Braided River and Avulsive Depositional Systems in the McMurray Formation - LIDAR and Subsurface Data Integration at Syncrude's Aurora North Mine*

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Abstract

The McMurray Formation in the Athabasca area of northeast Alberta represents a world class oil sands resource that is under development using surface mining and *in-situ* thermal recovery technologies such as steam-assisted gravity drainage (SAGD). The commercial success of these developments is dependent on reservoir quality and heterogeneity, parameters that are closely linked to depositional environment. In 2007, pit exposures at Syncrude's Aurora North mine, together with closely spaced coreholes, provided an excellent opportunity to study McMurray depositional systems from core to outcrop scale.

Database

The Aurora North study was based on core, gamma ray, dipmeter, and Syncrude lithofacies descriptions from 380 wells with an average spacing of 100 meters. Mine faces were captured using photo-pans and GPS calibrated LIDAR images (laser scans) that enhance the 3D visualization and analysis of outcrop stratigraphy. Rendering the well log curves as a 3D seismic volume (LogVu3D) facilitated stratigraphic interpretation. These data were tied to the regional sequence stratigraphic framework constructed for the northern Athabasca (Nardin et al., 2007) and integrated to develop predictive models for low-sinuosity/braided river and avulsion channel deposits.

Stratigraphy and Facies

The McMurray Formation is a deepening-upward fluvial-estuarine complex deposited within an Early Cretaceous paleo-valley system (Cant and Abrahamson, 1996; Hein and Cotterill, 2006). Deposition was strongly controlled by the structural configuration of the sub-Cretaceous unconformity. Movement along the unconformity during McMurray time increased stratigraphic complexity and augmented the development of high-relief unconformities. Three major sequences are recognized at the Aurora North mine.

Thick low-sinuosity to braided river deposits overlain by a floodplain mudstones, paleosols and coals were deposited within the basal SB100 sequence and are preserved primarily within structural lows above the sub-Cretaceous unconformity. These facies are characterized by high N/G sands dominated by trough and tabular cross beds and intense scouring. Grain sizes range from mL – vcU and sorting is variable. Beds and bedsets are upward-fining. Multi-story, stacked bedsets form bars which, in turn, form barsets and bar-dominated complexes.

The basal section of the overlying SB500 sequence is dominated by similar fluvial deposits whose distribution was controlled by topography created through contemporaneous structural movements and erosion of the SB100 sequence. In the mine, depositional remnants of SB100 paleosols and fluvial deposits are observed to be tilted along the flanks of Devonian structural highs, forming SB500 interfluves.

Subsequent deposition within the SB600 sequence was more strongly influenced by estuarine conditions. Where exposures of the SB600 were observed, the 50-meter thick upward-fining succession consists of avulsion channel and bar complexes. Half-bell, upward-fining gamma-ray log motifs and grain-size trends are similar to those observed in comparably scaled point bars such as those observed at Syncrude's Mildred Lake Mine. However, dipmeter patterns and outcrops demonstrate large-scale cut-and-fill stratal geometries which are interpreted to have formed through avulsion processes. Channel fills are compound and can be described in the context of a stratigraphic hierarchy containing bars, barsets and bar complexes. Fills commonly contain basal sand-prone sub-tidal bars overlain by side-attached longitudinal bars which tend to be mud-prone and highly bioturbated. Longitudinal bars downlap onto the tidal bars.

Mudstone clasts formed during avulsion events are derived from older channel fills and are observed at channel boundaries and downlap surfaces. Barsets are grouped into bar complexes that are capped by coastal plain deposits. The lateral spacing between avulsion channel remnants observed in outcrop is comparable to the 100 meter corehole spacing making it difficult to demonstrate the coevality of individual channels. However, channel and bar complexes are mappable. Within any complex, lithofacies mapping shows that the thickest reservoirs are located up-valley and grain size distributions fine overall in the down-valley direction. It is probable that alluvial architecture changes from one characterized by avulsion down-valley to non-avulsive channels and point bars up-valley.

Conclusions

Using closely-spaced coreholes that are tied to outcrop, this study has provided conceptual models for two distinct depositional systems in the McMurray Formation: low sinuosity to braided river and estuarine avulsion complexes. Together with the large-scale point bar complex described at Syncrude's Mildred Lake Mine (Nardin et al., 2005; Nardin et al., in prep) these analogs can be used to guide subsurface interpretation of similar depositional environments and to facilitate resource characterization, assessments and reservoir modeling at the development scale.

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Imperial Oil

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Study Approach and Themes

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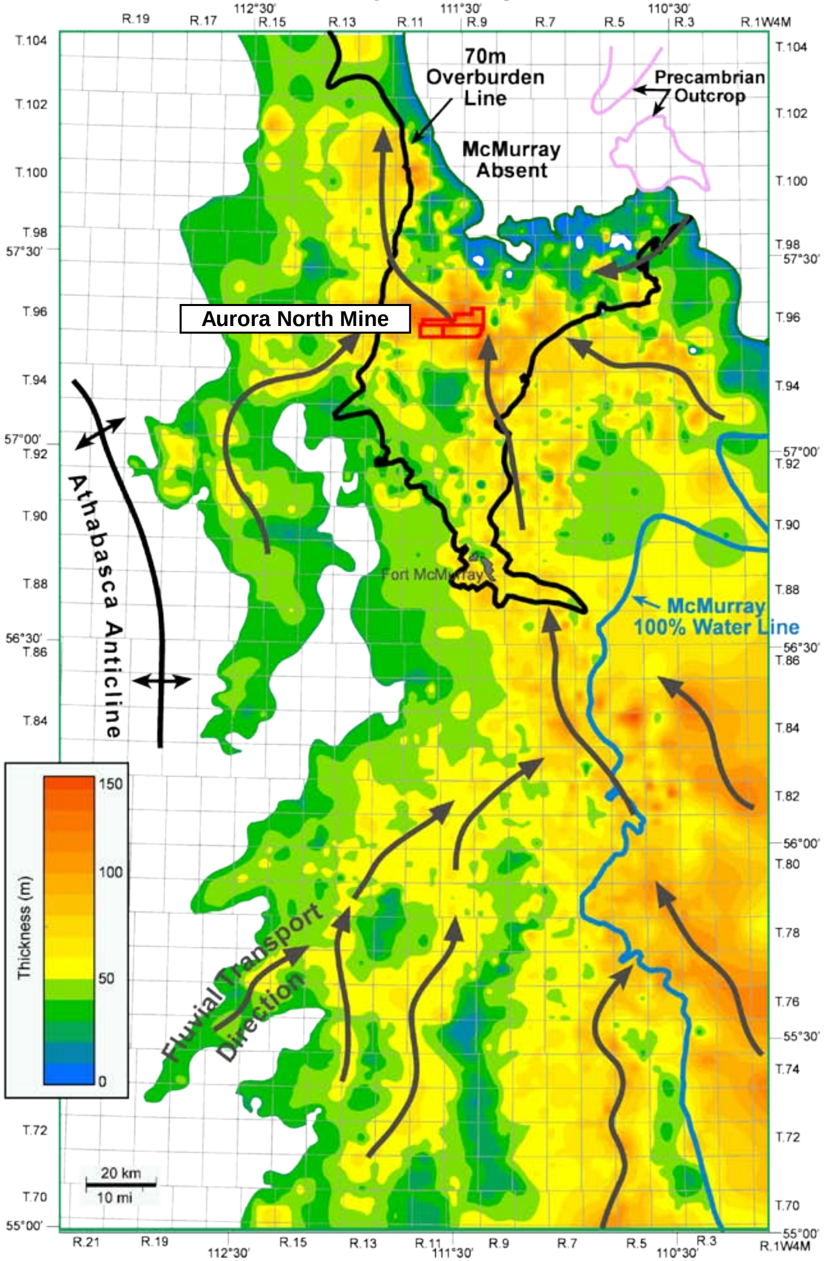


Oil sands mines provide laboratories which allow study of the stratigraphy and depositional systems within the McMurray Formation

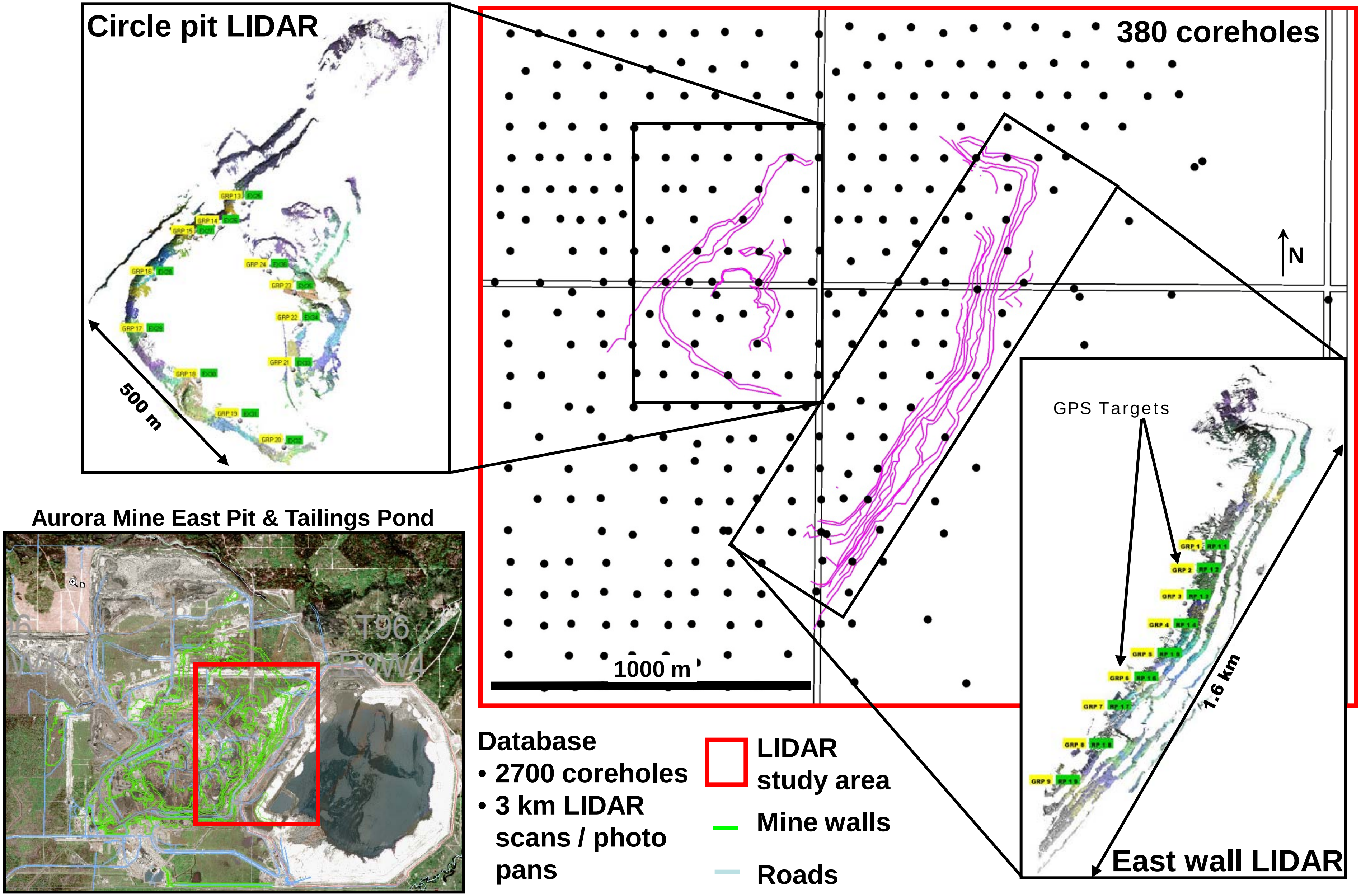
Approach

- 3D outcrop exposures tied to closely spaced log and core data at Syncrude's Aurora North mine
- Data integration and visualization aided by
  - LIDAR scans of mine walls
  - LogVu3D
- Show observations and interpretations for two depositional systems
  - Braided river deposits
  - Large-scale cut and fill channel complexes

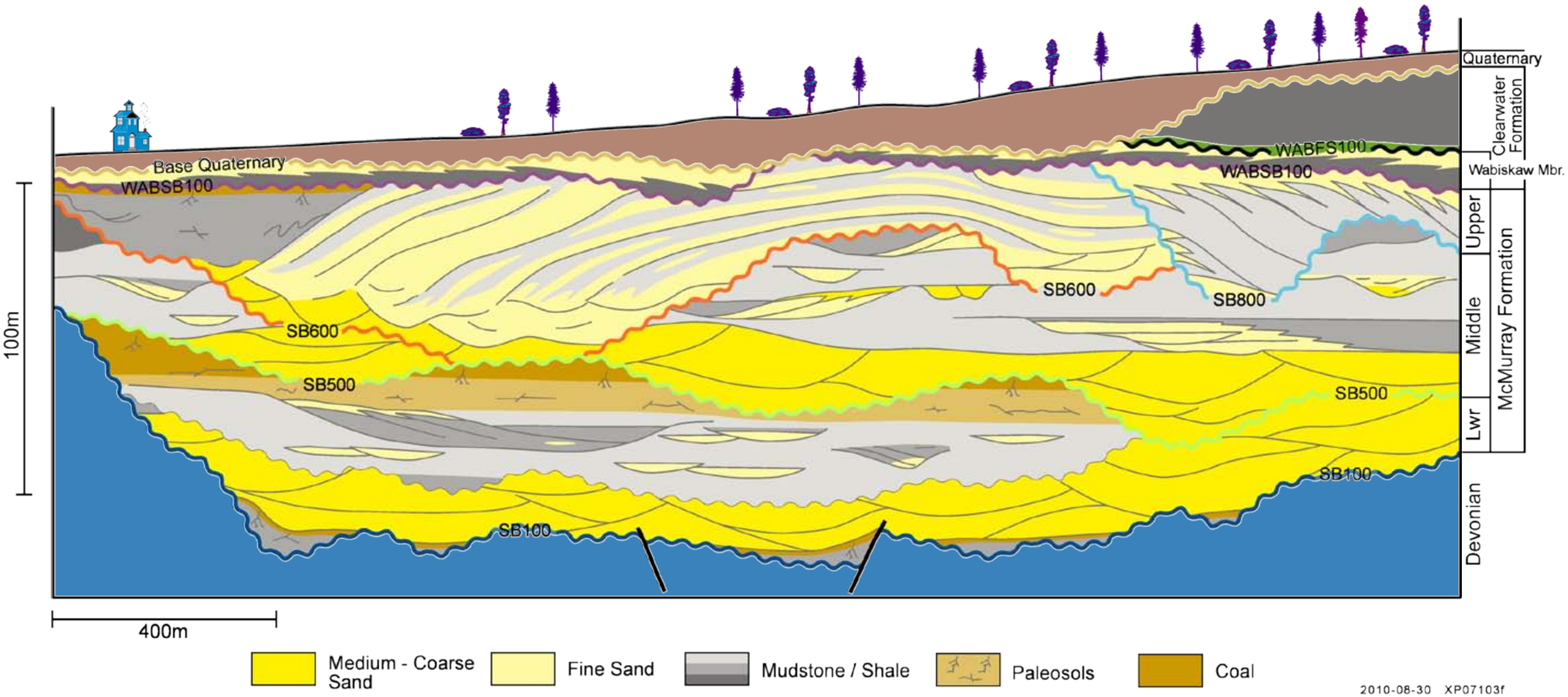
Themes

- Importance of syn-depositional structural movements on development of these depositional systems
- Integration of conventional subsurface data with outcrop development of subsurface recognition criteria
  - Reservoir and non-reservoir distributions
  - Implications for exploration and development

Aurora North Mine Database

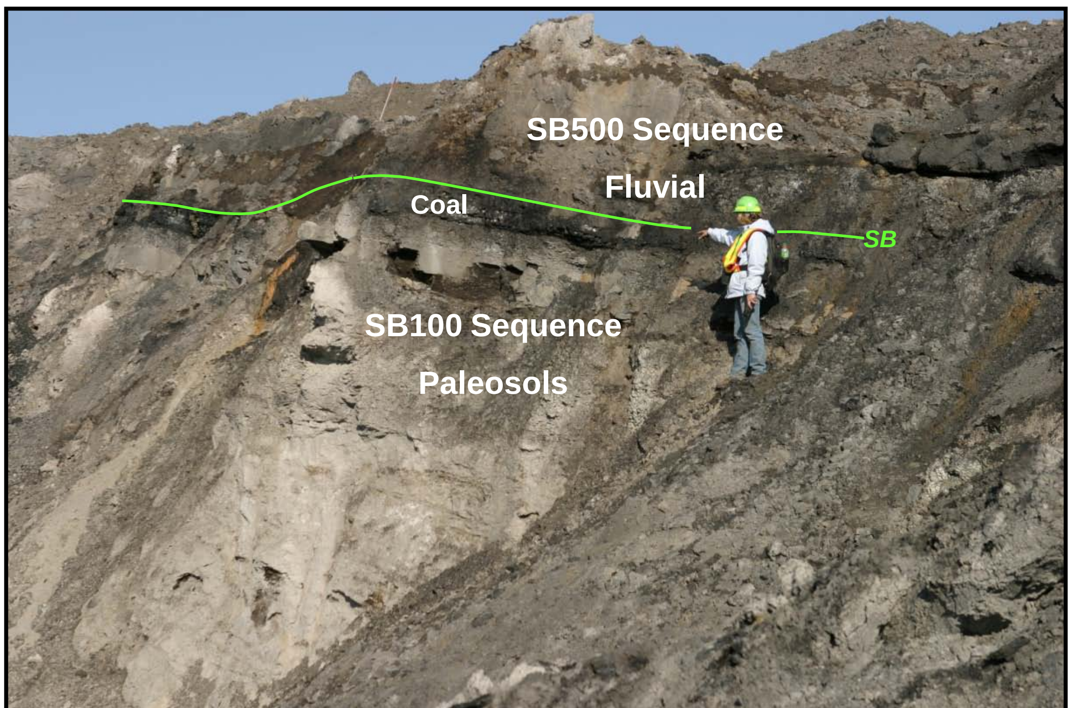


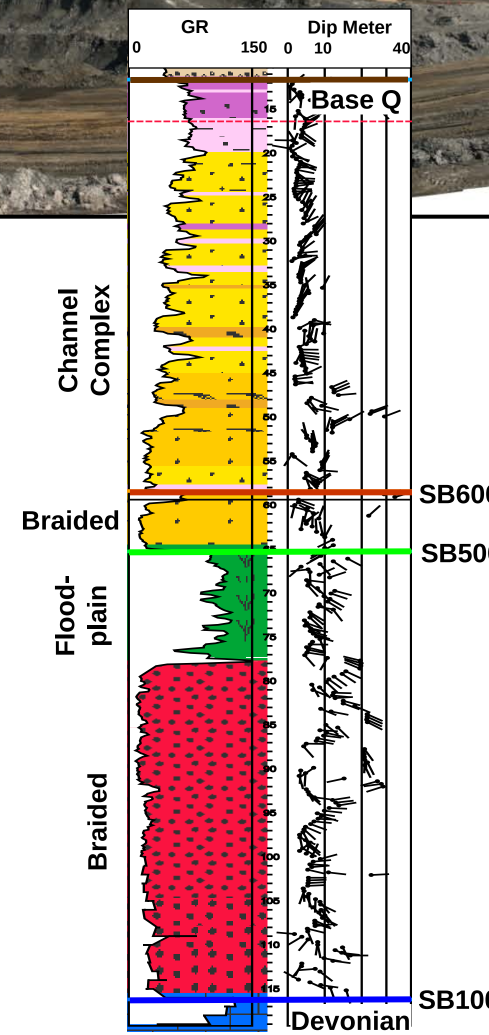
McMurray Sequence Stratigraphy and Depositional Systems



Aurora North Stratigraphy

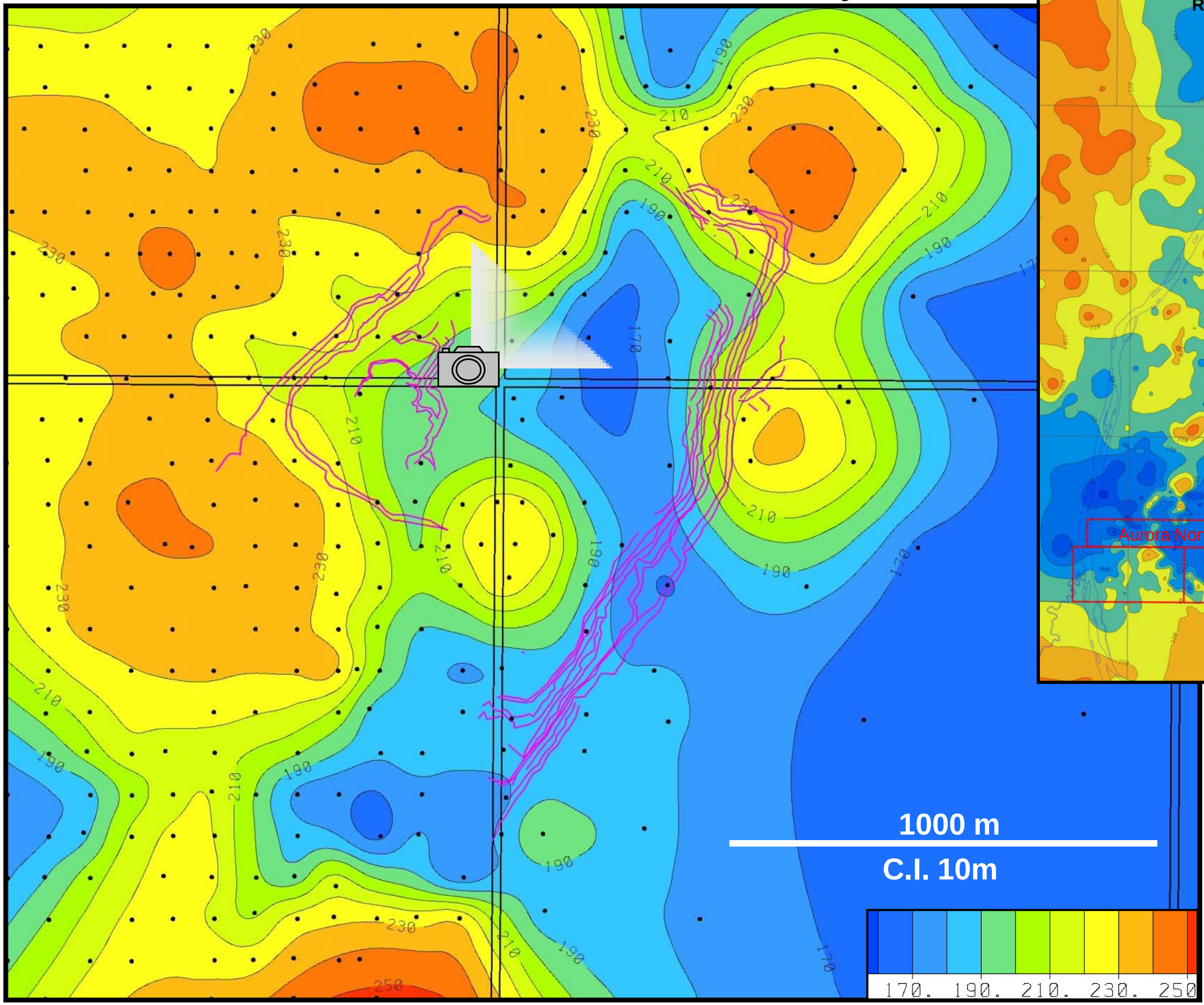
East Pit - View to Northeast



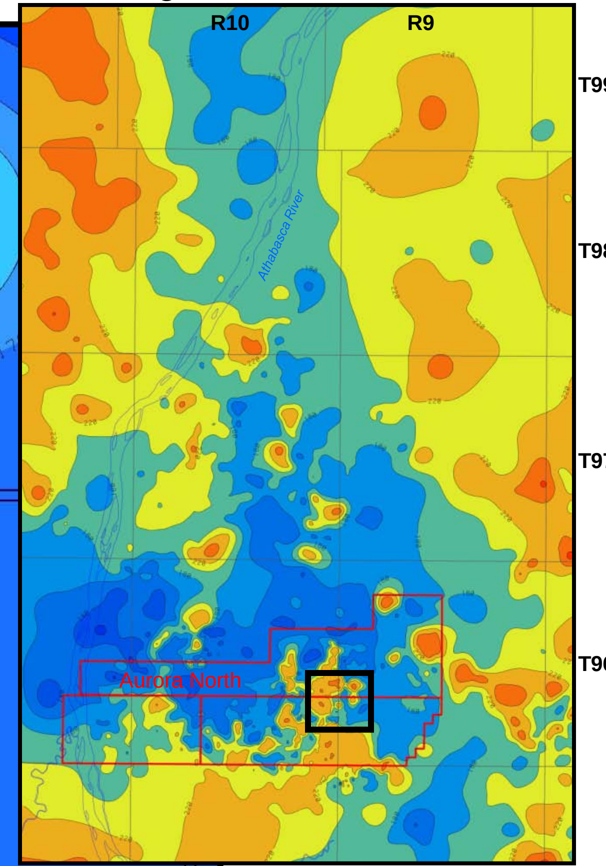


Structural Control on Stratigraphy

Structure Sub-Cretaceous Unconformity



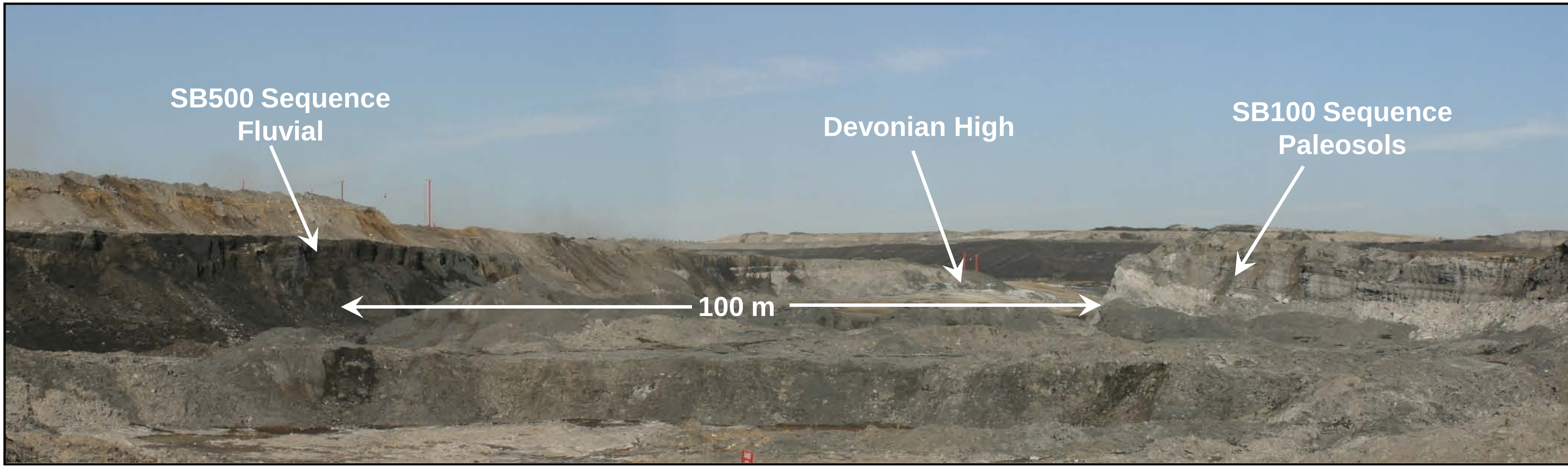
Regional Sub-K Structure



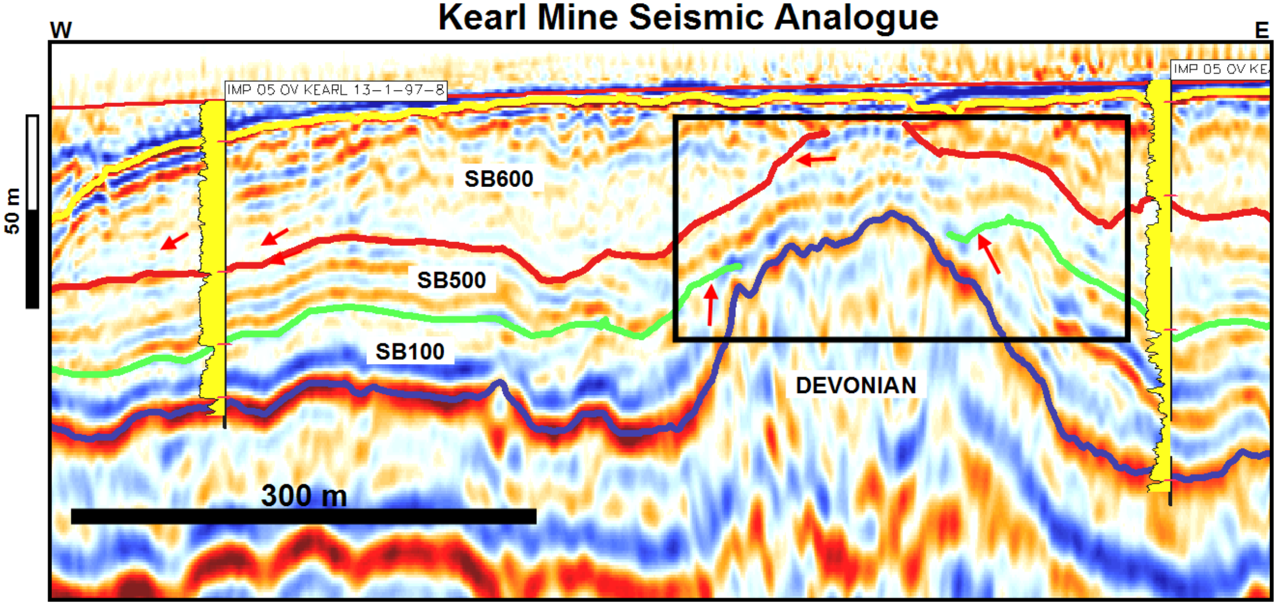
Aurora North located along an escarpment at margin of the Bitumount Basin

Syn-Depositional Movement of Sub-Cretaceous Unconformity

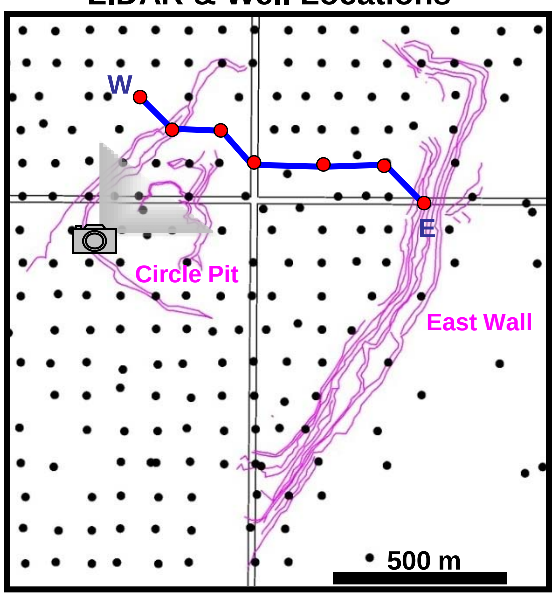
Circle Pit - View to Northeast



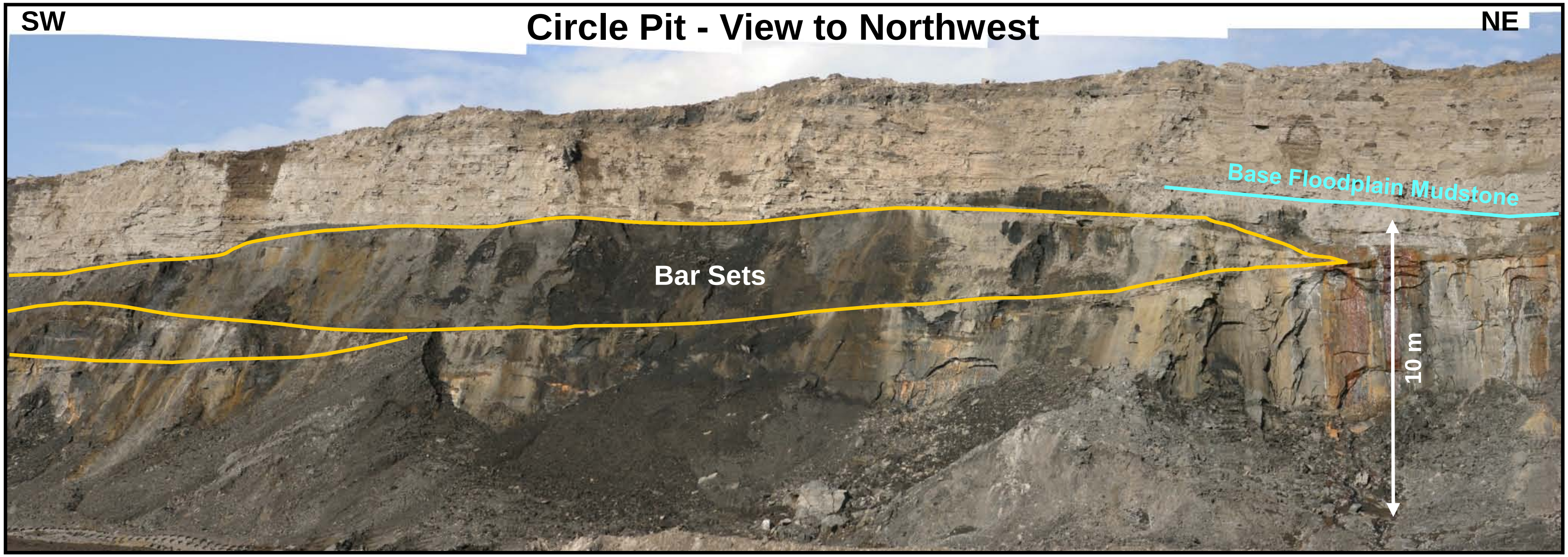
Kearl Mine Seismic Analogue

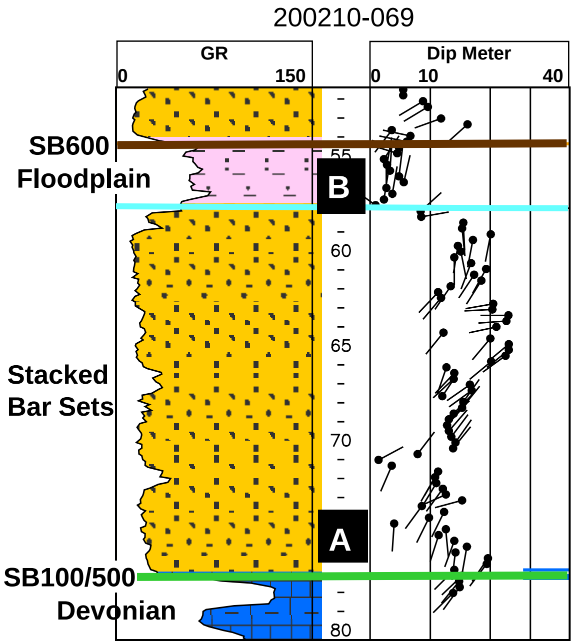


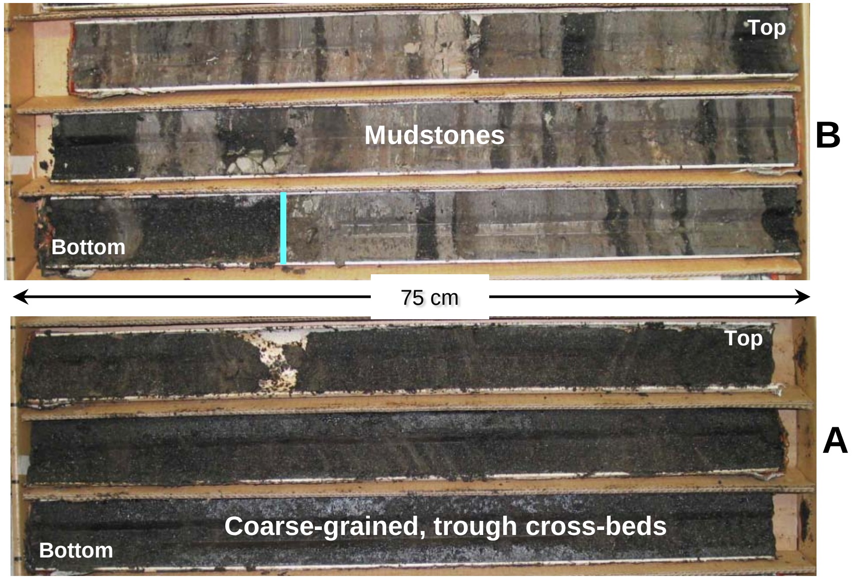
LIDAR & Well Locations

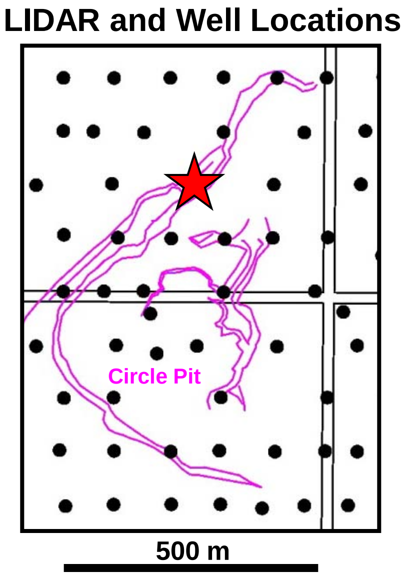


SB500 Fluvial - Core and Log Calibration to Outcrop

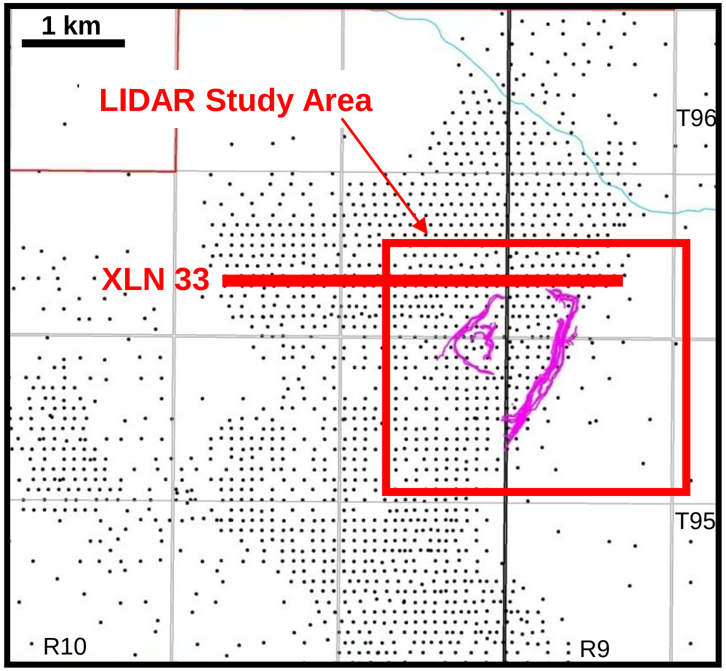






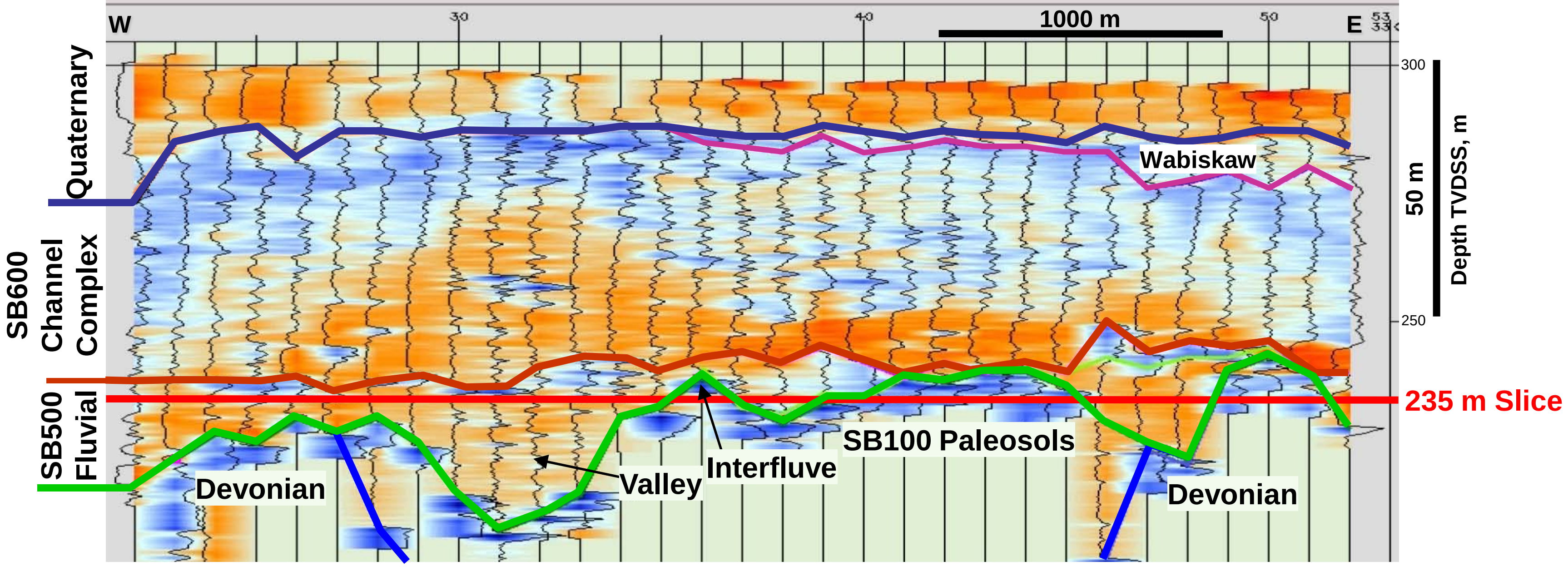


LogVu3D Cube

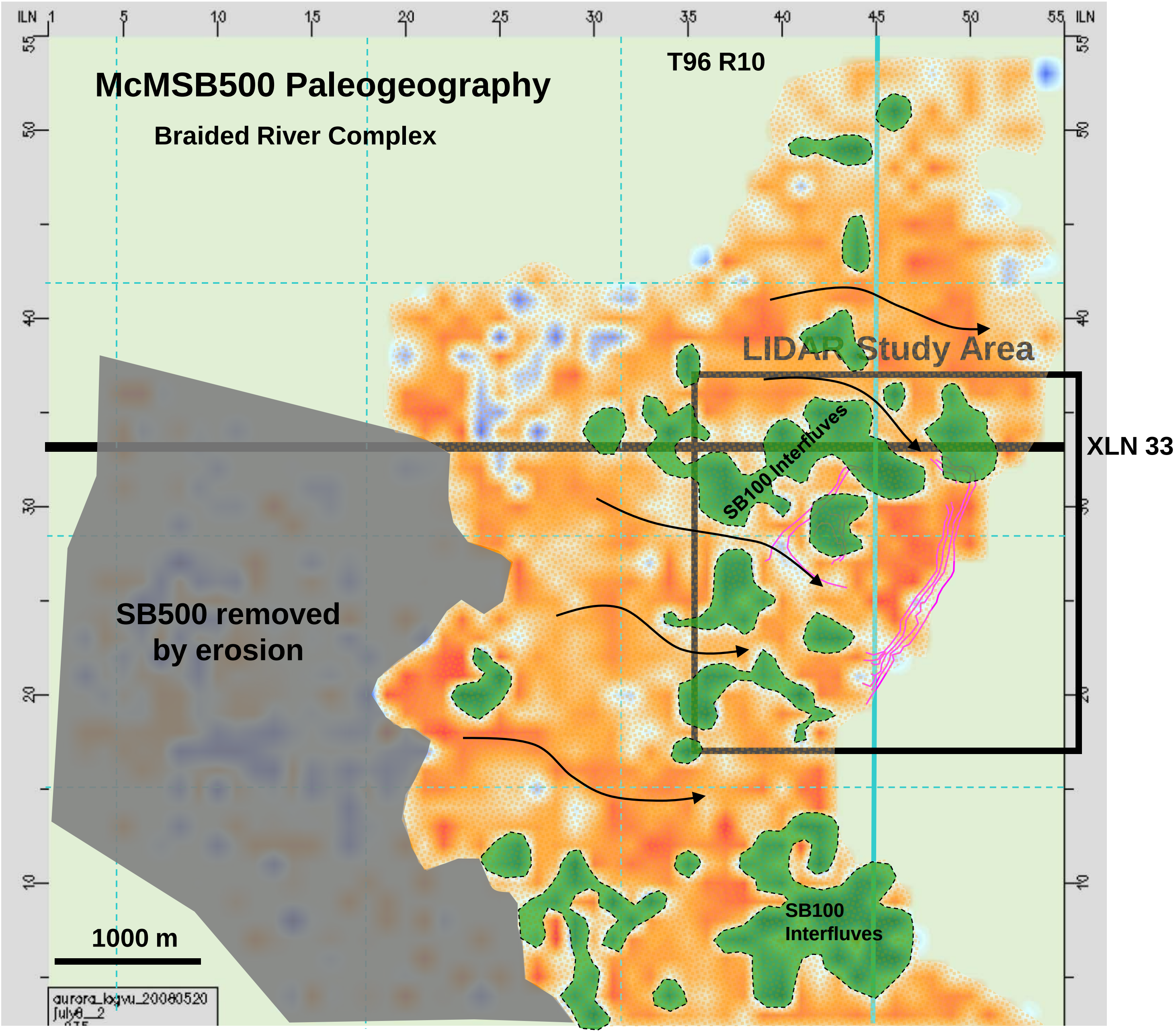


- Pseudo-3D seismic using GR traces
  - Renders very large well log data sets as 3D volume
  - Enhances visualization of facies changes and depositional trends
- X-Line 33 shows SB500 (green) unconformity structural relief infilled with fluvial sands
- 235 m depth slice images SB500 fluvial sand distribution and interfluves composed of SB100 paleosols

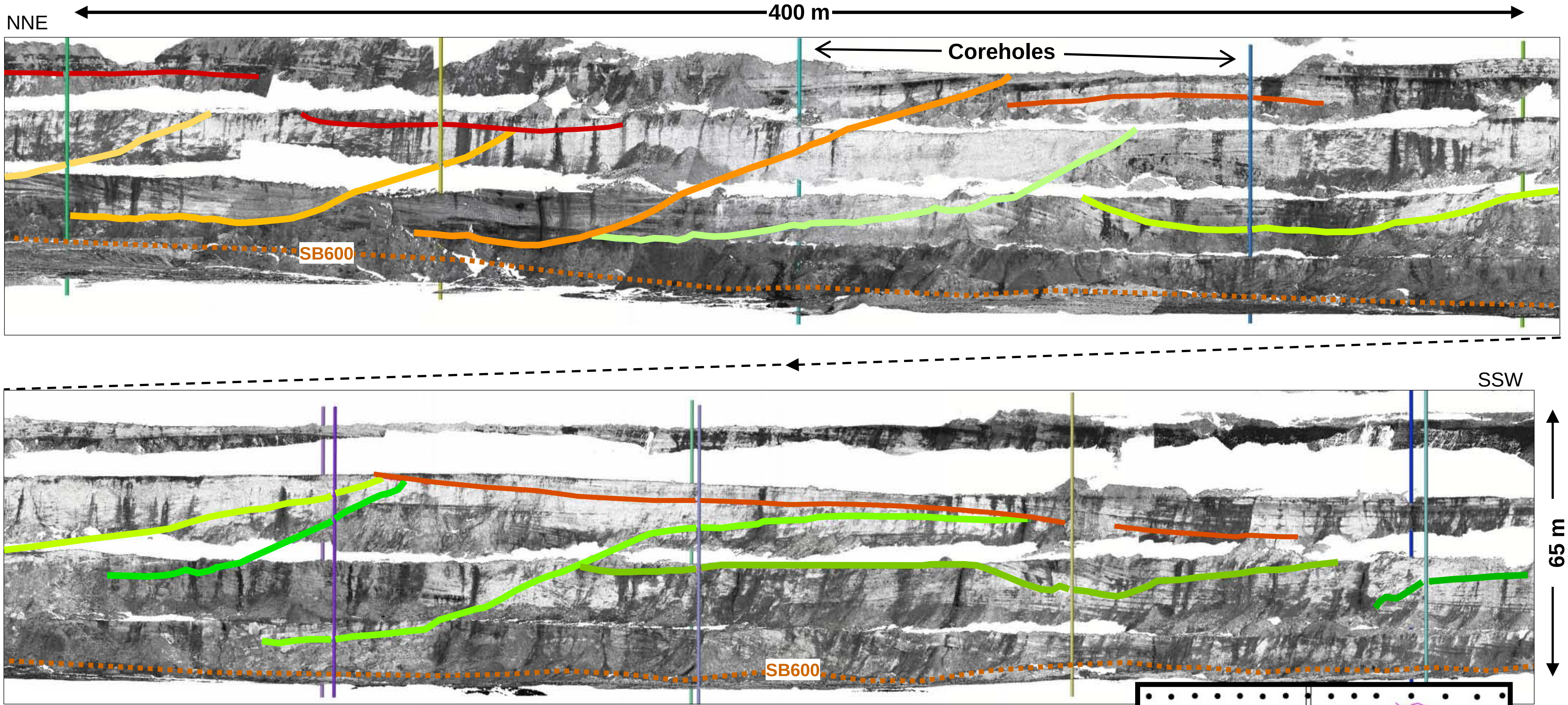
X-Line 33

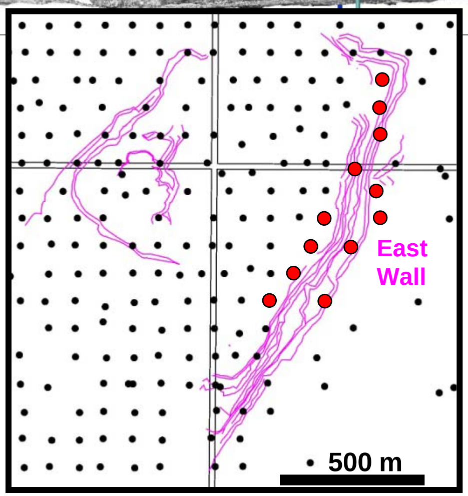


LogVu3D - Depth Slice through SB500 Sequence



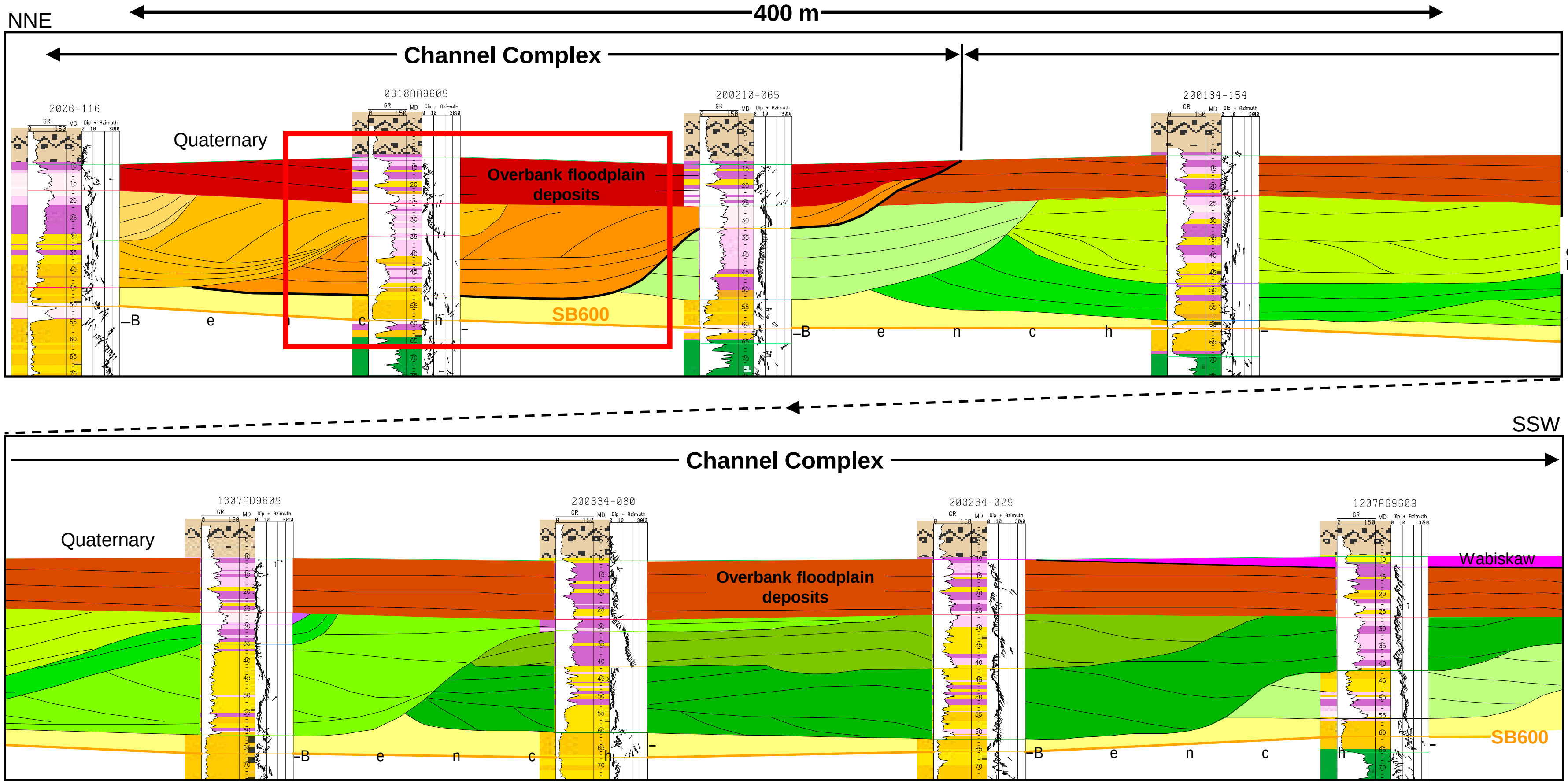
LIDAR Scan – East Wall Channel Complex





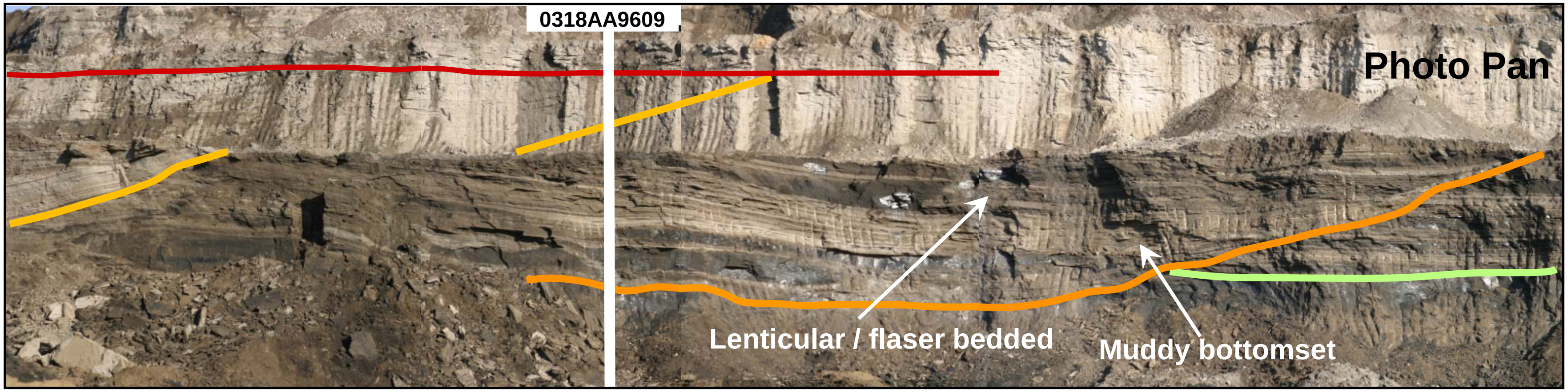
- **The SB600 succession is up to 55 m thick**
- **Concave-upward erosional surfaces define channels that incise up to 35 m to a common elevation within SB600 basal sands**
- **Channels contain distinct stratigraphic units that stack laterally and systematically become younger northward**
- **Two channel complexes are observed (green and orange) that also young northward**
- **Each channel complex is overlain by abandonment floodplain deposits along an erosional contact**

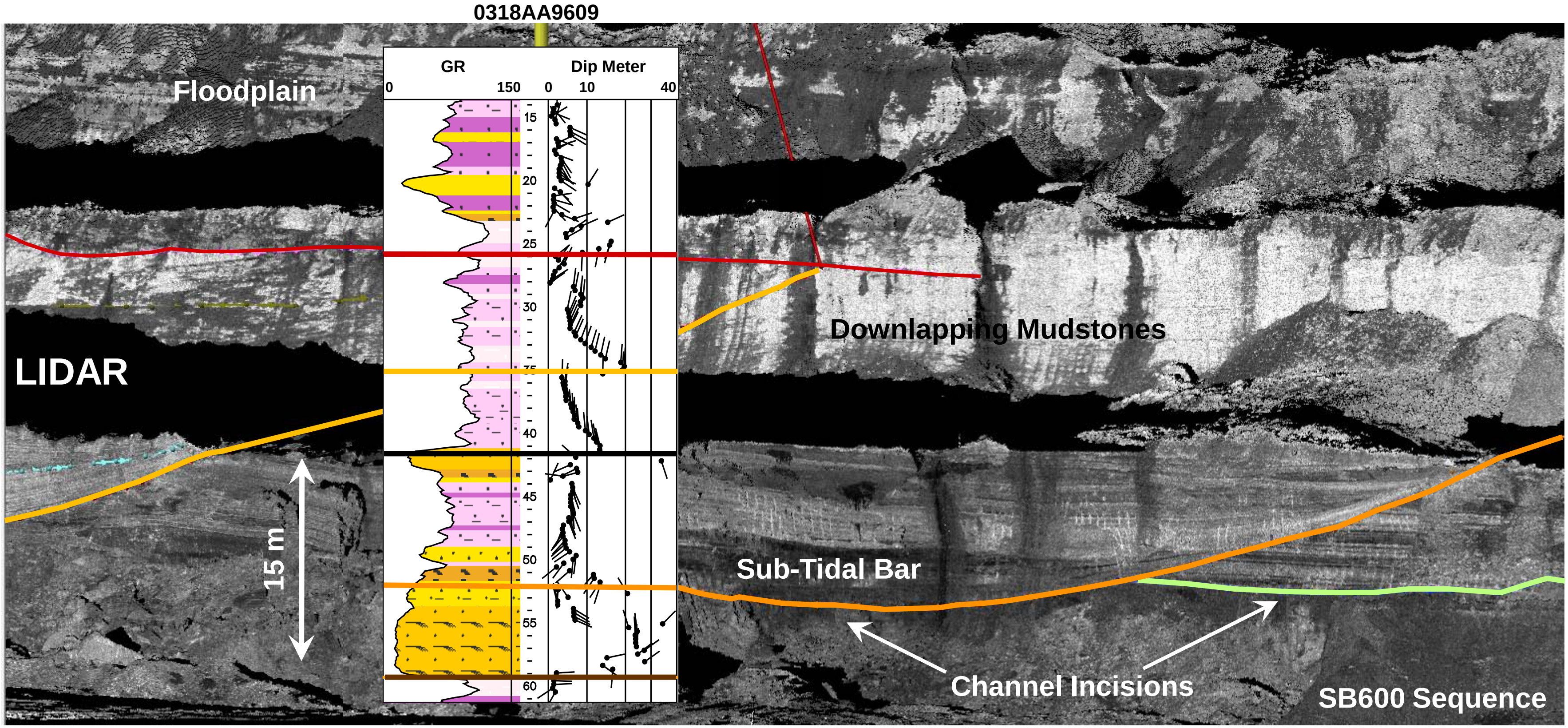
Corehole Cross Section - East Wall Channel Complex



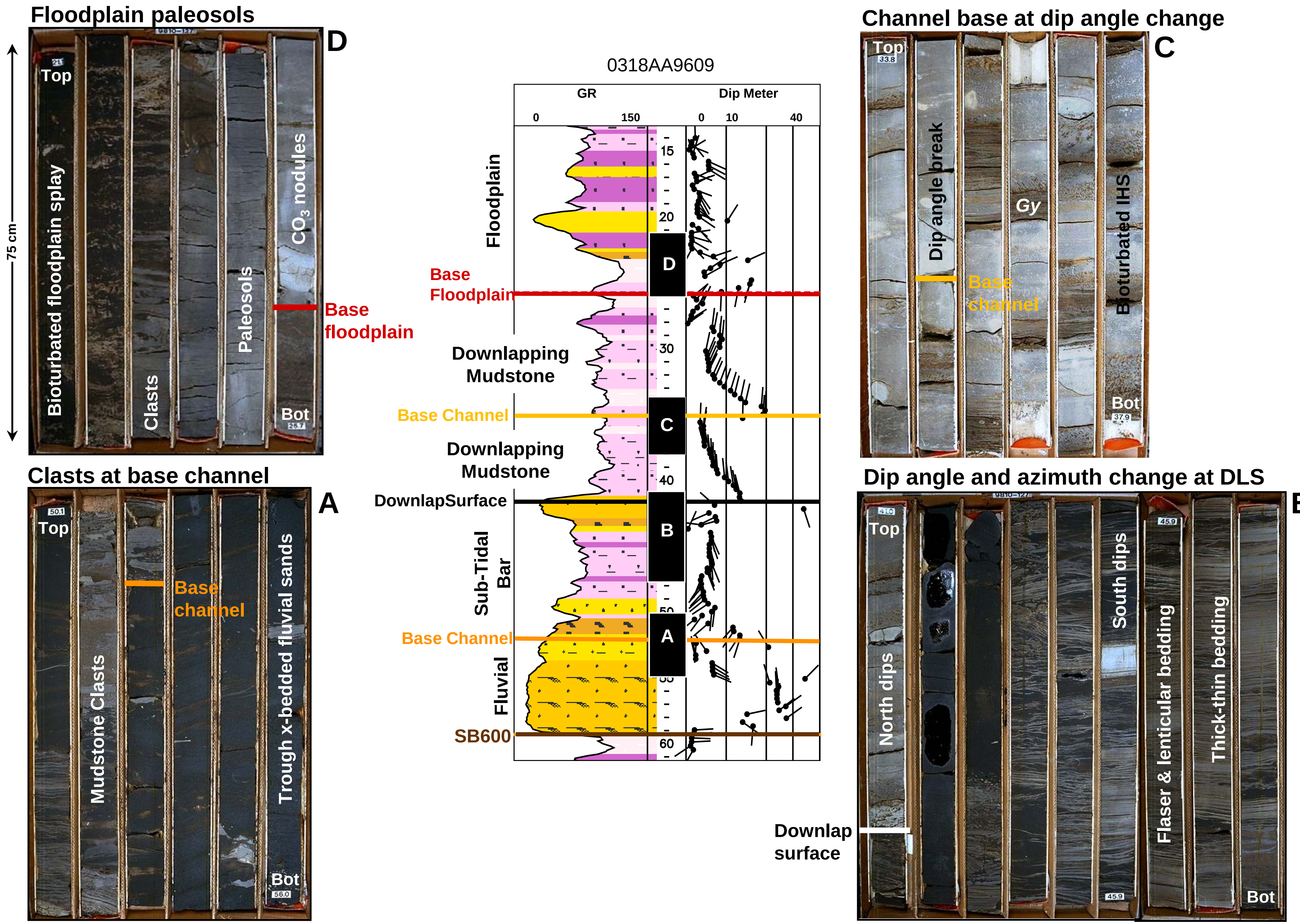
- Succession is upward-thinning / fining overall but also contains upward-coarsening units
- Channels have complex fills but commonly have basal sand-prone bars and downlapping mud-prone inclined heterolithic strata (IHS)
- IHS dips range from 2 to more than 20 degrees northward (orange complex) and eastward (green complex)
- Channel margins and downlap surfaces are depicted by abrupt bed dip and/or azimuth changes
- 100 m corehole spacing does not completely capture the lateral stratigraphic variability

Subsurface Corehole Calibration to Outcrop

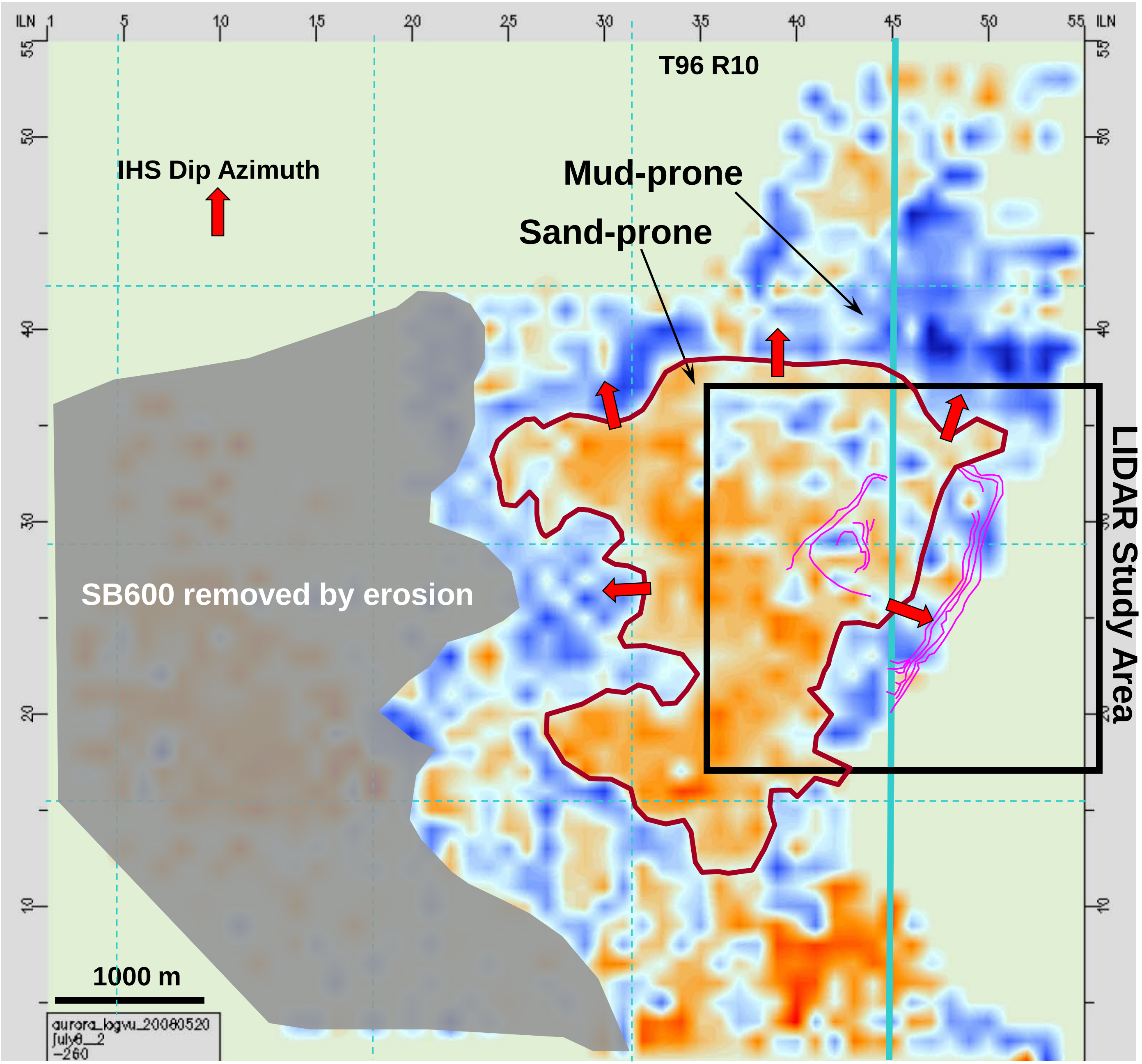




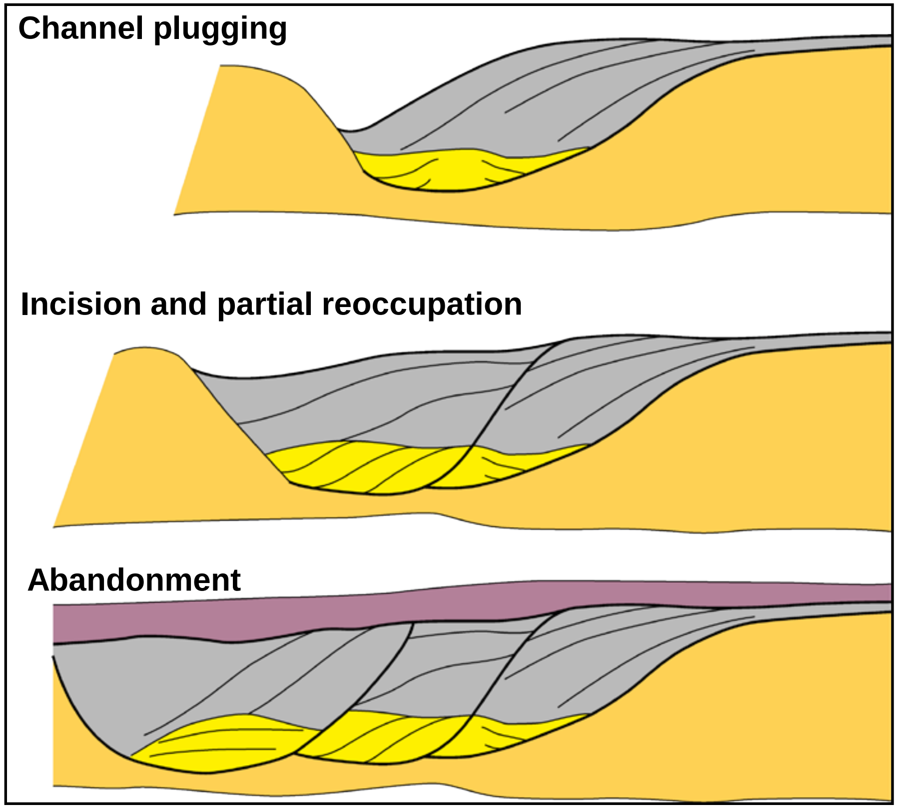
Core Lithofacies Calibration to Outcrop



LogVu3D SB600 Depth Slice



Channel Complex Depositional Environment



Key Observations

- Deep, narrow channels with cut and fill architecture
- High spatial frequency
- Tidally influenced deposition with basal bar forms and downlapping IHS that flatten upward
- Channels stack laterally into complexes capped by abandonment deposits
- IHS dip azimuths radiate from central sand body

Model

- Point bar in which repeated and systematic channel incision is common
- Renewed incision possibly triggered by a combination of
    - Partial channel filling
    - Flow diversion
    - Syndepositional movement of the sub-K unconformity

Final Thoughts

- **Mine exposures tied to closely spaced corehole data provides a powerful approach to study of McMurray stratigraphy and depositional systems**

- **Continued exploitation of these data-rich areas can be used to develop subsurface recognition criteria for a variety of facies and depositional environments where well control sparse**

- **Additional insights into McMurray depositional systems will come from combining mine studies with 3D seismic imaging of depositional and geomorphic systems documented at in-situ developments**