[PS]Integrated Ichnology and Sedimentology of Mixed River- and Wave-Influenced Delta Complexes, Upper Cretaceous Basal Belly River Fm, Central Alberta, Canada*

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Abstract

The Upper Cretaceous (early-mid Campanian) basal Belly River Formation of central Alberta comprises eight progradational, mixed river- and wave-influenced delta lobes (cycles A-H). Successive cycles intertongue with the underlying marine shales of the Lea Park Formation, and young to the east-northeast. A detailed subsurface analysis of cycles E-G was initiated within the Ferrier, Willesden Green, Gilby and Wilson Creek fields of central Alberta, to complement a previous study in the Ferrybank and eastern Pembina/Keystone fields. Expansion of the study area and study interval will serve to enhance our understanding of facies characteristics and depositional architectures within ancient, mixed river- and wave-influenced deltaic systems. Such refinements in the facies model will shed light on the degree of predictability in reservoir heterogeneities within such settings.

Fifty subsurface cores were selected, with the aim of optimizing spatial coverage and cycles intersected. Cored intervals were evaluated using ichnology and sedimentology in order to establish a high-resolution facies framework. Initial results reveal 12 discrete facies, which can be distilled into three distinct facies associations: (1) mixed river- wave- and storm-influenced deltas; (2) river-dominated, storm-influenced deltas; and (3) fluvio-estuarine distributary channels. Differentiation between FA1 and FA2 is based on the prevalence of river-generated features, such as soft-sediment deformation, syneresis cracks, current-generated structures, and drapes of fluid mud origin. FA3 is erosionally based, coarser-grained, and dominated by high-angle cross-stratification and current ripples. Although both FA1 and FA2 exhibit stressed ichnological suites consistent with a deltaic signal, FA2 is characterized by lower diversities and sporadically distributed traces dominated by facies-crossing elements. FA1 suites are more diverse, whereas FA3 units are mainly devoid of bioturbation.

Preliminary evaluations indicate that sandier deposits of FA1 are concentrated in updrift positions, whereas more heterolithic deposits of FA2 prevail in positions downdrift of the distributary channels. These distributions compare favorably with those predicted by the asymmetric delta model. Continued research will focus on along-strike variations in facies distributions for these Belly River lobes, in order to construct a paleogeographically accurate depositional model.

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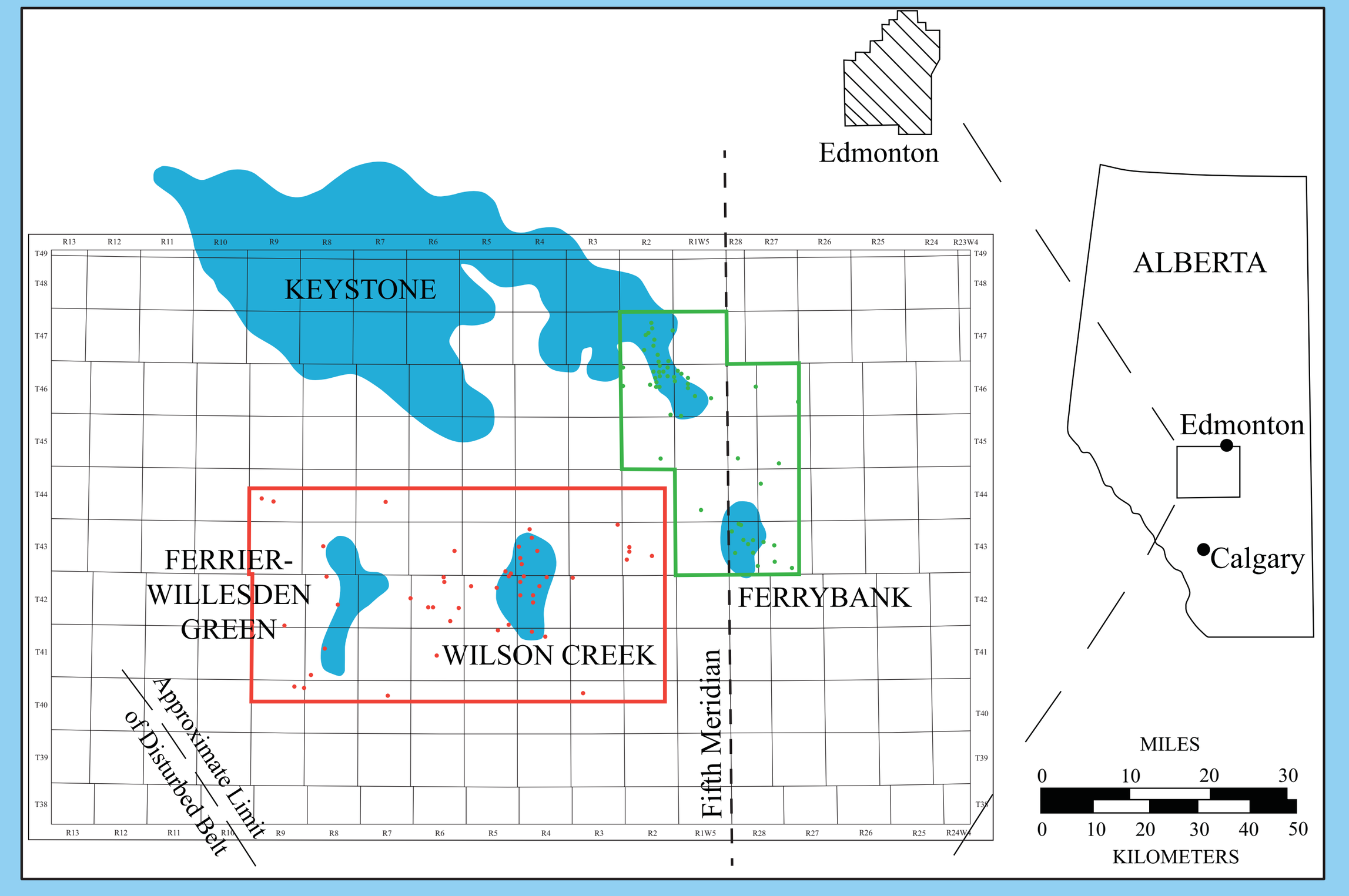
Introduction

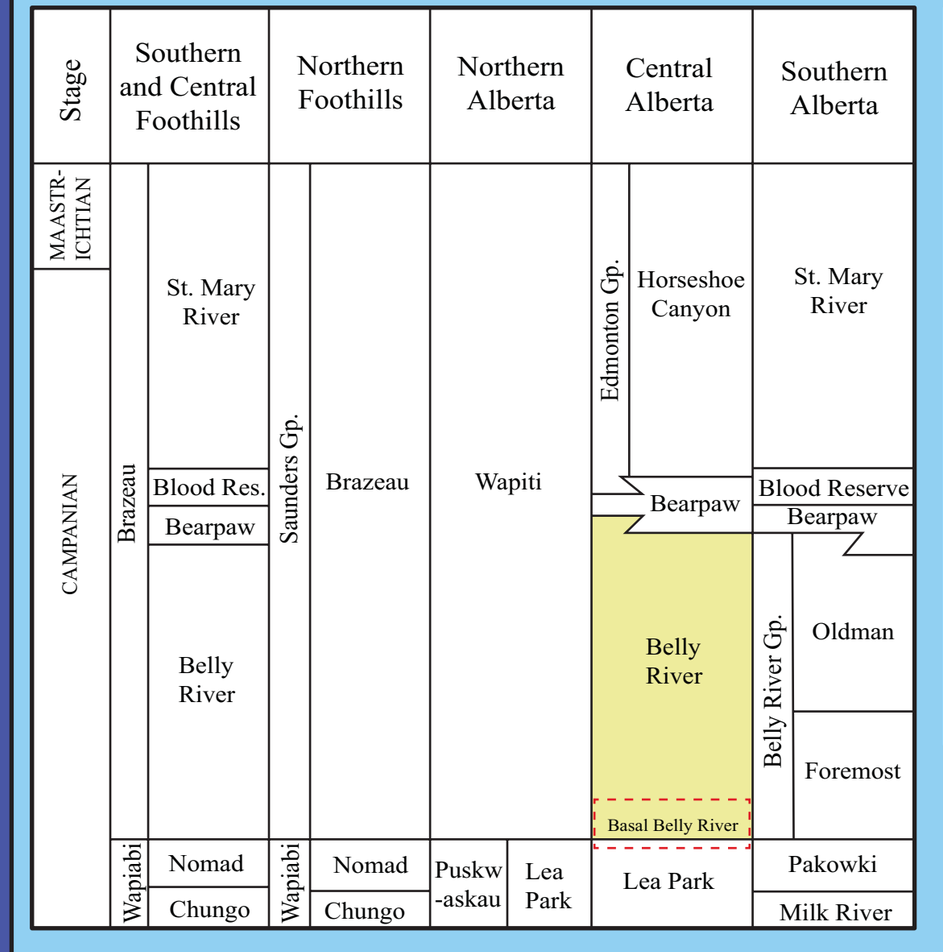
The Upper Cretaceous (early-mid Campanian) basal Belly River Formation of central Alberta comprises eight progradational, mixed river- and wave-influenced delta lobes (cycles A-H). Successive cycles intertongue with the underlying marine shales of the Lea Park Formation, and young to the east-northeast (Power and Walker, 1996). A detailed subsurface analysis of cycles D-G was initiated within the Ferrier, Willesden Green, Gilby and Wilson Creek fields of central Alberta, to complement a previous study in the Ferrybank and eastern Pembina/Keystone fields (cf. Hansen, 2007; Hansen and MacEachern, 2007). Expansion of the study area and study interval will serve to enhance our understanding of facies characteristics and depositional architectures within ancient, mixed river- and wave-influenced deltaic systems. Such refinements in the facies model will shed light on the degree of predictability in reservoir heterogeneities within such settings.

Study Area

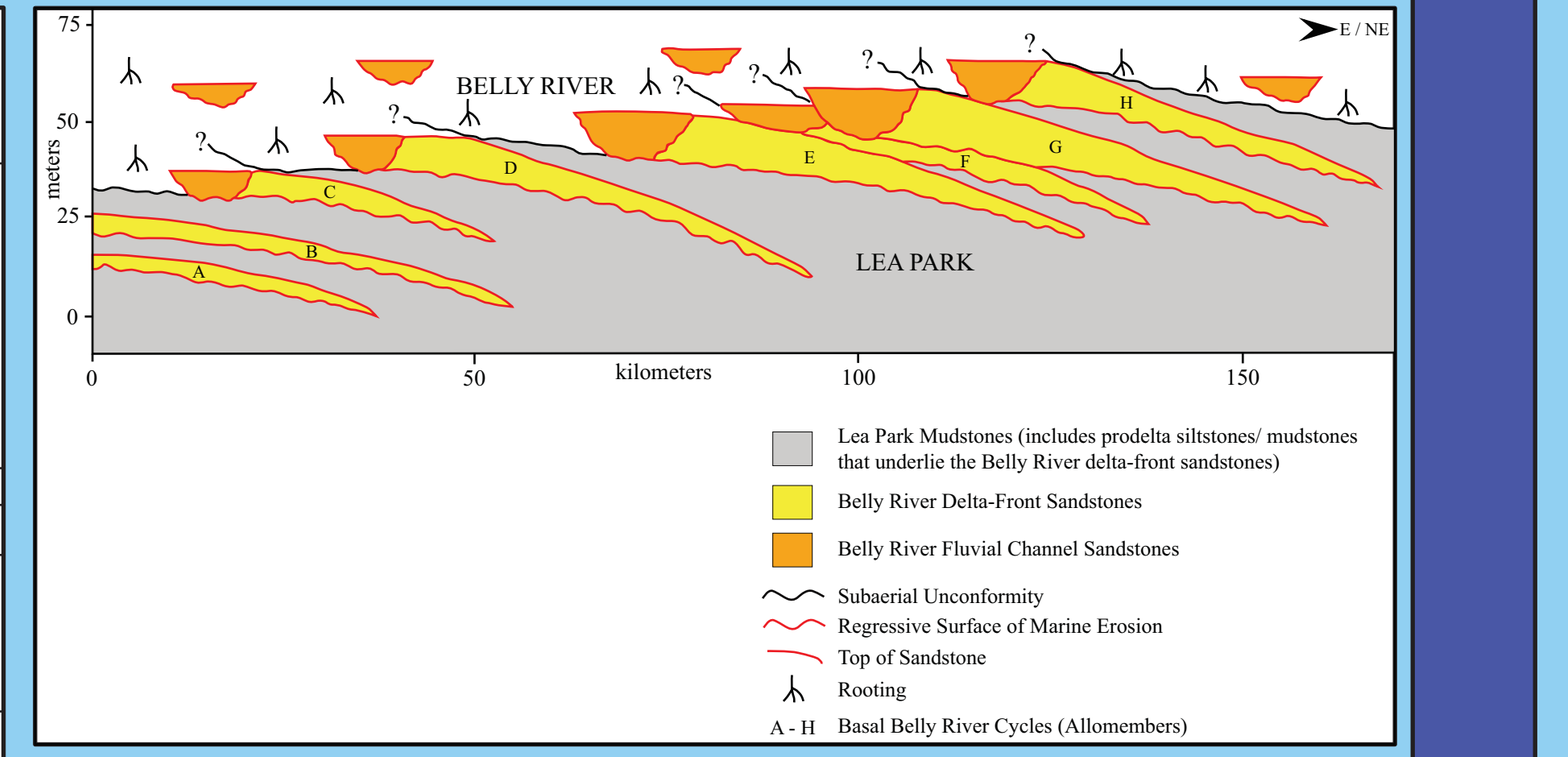


Location map with the major Belly River fields in central Alberta (modified after Power and Walker, 1996). The red border outlines the current study area. The green border outlines the study area of Hansen (2007).

Stratigraphy



Lithostratigraphy of the Belly River and Lea Park formations (modified after Hansen, 2007). The red, dashed border outlines the interval of interest.

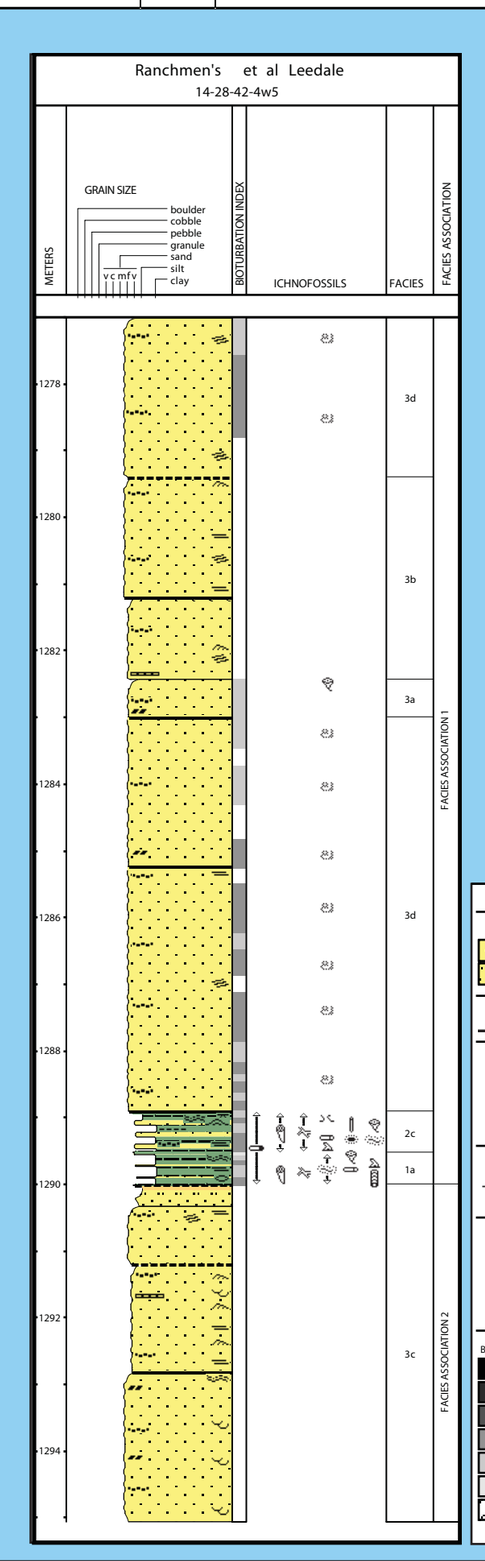


Schematic, dip-oriented cross-section, showing the proposed allostratigraphy of the Lea Park - Belly River transition (modified after Power and Walker, 1996).

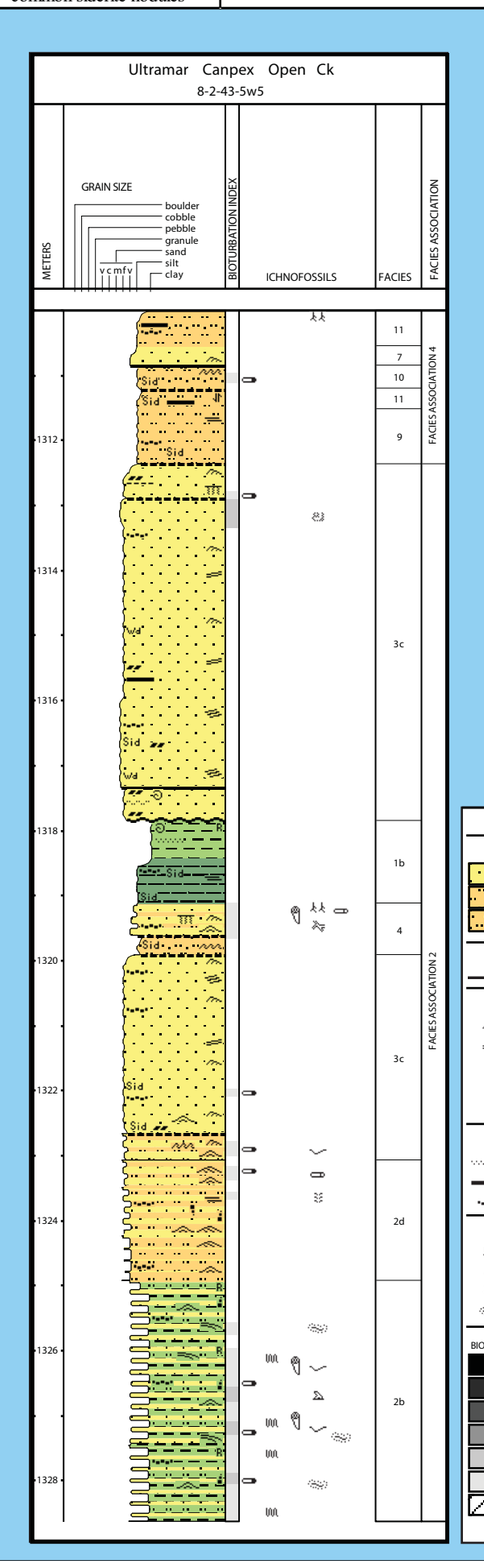
Methods and Results

Fifty subsurface cores were selected, with the aim of optimizing spatial coverage and the cycles intersected. Cored intervals were evaluated using sedimentology and ichnology, establishing a high-resolution facies framework.

Facies Association	Facies	Description	Sedimentology	Lithologic Accessories	Trace Fossil Suite	B.I.	Depositional Environment
(1) Storm-Dominated, Mixed River- and Wave-Influenced Delta Deposits	3d	Cryptically bioturbated to bioturbated sandstone	Local horizontal to low-angle planar parallel lamination	Carbonaceous detritus	*Macaronichnus* and cryptic bioturbation	1 - 5	Proximal Upper Shoreface to Foreshore or Proximal Delta Front
	3b	Oscillation rippled and planar parallel laminated sandstone	Curvilinear and oscillation-ripple lamination; horizontal to low-angle planar parallel lamination (HCS/SCS); local trough and planar tabular cross-stratification; rare claystone drapes	Carbonaceous detritus, mudstone/siltstone rip-up clasts, coal fragments, pyrite nodules, plant fragments, shell fragments	*Rosselia, Diplocraterion, Rhizocorallium, Ophiomorpha, Cyclindrichnus, Thalassinoides, Planolites, Macaronichnus,* and fugichnia	0 -3	Middle Shoreface or Proximal Delta Front
	3a	Apparently structureless (massive) sandstone and silty sandstone	Bedding is not discernable	Carbonaceous detritus, mudstone rip-up clasts, and minor siderite cement	*Diplocraterion, Ophiomorpha, Rosselia*	0 -1	Distal to Proximal Delta Front
	2b	Moderately bioturbated, interstratified sandstone, muddy sandstone, silty mudstone, and organic-rich claystone	Mud-prone heterolithic unit; similar physical sedimentary structures to those in 2b, however syneresis cracks are rare	Common carbonaceous detritus and cm-scale siderite banding; local mudstone rip-up clasts	*Planolites, Thalassinoides, Teichichnus, Zoophycos, Asterosoma, Palaeophycus, Cylindrichnus, Diplocraterion, Rhizocorallium, Skolithos, Arenicolites, Siphonichnus, Rosselia, Conichnus, Bergaueria, Chondrites, Phycosiphon, Helminthoida, Lockeia,* navichnia, equilibrichnia, and fugichnia	0 - 4	Distal to Proximal Prodelta
	1a	Bioturbated silty/sandy mudstone	Mud-prone unit; physical sedimentary structures are commonly obscured by biogenic reworking; local lenticular bedding and way-parallel lamination.	Local carbonaceous detritus and minor siderite cement	*Planolites, Thalassinoides, Cylindrichnus, Teichichnus, Palaeophycus, Asterosoma, Rosselia, Chondrites, Phycosiphon, Helminthoida,* navichnia and fugichnia	3 - 5	Offshore Marine Deposits
(2) River-Dominated, Storm-Influenced Delta Deposits	3c	Spherulitic siderite-bearing, cross-stratified and current ripple-laminated sandstone	Common current-ripple lamination, planar tabular and trough cross-stratification, aggradational current-ripple lamination, and small-scale convolute bedding; common mm-cm thick mudstone drapes locally accociated with syneresis cracks; common wavy-parallel lamination, and combined-flow ripples	Carbonaceous detritus (commonly marking forsets), spherulitic siderite granules, mudstone rip-up clasts, coal fragments, shell fragments	*Thalassinoides, Planolites, Chondrites, Skolithos, Arenicolites, Cylindrichnus, Palaeophycus, Macaronichnus*	0 - 2	Bay-Head Delta
	1b	Apparently structureless (massive) mudstone with locally interlaminated silty sandstone	Mud-prone unit with locally admixed silt and sand; common massive bedding, convolute bedding and lenticular bedding; local sandstone laminations display wavy-parallel lamination and ocillation ripples	Abundant carbonaceous detritus, oyster shell fragments, and coal fragments; minor siderite cement	*Planolites, Cylindrichnus,* and navichnia (difficult to distinguish biogenic structures due to the convolute character of the facies)	0 - 1	Restricted Bay
	4	Sporadically bioturbated, current-ripple laminated to convolute-bedded sandstone and siltstone	Lithologically variable, soft-sediment deformed admixtures of silt, sand and mud interbedded with current-ripple laminated sandstone; local wavy-parallel lamination, aggradational current ripples, mm-cm thick mudstone laminations, micro-faulting, syneresis cracks, and pedogenic features	Carbonaceous detritus and moderate amounts of siderite cement	*Planolites, Cylindrichnus, Thalassinoides, Naktodemasis* and root structures	0 - 2	Abandoned Mouth-bar/Terminal Distributary Channel Complex
	3c	Spherulitic siderite-bearing, cross-stratified and current ripple-laminated sandstone	Common current-ripple lamination, planar tabular and trough cross-stratification, aggradational current-ripple lamination, and small-scale convolute bedding; common mm-cm thick mudstone drapes locally accociated with syneresis cracks; common wavy-parallel lamination, and combined-flow ripples	Carbonaceous detritus (commonly marking forsets), spherulitic siderite granules, mudstone rip-up clasts, coal fragments	*Thalassinoides, Planolites, Chondrites, Skolithos, Arenicolites, Cylindrichnus, Palaeophycus, Macaronichnus*	0 - 2	Mouth-Bar/Terminal Distributary Channel Complex
	2c	Laminated to soft-sediment deformed, interbedded clayey siltstone, sandy siltstone, and silty sandstone	Heterolithic unit; abundant dewatering or degassing structures; normally graded bedding; composite graded bedsets; planar parallel to curvilinear lamination; apparently structureless (massive) bedding; micro-faulting; local wavy bedding	Carbonaceous detritus and minor siderite cement	*Planolites,* fugichnia	0 -2	Proximal Prodelta to Distal Delta Front
	2a	Sparsely bioturbated, interstratified sandstone, muddy sandstone, silty mudstone, and organic-rich claystone	Mud-prone heterolithic unit; common wavy to lenticular bedding, low-angle planar parallel to wavy-parallel lamination (micro-HCS), oscillation ripples, local combined-flow ripples, small-scale convolute bedding, loading structures, gutter casts and syneresis cracks	Common carbonaceous detritus and cm-scale siderite banding; local mudstone rip-up clasts	*Planolites, Thalassinoides, Teichichnus, Cylindrichnus, Palaeophycus, Chondrites, Lockeia, Siphonichnus, Phycosiphon*	0 - 2	Distal to Proximal Prodelta
(3) Fluvio-Estuarine Distributary Channel Deposits	8	Sandstone with interlaminated silty mudstone	Heterolithic unit; common current-ripple lamination and local curvilinear lamination, trough cross-stratification, aggradational current ripple lamination, and small-scale convolute bedding in sandstone; silty mudstone displays wavy-parallel laminations and drapes underlying sandstone bedforms; pedogenic slickensides are common	Moderate to abundant carbonaceous detritus, mudstone and siderite rip-up clasts	*Planolites, Thalassinoides, Cylindrichnus, Skolithos, Palaeophycus, Naktodemasis,* fugichnia and root structures	0 - 2	Uppermost Portion of Point Bar
	7	Current-ripple laminated sandstone	Abundant current-ripple lamination; local aggradational current-ripple lamination, trough cross-stratification, combined-flow ripples, wavy-parallel lamination; locally diplay erosive basal contacts	Abundant carbonaceous detritus; local coal fragments and mudstone rip-up clasts	*Planolites, Cylindrichnus,* root structures	0 - 1	Lowermost to Middle Portion of Point Bar
	6	Cross-bedded sandstone	Amalgamated simple bedsets; low to high angle planar tabular and trough cross-stratification dominate; local apparently structureless bedding, current-ripple lamination, horizontal planar parallel lamination, curvilinear lamination and small-scale convolute bedding	Abundant carbonaceous detritus (commonly marking laminae), dispersed pebbles, siderite nodules, coal fragments, mudstone rip-up clasts	Roots structures (typically restricted to the top of the facies)	0	Lowermost to Middle Portion of Point Bar
	5	Pebbly conglomerate to pebbly sandstone	Poorly sorted, subrounded to rounded pebble clasts of variable composition; lower medium- to upper coarse-grained sandstone matrix; trough and planar tabular cross-stratification; apparently structureless (massive) bedding	Carbonaceous detritus, mudstone rip-up clasts, coal fragments	No trace fossils observed	0	Channel Lag
(4) Delta Plain / Coastal Plain Deposits	12	Root-bearing silty mudstone and muddy siltstone	Lithologically variable; primary sedimentary structures are commonly absent or present as indistinct mottles; local horizontal laminations, apparently structureless (massive) bedding, convolute bedding, and pedogenic slickensides; intercalated sandstone stringers	Abundant carbonaceous detritus, coal fragments, and irregularly shaped siderite nodules	*Naktodemasis,* and root structures	0 - 1	Floodplain
	7	Current-ripple laminated sandstone	Abundant current-ripple lamination; local aggradational current-ripple lamination, trough cross-stratification, combined-flow ripples, wavy-parallel lamination; locally diplay erosive basal contacts	Abundant carbonaceous detritus; local coal fragments and mudstone rip-up clasts	*Planolites, Cylindrichnus,* root structures	0 - 1	Crevasse Splay
	11	Convolute-bedded, muddy siltstone and sandy siltstone	Various admixtures of mudstone and siltstone, with intercalated sand; pervasive convolute bedding and associated penecontemporaneous micro-faults	Abundant carbonaceous detritus, coal fragments, irregularly shaped siderite nodules, local carbonate-cemented intervals	*Planolites, Naktodemasis, Cylindrichnus* and root structures	0 - 1	Floodplain
	10	Sporadically bioturbated, thinly interlaminated to interbedded sandstone and clayey siltstone	Heterolithic unit with a variable sandstone to clayey siltstone ratio; common wavy bedding and rare lenticular bedding; abundant wavy-parallel lamination; common syneresis cracks; local current ripples, combined flow ripples, and convolute bedding	Carbonaceous detritus, mm-cm thick siderite bands, coal fragments	*Planolites, Cyclindrichnus, Siphonichnus, Palaeophycus, Teichichnus, Arenicolites, Skolithos, Lockeia,* navichnia and fugichnia	0 - 4	Interdistributary Bay
	9	Carbonaceous mudstone, siltstone, sandstone, and coal	Lithologically variable; intercalated coal beds/laminations; horizontal planar parallel lamination; local sandstone stringers display current ripples and curvilinear lamination; rare convolute bedding	Anomalously high concentrations of intercalated carbonaceous debris; plant debris; moderate amounts of coal fragments; common siderite nodules	*Planolites, Naktodemasis,* and root structures	0 - 1	Terrestrial Peat and Swamp



Typical example of Facies Association 1 (FA1): Storm-dominated, mixed river- and wave-influenced delta deposits of Cycle E. See next column for photos. Well 14-28-42-4W5.



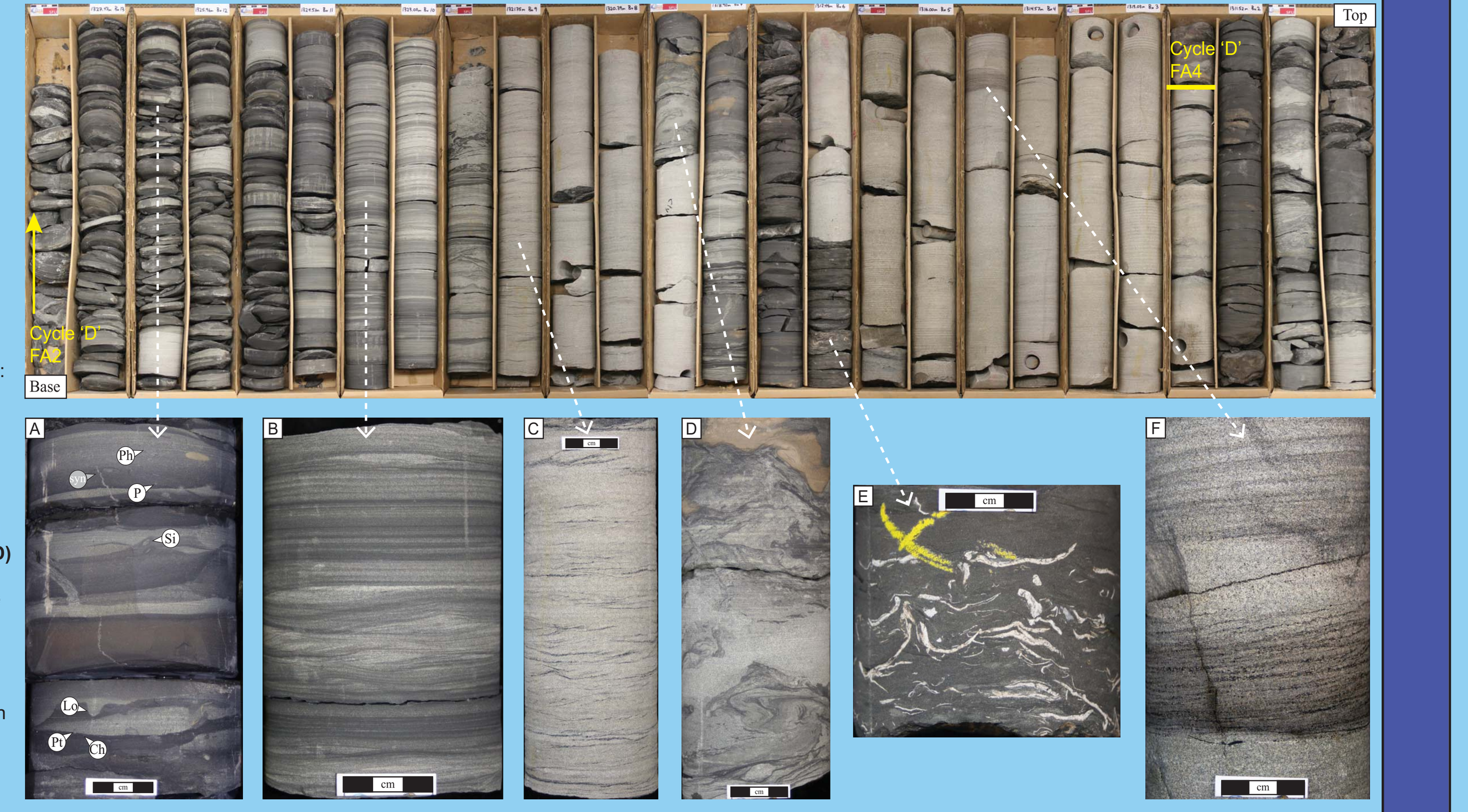
Typical example of Facies Association 2 (FA2): River-dominated, storm-influenced delta deposits of Cycle D. See next column for photos. Well 8-2-43-5W5.

FA1:

Representative photographs of the individual facies ,which typically comprise Facies Association 1 (FA1). **(A)** Facies 2b: moderately bioturbated, interstratified sandstone and silty mudstone. Physical structures include local curvilinear lamination. Ichnogenera include *Rhizocorallium* (Rh), *Diplocraterion* (Di), *Planolites* (P), *Chondrites* (Ch), *Siphonichnus* (Si), *Asterosoma* (As), and *Helminthopsis* (H). **(B)** Facies 2b: sandstone with interlaminated organic-rich claystone. Physical structures include low-angle to horizontal planar parallel lamination and curvilinear lamination. Ichnogenera include *Cylindrichnus* (Cy), *Arenicolites* (Ar), *Thalassinoides* (Th), *Asterosoma* (As), *Planolites* (P), and *Phycosiphon* (Ph). **(C)** Facies 3a: apparently structureless (massive) sandstone with a single mudstone rip-up clast (ruc). **(D)** Facies 3a: apparently structureless (massive) sandstone with local curvilinear lamination and an allochthonous *Rosselia* mud ball (Ro). **(E)** Facies 3b: low-angle planar parallel laminated sandstone with an escape structure (fugichnia) disrupting laminae. **(F)** Facies 3d: cryptically bioturbated to bioturbated sandstone with *Macaronichnus* (Ma). All photos taken from Cycle E (well 14-28-42-4W5).

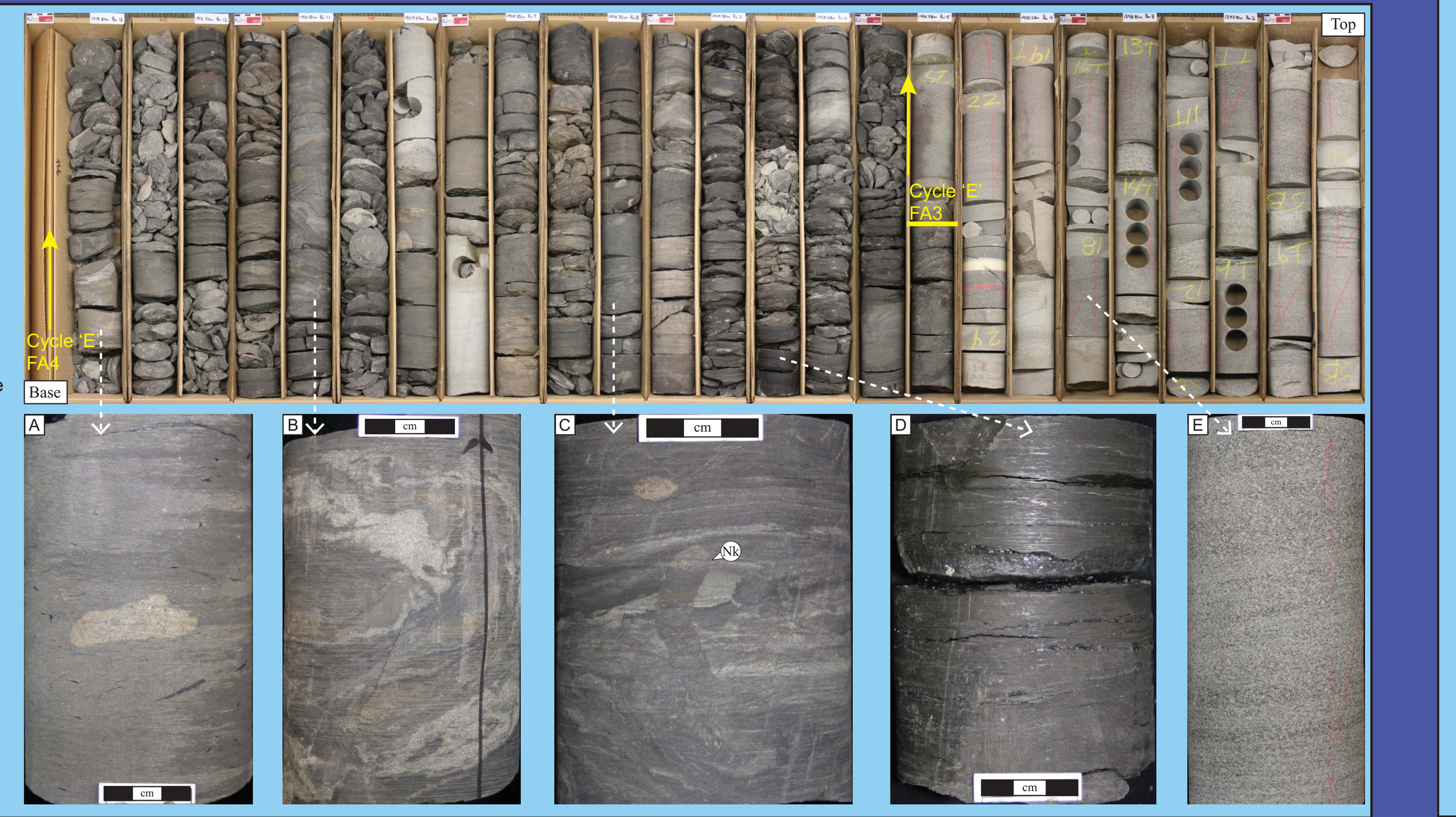
FA2:

Representative photographs of the individual facies, which typically comprise Facies Association 2 (FA2). **(A)** Facies 2a: sparsely bioturbated, interstratified sandstone, muddy sandstone, silty mudstone, and organic-rich claystone. Physical structures include wavy bedding, curvilinear lamination, syneresis cracks (syn), and normally and inversely graded beds. Ichnogenera include *Palaeophycus tubularis* (Pt), *Siphonichnus* (Si), *Chondrites* (Ch), *Planolites* (P), *Lockeia* (Lo), and *Phycosiphon* (Ph). **(B)** Facies 2c: interlaminated clayey siltstone, sandy siltstone, and silty sandstone. Physical structures include a composite, normally and inversely graded bedset, as well as, curvilinear lamination, current ripples, and combined-flow ripples. **(C)** Facies 3c: spherulitic siderite-bearing, cross-stratified and current ripple-laminated sandstone. **(D)** Facies 4: sporadically bioturbated, convolute-bedded sandstone and siltstone with siderite cement. **(E)** Facies 1b: apparently structureless (massive) silty mudstone. Note the abundance of shell fragments. **(F)** Facies 3c: trough cross-stratified sandstone. All photos taken from Cycle D (well 8-2-43-5W5).

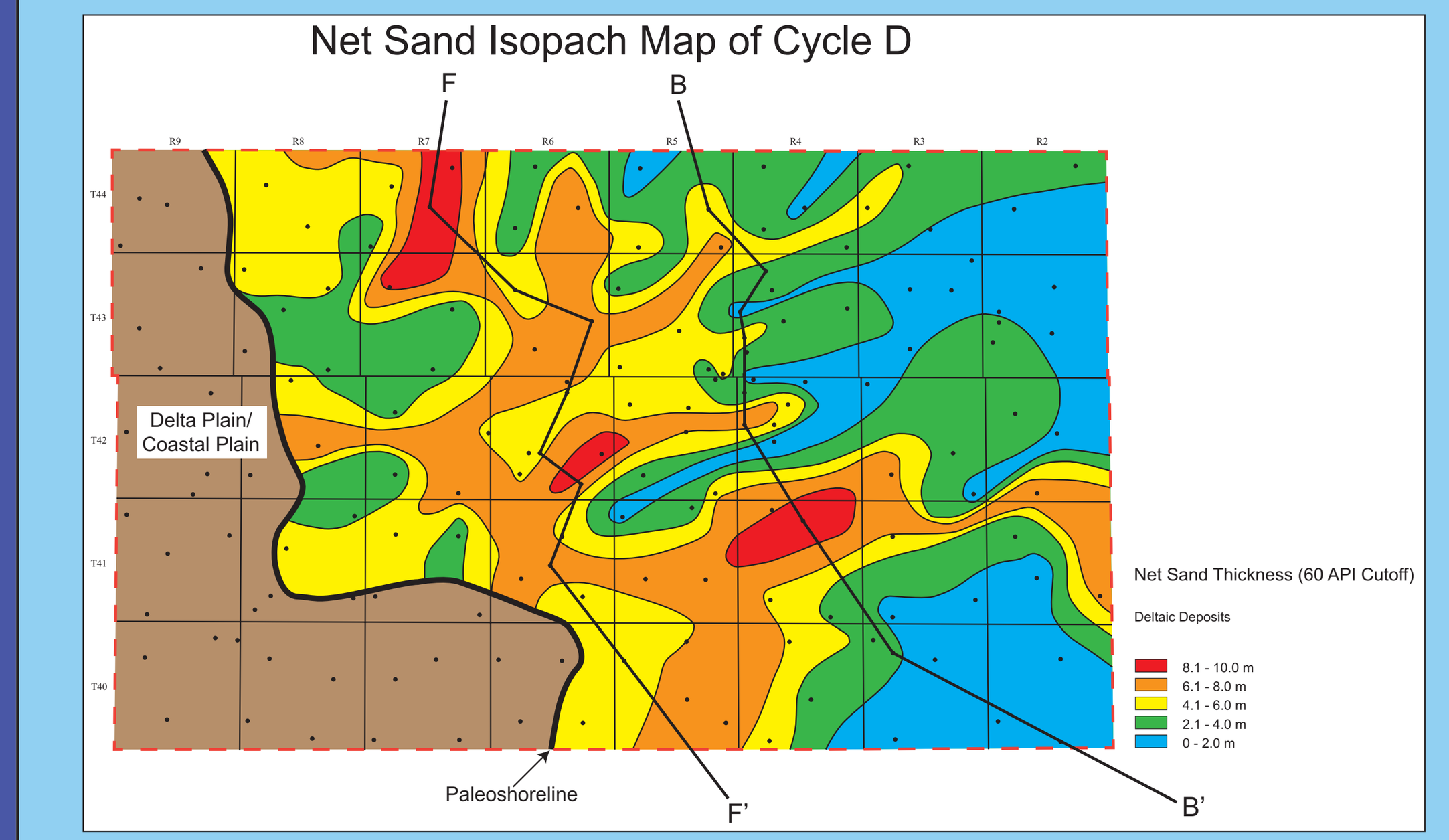


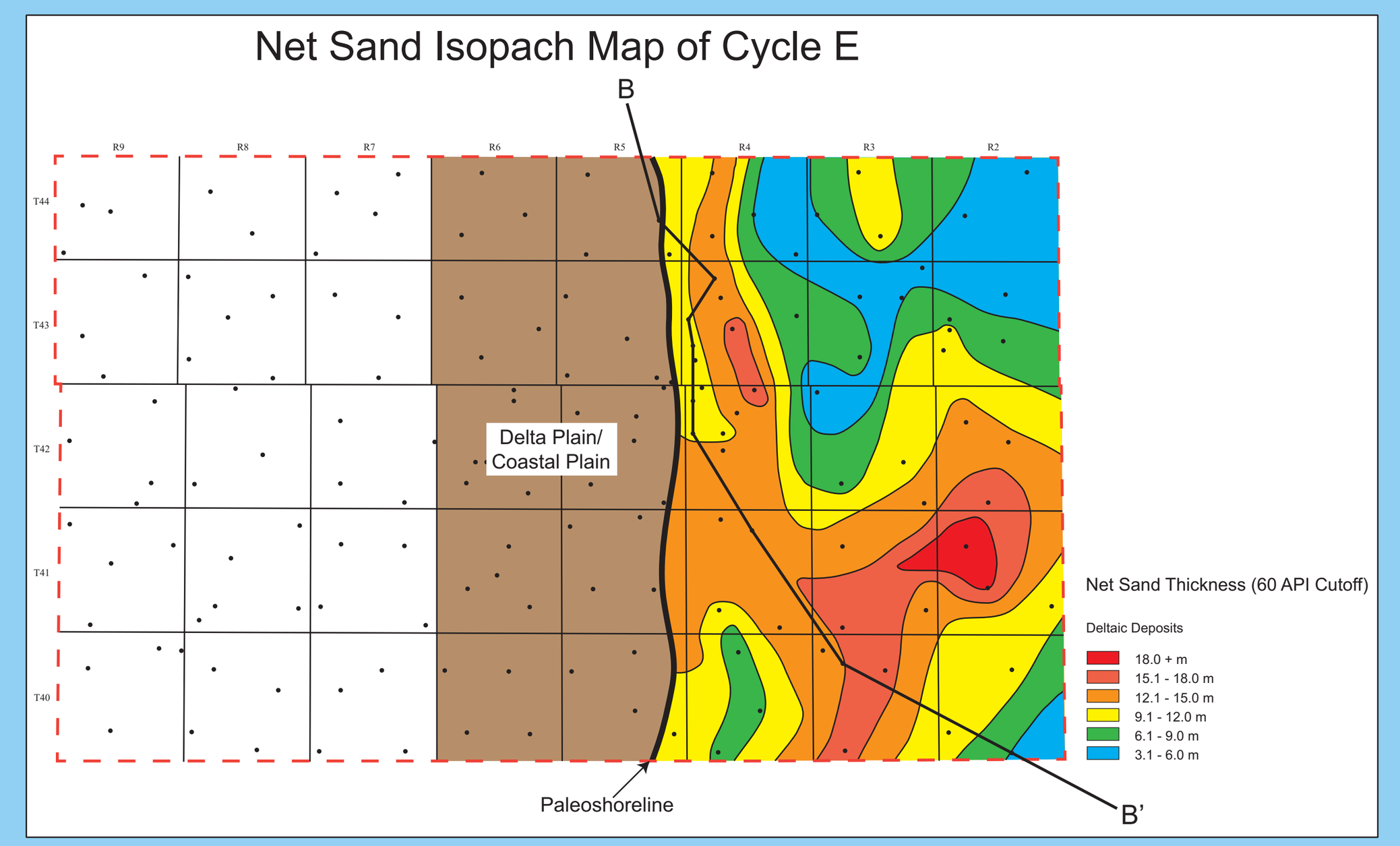
FA3 / FA4:

Representative photographs of the individual facies, which typically comprise Facies Association 3 and Facies Association 4 (FA3 and FA4). **(A)** Facies 12 (FA4): silty mudstone/muddy siltstone. Lithologic accessories include abundant coal fragments and a single siderite nodule. **(B)** Facies 11 (FA4): convolute-bedded, muddy/sandy siltstone. Siderite cement is common. **(C)** Facies 12 (FA4): silty/sandy mudstone. Physical structures include convolute bedding and curvilinear lamination. Ichnogenera include *Naktodemasis* (Nk). **(D)** Facies 9 (FA4): coal bed. **(E)** Facies 6 (FA3): cross-bedded sandstone. All photos taken from Cycle E (well 12-13-43-6W5).



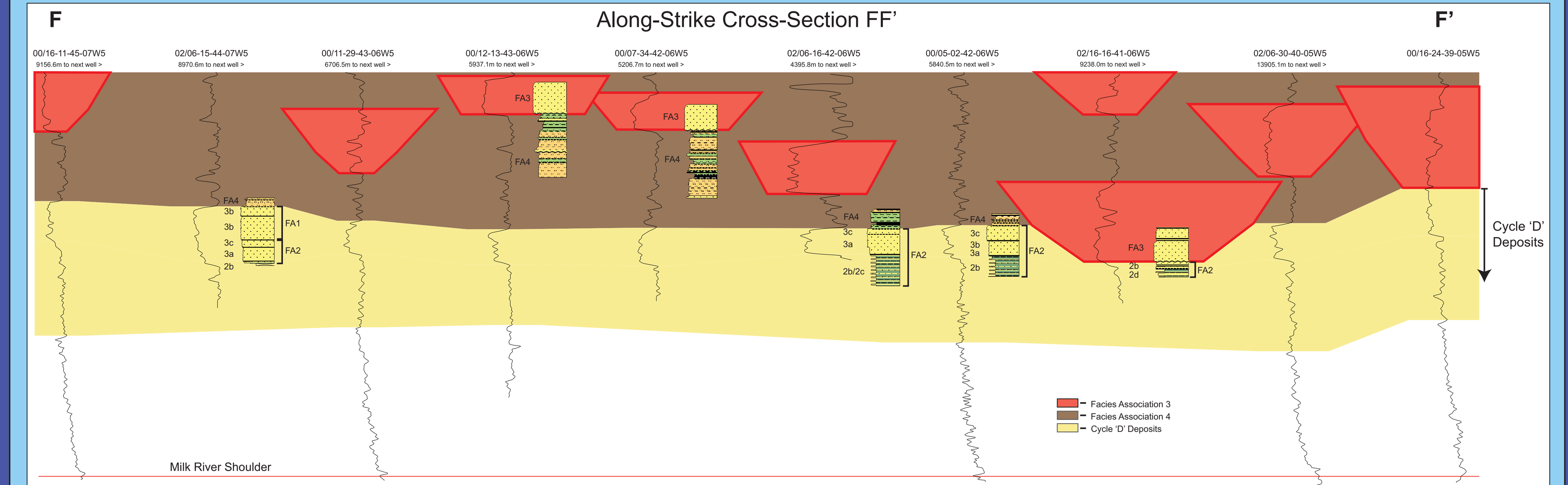
Isopach Mapping

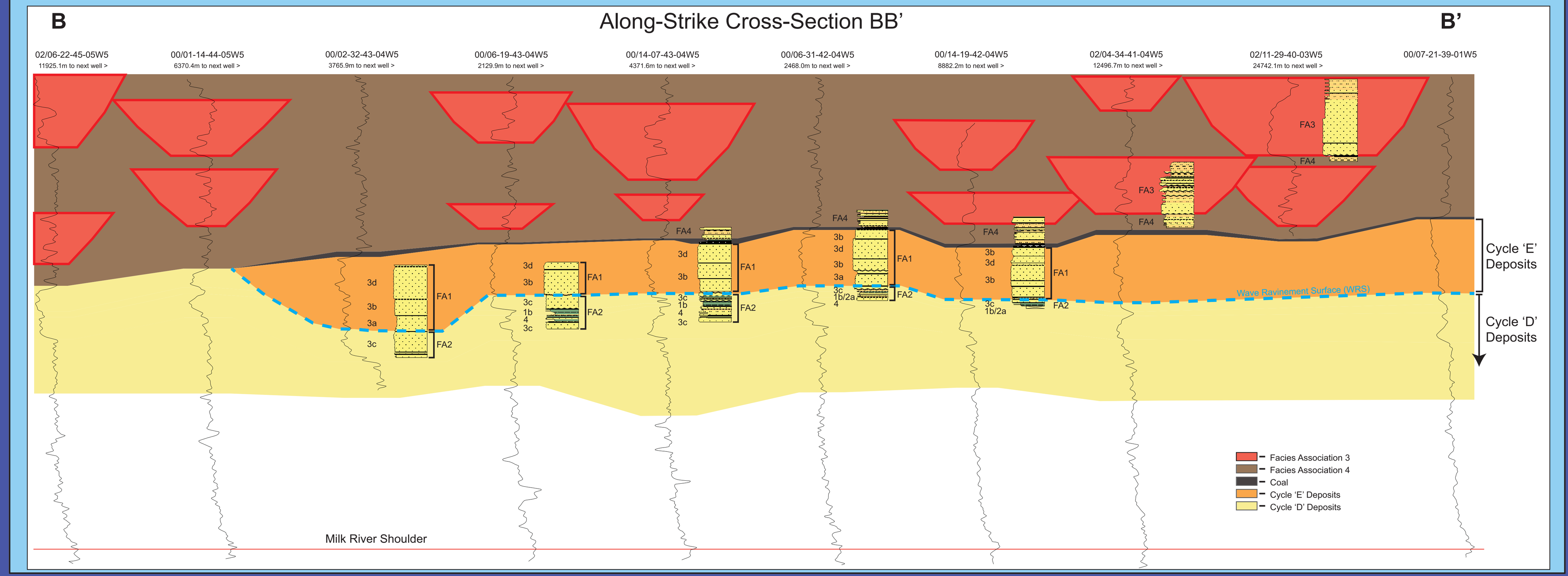




Net sand isopach maps of Cycle D and Cycle E deposits, respectively. Locations of two strike-oriented cross-sections (F-F' and B-B') are also shown. Dots indicate data points.

Cross-Sections





Conclusions

(1) Integration of the preserved physical sedimentary structures with ichnology reveals 12 discrete facies.

(2) The facies are grouped into 4 distinct facies associations: FA1 (storm-dominated, mixed river- and wave-influenced delta deposits); FA2 (river-dominated, storm-influenced delta deposits); FA3 (fluvio-estuarine distributary channel deposits); and FA4 (delta plain/coastal plain deposits).

(3) Well-log correlations completed within the study area indicate that FA1 successions are predominantly linked to Cycle E deposits, whereas FA2 successions are more prevalent in Cycle D deposits.

(4) FA1 successions are dominated by an abundance of wave- and storm-generated physical sedimentary structures, with subordinate amounts of river-generated features. Bioturbation is sporadically distributed and characterized by low to moderate intensities (BI 0-4), with low to moderate diversities. Overall, the ichnological suite is interpreted to represent a stressed, distal to proximal expression of the *Cruziana* Ichnofacies.

(5) FA2 successions are characterized by an abundance of river-generated features. Lesser amounts of wave- and storm-generated physical sedimentary structures are also locally present. Bioturbation is sporadically distributed, with intensities ranging from absent to uncommon (BI 0-2). Trace fossil suites display low diversities with abundant facies-crossing elements, and are attributable to a stressed, distal to proximal expression of the *Cruziana* Ichnofacies (cf. MacEachern and Bann, 2008).

(6) Isopach mapping of Cycles D and E shows two unique and characteristic sand-body morphologies. Cycle D geometries reflect a river-dominated deltaic system, whereas Cycle E geometries reflect a more wave-influenced deltaic system. This corresponds with facies distribution data.

(7) Continued research will focus on further delineating the along-strike variations in facies distributions within Cycles D and E, in order to construct a paleogeographically accurate depositional model for the area.

Acknowledgements

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