral) oblique onlaps of turbidite lobes in an Oligocene confined slope-basin (Cengio Turbidite System - CTS, Tertiary Piedmont Basin, Italy) provide good outcrop analogues. The Marulk frontal onlap area is recognized in the north-east sector of the structural high, located in front of the main channel feeding the system, basinward of a flow-expansion zone. The major distinctive features of the frontal onlap deposits are: abrupt base, very high sand/shale ratio, quick seismic termination. The high-angle CTS onlaps show similar features: sharp base, rapid pinch-out of sandstone bodies, pronounced increase of net-to-gross ratio and bed amalgamation toward the slope and decrease of sandstone beds thickness away from the slope. The Marulk lateral onlap area occurs in a more downcurrent sector along the south-eastern flank of the syndepositional high. Distinctive features are chiefly: transitional base with the underlying mudstones, thickening-

upward basal portion, gradual seismic termination. Comparable features characterize the low-angle onlaps above the gentle lateral slopes of the CTS analogue: gradual pinch-out, increase of net-to-gross and amalgamation ratios and moderate thickening of some sandstone beds away from the slope.

Introduction

The Marulk Field in Block 6507/2 (PL122) is located on the Dønna Terrace, Norwegian Sea. A Cretaceous structure above a Jurassic horst block defines the trap. The main reservoir (Lysing Formation,Turonian-Coniacian) consists of a turbidite system fed from east and north-east, i.e., the Marulk Turbidite System (MTS), pertaining to the Snadd Turbidite Complex (Figure 1) (Fugelli and Olsen, 2007). The base of Lysing Formation represents a discontinuity generated by the reactivation of the Marulk syndepositional high. Regionally, it corresponds to a sequence boundary related to a basin-modification phase responsible for the increase of sand flux toward the basin.

The integration of facies, stratigraphic, image logs and elastic seismic inversion analyses (Calabrese et al., 2011) permitted us to identify the external shape of the system, the 3-D distribution of depositional elements and their relationships with the syndepositional high.

The Marulk Turbidite System

The MTS records the infilling of an intra-slope basin plunging toward the south and confined by a syndepositional high, in which gravity flows tend to be deflected southward along the axial plunge. The main feeder channel is located in the north-east, so that the flows exiting from there are expected to run toward south-west, at least in their early stage. Minor source areas can be locally outlined along the Nordland Ridge, providing some supply to the MTS.

The turbidite system consists of sandstone lobes, up to 40 m thick, fed from the major feeder channel. Between the channels and the lobes, flow-expansion facies are recognized. Close to the basin margin, the channel facies are overlain by sandstone lobes, suggesting a retrogradational stacking pattern. Facies analysis on bottom cores permitted us to establish a facies tract related to downcurrent flow transformations, from hyperconcentrated flows to high-density turbidity currents and then to low-density turbidity currents in the lobe fringe region (Figure 2).

Along the eastern flank of the structure, the sandstone lobes onlap the crest of the tilted block. Two types of marine onlap are recognized: frontal onlap in the north-eastern sector of the field, located in front of the main channel feeding the system, and lateral onlap in a more downcurrent sector along the south-eastern flank of the field (Figure 3).

In the northern segment of the field, flow interference with the syndepositional high gave way to sudden deceleration and rapid sedimentation, generating soft-sediment deformation and large clay clasts (impact features). FMI data show current ripple lee sides mainly indicating southward paleocurrents in thin-bedded turbidites at the transition with the overlying Kvitnos Formation (undersupplied stage), in agreement with the southward axial plunge of this segment of the Dønna Terrace. During the sedimentation of Lysing Formation (oversupplied stage), when the flow volumes outpaced the size of the basin, flow reflection (toward NNE) and deflection (toward E) are recorded (Figure 3).

Comparison with the Outcrop Analogues

The marine onlaps of turbidite lobes filling an upper Oligocene confined intra-slope basin in the western part of Tertiary Piedmont Basin (TPB), NW Italy (Gnaccolini et al., 1998), are considered. The intra-slope basin developed over an area controlled by a transtensional-transpressional regime (Rossi et al., 2009) that can be estimated approximately as wide as half of the MTS area. The turbidite sandstone lobes of the Cengio (CTS) and Bric la Croce-Castelnuovo (BCTS) Turbidite Systems (Bersezio et al., 2009 with references therein; Figure 4) show nicely exposed onlap terminations, both downcurrent ("rapid pinch-outs", i.e., frontal onlaps) and parallel to paleo-slope ("gradual pinch-outs", i.e., oblique and lateral onlaps). Thickness, size, geometry, sediment textures, and facies are quite comparable to those described for the Lysing Formation of the MTS.

In the TPB case, initial aggradation and forestepping was followed by the back-stepping of turbidite lobes. This evolution is due to partial ponding of the CTS that is thicker and shows more numerous very thick beds than the BCTS, confined but not ponded and spread over a wider area. Owing to partial ponding, the TPB succession is thicker than the turbidite sequence of the MTS. The frontal onlap of the underlying CTS provides the analogue for the main reservoir of the Lysing Formation, as well as the lateral onlap of the Cengio and Castelnuovo systems provide the analogue for the lateral terminations of the entire turbidite succession of the MTS. The frontal onlaps of the Cengio-Castelnuovo systems show sharp base, rapid pinch-out of sandstone bodies, pronounced increase of net-to-gross ratio and bed amalgamation toward the slope (compared to the depocentres; Figure 5) and decrease of sandstone beds thickness away from the slope. The lateral onlaps above the gentle lateral slopes of the CTS analogue show gradual pinch-out, moderate increase of net-to-gross and amalgamation ratios (compared to the depocentres and frontal onlaps; Figure 5) and moderate thickening of some sandstone beds away from the slope.

Conclusions

In the Marulk Field, along the eastern flank of the structure, it has been demonstrated that the two types of termination of sandstone lobes (frontal onlap and lateral onlap) greatly impact net-to-gross ratios and petrophysical properties. The ability to integrate several tools capable of recognizing these features is, therefore, of paramount importance in these types of reservoir to predict reservoir architecture and quality.

Major distinctive features of the frontal onlap deposits are: abrupt base, very high sand/shale ratio, quick amplitude dimming. Major distinctive features of the lateral onlap deposits are: transitional base with the underlying mudstones, thickening-upward basal portion, gradual amplitude dimming (Figure 6).

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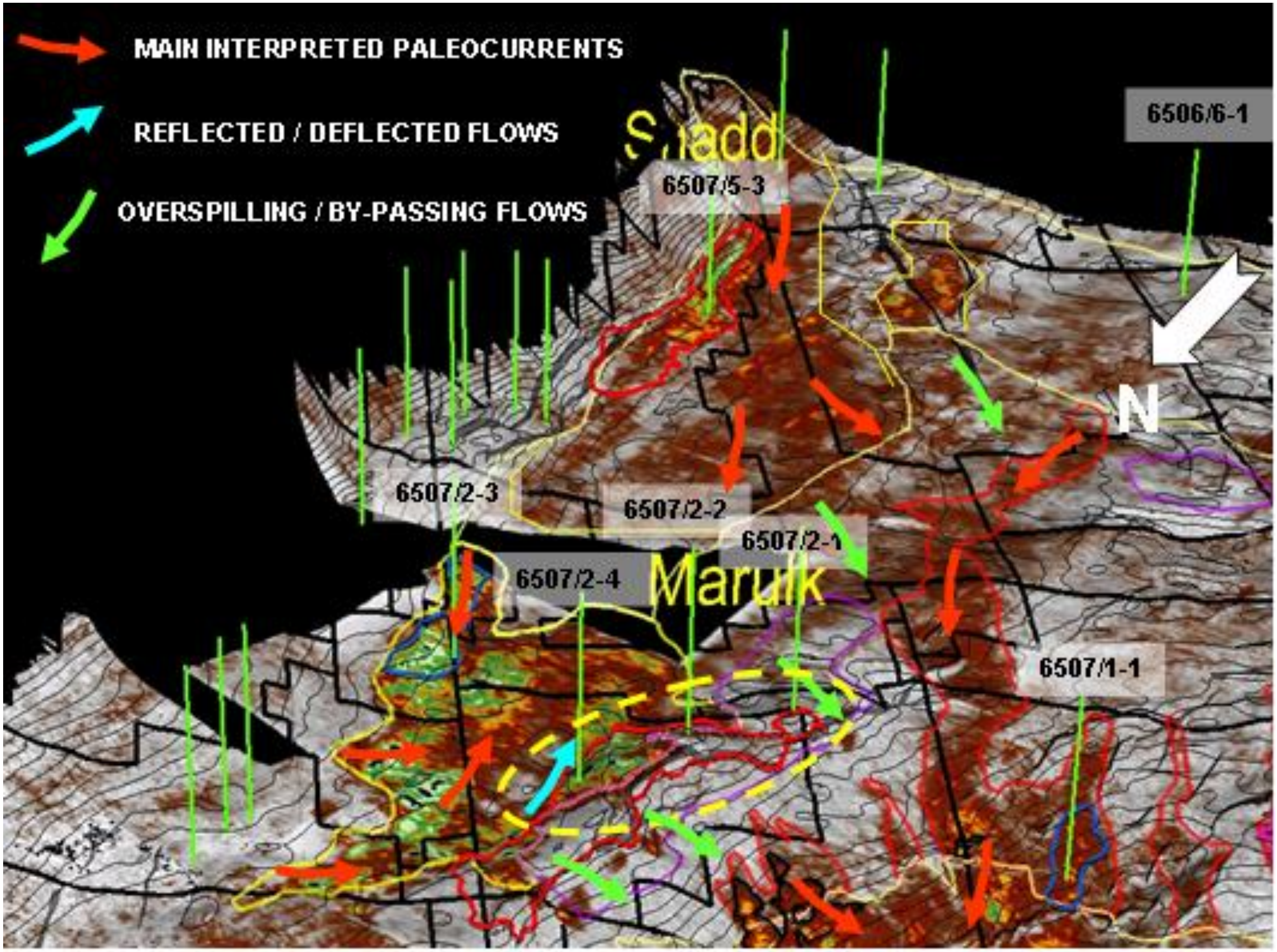

Figure 1. Amplitude extraction showing the Snadd Turbidite Complex. View is from NW.

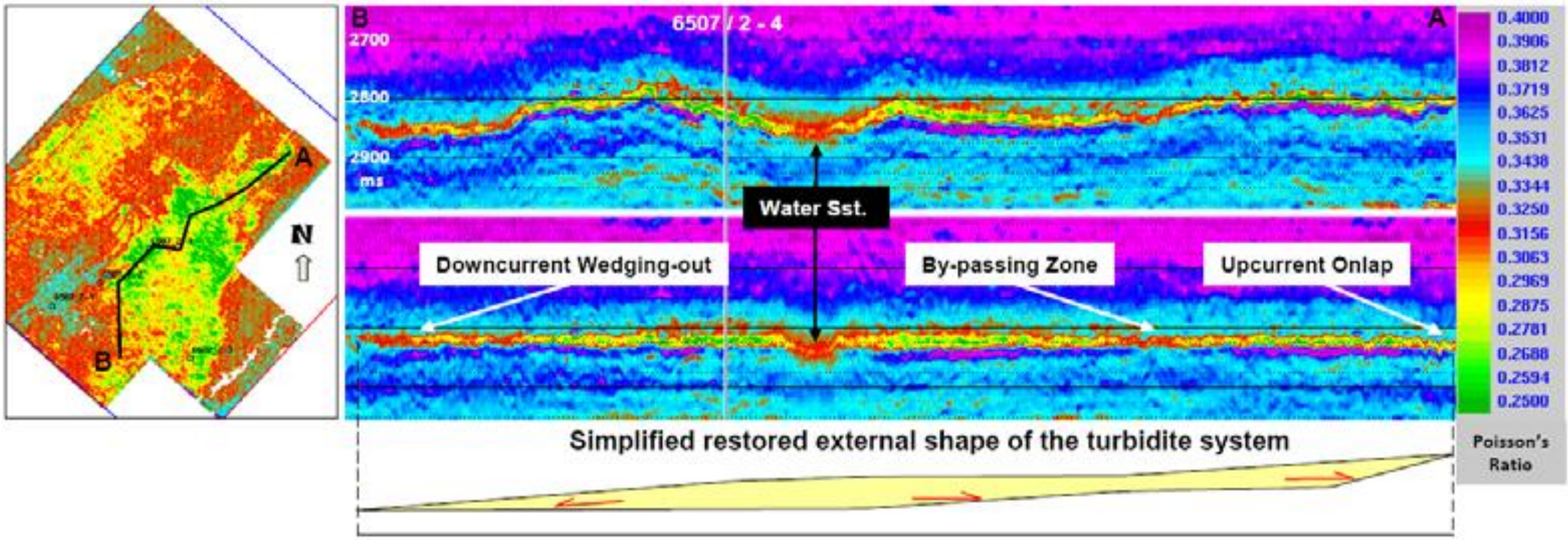

Figure 2. Shape and internal characteristics of the Marulk Turbidite System shown by Poisson's ratio. The present depth profile suggests that HC-bearing sandstones display lower PR values than water-bearing sandstones; the flattened profile restores the original configuration of the system. High PR values shown in the map record mudstones and thin-bedded turbidites, while very high values are related to shadow areas where thin, very fine-grained tight sandstones occur.

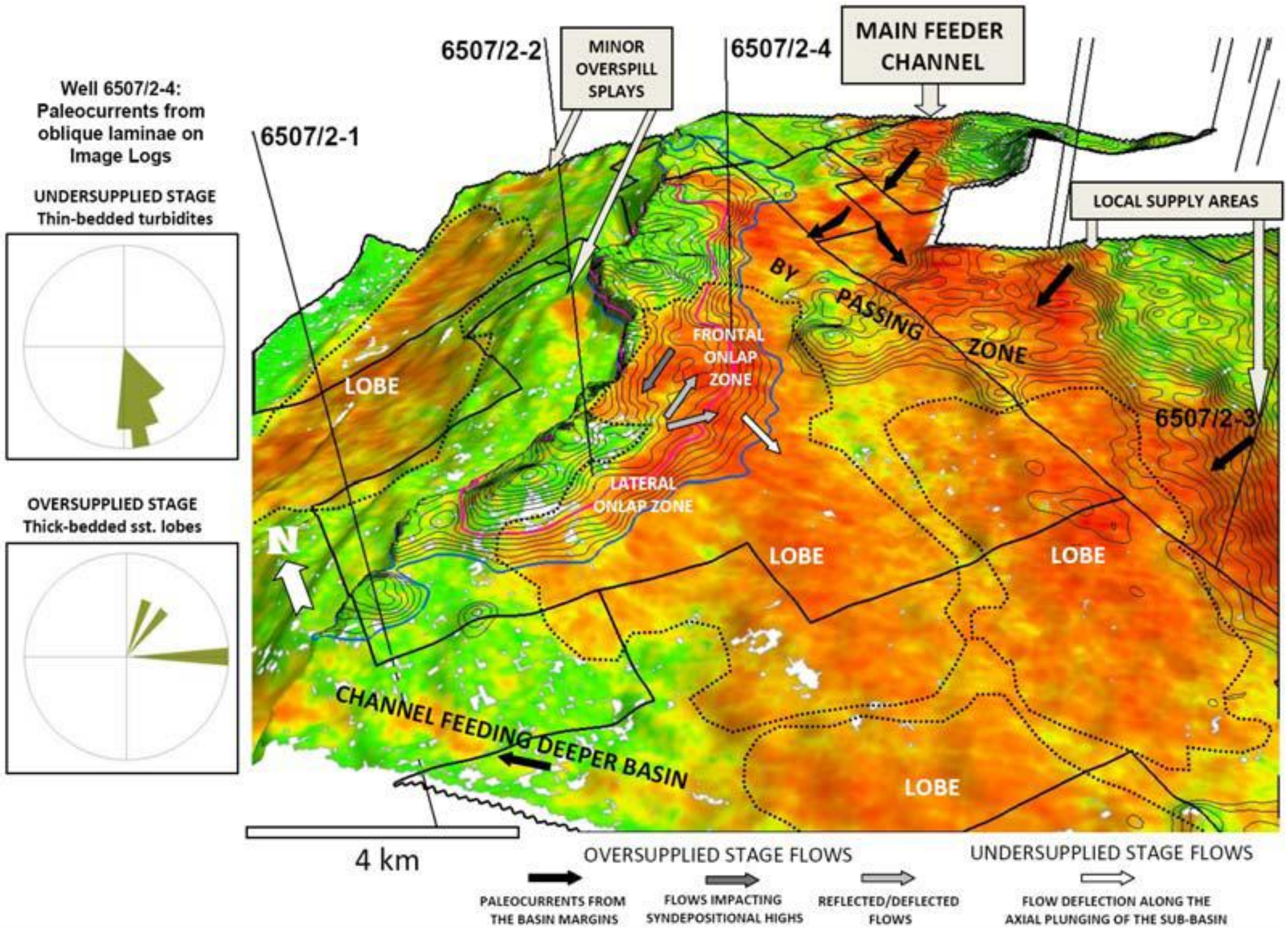

Figure 3. The Marulk Turbidite System viewed from SW shown on a combined depth/amplitude map. Note the different sediment dispersion (given by ripple cross laminae measured by image logs) recorded along the north-eastern flank of the structure during the oversupplied stage, suggesting paleocurrent reflection and deflection after flow impact against a syndepositional high.

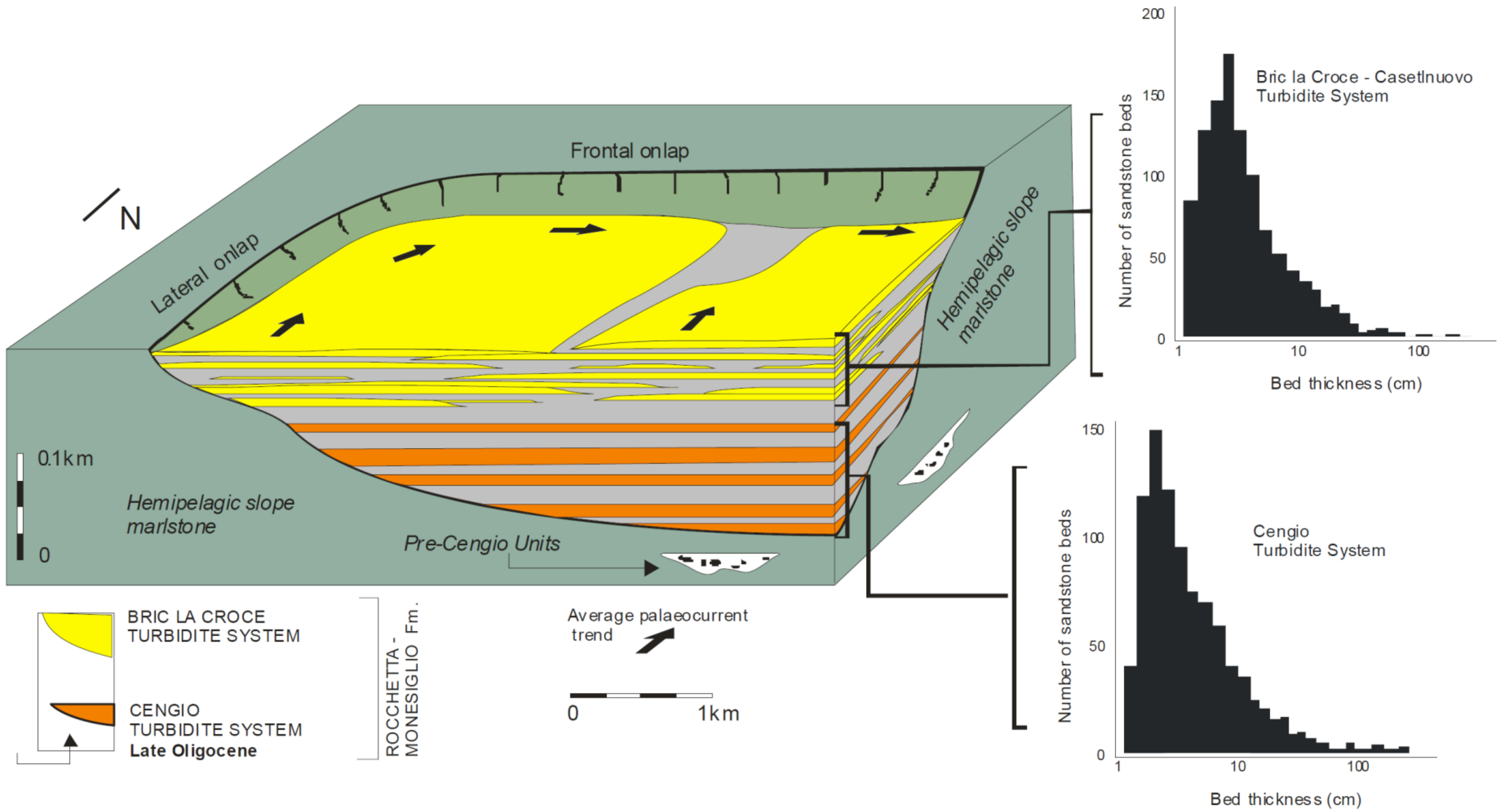

Figure 4. Outcrop analogue of the Marulk Turbidite System. Two upper Oligocene intra-slope systems are shown in relation to their different degree of confinement (Tertiary Piedmont Basin, NW Italy). The decreasing degree of basin confinement from the lower Cengio system to the upper Castelnuovo system, due to the aggradational stacking pattern and progressive widening of the depositional area after filling, is documented by the different histograms of the bed-thickness distribution (modified after Felletti and Bersezio,. 2010).

	Sand/Mud ratio		Graded/massive ratio		% Amalgamation	
	Onlap	Depocentre	Onlap	Depocentre	Onlap	Depocentre
Sandstone body VIII	0.8 - ***2.7***	7.2	1.6 - ***1.9***	3.1	8.1 % - ***23.9*** %	48.8 %
Sandstone body VII	2.8 - ***3.7***	-	0.7 - ***9***	-	10.8 % - ***26.3*** %	-
Sandstone body VI	3.5	2.3	1.1	1.7	46.4 %	36.4 %
Sandstone bodies IV/V	4.2	1.9	2.3	0.4	24.2 %	27 %
Sandstone body III	1.1	-	1.1	-	22.1 %	-
Sandstone body I	1.6 - ***5.2***	1.3	0.8 - ***2.0***	1.6	24 - ***48*** %	11 %

Figure 5. Summary of the most significant statistics of the Cengio Turbidite System analogue, helping to predict the net-gross ratio in different segments of the Marulk Field (modified after Bersezio et al., 2009). The values are based on bed-by-bed measured sections relative to every sandstone body, separating the onlap and the depocentral areas. Double values refer to the two different onlap types: lateral onlaps are in normal letters, frontal onlaps are in bold-italics. Arrows highlight the transitions from lower to higher values. Note the opposite behavior of the least ponded sandstone bodies VII and VIII compared to all the other underlying bodies.

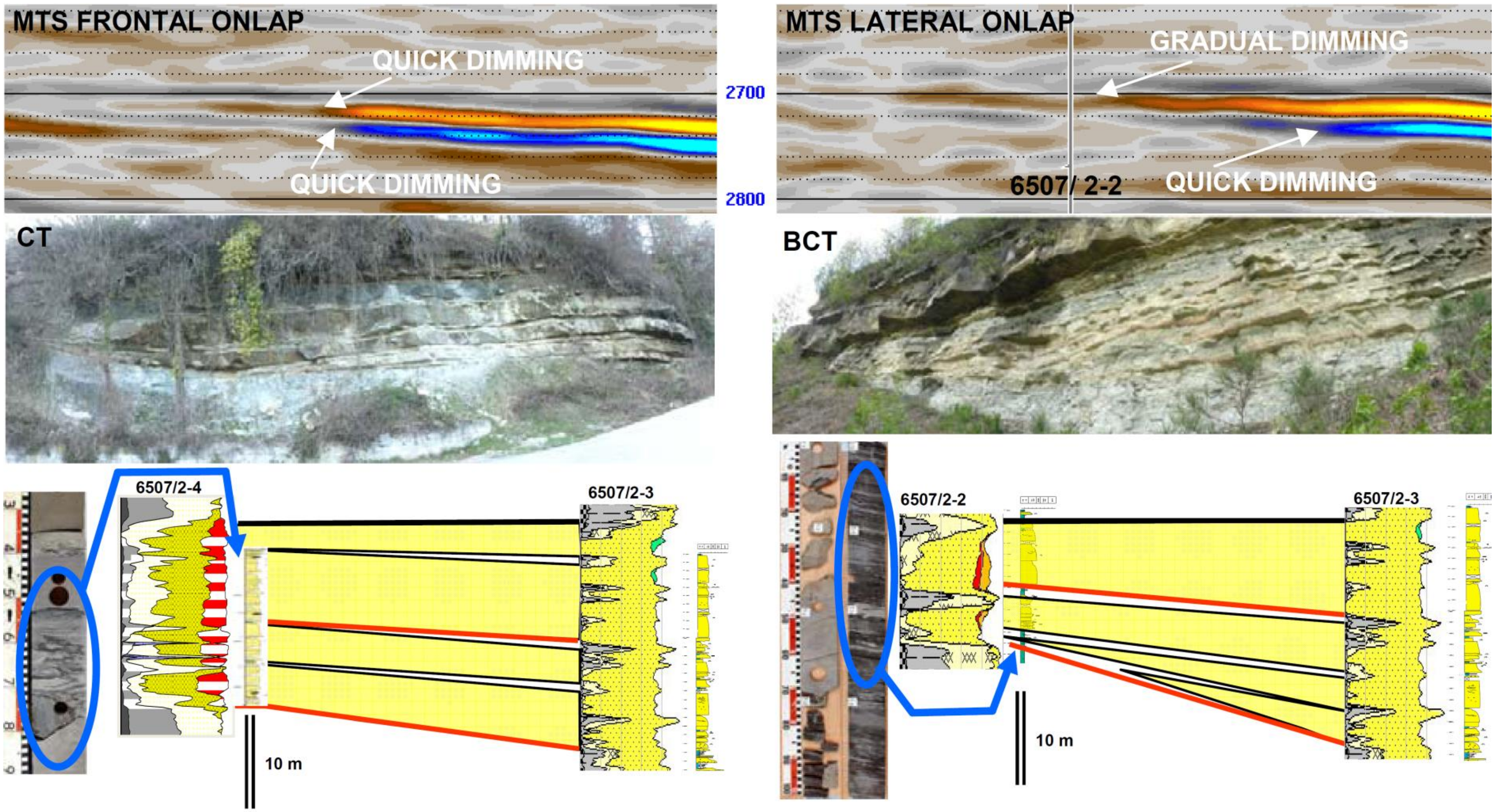

Figure 6. Outcrop, core, log, and seismic signatures of frontal onlap and lateral onlap in intra-slope reservoirs. Note impact features in the frontal onlap case (6507/2-4) and thin beds associated with lateral fringing in the lateral onlap case (6507/2-2). Note also how the thickness of mudstone intervals separating the individual sandstone lobes increases toward the depocentre in the frontal onlap case, while an opposite behavior occurs in the case of lateral onlap.