Sequence Stratigraphic and Depositional Facies Framework of the Lower Cretaceous McMurray Formation, Kearl Oil Sands Project, Alberta*

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Abstract

The McMurray Formation in the Athabasca area of northern Alberta represents Canada's most important oil sands resource with an estimated 800 billion bbl in place. Approximately 15% of this resource can be exploited by surface mining. Imperial Oil and ExxonMobil have proposed to develop 4.4 billion bbl of bitumen at 300,000 bpd over a 50-year period at their Kearl Mine. A sequence stratigraphic and facies framework was constructed at Kearl to establish the basis for reservoir prediction that is essential for mine planning and development.

Regionally, the McMurray Formation is a deepening-upward fluvial-estuarine complex deposited within a paleo-valley system controlled by the configuration of the Sub-Cretaceous unconformity. The Kearl stratigraphic study was based on ~1000 wells (75% cored), 43 km of 2D seismic and integration with previous regional work. These data show that the McMurray Formation is characterized by abrupt lithofacies changes, inclined stratal geometries and high-relief unconformities. This stratigraphic complexity can be organized within a sequence framework. Four major sequences are recognized. The oldest sequence (I) is dominated by thick amalgamated braided stream deposits overlain by a shoaling-upward succession of lacustrine muds, paleosols and coals. Sequence II is a thick, heterolithic assemblage of fluvial, floodplain, and estuarine deposits. Sequence III is distinguished by large-scale fluvial-estuarine point bars that are up to 70 m thick and represent the primary reservoirs at Kearl. Bayhead delta muds contained within deeply incised valleys typify Sequence IV.

This study has resulted in an enhanced understanding of McMurray depositional systems that is utilized for resource characterization and assessment, reservoir modeling, pit design, drilling programs, ore processing and substrate stability evaluations.

Introduction

The Lower Cretaceous McMurray Formation in the Athabasca area of northern Alberta represents Canada's most important oil sands resource with an estimated 800 billion bbl in place (Figure 1). Approximately 15% of this resource can be exploited by surface mining. Imperial Oil and ExxonMobil have obtained regulatory approval to develop 4.4 billion bbl of bitumen at 300,000 bpd over a 50-year period at their Kearl Mine.

Objective

By integrating well, core and seismic data, a sequence stratigraphic framework was constructed for the McMurray Formation at Kearl to establish the basis for reservoir models that are essential for resource assessment, ore grade prediction mine planning and pit design. Observations from outcrop and Syncrude mine exposures also were incorporated to help identify regionally significant sequence boundaries, establish facies recognition criteria, interpret depositional environments and determine reservoir dimensions and distributions.

Database

The Kearl study was based on 840 wells (75% cored) with an average spacing of 600 m and 43 km of high-quality 2D seismic (Figure 2). These data were integrated with previous stratigraphy and facies studies at Syncrude's North Mine (Nardin et al, 2005) and regionally (e.g., Hein et al, 2001; Mossop and Flach, 1983; Nardin, 2005).

Stratigraphy and Facies

Regionally, the McMurray Formation is a deepening-upward fluvial-estuarine complex deposited within an Early Cretaceous paleo-valley system (Figure 1) controlled by the structure on the Sub-Cretaceous unconformity. The main valley trended north-northwest toward the Boreal Sea. Tributary systems are evident in isopachs along the flanks of the Athabasca Anticline to the west and the Pre-Cambrian shield to the east. Kearl is optimally located near the confluence of this eastern tributary with the main valley resulting in high-quality reservoirs comprised of thick deposits of quartz-rich, coarse sands.

In the northern Athabasca area, the McMurray Formation is characterized by abrupt lithofacies changes, inclined stratal geometries and high-relief unconformities. Facies are commonly preserved as erosional / depositional remnants. This stratigraphic complexity can be organized within a sequence framework in which four major sequences are recognized (Figure 3 and Figure 4). The oldest sequence (I) is dominated by thick amalgamated braided stream deposits overlain by a shoaling-upward succession of lacustrine muds, paleosols and coals. Sequence II is a thick, heterolithic assemblage of fluvial, floodplain, and estuarine deposits. Sequence III is distinguished by large-scale fluvial-estuarine point bars that are up to 70 m thick and represent the primary reservoirs at Kearl. Bayhead delta muds contained within deeply incised valleys typify Sequence IV. Pleistocene tills, sands and gravels directly overlie the McMurray over most of the area but where the Wabiskaw Member ("D" facies) of the Lower Cretaceous, Clearwater Formation is preserved it unconformably overlies the McMurray Formation.

Sequences I and II - Braided Stream Facies

Braided stream sands are one of the most important reservoirs in the McMurray Formation. They are the dominant fluvial deposit in Sequence I, forming sheet sands and amalgamated channel successions that can be up to 40 m thick. At Kearl, these sand bodies tend to be water bearing in sub-Cretaceous structural lows and bitumen bearing on structural highs. Bitumen-bearing braided stream deposits commonly occur at the base of Sequence II. In places, Sequence II braided stream sands are overlain by lower point bar sands where the Sequence III unconformity has incised deeply into the floodplain/coastal plain section resulting in amalgamated sandstone successions.

The braided stream facies is characterized by thick, high net to gross sands dominated by trough and tabular cross beds and intense scouring (Figures 5a and 5b). Grain sizes range from vcU – mL and sorting is variable. Beds and bedsets are upward fining. Multi-story, stacked bedsets are interpreted to represent braid bar-dominated complexes.

Braided stream deposits are associated with a variety of floodplain facies. Mudstones, if present within the sand bodies, are a few centimeters thick and are probably discontinuous due to channel erosion (Figure 5b). Mudstone clasts occur locally and may be pyritized. Soft sediment deformation features are common. Bioturbation is very low and consists primarily of *Planolites* and *Skolithos* burrows suggesting fresh water to mildly saline fluvial environments. The gamma ray log has a blocky, low API response (Figure 3 and Figure 4). Dip meter angles are generally high and azimuths are variable, reflecting large-scale bedforms and scouring. On seismic lines thick braided stream deposits are represented by low-amplitude discontinuous reflections in Sequence I and by one or two moderate-amplitude, continuous reflections in Sequence II (Figure 4).

Sequences I and II - Floodplain / Coastal Plain Facies

Floodplain facies are commonly associated with braided stream deposits in Sequence I. Both floodplain and coastal plain successions are typical of Sequence II and, where preserved, are up to 70 m thick. Floodplain environments include lakes and ponds, coal swamps, deltas, small point bars and channels, crevasse splays, terminal splays, sheetflood sands and paleosols. Coastal plain facies are represented by tidal channels and bars, heterolithic tidal flats, bay head deltas and bay fill. The flood plain and coastal plain facies associations tend to be mud-prone, however locally in Sequence II thick fluvial sands form important reservoirs. The floodplain facies association is characterized by a heterolithic assemblage of gray to varicolored thick- to thin-bedded mudstones interbedded with silty mudstones, siltstones, sandstones and coals (Figure 6a). Floodplain mudstones are characterized by contorted and slumped bedding, wavy bedding, carbonaceous debris and roots. Waxy and mottled fabrics are common in the paleosols.

Point bar and channel sands are 1 m to 5 m thick with upward-fining grain size trends. Grain sizes are generally in the fL to mL range. Sedimentary structures include trough and tabular cross beds and current ripples. Bedform scales tend to decrease up-section. Channel bases are erosional and locally contain cm scale lags composed of granular to pebbly quartz grains. Channel sands are interbedded with floodplain mudstones and commonly contain clasts, which are products of floodplain erosion.

Bioturbation is low to absent in fresh water environments with *Planolites* and *Skolithos* the dominant forms. In brackish water coastal plain or estuarine settings, the degree of bioturbation tends to be higher and the trace fossil assemblage includes *Paleophycus*, *Cylindrichnus* and, rarely, *Gyrolithes* (Figure 6b).

Thick successions of aggrading floodplain deposits lack overall upward fining or coarsening trends and are characterized by a serrated gamma ray response and abrupt azimuth changes as depositional facies change (Figure 3 and Figure 4). Where thick channel sands are present the gamma ray signature is typically blocky, associated with high angle, variable dip azimuths. The seismic response in floodplain facies is variable but is commonly represented by sub-parallel, high frequency, variable-amplitude, hummocky reflections. Thick coals immediately below the Sequence II are expressed as a high-amplitude, continuous reflection that is easily carried throughout the survey.

Sequence III - Fluvial - Estuarine Point Bar Facies

Large-scale estuarine point bar sand bodies are the most important reservoir type at Kearl. Within Sequence III, they were deposited within valleys incised into the thick, aggradational floodplain or coastal plain successions of Sequence II. The main features in the large-scale fluvial - estuarine point bar association are basal channel sands, Inclined Heterolithic Stratification (IHS) and sand-rich Inclined Stratification (IS; Thomas et al, 1987). This facies association forms a succession up to 70 m thick and is characterized by a hierarchy of beds, bedsets and stories that stack to form an overall upward-thinning / fining pattern. Observations in the Kearl area are consistent with the results of studies at Syncrude's North Mine (Nardin et al, 2005), where logs and core were tied to large-scale point bar outcrops to develop recognition criteria that are used to interpret depositional environments from subsurface data.

Amalgamated basal channel sands are up to 10 - 15 m thick and are characterized by trough and tabular cross-bedding (Figure 7). Grain size is variable and ranges from vfL to mL. Fine grained, current rippled IHS and IS facies are associated with the basal channel sands. Where preserved, capping, muddy floodplain/coastal plain deposits may be rooted and contain paleosols.

IHS is formed by lateral accretion of the point bar and several facies types are recognized at the bedset to story scales. In core, they are defined by mudstone bed thickness and frequency, degree of bioturbation, sedimentary structures and the presence or absence of mudstone clast associations. These IHS facies are members of a continuum that is a function of changing flow and sediment transport conditions. Estuarine conditions are indicated by brackish water trace fossil assemblages including *Paleophycus*, *Cylindrichnus*, *Planolites*, *Skolithos* and, less commonly, *Gyrolithes* and *Teichichnus*.

Thick, extensive IS sand bodies also form by lateral accretion. They develop during prolonged periods of relatively high discharge and/or increased caliber of sediment load. Periods of lower energy conditions result in mud-rich bars with upward-thinning/fining profiles and thinner basal sand bodies. Large-scale sand prone and mud-prone point bar deposition may be co-directional, alternate through time and result in a laterally stacked bar set. Matrix-supported, angular mudstone clasts are a common feature at all levels in the point bars. The clasts are derived primarily from erosion of lateral accretion beds and not from cutbank erosion as the sedimentary characteristics of the clasts are identical to the interbedded IHS mudstones (Figure 7).

The overall upward thinning / fining stratal pattern results in a half-bell gamma ray log profile (Figure 3 and Figure 4). IHS and IS bed dip azimuths generally vary by no more than 90o and change systematically. Dips range from 3-20° but are most commonly approximately 10°. Upward-steepening, upward-flattening and constant dip profiles are observed. IHS is depicted on seismic dip lines as moderate- to high-amplitude, discontinuous, inclined reflections that appear to downlap close to the underlying sequence boundary (Figure 4).

The large size of the Kearl and Syncrude North point bars indicates channel dimensions consistent with high water discharge and a large drainage area. The drainage area of the Cretaceous Western Interior that fed through the Athabasca area is estimated to have been 2-3 million km^2. As suggested by Mossop and Flach (1983) and Nardin et al. (2005) the Mississippi River with a drainage area of 3.2 million km^2 is a close analog.

Sequence IV - Bayhead Delta / Bayfill Facies

The bayhead delta and bayfill facies association is characterized by a mud-prone succession up to 40 m thick. The succession is deposited above the Sequence IV boundary in deep valleys incised into underlying point bar or floodplain/coastal plain deposits. The valleys are up to 2 km wide and have trends that appear to be controlled by subsidence of the sub-Cretaceous unconformity. Parasequence stacking patterns are retrogradational in the transgressive systems tract and progradational in highstand systems tracts (Figure 8).

Locally, a basal lowstand to early transgressive systems tract up to 10 m thick is present. It consists of fluvial sandstones, proximal bayhead sandstones and mudstones and mudstone clasts. The clasts appear to be derived from erosion of the bayhead during transgressions and/or 4th-order relative sea level falls. Transgressive surfaces of erosion are also observed.

Highstand bayfill deposits are dominated by thick, mud-prone prodelta to distal bayfill facies. The mudstones are commonly homogeneous, virtually unbioturbated and nearly devoid of sand. Laminae are lenticular with irregular surfaces suggesting transport and deposition by low-density, low-velocity turbidity currents, or turbid layers. In places, a more proximal facies containing wavy bedded, fine-grained sands and bioturbated muddy sands with *Planolites*, *Paleophycus* and *Cylindrichnus* burrows occurs.

Bed dips tend to be low and unidirectional in muddy successions but locally azimuths may vary widely (Figure 4). For low dip angles, azimuths are probably affected by differential compaction along the valley walls and post-depositional structuring. The Sequence IV unconformity is generally expressed as a very broad reflection below which contrasting point bar or floodplain/coastal plain reflections are truncated. Mud-prone bayfill deposits are depicted seismically by moderate-amplitude, low frequency, irregular reflections that onlap the incised valley (Figure 4). Locally, downlapping clinoforms are observed.

Conclusions

This study has resulted in an improved understanding of McMurray depositional systems that is utilized for reservoir modeling, resource characterization and assessment, mine pit and tailings pond design, drilling programs, ore processing and substrate stability evaluations. It has also provided a conceptual model and analog that can be used to guide interpretation where subsurface control is sparse. An additional application of the model includes in-situ thermal research and development where understanding steam chamber growth as a function of reservoir heterogeneity is critical.

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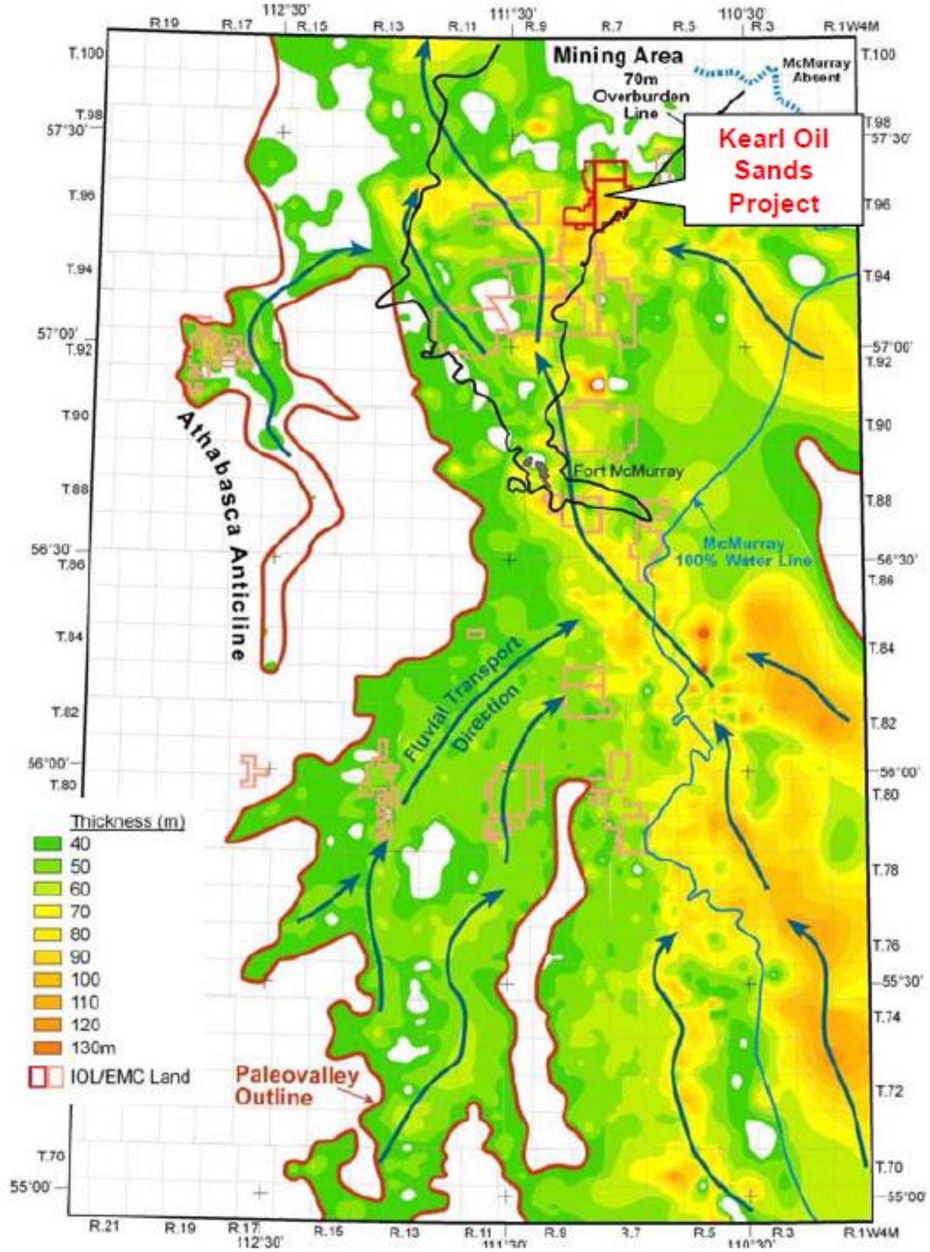

Figure 1. McMurray Formation isopach illustrating an Early Cretaceous fluvial / estuarine paleovalley system trending north-northwest toward the Boreal Sea. Note tributaries on the flanks of the Athabasca Anticline and the Pre-Cambrian Shield.

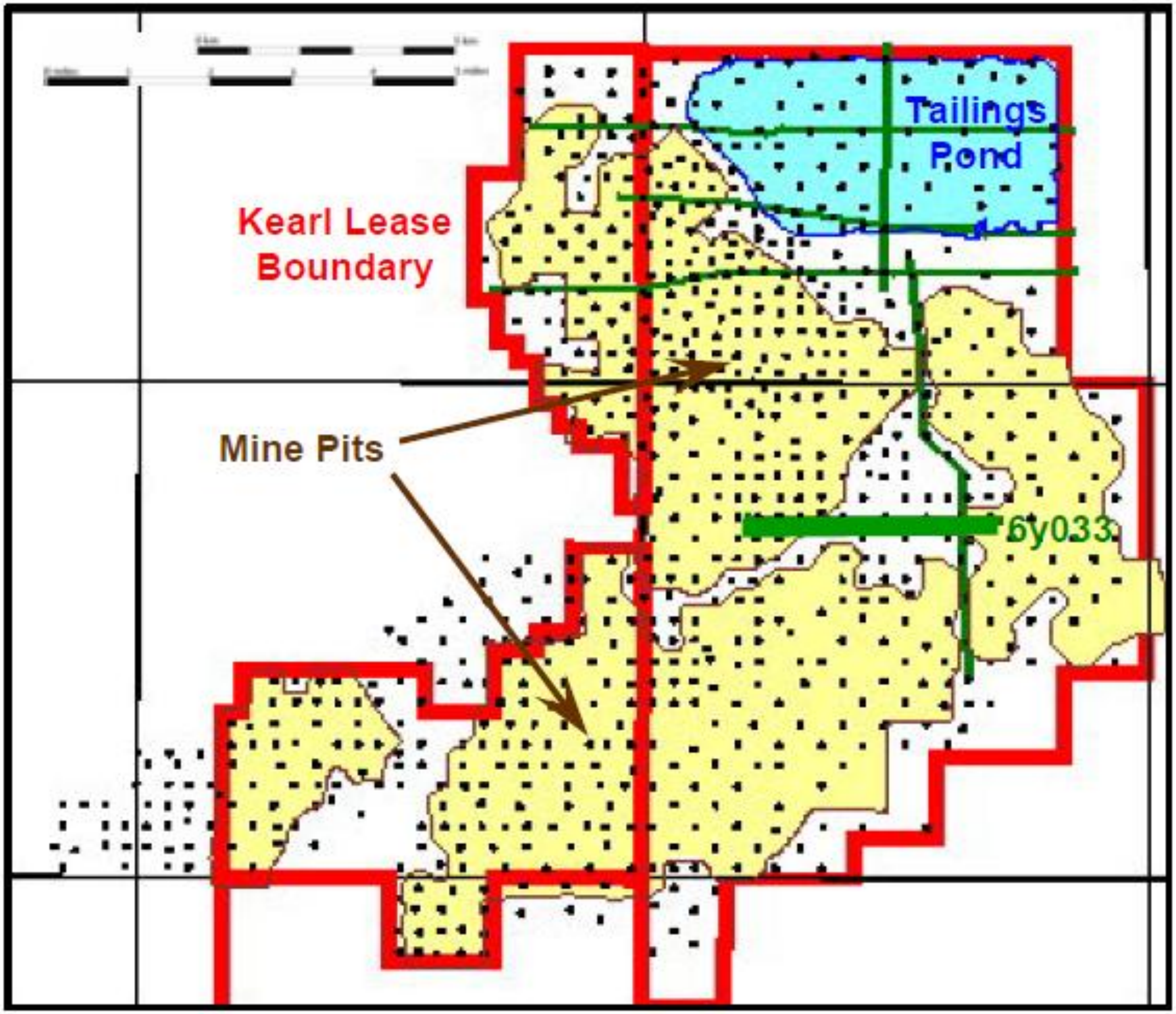

Figure 2. Kearl database. Heavy green line indicates the seismic illustrated in Figure 4.

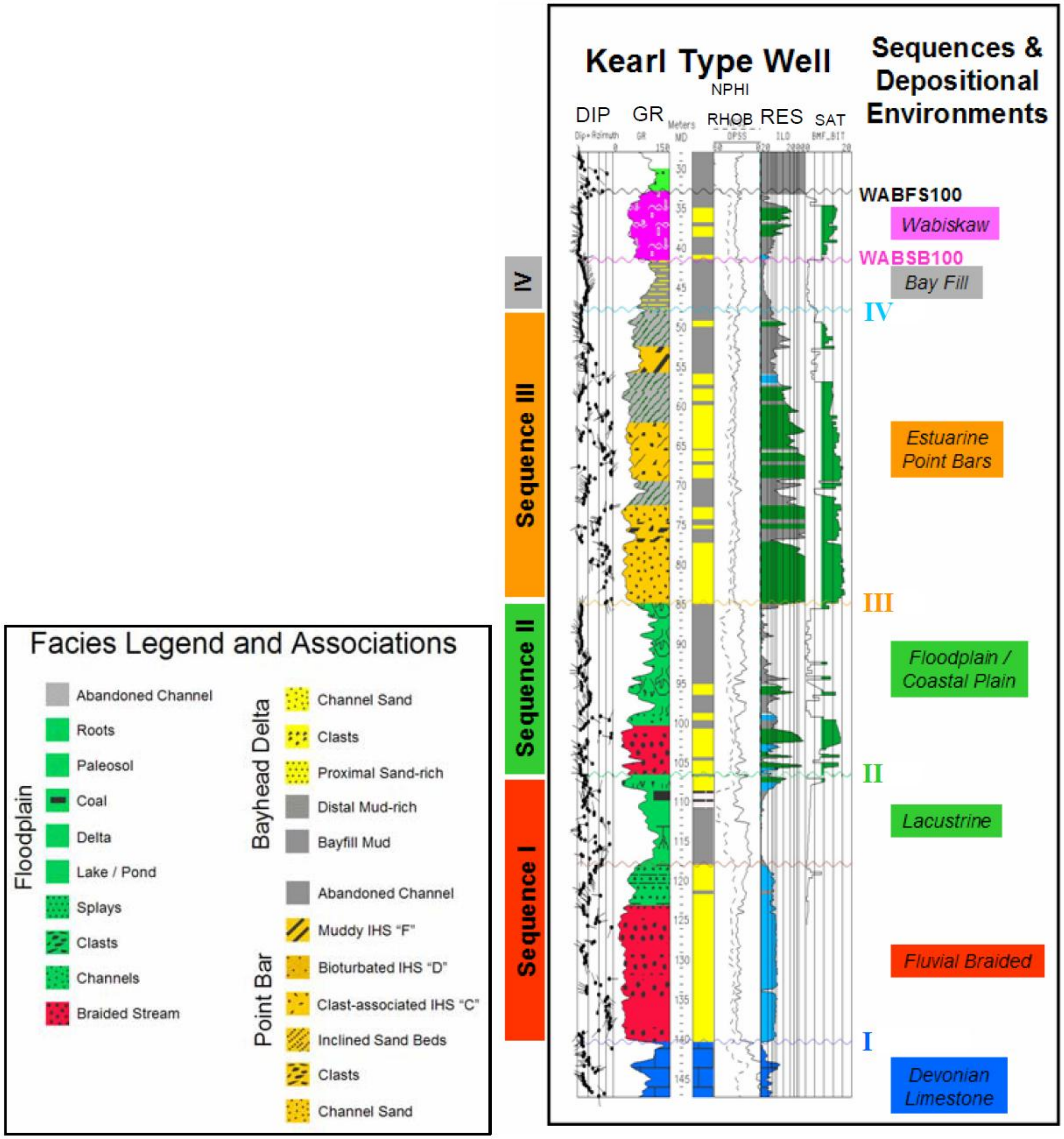

Figure 3. Typical McMurray section at Kearl showing sequences and major depositional systems. Green in resistivity track indicates saturations greater than 7 wt%.

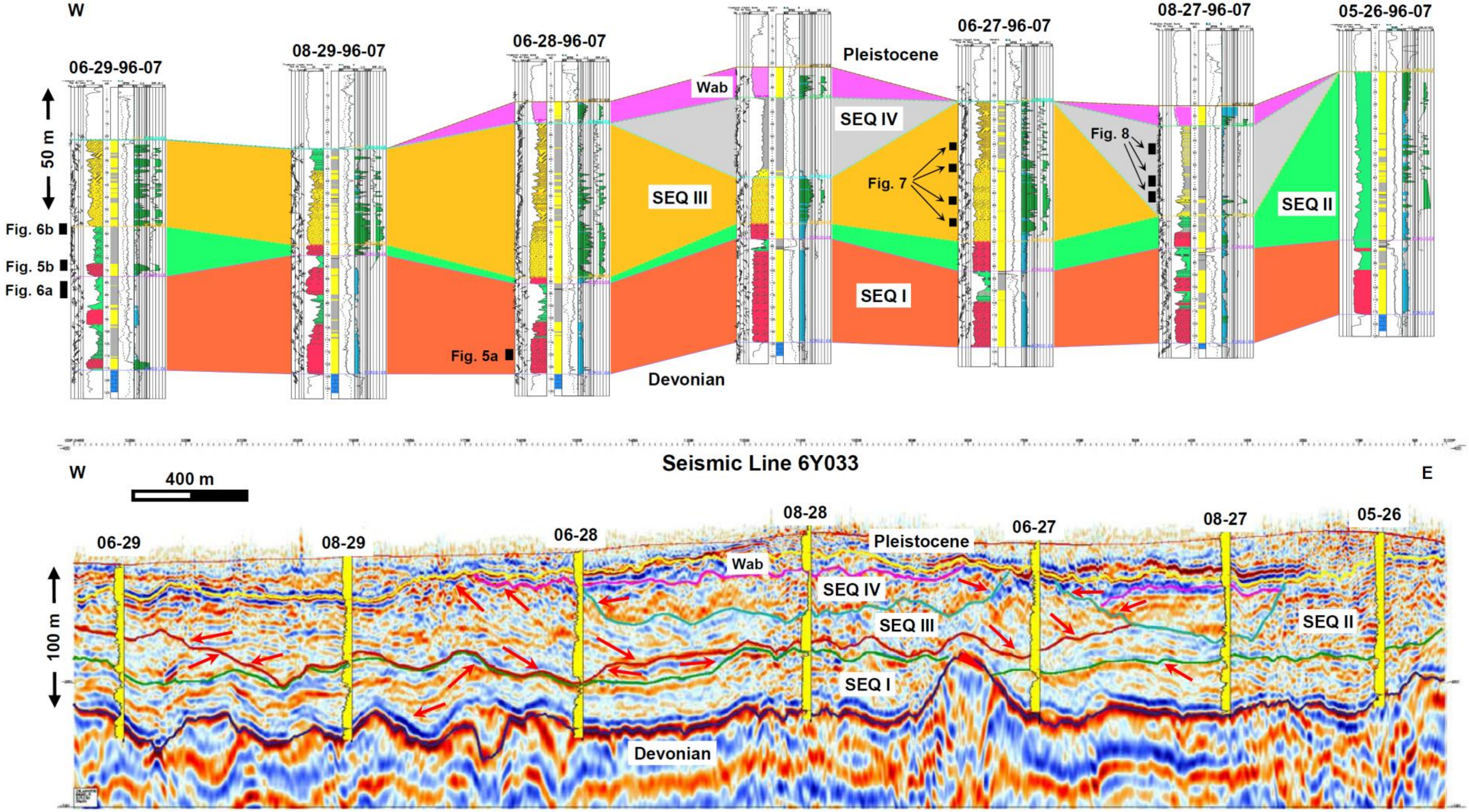

Figure 4. Seismic line 6Y033 with well ties and sequence stratigraphic interpretation (see Figure 2 for location). Reflection termination at sequence boundaries are indicated by red arrows. Seismic facies, log motifs and core facies are discussed in the text. The locations of the cores illustrated in the following figures are shown on the cross section. The log template is identical to that in Figure 3. Note that the structural relief on the sub-Cretaceous unconformity is aliased by the well control.

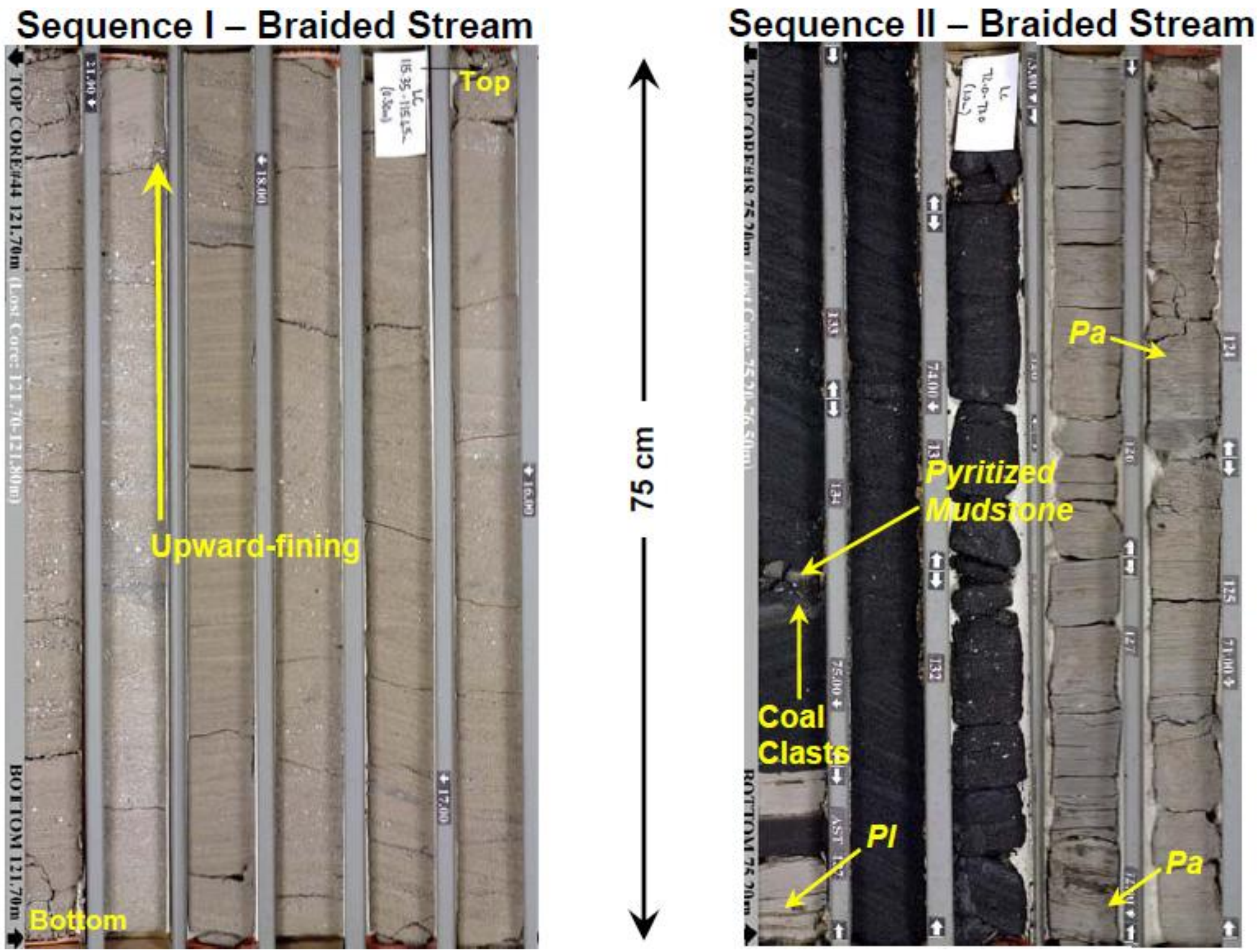

Figure 5. a) Sequence I - Well 06-28-96-07. Water-bearing braided stream sands with trough cross beds and upward-fining beds and bedsets. b) Sequence II - Well 06-29-96-07. Bitumen bearing braided stream sands overlain by finely laminated coastal plain muds.

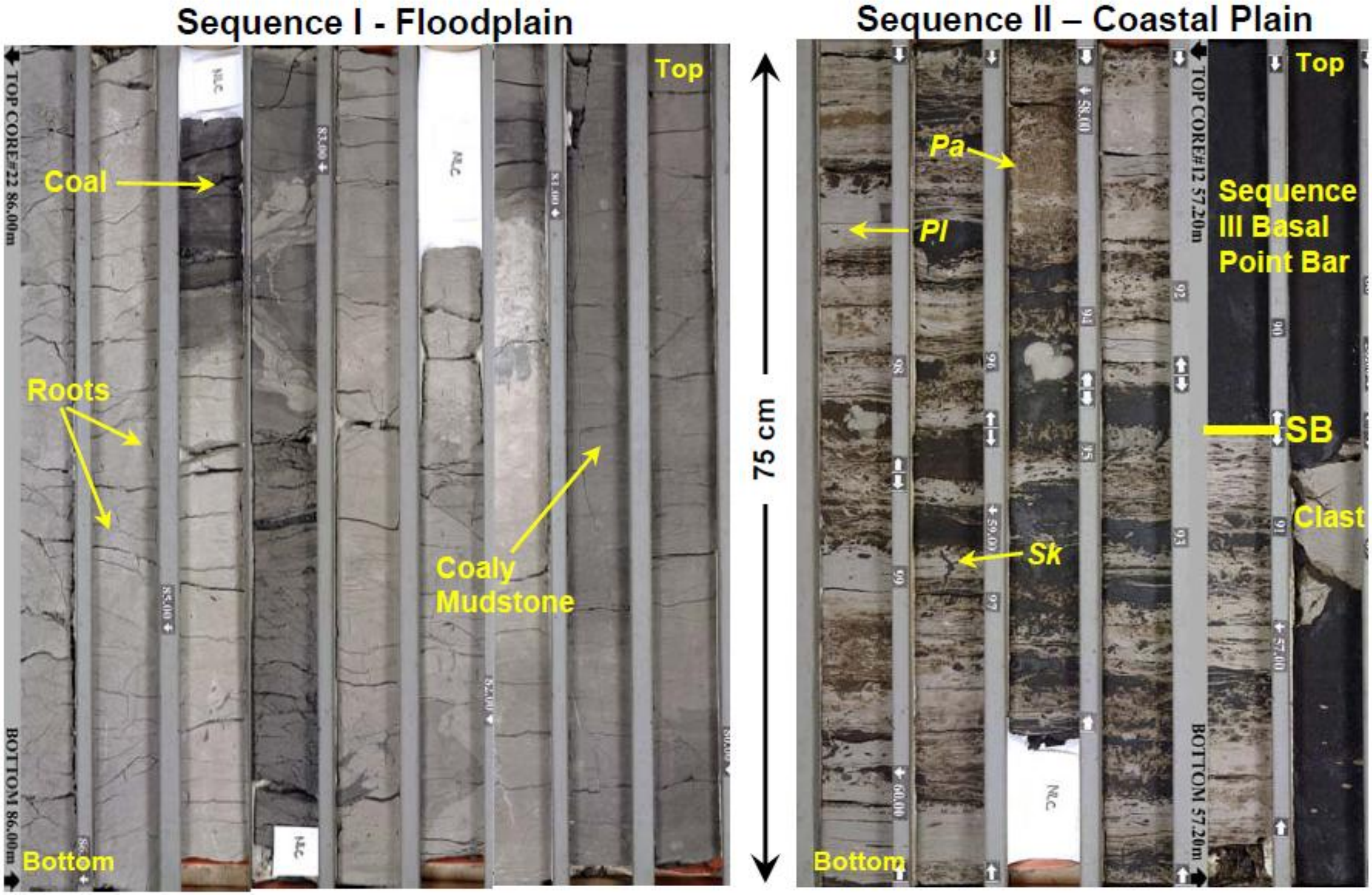

Figure 6. a) Sequence I - Well 06-29-96-07. Varicolored floodplain mudstones with roots, syndepositional deformation features and pedogenic fabrics interbedded with coaly mudstones and coals. b) Sequence II – Well 06-29-96-07. Bioturbated coastal plain delta section beneath Sequence III point bar channel sands. Note *Paleophycus*, *Planolites*, and *Skolithos* burrows.

Sequence III – Large-Scale Estuarine Point Bar

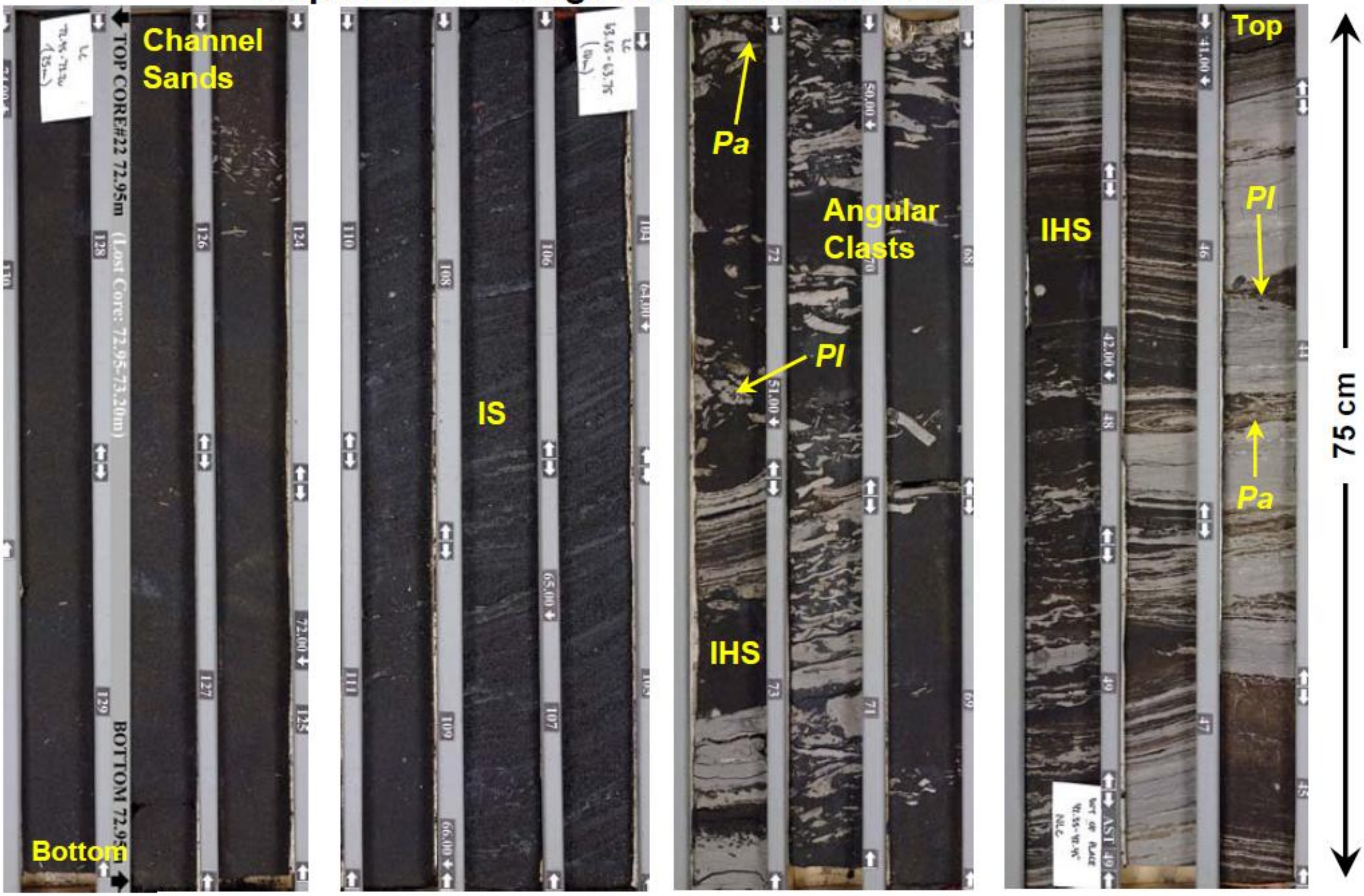

Figure 7. Sequence III – Well 06-27-96-07. Large-scale estuarine point bar. Fine-grained basal channel sands overlain by fine-grained IS and IHS beds with dip azimuths consistently toward the east (see seismic expression). Note clast-associated IHS in panel 3.

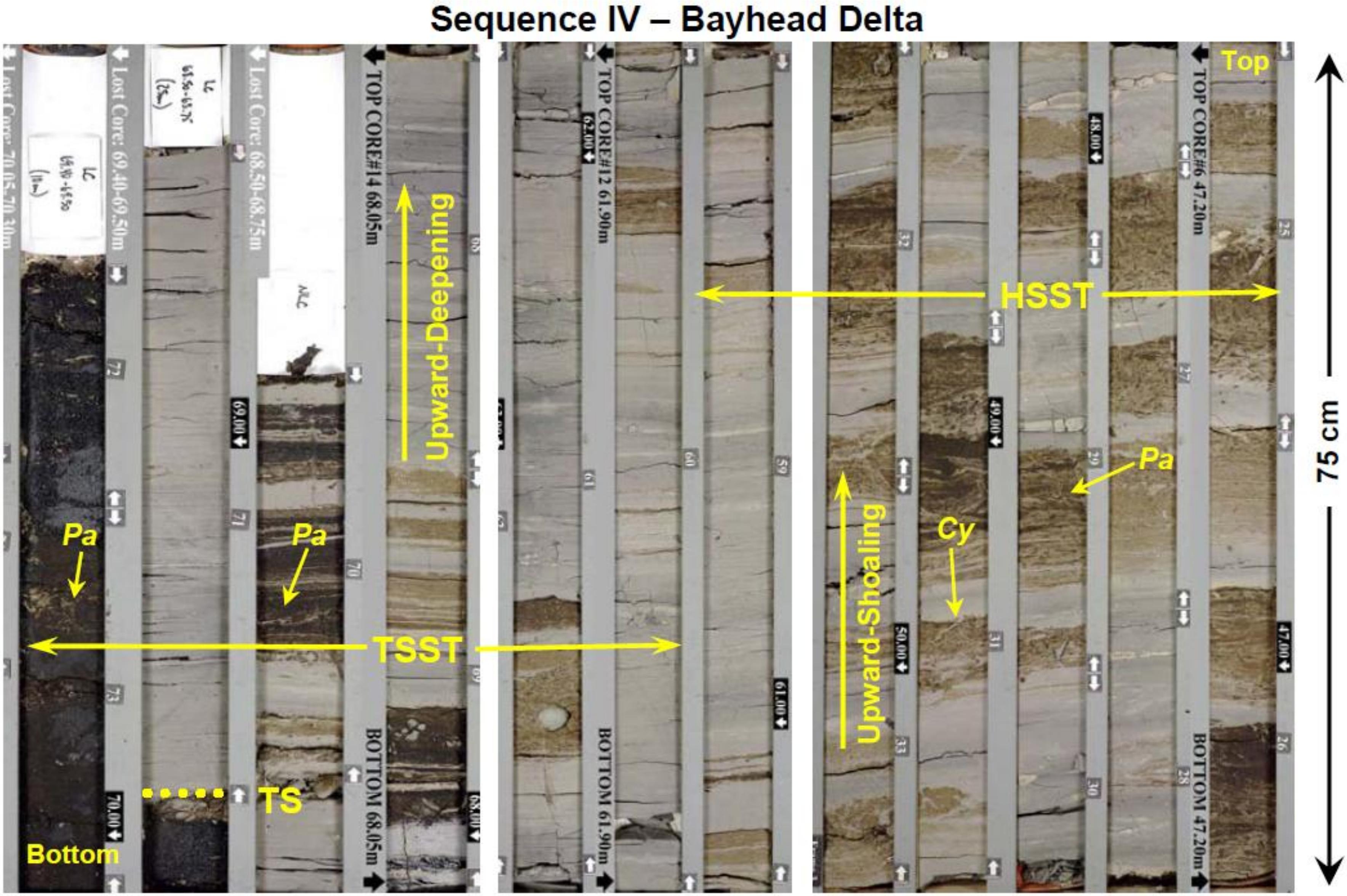

Figure 8. Sequence IV - Well 08-27-96-07. Bayhead delta / bayfill section showing basal fine-grained, current rippled sand of the early transgressive systems tract (TSST) overlain by mud-prone upward-deepening parasequences. More sand-prone upward-shoaling parasequences define the highstand systems tract (HSST). Dip azimuths are consistently toward the west. Bioturbation is concentrated within the sandy intervals (*Paleophycus*, *Cylindrichnus*).