Integrated Ichnologic-Sedimentologic approach to reconstruct marginal to shallow marine paleoenvironments: The Lower Cretaceous Wabiskaw Member, Clearwater Formation, Alberta-Canada, Lower Permian Dandot Formation, and the Early Cambrian Khussak Formation, east-central Salt Range, Pakistan

by

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ABSTRACT

The interplay of independent variables (wave, river, and tidal input) in marginal and shallow-marine environments complicates identifying facies and interpreting paleoenvironments in the rock record. Therefore, predicting, correlating facies, determining facies thickness and distribution, and assessing the quality of shallow marine clastic reservoir facies remains challenging. This study integrates sedimentology and ichnology to characterize the depositional environments of the Lower Cretaceous Wabiskaw Member of the Clearwater Formation in north-east Alberta, Canada, the Lower Permian Dandot Formation of east-central Salt Range, Pakistan, and the Early Cambrian Khussak Formation of east-central Salt Range, Pakistan. The Wabiskaw Member (deltaic, strand plain shoreface-offshore deposits), the Dandot Formation (tide-dominated estuarine and deltaic deposits), and the Khussak Formation (tidal flat deposits) provide excellent case studies to evaluate the ichnological and sedimentological characteristics associated with laterally and vertically variable stresses in wave-tide, and river influenced nearshore settings.

Ten sedimentary facies describe the Wabiskaw Member. The recurring facies are grouped into four facies associations representing both proximal and distal marginal marine environments, including 1) fluvial-influenced prodelta, 2) wave-storm influenced delta front to a mouth bar, 3) storm-influenced offshore, and 4) distal lower to middle shoreface. Characteristic sedimentological and ichnological signatures differentiate Wabiskaw Member deltaic (prodelta-delta front) deposits from related strand plains. The deltaic deposits exhibit soft-sediment deformation structures, fluid mud, syneresis cracks, and low-diversity and diminutive trace-fossil suites under comparable stress conditions. In contrast, fully marine strand plain shoreface-offshore complexes display comparatively robust trace fossils with high ichno-diversity and

bioturbation intensities. To evaluate the reservoir quality of various reservoir facies (F-3, F-4, F-7, F-8) of the Wabiskaw Member, their reservoir characteristics (porosity, permeability, pore throat radii, flow-storage capacity, oil saturation, and thickness) are compared. Among the studied reservoir facies, F-4 has the highest quality and is the most productive (pore throat radius >20 μm, 18% flow, and 4% storage capacity). Whereas F-3, with micro-porous characteristics (pore-throat radii ranging from 2 to 4 μm), has the lowest quality among the Wabiskaw Member reservoir facies, with 37% storage and ≤5% capacity flow.

The Dandot Formation in northwest Pakistan is a 35-40 m thick succession of tide-dominated estuarine and deltaic deposits, which have been characterized using sedimentologic and ichnologic datasets. Thirteen sedimentary facies describe the lower Permian Dandot Formation (Salt range, north-west Pakistan). The recurring facies are grouped into eight facies associations representing both fluvial and marginal marine environments, including 1) Fluvial channel deposits, 2) Paleosol deposits, 3) Intertidal mud-flat to mixed-flat deposits, 4) Estuarine tidal bars, 5) Prodelta deposits, 6) Delta front deposits, 7) Proximal delta front-mouth bar, and 8) Tidally influenced channel deposits. The estuarine deposits show a fining-upward trend, are cleaner, and have better sorting than deltaic deposits, which form a coarsening-upward sequence. Additionally, trace fossils in deltaic deposits are more diverse and heterogeneously distributed than those in estuarine deposits, serving as a valuable criterion for distinguishing between the two settings.

The Early Cambrian Khussak Formation of the east-central Salt Range, Pakistan, is studied to identify its ichnological and sedimentological characteristics. This integrated study resulted in identifying thirteen lithofacies and six recurring facies associations, including 1) Upper intertidal mud flat deposits, 2) Middle intertidal mixed flat deposits, 3) Lower intertidal sand flat deposits, 4) Inter-tidal creek point bar deposits, 5) Subtidal bar deposits and 6) Subtidal bay deposits. The Khussak Formation's tidal flat deposits exhibit a distinct trend in ichnofacies. The Cruziana Ichnofacies characterize the lower energy proximal deposits. In contrast, the Skolithos Ichnofacies represent high-energy distal deposits. The mud flat, mixed flat, sand flat, and sub-tidal deposits of the Khussak strata exhibit subtle and gradual ichnologic variation but are distinct enough to indicate facies.

The work on the Wabiskaw Member in northeast Alberta (Township 95-98, Range 10-14), and the Lower Permian (Dandot Formation) and Lower Cambrian (Khussak Formation) strata of east-central Salt Range, Pakistan, is one of the first integrated sedimentologic-ichnologic studies of these units. Establishing a geological model for these units allows us to better understand the depositional process at the time of their formation. In addition, this study effectively addresses the gaps in our geological knowledge of the areas and contributes to the prediction and correlation of facies with greater confidence.

PREFACE

This thesis represents the original work of Waqar Ahmad.

Chapter 2 of this thesis is published as: Ahmad, W., and Gingras, M. K. (2022). Ichnology and Sedimentology of the Lower Cretaceous Wabiskaw Member (Clearwater Formation) Alberta, Canada. *Marine and Petroleum Geology*, *143*, 105775. I performed data collection, and wrote the manuscript; and Gingras, M.K. provided the majority of support, edits and expert input.

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Chapters 1 (Introduction) and 6 (Conclusions) are my own work.

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My parents, Mom and Dad, have been my life's everlasting inspiration. Their humility and unwavering work ethic, evident in their daily lives, have been my constant motivation. I envision them diligently continuing their daily routines, a poignant reminder that my achievements are rooted in their honest and hardworking values.

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CHAPTER 1: INTRODUCTION

INTEGRATED ICHNOLOGIC-SEDIMENTOLOGIC APPROACH TO RECONSTRUCT MARGINAL TO SHALLOW MARINE PALEOENVIRONMENTS: AN OVERVIEW

Marginal and shallow marine environments are often subject to the influence of multiple independent variables, such as waves, rivers, and tides, which can interact with one another in complex and sometimes unpredictable ways (Bhattacharya and Giosan, 2003; Buatois and Mángano, 2011; Bhattacharya et al., 2020; Dashtgard et al., 2021). The interplay of these variables can significantly impact the depositional processes in these environments (Boyd, 2010; Plint, 2010). Furthermore, the interaction of these processes can lead to a wide range of sedimentary features and landforms, such as beaches, dunes, deltas, and estuaries (Boyd, 2010; Plint, 2010). Therefore, it is important to understand the complex interplay of these processes to accurately predict and manage the sedimentary dynamics of a coastline in both modern and ancient settings. Benthic animals, which live on or near the bottom of a body of water, can be very sensitive to the sedimentary processes in their environment (Frey et al., 1990; McIlroy, 2004; MacEachern et al., 2005; Gingras et al., 2007; Dafoe et al., 2010; Buatois and Mángano, 2011; Gingras et al., 2011). As a result, the traces or tracks they leave behind (ichnofossils) can provide valuable information about the sedimentary processes that took place when the traces were formed. These trace fossils can provide information on the behavior and activities of ancient organisms, such as how they moved, what they ate, and how they interacted with their environment (Pemberton et al., 1982; Pemberton and Frey, 1984; Pearson and Gingras, 2006; MacEachern et al., 2010; Buatois and Mángano, 2011; Gingras et al., 2012; Pemberton et al., 2012). Geologists commonly use ichnology to establish sedimentological insight into the depositional setting of a particular rock or sedimentary deposit (Seilacher, 1978; Howard and Frey, 1984; Ranger and Pemberton, 1991; Pemberton and Wightman, 1992; Taylor and Goldring, 1993; Pemberton et al., 1997; Gingras et al., 1999; Zonneveld et al., 2001; Taylor et al., 2003; Pearson and Gingras, 2006; MacEachern et al., 2007b; Seilacher, 2007; McIlroy, 2008; Buatois and Mángano, 2011; Dashtgard et al., 2014; Solórzano et al., 2017; Polo et al., 2018; Rodríguez et al., 2018; Shchepetkina et al., 2020). Physical sedimentology and ichnology are two important tools that geologists use to understand ancient depositional environments. Physical sedimentology involves studying the characteristics of the sediment itself, such as its lithology (the type of rock or mineral), grain size, and bedding (Reineck et al., 1973; Collinson, 2019). Ichnology can be particularly valuable in this process because it provides information about the behavior and activities of ancient organisms, which can reveal clues about the physical and chemical conditions present during the deposition (Pemberton et al., 1982; Frey et al., 1990; Gingras et al., 1999; Buatois et al., 2005; Gingras et al., 2007; MacEachern et al., 2007a; Carmona et al., 2009; Hauck et al., 2009). By examining the ichnofossils suite, bioturbation intensity, and trace fossil diversity, geologists can get a sense of the types of physical and chemical stresses that were present during deposition, which can help them to reconstruct the ancient environment more accurately.

Overall, integrating ichnology with physical sedimentology can be a powerful tool for understanding ancient sedimentary environments and the processes that shaped them.

This PhD project is based on three case studies: 1) The Lower Cretaceous Wabiskaw Member of Clearwater Formation, 2) The Lower Permian Dandot Formation of east-central Salt Range, Pakistan, and 3) The Early Cambrian Khussak Formation of east-central Salt Range, Pakistan. Previous studies addressing the depositional environment of these units are scarce, and a comprehensive geological model has yet to be put forward. This research combines sedimentology and ichnology to delineate the depositional environments of these units within the study area.

LOWER CRETACEOUS WABISKAW MEMBER (CLEARWATER FORMATION) ALBERTA, CANADA

The Wabiskaw Member of the Clearwater Formation plays a crucial role as a reservoir unit in western Canada. However, researchers have primarily emphasized stratigraphic characterization instead of sedimentological analysis, despite having access to thousands of Wabiskaw Member cores (Hein et al., 2006; Hein and Cotterill, 2006; Shields and Strobl, 2010; Hein, 2015). The Wabiskaw in general is comparatively well understood. It is the Wabiskaw D unit that is not. To address this gap in sedimentological understanding, this study combines detailed sedimentology and ichnology to investigate the Wabiskaw Member strata for refining its depositional setting.

Geological setting

The Western Canada Sedimentary Basin (WCSB) is a large sedimentary basin that covers a significant portion of Western Canada and is known for its abundant conventional and unconventional petroleum resources. The Wabiskaw Member is located in the WCSB in northeast Alberta. The western margin of the North American plate experienced successive collisions with allochthonous terranes, which induced tectonic loading and lithospheric flexure. As a result, the Alberta foreland basin formed in the interior region (Jordan, 1981; Stockmal and Beaumont, 1987; Johnson et al., 1995).

As a result of subsidence and lithosphere flexure in the foreland basin, three main paleo-valleys formed, including the Assiniboia Valley, Edmonton Valley, and Spirit River Valley (Ranger and Pemberton, 1997). In central and northeast Alberta, the Assiniboia Valley, also known as the McMurray Valley System, was the farthest east Lower Cretaceous drainage system to develop, extending to the east beyond the Wainwright Ridge (Ranger and Pemberton, 1997). While the Canadian Shield serves as the northeastern boundary for this drainage system, extensive erosion during the Pleistocene and Holocene has resulted in the loss of a significant portion of its stratigraphic record (Ranger and Pemberton, 1997). This valley system contains the Athabasca Oil Sands deposits (Ranger and Pemberton, 1997). The Athabasca Oil Sands Deposit holds the world's largest natural bitumen resource, with an estimated 1.7 trillion barrels of in-place oil (Energy Resources Conservation Board, 2013). The Aptian-Albian McMurray Formation and Wabiskaw Member (Clearwater Formation) contain the bitumen of the Athabasca Oil Sands Deposit (Figure 1.1A). The McMurray Formation underlies the Wabiskaw Member, while shales of the the Clearwater Formation overlies it (Figure 1.1C). The lateral and vertical complexity of lithologies makes correlation through lithostratigraphy significantly trick where the basal Wabiskaw D is present. Consequently, earlier researchers have proposed multiple depositional settings for the Wabiskaw Member strata (Bayliss and Levinson, 1976; Evans and Outtrim, 1977; Jackson and Masters, 1984; Ranger et al., 1988).

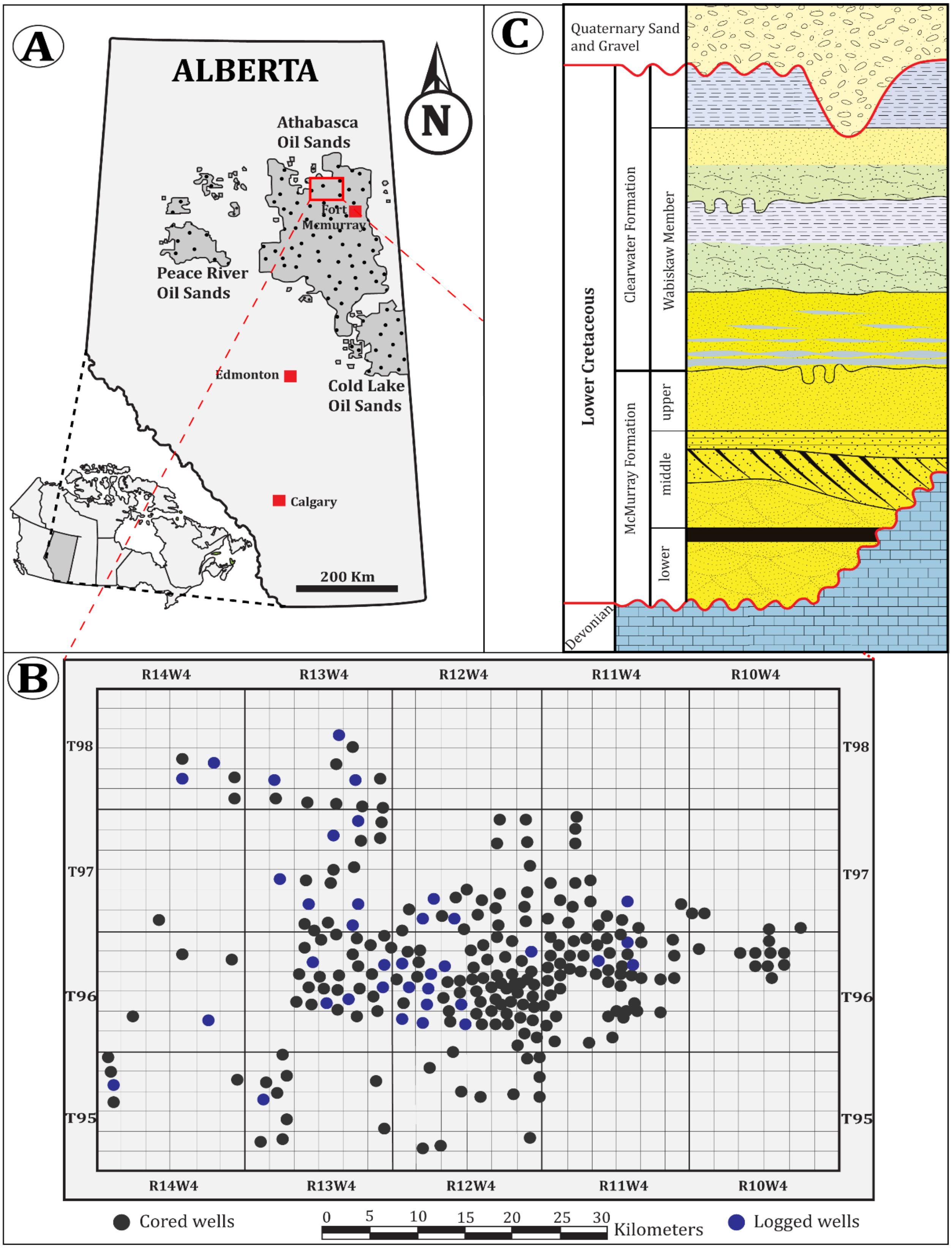

Figure 1. 1 A-B) Map showing the location of oil sands deposits in Alberta and wells that were logged. C) Stratigraphic column of the study area (Hayes et al., 2017).

LOWER PERMIAN DANDOT FORMATION, NORTH PAKISTAN.

Differentiating the deposits of tide-dominated estuaries from tide-dominated deltas can be challenging. Although physical sedimentary structures and associated facies may help establish tidal influence, it can be challenging to determine if these facies formed in an estuary, delta, or open-marine environment because these facies can occur in multiple depositional environments. This study systematically documents facies and facies associations for the deltaic and estuarine systems in the Dandot Formation (Lower Permian), north Pakistan. The Dandot strata show distinct tidal estuarine and tidal deltaic characteristics. However, a detailed geological model for Dandot Formation in the study area has not yet been developed.

Geological setting

The Salt Range in the sub-Himalayan region of Pakistan showcases exceptional Lower Permian Nilawahan Group exposures, explicitly the Dandot Formation (Figure 1.2). The study area covers the eastern and central parts of the Salt Range in the active Himalayan foreland, which formed due to the collision between the Indian and Eurasian Plates in the Tertiary age, resulting in the continuously evolving Himalayan fold and thrust belt (Searle and Tirrul, 1991; DiPietro and Pogue, 2004). The Main Boundary Thrust (MBT) bounds the sub-Himalayan region's north, while the Salt Range Thrust (SRT) limits its south. The Salt Range Thrust causes the Precambrian to Pliocene strata to thrust over the Quaternary strata of the Punjab plains (Ghani et al., 2018). Sedimentary deposits in the Salt Range span from Precambrian to Pliocene and display four major unconformities (Figure 1.2) (Gee and Gee, 1989).

The Gondwana realm's deposition is represented by the Nilawahan Group and shows a disconformable lower contact with either Cambrian or Precambrian strata (Gee and Gee, 1989; Wardlaw and Pogue, 1995). The Permian Amb Formation or Paleocene units overlie the Nilawahan Group with an unconformable contact (Gee and Gee, 1989; Wardlaw and Pogue, 1995). The Dandot Formation of the Nilawahan Group comprises interbedded sandstone and mudstone, carbonaceous, fine-grained sandstone. Previous studies have suggested different depositional settings for the Dandot Formation, ranging from shallow marine to marginal marine, shoreface, inner shelf, tidal flat, and estuarine (Ghazi et al., 2012; Jan et al., 2016).

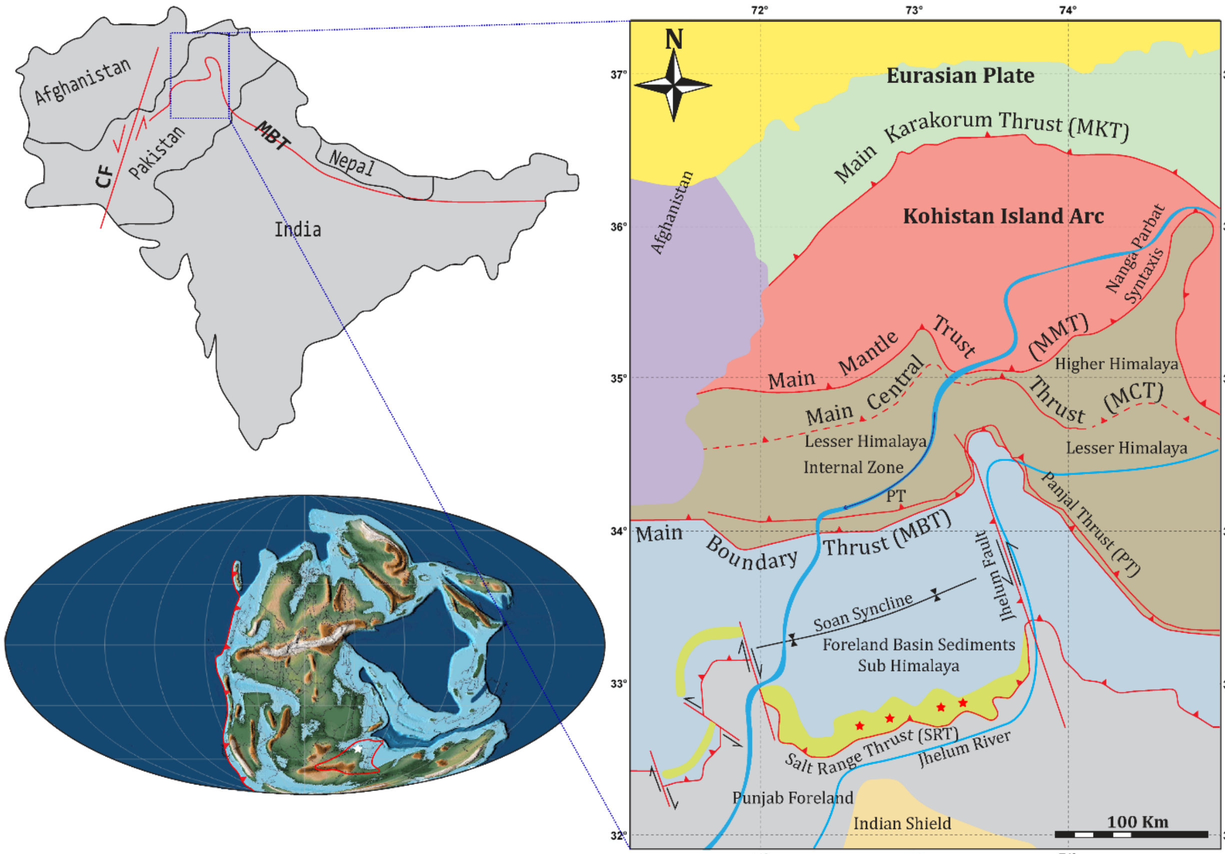

Figure 1. 2 Map of NW Himalayas in North Pakistan. The Lower Permian Dandot Formation is exposed in the salt range in the sub-Himalayas, Pakistan denoted by red stars. The paleogeographic map showing the location of the study area in the Paleozoic (white star).

EARLY CAMBRIAN KHUSSAK FORMATION, EAST-CENTRAL SALT RANGE, NORTH-WEST SUB-HIMALAYAS, PAKISTAN.

The Lower Cambrian Khussak Formation is a significant conventional petroleum reservoir in the Potwar Basin and has produced oil and gas (Misa Kiswal Field) (Khan et al., 1986; Wandrey et al., 2004a, b) (Petroconsultants, 1996). So far, the Khussak Formation has had limited production. Limited production from the Khussak Formation is due to uncertain reservoir distributions, thicknesses, and quality. Despite the Khussak Formation being a significant petroleum reservoir, few previous facies analyses have addressed its depositional environment, and no one has yet put forward a comprehensive geological model. The main goal of this study is to analyze the sedimentology and trace fossil assemblages of the Khussak Formation in the eastern and central Salt Range. This analysis will provide insights into the depositional process, facies distribution, and Early Cambrian depositional system.

Geological Setting

Located in the sub-Himalayas (Figure 1.2), the Salt Range in Pakistan exposes Cambrian Jhelum Group rocks. The study focuses on the Lower Cambrian Khussak Formation (consisting of bioturbated mudstone, sandstone, and dolomitic and glauconitic sandstone) of the Jhelum Group. The Jhelum Group comprises four litho-stratigraphic units: Khewra sandstone, Khussak Formation, Jutana Formation, and Bhaganwalla Formation (Figure 1.3) (Wynne, 1878; Middlemiss, 1891; Gee, 1934; Fatmi, 1973; Shah, 1977; Gee and Gee, 1989). The thickness of this Group varies laterally due to regional erosion along the sub-Permian unconformity, with a thickness of approximately 300 meters in the eastern salt range (Shah, 1977). The Khewra sandstone is the lowermost unit that disconformably overlies the Pre-Cambrian Salt Range Formation (Shah, 1977). Furthermore, it consists of maroon, brick red, massive to laminated mudstone in the lower part, interbedded fine to medium-grained maroon sandstone and mudstone in the middle part, and massive to cross-bedded, medium to coarse-grained sandstone with minor granule conglomerate in the upper part (personal observations). Physical bed forms include planar laminae, tabular and trough cross-stratification, and soft sediment deformation structures. Existing literature and personal observations suggest that the deposition occurred in a fluvio-deltaic setting (Khan et al., 2022). The Khussak Formation (lower Cambrian) overlies the Khewra Sandstone (Fatmi, 1973; Shah, 1980; Kadri, 1995; Bhargava, 2011). Evidence indicates that the contact between Khewra sandstone and Khussak Formation is disconformable, as suggested by a basal conglomerate lag and truncated strata. This shows that the surface represents a sequence boundary (Hughes et al., 2019). According to Hughes et al. (2019), the Khussak Formation of the Jhelum group consists of bioturbated mudstone and sandstone, as well as dolomitic and glauconitic sandstone, and was deposited in a shallow marine environment during the Lower Cambrian. The third unit overlying the Khussak Formation is the Jutana Formation, which comprises massive to bedded dolomite, sandy dolomite, dolo-mudstone, dolo-grainstone, and bioturbated mudstone (Sajid et al., 2015; Hughes et al., 2019). Deposition in shallow marine settings is indicated by the physical attributes, body fossils, and trace fossils (Schindewolf and Seilacher, 1955; Seilacher, 1955; Seilacher and Schindewolf, 1955; Teichert, 1964; Hughes et al., 2019). Resting on the Jutana Formation, the Bhaganwalla Formation is composed of red to gray shale and very thin to medium-limestone beds. The Formation also contains halite pseudomorphs, which suggest the occurrence of episodic hypersaline conditions (Hughes et al., 2019).

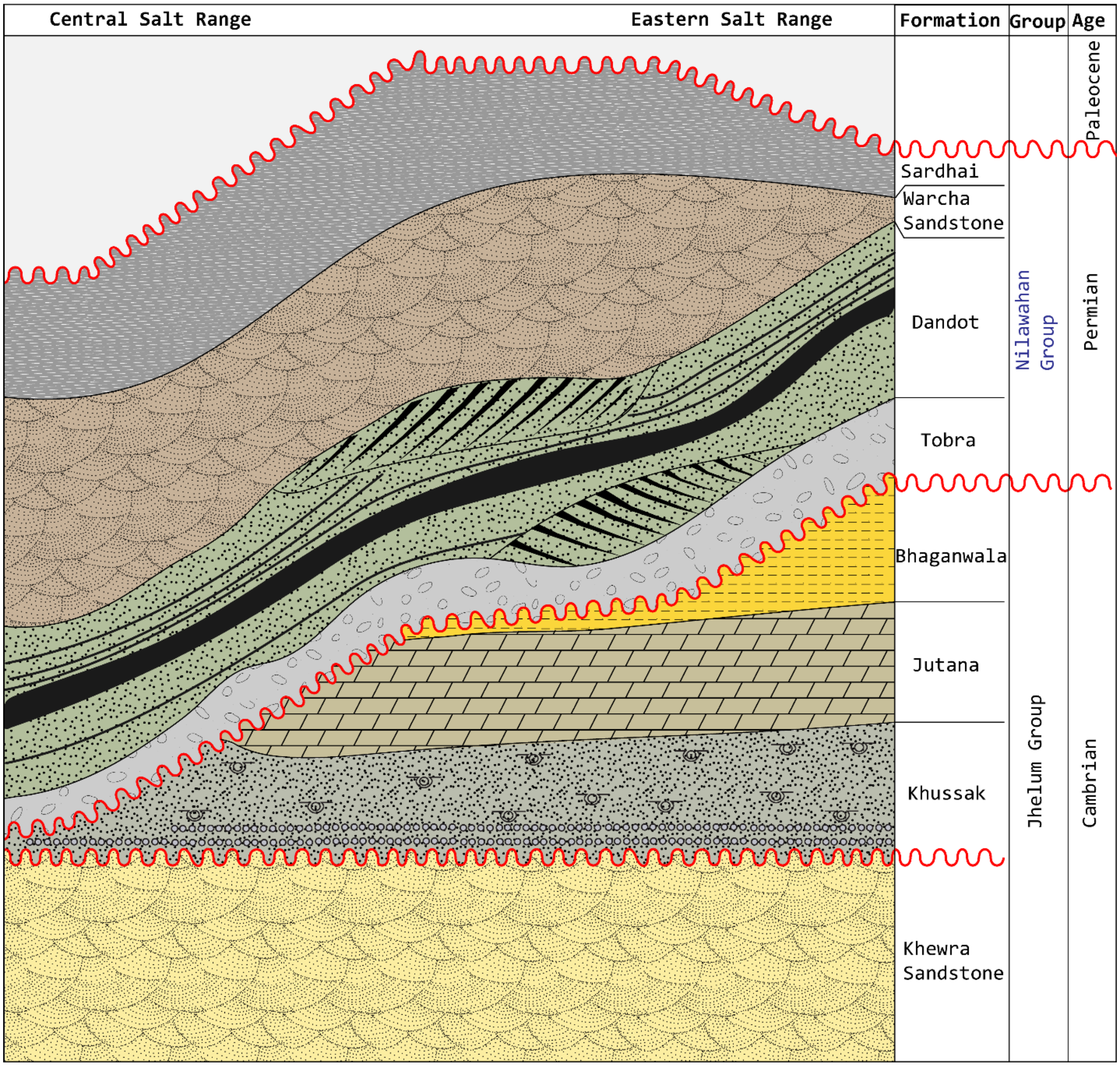

Figure 1. 3 Stratigraphic column of the eastern and central Salt Range.

ORGANIZATION AND AIM OF THIS STUDY

This Ph.D thesis is focused on the detailed sedimentological and ichnological characterization of 1) The Lower Cretaceous Wabiskaw Member of Clearwater Formation, 2) The Lower Permian Dandot Formation of east-central Salt Range, Pakistan, and 3) The Early Cambrian Khussak Formation of east-central Salt Range, Pakistan. The objectives of this thesis are to address the depositional environments of these units and propose comprehensive geological models using integrated (sedimentology and ichnology) approach. A key challenge with these litho-stratigraphic units is the absence of integrated geological studies, which has hindered the refinement of facies and facies associations and prevented the establishment of a proper depositional framework in the study areas. The work on Wabiskaw Member in northeast Alberta (Township 95-98, Range 10-14), and the Lower Permian (Dandot Formation) and Lower Cambrian (Khussak Formation) strata of east-central Salt Range, Pakistan, is one of the first integrated sedimentologic-ichnologic studies of these units. Establishing a geological model for these units allows us to better understand the depositional process at the time of their formation. By integrating various geological data, this study successfully fills in the gaps in our understanding of the studied areas. It improves our ability to predict and correlate facies with greater accuracy.

This thesis has significance beyond just improving the knowledge of the study areas and prediction and correlation of facies. This integrated sedimentologic-ichnologic work will further improve our ability to identify facies linked to different hydrodynamic conditions and environmental stresses such as storm influence, tidal influence, changes in salinity and oxygen levels, and substrate consistency in shallow and marginal marine environments.

This thesis is divided into six chapters, including an introduction and a conclusion. The thesis follows a paper format, intending to publish each chapter in peer-reviewed journals. Due to this format, significant portions of the thesis may be repeated across multiple chapters to provide the required context. Therefore, each chapter is briefly summarized below.

Chapter 2 is about the ichnology and sedimentology of the Lower Cretaceous Wabiskaw Member (Clearwater Formation) Alberta, Canada. It presents detailed sedimentological and ichnological descriptions for all facies identified in the study area and explores the depositional processes and environments that gave rise to these facies.

Chapter 3 effectively characterizes the reservoir units of the Wabiskaw Member strata in northeast Alberta using a holistic approach (combining sedimentology-ichnology with rock typing and flow units). The sedimentologic-ichnological data (obtained from detailed core logging) is integrated with core analysis data (porosity, permeability) to investigate facies, the depositional processes, and reservoir quality. This holistic approach resolved the gaps in the geological understanding of the area, resulting in improved reservoir prediction and correlation.

Chapter 4 utilizes an integrated sedimentological-ichnological approach to establish a geological model for the Lower Permian Dandot Formation, North Pakistan. The integrated sedimentological-ichnological analysis of the Dandot Formation allowed the identification of a tide-dominated estuarine system (comprised of an estuarine tidal bar, intertidal mud to mixed flat, and supratidal deposits) and a tide-influenced deltaic succession (consisting of a prodelta, delta front, distributary mouth bar, and channels).

Chapter 5 deals with the ichnology and sedimentology of the Early Cambrian Khussak Formation, east-central Salt Range, North-west Sub-Himalayas, Pakistan. The primary objective of this chapter is to analyze the sedimentology (physical characteristics) and trace fossil assemblages in detail within the Khussak Formation of the Salt Range to better understand the depositional processes, facies distribution, and the Early Cambrian depositional system as a whole.

Chapter 6 provides a concise summary of the significant findings of this thesis in relation to the project objectives.

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CHAPTER 2: ICHNOLOGY AND SEDIMENTOLOGY OF THE LOWER CRETACEOUS WABISKAW MEMBER (CLEARWATER FORMATION) ALBERTA, CANADA

ABSTRACT

Identifying facies and paleoenvironmental interpretation of the rock record is complicated due to the interplay of independent variables (i.e. wave-, river- and tidal-input) in marginal- and shallow-marine environments. This study integrates sedimentology and ichnology to characterize the depositional environments of the Lower Cretaceous Wabiskaw Member. The deltaic and strand plain shoreface-offshore deposits of Wabiskaw Member of Clearwater Formation of northeast Alberta provide an excellent case study to evaluate the ichnological and sedimentological characteristics associated with laterally and vertically variable stresses in wave-influenced nearshore settings. The Wabiskaw Member is studied using four sedimentary facies associations (Ten sedimentary facies). Facies association 1(FA-1) consists of massive, sharp-based mudstones and lenticular sandstone with small-scale soft-sediment deformation features, syneresis cracks and small-scale oscillation ripples. The ichnological suite mainly includes small grazing and deposit-feeding traces, representing the *Phycosiphon* Ichnofacies. Facies association 1(FA-1) is interpreted to record deposition in a prodeltaic setting. Facies association 2 (FA-2) is fine-to-medium-grained sandstone and thin mudstone with current, oscillation and combined flow ripples. The low angle and trough cross-beds, soft-sediment deformation structure, mud chips and coal debris are common. The trace fossil suite includes sporadically distributed deposit-feeding traces belonging to the *Rosselia* Ichnofacies. This facies association is interpreted to be deposited in the delta front to a mouth bar setting. Facies association 3 (FA-3) is gray to bluish-gray mudstone with minor sandstone interbeds (massive, planar parallel to hummocky cross-stratified). FA-3 is moderate to highly bioturbated. The ichnodiversity and abundance is high with dominant horizontal and subordinate vertical traces, including the dominance of deposit and detritus feeding traces representing the archetypal *Cruziana* Ichnofacies ichnological suite. Facies association 3 (FA-3) is interpreted as being deposited in a storm-influenced offshore environment. Facies association 4 (FA-4) is upper fine to fine-grained glauconitic sandstone with minor mudstone interbeds at the base. Physical sedimentary structures including massive and planar (horizontal and low angle), hummocky, and swaley crossing-stratification. FA-4 is heavily burrowed with a diverse suite of horizontal and vertical traces of

deposit and detritus-feeding structures, representing a proximal expression of *Cruziana* Ichnofacies. Facies association 4 (FA-4) represents distal lower to mid shoreface deposition. The Wabiskaw Member deltaic (prodelta-delta front) deposits, producing characteristic sedimentological-ichnological signatures, distinguishing these deposits from related strand plains. In addition to characteristic deltaic traits (e.g. soft-sediment deformation structures, fluid mud and syneresis cracks), these deposits commonly contain comparably stressed low-diversity and diminutive trace-fossil suites. On the other hand, fully marine strand plain shoreface-offshore complexes are characterized by comparably robust trace fossils with high ichno-diversity and bioturbation intensities.

INTRODUCTION

The interplay of independent variables (wave, river and tides) in marginal and shallow marine environments is exceedingly complicated. It is not uncommon for this spectrum of processes to coexist and impact the sedimentary dynamics of the same coastline simultaneously (Bhattacharya and Giosan, 2003; Buatois and Mángano, 2011; Bhattacharya et al., 2020; Dashtgard et al., 2021). Benthic (i.e. trace-making) animals respond to sedimentary processes such as shifting sediment, current velocity, turbidity and sedimentation rate that are imposed by the characteristic wave-, fluvial- and tidal-energy in a sedimentary environment and, thus, ichnology is commonly used to establish sedimentological insight into the depositional setting (Gingras et al., 1998; Gingras et al., 2002; Buatois et al., 2005; MacEachern et al., 2005; Gingras et al., 2007; MacEachern et al., 2008; Bhattacharya and MacEachern, 2009; Gingras et al., 2011; Gingras and MacEachern, 2012; Pemberton et al., 2012; Solórzano et al., 2017; Rodríguez et al., 2018; Buatois et al., 2019; Shchepetkina et al., 2020; Zheng et al., 2021). The integrated ichnologic-sedimentologic approach has proven to be a valuable tool in the identification of facies and refined paleoenvironmental interpretation (Howard and Frey, 1984; Frey and Pemberton, 1985; Frey and Pemberton, 1987; Savrda and Bottjer, 1989; Frey et al., 1990; MacEachern et al., 1994; Buatois and Mángano, 1995; Bromley and Uchman, 2003; Bann et al., 2004; McIlroy, 2004; Coates et al., 2007; Hansen et al., 2007; Bann et al., 2008; MacEachern et al., 2008; Carmona et al., 2009; MacEachern et al., 2010; Gingras et al., 2011, 2012; Knaust and Bromley, 2012; Botterill et al., 2016; Dasgupta et al., 2016). Trace-making organism's activities are influenced by several syn-depositional physico-chemical stresses (salinity, oxygenation, turbidity, substrate, sedimentation rate, and temperature) within sedimentary environments (Seilacher, 1967; Seilacher and Basan, 1978; Frey and Pemberton, 1985; Frey and Pemberton, 1987; Frey et al., 1990; Buatois and Mángano, 1995; Taylor et al., 2003; Seilacher, 2007; McIlroy, 2008; MacEachern et al., 2010; Gingras et al., 2011; Gingras and MacEachern, 2012; Gingras et al., 2012; Ainsworth et al., 2017; Collins et al., 2020). Thus, integrating ichnology with physical sedimentology can bolster the interpretations of depositional processes and the sedimentary environment. The Wabiskaw Member is an important bitumen producer in northeast Alberta, Canada. A detailed sedimentological model for much of its large area has yet to be proposed. To address the lack of spatial sedimentological knowledge, this study combines sedimentology with ichnology to characterize the depositional environments of the Wabiskaw Member strata in the study area.

This study's first and foremost aim is to establish a sedimentological ichnological framework for an important reservoir unit in western Canada. In spite of the existence of thousands of Wabiskaw Member core, the Wabiskaw Member has been better characterized stratigraphically (Hein et al., 2006; Hein and Cotterill, 2006; Shields and Strobl, 2010; Hein, 2015) than it has sedimentologically. The reasons for the comparably sparse literature on the Wabiskaw Member are speculatively the abundance of petrophysical (well log) data and the general acceptance that the Wabiskaw Member is broadly speaking composed of shoreface and offshore deposits (Jackson and Masters, 1984; Hein and Cotterill, 2006).

The secondary aim of this paper is to use the ichnological data available in a reservoir area rich in core and wireline data to provide sedimentological and ichnological evidence for refinement of the sedimentary environments proposed and to understand ichnological distributions better. In this context, the paper’s greater purpose is to build on our understanding of shallow-marine trace fossils and how ichnofossils can be used to better interpret these settings.

Shallow marine successions show substantial sedimentological and ichnological variability due to differing physicochemical conditions (MacEachern and Pemberton, 1992a; Pemberton et al., 2012). Accordingly, integrated sedimentologic-ichnologic datasets improve our ability to recognize facies influenced by environmental stresses such as storm influence, salinity, oxygenation, and substrate consistency.

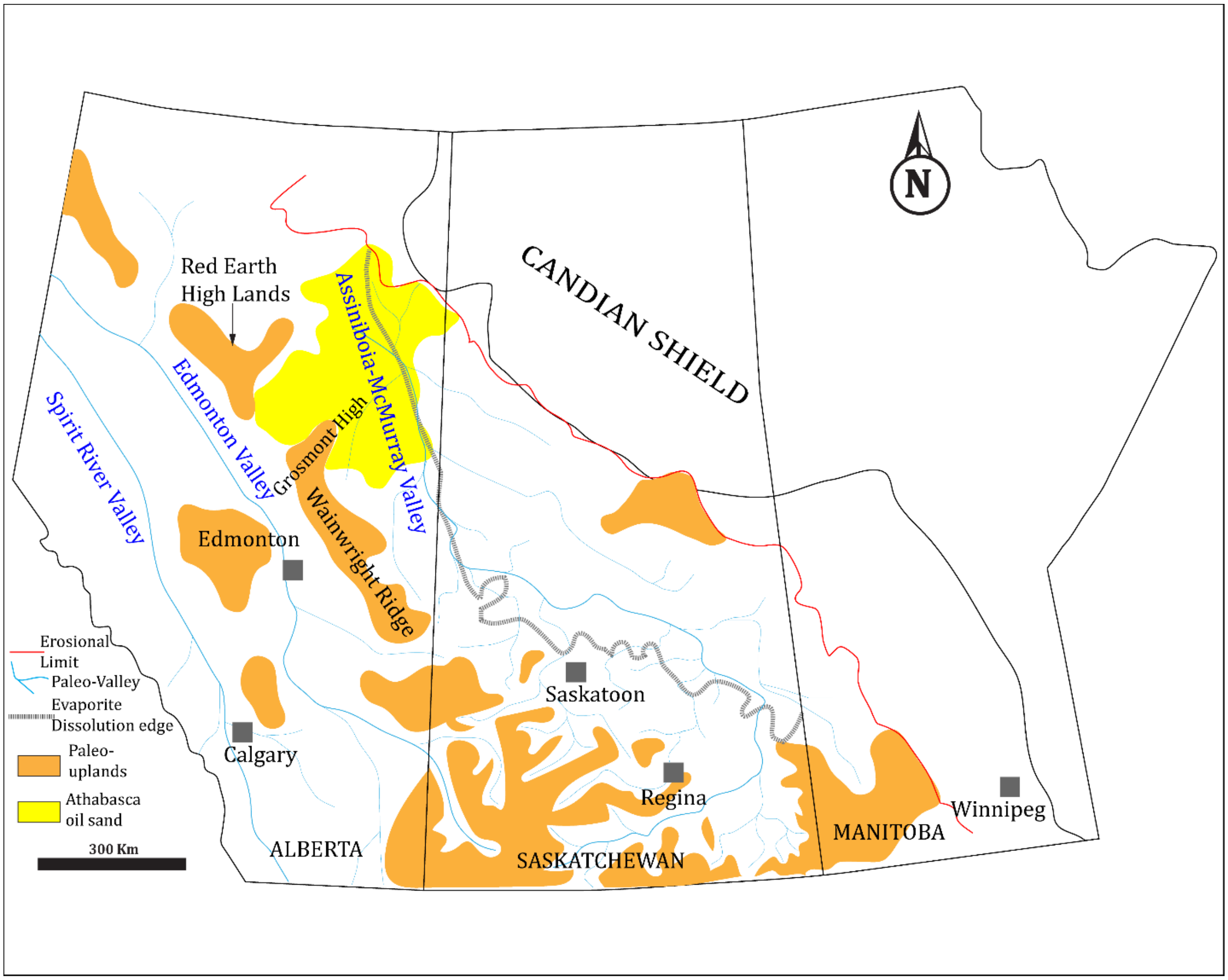


Figure 2. 1 Paleovalley systems (Assiniboia Valley, Edmonton Valley, and Spirit River Valley) formed due to the lithosphere flexure and subsidence in the foreland basin (Ranger and Pemberton, 1997).

REGIONAL GEOLOGICAL FRAMEWORK

The Lower Cretaceous Wabiskaw Member of Clearwater Formation of the Mannville Group is located in the Western Canada Sedimentary Basin (WCSB). The Alberta retro-arc foreland basin is part of the WCSB that developed in front of the Western Canadian Cordillera of North America during the Late Jurassic to Early Eocene time. Successive collision of allochthonous terranes with the pacific margin of the North American plate resulted in lithospheric flexure due to tectonic loading. This tectonic-induced lithospheric flexure led to the formation of the Alberta foreland basin in the plate interior (Jordan, 1981; Stockmal and Beaumont, 1987; Johnson et al., 1995).

Three main paleo-valleys (Assiniboia Valley, Edmonton Valley, and Spirit River Valley) formed due to the lithosphere flexure and subsidence in the foreland basin (Ranger and

Pemberton, 1997) (Figure 2.1). The Spirit River Valley system is the westernmost drainage that runs parallel to the axis of the developing foreland trough in western Alberta. The medial Edmonton Valley system originated in Alberta (southeast) and Saskatchewan (southwest) and flowed toward the north-northwest (Jackson and Masters, 1984; Ranger and Pemberton, 1997). The Assiniboia Valley (i.e. the McMurray Valley System in Alberta) is the easternmost Cretaceous drainage developed to the east of the Wainwright Ridge and Grosmont High in central and northeast Alberta (Ranger and Pemberton, 1997). The Canadian shield bounds this drainage valley system to the northeast; however, Pleistocene and Holocene erosion have removed much of that stratigraphic record (Christopher, 1997; Ranger and Pemberton, 1997) (Figure 2.1). The tectonic uplift in conjunction with sea-level fall led to the erosion of the Assiniboia / McMurray Valley system down into Upper Devonian carbonate strata in eastern Alberta (Wightman et al., 1997; Ranger, 2006). This erosion and dissolution of the Devonian carbonates resulted in the formation of the sub-Cretaceous unconformity (Hauck et al., 2017). Erosion and dissolution of the Devonian carbonates also resulted in additional subsidence in the McMurray Valley system before and during deposition of the McMurray Formation and Wabiskaw Member. The Athabasca Oil Sands deposits are confined within this Valley system (Ranger and Pemberton, 1997). The Wabiskaw Member of Clearwater Formation in the Athabasca Oil Sands area is the focus of this study.

Study Area

Athabasca Oil Sands Deposit, Canada (northeastern Alberta), has the largest natural bitumen resource in the world with in-place oil of 1.7 trillion barrels (Energy Resources Conservation Board, 2013). The bitumen of northeast Alberta is found in the Aptian-Albian McMurray Formation and Wabiskaw Member (Clearwater Formation) (Figure. 2A). This study applies the integrated sedimentologic-ichnologic approach to a core dataset from the Aptian-Albian Wabiskaw Member of the Clearwater Formation, Alberta (Figure 2.2B). The Wabiskaw Member is bounded between the underlying Mcmurray Formation and the overlying Clearwater Formation (Figure. 2C). The Wabiskaw Member is the lithostratigraphic equivalent of Glauconitic Member, Cummings Formation, and Bluesky Formation of the southern, eastern, and western (Peace River area) Alberta. The Wabiskaw Member strata was deposited during the overall transgression of the Boreal Sea. Lithostratigraphy-based correlation proves extremely difficult due to lithologies' lateral and vertical complexity. This lack of lateral and vertical correlation has led previous workers to identify various depositional environments for the Wabiskaw Member strata (Bayliss and Levinson, 1976; Evans and Outtrim, 1977; Jackson and Masters, 1984; Ranger et al., 1988). The Wabiskaw Member is informally subdivided into four distinct, overlapping sand units, the Wabiskaw 'A', 'B' 'C' and 'D' sands (named, from the top down) (Ranger et al., 1988). Together with McMurray Formation sand bodies, these sand units are the reservoir for Athabasca Oil Sands Deposit (AOSD).

METHODS AND DATABASE

Cores and wireline logs are the primary dataset for this study. The study area includes several unstudied cores penetrating the Wabiskaw Member (Figure 2.3. B). Forty cored wells were examined, and detailed cored logs were drafted in AppleCORE (GeoMEM advanced borehole log production application for windows and Mac). Core logging was carried out at the Alberta energy regulator (AER) core research Center in Calgary. Through the detailed analysis of these cores, particularly in documenting sedimentary structures, the distribution of trace fossils, and the various lithologies present, sedimentary environments were interpreted throughout the interval (Figure 2.3) (Figure 2.5). The ichnological analysis includes identifying the ichnological suite present, the size of trace fossils, and assessing the bioturbation index (BI) (Figure 2.3-4) (Figure 2.5). The degree of biogenic reworking is determined according to (Taylor and Goldring, 1993), who devised a bioturbation index (BI), ranging from 0 (no bioturbation) to 6 (complete bioturbation). Facies associations were identified based on the sedimentological-ichnological signatures of facies, allowing the interpretation of depositional system.

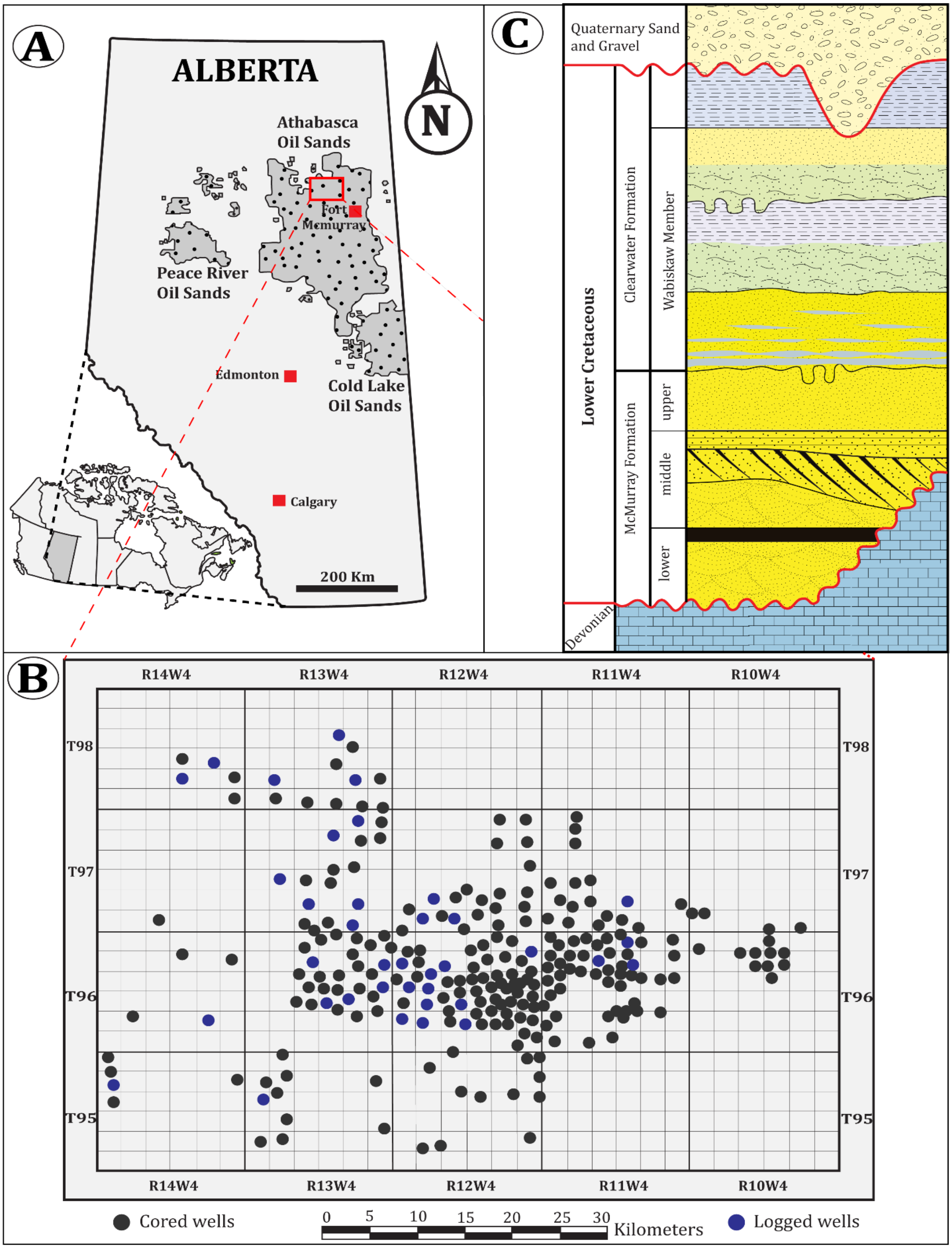


Figure 2. 2 Map showing the location of oil sands deposits in Alberta and wells that were logged. C) Stratigraphic column of the study area (Ahmad and Gingras, 2022).

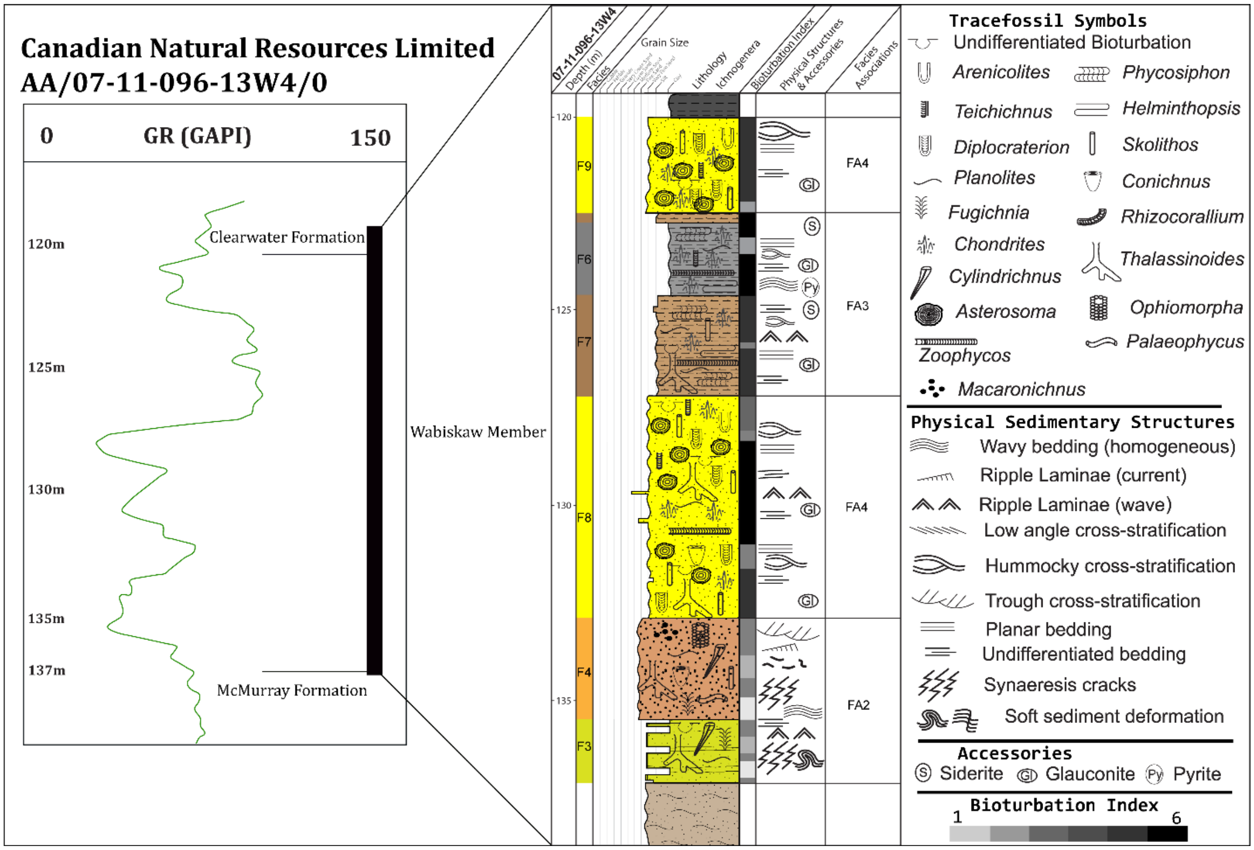


Figure 2. 3 Representative gamma-ray and strip log showing the recorded sedimentological and ichnological attributes, facies and facies associations.

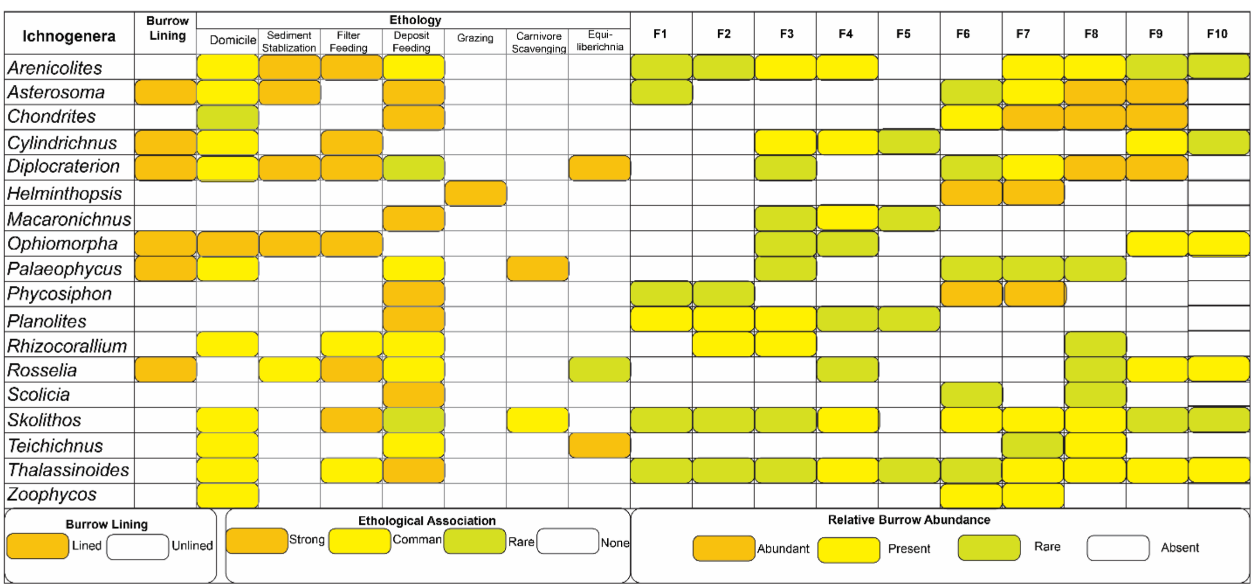
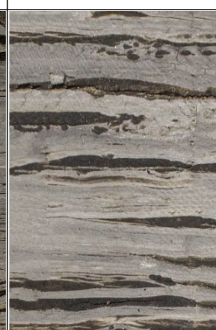
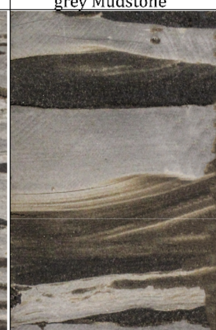


Figure 2. 4 Distribution, facies abundance and range of ethologies of ichnogenera identified in the core. Modified after (MacEachern et al., 2008; MacEachern et al., 2010).

RESULTS AND INTERPRETATION

Ten facies (F1-10) are identified based on their distinctive ichnological and sedimentological attributes. These facies can be grouped together into four facies associations, namely FA-1 (Prodelta), FA-II (Delta front), FA-III (offshore) and FA-IV (lower to middle shoreface). These facies are summarized in Figure 2.5 and Figure 2.6 and described in detail below.

Facies	F-1 Bioturbated Lenticular Mudstone	F-2 Interbedded Blush grey Mudstone and Thin Sandstone	F-3 Heterolith Fine-Grain Sandstone Interbeddedwith blush grey Mudstone	F-4 Fine to medium grained sandstone with thin mudstone	F-5 Planar, wavy laminated medium-grained sandstone
Typical Core Ecxpression					
Sedimentological Characteristics	• Laminated to massive mudstone with sand interbeds. • Wavy to planar parallel with oscillation and current ripples. • Synaeresis cracks. • Soft-sediment deformation	• Interbedded mudstone sandstone. • Planar to lowangle planar to wavy with some current ripples. • Synaeresis cracks • Soft-sediment deformation • Mudstone drapes.	• Hetrolitth sandstone and mudstone. • Planar parallel to low angle planar to wavy • Combined flow ripples • Load and flame structures • Synaeresis cracks	• Massive, wavy, planar parallel to low angle cross stratified. • Trough and hummocky cross- stratification. • Soft sediment deformation. • Thin mudstone laminae. • High bitumen saturation	• Planar, wavy, low-angle laminated, massive to trough cross-stratified sandstone. • Soft-sediment deformation, wood fragments, mudstone rip-up clasts • Oil saturation very high
Ichnological Characteristics	BI: (1-4). Bioturbation is weak to moderate. impoverished trace-fossil suite. Traces include: *Ar, As, Ch, Cy, Dp, Lo, Pl, Rh, Sk, Te* and*Th*	BI: (0-4). Bioturbation is sporadic. Diversity of trace fossils is low to moderate. Traces present, include:*Ar, As,Cy, fu, Pa,Pl, Si, Sk,* and *Th.*	BI: (0-3). Bioturbation is sporadic. Diversity is moderate. Trace fossil suite include: *Ar, As,Cy, Dp,fu,Pa,Pl, Ma, Si,Sk,Te,* and*Th.*	BI: (0-3). Bioturbation is very sporadic.Low abundance and low diversity trace fossil assemblage include :*Ar,Cy,Pl,Rh,Ma,Op,Co* and *fu*	BI: (0-2). Common traces include: *Cy, Dp,Pa, Pl,Ma,Th, Op, crp* and *fu.*
Lithological Accessories	Lithological accessories are rare and include siderite, glaucony, organic fragments, pyrite	Pebbles, mudstone rip-up clasts, shell debris, phytodetrital material, coal laminae, pyrite nodules	Lithological accessories include mud rip-up clasts carbonaceous material, granules and coal fragments.	Thin mud laminae, glauconite, coal and carbonaceous material, sideritized zones, scour surfaces and gutter cast.	Cabonaceous material wood fragments, coal fragments.
Environmental Stresses	Rapid deposition, periodic hyperpycnal flows, event bed deposition, salinity flucation.	Rapid deposition, periodic hyperpycnal flows, event bed deposition, periodic salinity flucation.	Shifting substrate,rapid deposition, hyperpycnal flows, event bed deposition, periodic salinity flucation, strom influence	Shifting substrate, high current energy, rapid deposition, flucating salinity, wave reworking, strom influence	Shifting substrate, high current energy, rapid deposition, flucating salinity, wave reworking, strom influence
Facies Association	**FA1**		**FA2**		
Environmental Interpretation	Distal Prodelta	Proximal Prodelta	Distal Delta Front	Proximal Delta Front	Proximal Delta Front-Mouth bar

Abbreviation Key

Trace Fossils

Ar-Arenicolites	*Cy-Cylindrichnus*	*He-Helminthopsis*	*Op-Ophiomorpha*	*Pl-Planolites*	*Sc-Scolicia*	*Te-Teichichnus*
As-Asterosoma	*Dp-Diplocraterion*	*Lo-Lockeia*	*Pa-Palaeophycus*	*Rh-Rhizocorallium*	*Si-Siphonichnus*	*Th-Thalassinoides*
Ch-Chondrites	*Fu-Fugichnia*	*Ma-Macaronichnus*	*Ph-Phycosiphon*	*Ro-Rosselia*	*Sk-Skolithos*	*Zo-Zoophycos*
Ne-Nereites	*Co-Conichnus*					

Bioturbation Index

0- Bioturbation Absent	*4-Common Bioturbation*
1-Saprse Bioturbation	*5-Abundant Bioturbation*
2-Uncommon Bioturbation	*6-Complete Bioturbation*
3-Moderate Bioturbation	

Figure 2. 5 Summary of the attributes of various recognized deltaic sedimentary facies.

Facies	F-6 Dark grey silty mudstone	F-7 Bioturbated Massive Sandyglauconitic Mudstone	F-8 Intensly Bioturbated Muddy GlauconiticSandstone	F-9 Bioturbated Silty-Muddy Glauconitic Sandstone	F-10 Massive to planar parallel well sorted sandstone
Typical Core Ecxpression					
Sedimentological Characteristics	• Dark grey to bluish grey mudstone with minor siltstone to fine grained sandstone interbeds. • Planar parallel, massive to lenticular bedded. Faint planar pinstripe, • wavy and discontinuous laminae.	• Light grey sandy glauconitic mudstone to very fine grained sandstone. • Planar parallel, hummocky,wave ripple cross stratified. • Partly bitumen saturated.	• Glauconitic sandstone Sandstone and mudstone homogenized by bioturbation. • Low angle planar to horizontal and wavy beding • Bitumen saturated.	• Upward coarsening glauconitic sandstone. • Wave ripple lamination thin trough, and hummocky cross-stratification. • good bitumen saturation.	• Fine to medium grained sandstone • Massive, planar horizontal, Low angle planar, hummocky and swaley cross-stratified. • Moderately to strongly saturated with bitumen
Ichnological Characteristics	BI: (2-6). Common traces include: *Ch* with subordinate *Ph, He,* and *Co.* Small *Te, Th, Sk, Ne, As, Ne, Pl* and *Zo.*	BI: (3-5). Bioturbation moderate to high. Trace fossil suite includes: *Ph Ro, Cy, As, Sc Te,Pa, Ne, Pl, Sk, Zo* and *Dp.*	BI: (3-6). High diversity, high density trace assemblage. Traces include: *Ch, Dp,Pl Sk,Te,Th,Zo, As* and *Ro.*	BI: (3-5). Hhigh abundance and high diversity traces. Traces are: *As,Ch, Dp,Pl, Sk Sc,Th,* and *Te.* subordinate *Ro* and *Op.*	BI: (0-3). Bioturbation is very sporadic. Trace fossil assemblage include: Robust *Ro,As, Cy, Op, Dp, Pl Sk,* and *Th.*
Lithological Accessories	Shell fragments, pyrite nodules, siderite, sand laminae glauconite laminae and grains	Lithological accessories include: glauconite laminae and grains, pyrite and siderite.	Lithological accessories include glauconite and pyrite. Bitumen saturation is good	Lithological accessories include glauconite and pyrite.	Thin mudstone laminae and rip-up clasts. pyrite and siderite. Coal and carbonaceous fragments.
Environmental Stresses	Well-oxygenated fully marine settings, lowered hydrodynamic conditions. Abundant food resources normal marine salinities. Reduced deposition rates	Fully marine settings, Abundant food resources normal marine salinities. Reduced deposition rates strom influence, event bed deposition,	Moderate to high energy, Stable chemical conditions. Abundant food resources, low sedimentation rates.	Moderate to high energy, Stable chemical conditions. Abundant food resources, low sedimentation rates.	High current energy, rapid deposition, wave reworking, strom influence
Facies Association	FA3		FA4		
	Lower Offshore	Upper Offshore	Distal Lower Shoreface	Lower Shoreface	Middle Shoreface

Figure 2. 6 Summary of the attributes of various recognized strand plain shoreface sedimentary facies.

Sedimentary Facies Description

Bioturbated Lenticular Mudstone (F-1)

Sedimentology: This facies comprises gray to blue-gray mudstone with thin, lenticular sandstone (Figure. 5). Rare carbonaceous mudstone beds are observed. Mudstones are sharp based, planar and wavy parallel laminated to massive appearing. Sandstone and siltstone beds are commonly sharp-based and less than 5cm thick. The sandstone beds are wavy to planar parallel laminated with rarer oscillation, current and combined flow ripples. Small-scale soft-sediment deformation features and synaeresis cracks are observed (Figure 2.7). This facies commonly occurs in the south-southeast part of the study area at the base of an upward coarsening succession and is typically 1m thick. Where present, its lower contact with the underlying McMurray Formation is erosional and sharp. The upper contact, most commonly observed with F-2, is gradational.

Ichnology: BI: 1-4. Biogenic reworking in this facies is moderate. The mudstone shows an impoverished trace-fossil suite. Robust as well as diminutive *Planolites* are most common (Figure 2.8). Other traces include comparably diminutive *Arenicolites*, *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Diplocraterion*, *Lockeia*, *Rhizocorallium*, *Skolithos, Teichichnus,* and *Thalassinoides*.

Interpretation: Small-scale soft-sediment deformation, massive appearing sharp-based mudstones, overall low bioturbation index, and the sporadic distribution of trace fossils are all indicators of elevated and episodic sedimentation. Although the physical sedimentary structures are not diagnostic, the presence of wave energy is evidenced by small-scale oscillation ripples. Many of the mudstone beds lack distinct lamination or bioturbation and are interpreted as fluid mud beds (Ichaso and Dalrymple, 2009). The intercalation of fluid mud beds with lenticular sandstone indicates iterative changes in the calibre of sediment transported to the sedimentary environment. The muds likely represent a range of sedimentary processes, including hyperpycnal, tempestite, and suspension fallout, whereas the sandstones accumulated more slowly and are winnowed by wave processes. This facies is characterized by variable bioturbation intensity (BI=. 1-4). The ichnological suite includes diverse, fully marine grazing and deposit-feeding traces intercalated with low-diversity, facies-crossing traces, common fugichnia and rare mantle and swirl structures. Such an ichnological suite of grazing and deposit-feeding traces, representing *Phycosiphon* Ichnofacies suggests a prodeltaic depositional environment characterized by alternating recurring stable marine and physico-chemically stressed conditions, episodic sedimentation, and rapid deposition (MacEachern and Bann, 2020). Notably, similarly impoverished (*Phycosiphon* Ichnofacies) suite with overall diminutive trace fossils and lowered ichnological diversity may indicate lowered or fluctuating salinities: an interpretation supported by the presence of syneresis cracks (Plummer and Gostin, 1981). Furthermore, Gingras et al. (1998) suggested that such impoverished suite can be consistent with the presence of turbid depositional waters, as filter-feeding is excluded as a viable feeding behaviour (later supported and expanded upon in MacEachern et al., 2005 and MacEachern et al., 2007). The abundance of mud beds and likely fluid muds is consistent with turbid depositional waters.

Elevated and episodic sedimentation in the presence of minor wave energy, stratigraphic occurrence (base of upward coarsening succession), and the presence of brackish and turbid waters in a proximal marine environment is interpreted to represent sedimentation in the prodelta of a wave-influenced delta.

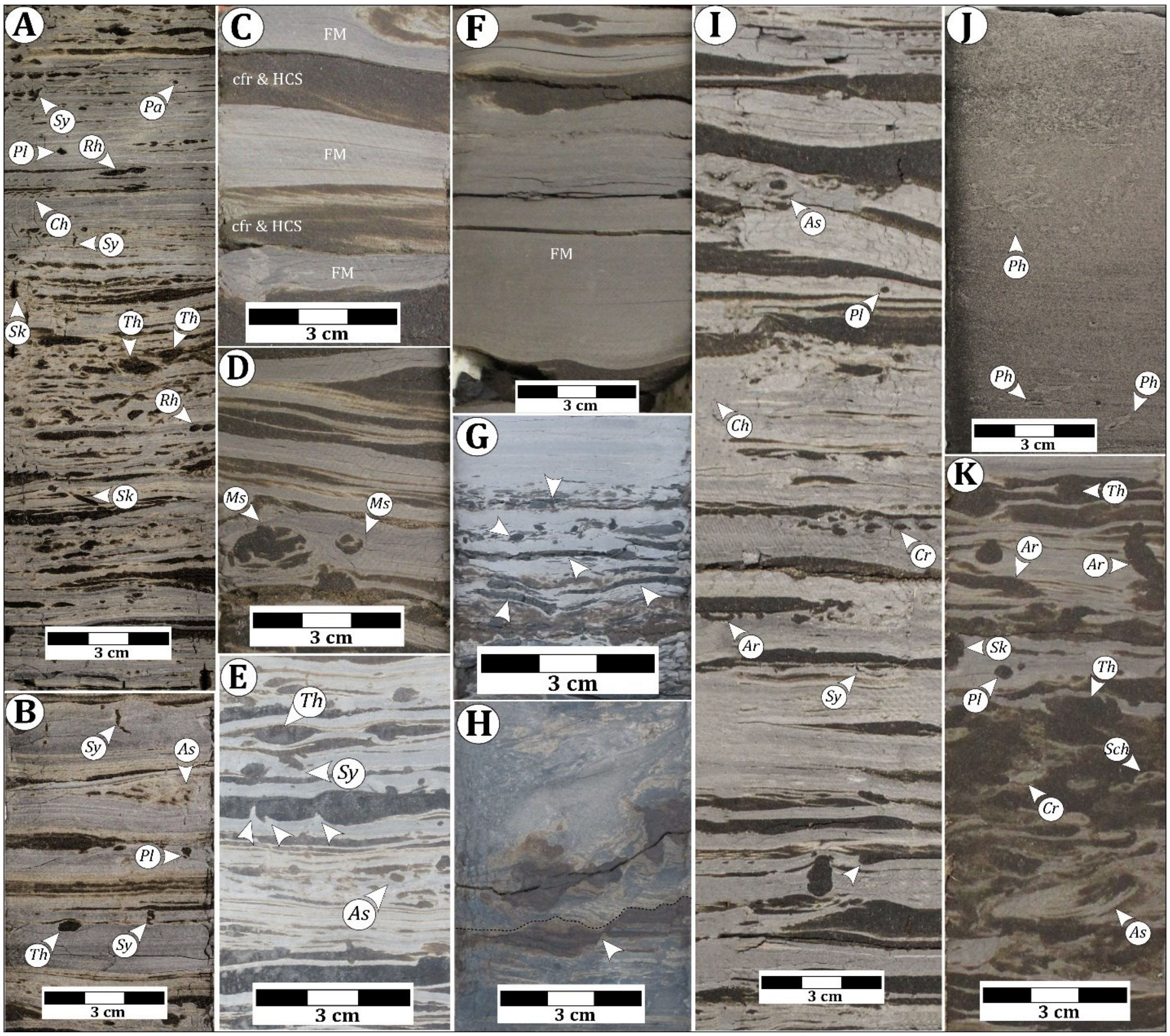


Figure 2. 7 Wabiskaw Member core photographs of facies F-1 and F-2. A) Lenticular ripple laminated sandstone interbedded with laminated to massive mudstone. Fuzzy planar laminae in F-1 is due to biogenic reworking (well AA-12-20-96-12W4M; depth 115.5m). B) Syneresis cracks in facies F-1 (well AA-10-17-96-12W4M; depth 73.10 m). C) Tempestite in the proximal prodelta (F-2), showing fluid mud (FM) immediately overlying combine flow rippled (cfr) , HCS sandstone (well AA-08-28-96-11W4M; depth: 66.12 m). D) Mantle and swirl structures in F-2 (well AA-08-28-96-11W4M; depth: 65.82 m) E) Small scale soft-sediment deformation (white arrows) syneresis cracks in facies F-2(well AA-10-17-96-12W4M; depth: 70.60m). F) Thick massive mudstone interpreted as fluid-mud in F-1 (well AA-08-28-96-11W4M; depth 65.82m). G) Coal laminae and fragments (white arrows) in facies F-

1. H) Soft-sediment features in facies F-2. I) Representative core photographs of facies F-2 with deformation features (arrow) (well AA-12-34-96-11W4M; depth: 69.2m). J, K) Highly bioturbated core photographs of facies F-2 (BI 3-4) (well AA-12-34-096-11W4M; depth: 68.10m). Trace fossils include *Ar = Arenicolites, As = Asterosoma, Ch = Chondrites, Pa = Palaeophycus, Pl = Planolites, Sk = Skolithos, Te = Teichichnus, and Th = Thalassinoides.*

Interbedded Bluish-Gray Mudstone and Thin Sandstone (F-2)

Sedimentology: This facies is mudstone-dominated and consists of thick, distinctive mudstone with a sharp base, with fine-grained sandstone interbeds. The mudstone are structureless to internally laminated (Figure 2.7 C). Most thick (5-7cm) mudstones are massive, unlaminated and unburrowed to sporadically bioturbated. Mudstone beds have thin laminations that locally appear as mud and silt couplets with sporadic internal bioturbation or bioturbated tops (Figure 2.7 C, I). Soft sediment deformation (load and flame structures) and convolute bedding are observed in some mudstone beds (Figure 2.7 H, I). Wavy, low-angle to planar bedded sandstone is commonly interlaminated with mudstone. Current ripples are widespread, although primary sedimentary structures are obscured by bitumen (Figure 2.7 I). Sandstone can be poorly developed locally, with its expression limited to a few sand-filled burrows within massive mudstone. F-2 varies in thickness from 0.5 to 2.5meters. Stratigraphically, this facies is present at lower levels at the base of a progradational sequence. The lower and upper contact of F-2 with the bounding facies (underlying F-1 and overlying F-3) is gradational.

Ichnology: BI: 0-4. Bioturbation is sporadically distributed and prevalent within thick mudstone beds or subtending from the sandstone beds than to mudstone beds. The trace fossils diversity is low to moderate. Burrows may show signs of soft-sediment deformation. Some mudstone display mantle and swirl structures at the top (Figure 2.7 D). Traces present include *Arenicolites*, *Asterosoma, Cylindrichnus, Palaeophycus, Planolites, Siphonichnus, Skolithos,* and *Thalassinoides*. Rare fugichnia may occur.

Interpretation: Sedimentological and ichnological characteristics (carbonaceous mudstone laminae, synaeresis cracks, load and flame structures, convolute bedding, low to moderate bioturbation intensities, and sporadic trace fossils distribution) are suggestive of fluctuating salinity, episodic and high rates of deposition and fluvial input. The sharp-based, carbonaceous mudstone indicates fluid mud deposition likely from hyperpycnites, tempestite, and suspension fallout processes. The sandstone (sharp-based) with minor HCS and combined flow ripples, capped by fluid-mud layers points to tempestites (Figure 2.7 C, F) (Ichaso and Dalrymple, 2009). The occurrence of combined flow ripples and parallel wavy bedding in the sandstone indicates wave action in a marine environment. The trace fossil suite has low to moderate diversity and intensity and is dominated by grazing and deposit-feeding traces of *Phycosiphon* Ichnofacies (MacEachern and Bann, 2020). Similar ichnological signatures may indicate several stresses ("See Section 5.2.1.1 for discussion"). Increased and persistent ichnological stress (reflected by low diversities and intensity of traces), and its stratigraphic position (gradationally overlies F-1) together with a more significant proportion of sandstone present in this facies might be related to proximity to the delta; therefore, this facies indicates a proximal setting than facies F-1.

In summary, stratigraphic position (base of upward coarsening succession), heightened sediment accumulation rates, the fine-grained nature, fluvial influx, and minor wave influence under turbid and brackish water conditions in a marine environment, in conjunction with increased and persistent ichnological stress, indicate sedimentation in a wave-impacted proximal prodelta setting.

Heterolithic Fine-Grained Sandstone Interbedded with Blue-Gray Mudstone (F-3)

Sedimentology: This facies is made up of thick, distinct, and often sharp-based mudstone interbedded with very fine-to-fine-grained sandstone. The sandstone and mudstone may show rhythmic sedimentation with prevalent wavy parallel bedding, ripple cross-laminations, and rare high-angle planar bedding. The lower part of this facies is dominated by mudstone. The mudstone appears structureless to internally laminated (Figure 2.8 A). Most thick mudstones are massive, unlaminated, and unbioturbated to sporadically bioturbated. Thin laminations may appear as mud and silt couplets with sporadic internal bioturbation or bioturbated tops (Figure 2.8 A). Soft sediment deformation may be observed in some mudstone (Figure 2.8). Thin mudstone drapes also occur. Sandstone is commonly interbedded with homogenous mudstone and silty mudstone. Thin (< 5 cm thick) sandstone with parallel to low-angle planar and wavy bedding is present. Although sedimentary structures are obscured by bitumen, rare current ripples and combined flow ripples occur (Figure 2.8 A). Rare high-angle planar beds and minor grain striping can be present. Lithological accessories may occur locally and include mud clasts carbonaceous and coal fragments. Stratigraphically, this facies is present at lower levels (base to lower-middle part of an upward coarsening sequence), and its contact with the underlying McMurray Formation is bioturbated to erosional (where F-1, F-2 are missing). Contact with bounding facies (F-2 and F-4) is gradational. The proportion of sandstone to mudstone in these heterolithic deposits is approximately equal. Facies F-3 is commonly 3-5 m thick.

Ichnology: BI: 0-3. This facies is characterized by low to moderate bioturbation intensities. Bioturbation is sporadic and prevalent within thick mudstone beds or subtends from the sandstone to mudstone beds in the lower part. Both sandstone and mudstone are moderately bioturbated in the middle and upper parts. The diversity of trace fossils is low to moderate. Trace fossil includes *Arenicolites*, *Cylindrichnus, Asterosoma, Macaronichnus*, *Planolites, Palaeophycus, Thalassinoides, Teichichnus*, and *Ophiomorpha.* Rare fugichnia may occur locally.

Interpretation: Sedimentological characteristics such as wavy parallel lamination, combined flow ripples, current ripples, truncated beds, sandy nature, and burrowed sediments indicate storm activity and wave reworking in a river influenced low-moderate energy marine setting. Soft-sediment deformation structures and massive carbonaceous mudstone suggest increased depositional rates and fluid mud deposition. Mud chips, organic detritus, and coal fragments imply riverine influx. This facies is characterized by variable bioturbation intensity and sporadic burrow distribution. The ichnological suite includes deposit and suspension-feeding structures with fewer grazing traces with abundant fugichnia. Such an ichnological suite of deposit and suspension-feeding structures with fewer grazing traces represents the *Rosselia* Ichnofacies (MacEachern and Bann, 2020) indicating deposition in a shallow marine setting (Figure 2.8). The ichnological signatures (low bioturbation index, diminutive trace fossils, low ichnodiversity) may indicate several physicochemical stresses such as heightened deposition rate, turbidity, and fluctuating salinity (See Section 5.2.1.2 for discussion) (Gingras et al., 1998; MacEachern et al., 2005; MacEachern et al., 2007a; MacEachern et al., 2007b; Buatois et al., 2008; Buatois and Mángano, 2011).

The depositional environment with heightened sedimentation rate, turbidity, brackish water, and a moderate wave reworking is interpreted as a wave-influenced distal delta front.

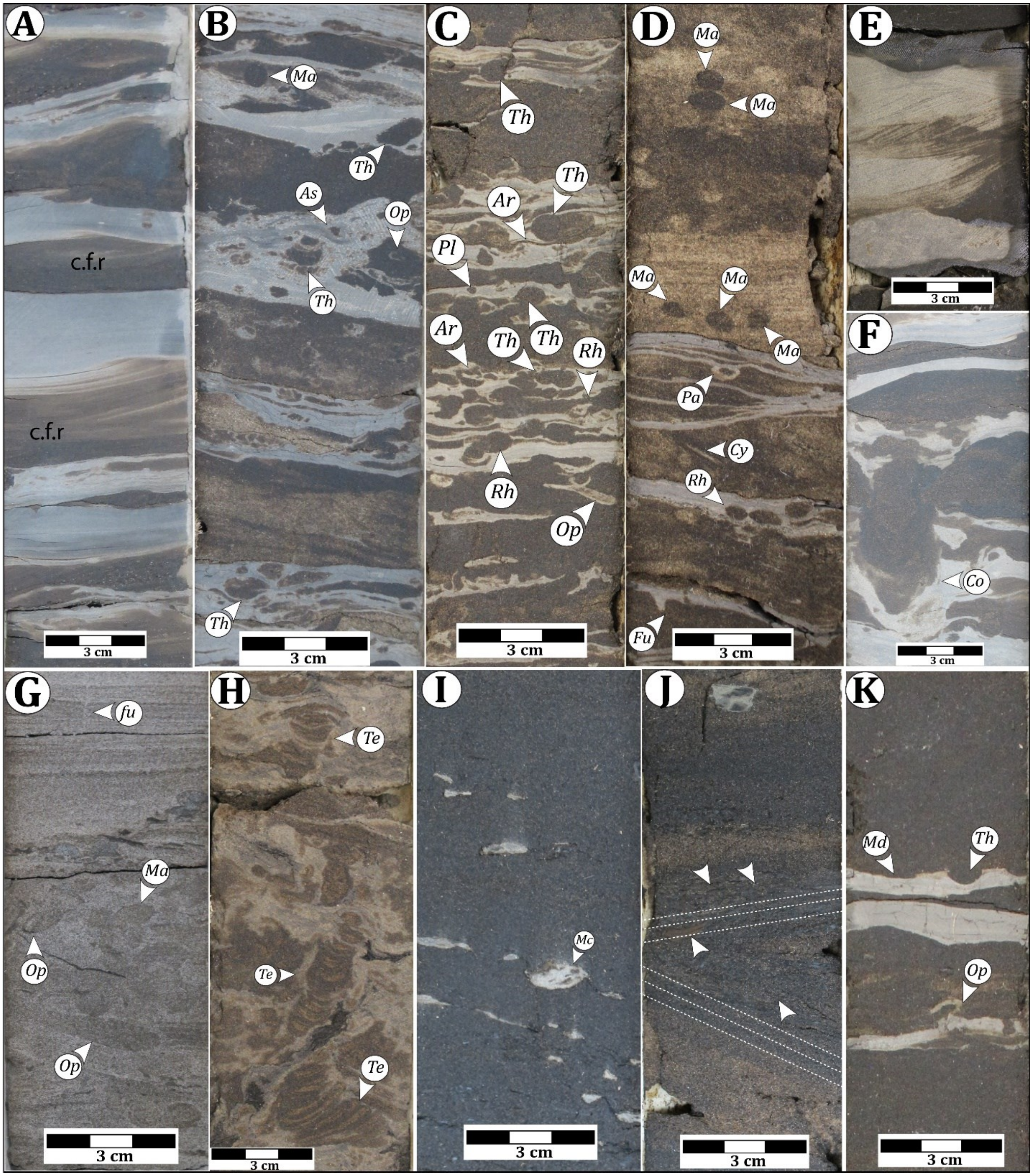


Figure 2. 8 The Wabiskaw Member core photographs of facies F-3, F-4 and F-5. A) Laminated to massive mudstone overlying combined flow rippled ((cfr) and HCS sandstone indicating tempestite event in F-3 (well AA-8-28-96-11W4M; depth: 64.79m). B) Oil-stained, bioturbated F-3 sandstone with wave ripples indicating wave-reworking. (well AA-1-27-96-11W4M; depth: 35.11m). C) Typical core photograph of facies F-4 with moderate to high bioturbation (Well AA-12-34-96-11W4M; depth: 60.42m). F) Macaronichnus and fugichnia in facies F-4 (well AA-12-34-096-11W4M; depth: 61.50). E) Trough cross-stratification in F-4 (well AA-8-28-96-11W4M; depth: 64.61m). F) Large Conichnus in F-4. G) Bioturbated and laminated (lam-scram) sandstone of F-4 with fugichnia. H) F-4 with a monogeneric suite of Teichichnus. I) Oil-stained, massive, cryptically bioturbated sandstone of F-5 with mud clasts. J) Carbonaceous material (white arrow), wood and coal fragments in F-5. K) Sparsely bioturbated F-5 with Ophiomorpha and mud drapes (well AA-6-17-97-13W4M; depth 416m).

Fine to Medium-Grained Sandstone with Thin Mudstone (F-4)

Sedimentology: This facies consists predominantly of upper fine to lower fine-grained sandstone thin mudstone interbeds (1-15%). The sandstone beds are thick (1-20 cm), whereas mudstone laminae are thin and discontinuous (0.2-1 cm) and may occur in couplets. Sandstone can be either upper fine or lower fine, whereas mudstone may be massive (apparently structureless) or contain fine internal laminae of silt and very fine-grained sandstone. Soft sediment deformation structures are common in the mudstone beds. The amount of sandstone increases towards the top of this facies. Bioturbation is very sporadic, and burrowed mudstone beds may be sharply overlain by very fine- to fine-grained sandstone beds (Figure 2.8). The sandstone appears to be massive, wavy to planar parallel with some low angle and hummocky cross laminae. Current and climbing ripples may occur. (Figure 2.8). Bitumen saturation is typically very high, though well-sorted sandstone with low bitumen saturation may be present. Lithological accessories include mud laminae, glauconite, and dispersed coal and carbonaceous material. Thin mud drapes and glauconite laminae may enhance the planar parallel character. The thickness of F-4 varies from 1 to 7 meters. Stratigraphically, F-4 is present at upper levels (middle to the upper part of an upward coarsening sequence). Its contact with the bounding facies (F-3 and F-5) is gradational. Where F-5 is missing, upper contact with F-8 is erosional.

Ichnology: BI: 0-3. Biogenic reworking is sporadic with low intensity and low diversity. The ichnological suite includes *Arenicolites*, *Planolites, Cylindrichnus, Conichnus, Asterosoma, Diplocraterion*, *Macaronichnus*, *Siphonichnus, Palaeophycus, Rhizocorallium, Skolithos, Thalassinoides, Teichichnus*, *Ophiomorpha,* and fugichnia.

Interpretation: The thin and discontinuous mudstone laminae may reflect high energy conditions during the deposition of F-4 compared to F-3. Sedimentary attributes such as planar parallel, low angle, and hummocky cross-stratification indicate unidirectional current and storm waves. The presence of soft-sediment deformation structures and massively bedded units indicate rapid deposition pertaining to periods of high sedimentation rates and proximity to a fluvial source. Low intensity of biogenic reworking and low ichnodiversity indicate environmental stress ("See Section 5.2.1.2 for discussion"). The paucity of bioturbation may be due to storm-generated oscillations, which lead to erosion and the amalgamation of tempestites (Leckie and Walker, 1982; MacEachern and Pemberton, 1992). Abundant deposit-feeding traces indicate high turbidity water conditions but very little suspension-feeding (Gingras et al., 1998). The occurrence of fugichnia suggests a high deposition rate (MacEachern and Pemberton, 1992; Gingras et al., 2012; Pemberton et al., 2012). High-energy conditions, high sedimentation rate, proximity to a riverine source, turbid and stormwater conditions, sandy nature, overall upward cleaning and coarsening character, stratigraphic position (gradationally overlies F-3) and ichnological suite consisting of *Rosselia* Ichnofacies suggest deposition in a proximal delta front setting.

In summary, this facies is interpreted as high-energy proximal delta front deposits in a mixed river- and wave-influenced setting.

Planar, Wavy Laminated Fine to Medium-Grained Sandstone (F-5)

Sedimentology: This facies consists of planar, wavy, low-angle laminated, massive to trough cross-stratified sandstone. The sandstone is fine to medium-grained with current and climbing ripple cross-lamination, soft-sediment deformation structures, abundant carbonaceous material, wood fragments, mudstone rip-up clasts, and organic mudstone drapes (Figure 2.8). Oil saturation is typically very high, partly obscuring the primary depositional fabric. This facies forms an overall upward coarsening trend (1-3 meters thick) and occurs at the top of the progradational sequence. Lower contact with F-4 is gradational, while upper contact with F-8 is erosional.

Ichnology: (BI=0-2). This facies is very sporadically bioturbated. Trace- fossil suite is dominated by indistinct or cryptic bioturbation. Trace fossils present include *Cylindrichnus, Diplocraterion*, *Palaeophycus, Planolites, Macaronichnus*, *Thalassinoides, Ophiomorpha,* cryptic and fugichnia

Interpretation: The presence of current and climbing ripple cross-lamination and massive to trough cross-stratification indicate unidirectional current. Soft-sediment deformation structures, abundant carbonaceous material, wood fragments, mudstone rip-up clasts, and organic mudstone drapes indicate strong riverine influence, high energy conditions and high deposition rate. The occurrence of planar cross-beds may signify the migration of dunes. The upward coarsening and thickening trend indicate progradation. Low bioturbation intensities and low ichnodiversity indicate environmental stress. The presence of deposit-feeding traces indicates turbid water conditions (Gingras et al., 1998). High hydrodynamic energy, heightened sedimentation, riverine influence, sandy nature, turbid and stormwater conditions, trace fossil suite of *Rosselia*

Ichnofacies and gradational occurrence over other deltaic deposits (F-3, F-4) indicate deposition in a proximal delta-front-mouth bar setting.

In summary, this facies is interpreted to represent deposition in a high-energy, mixed river- and wave-influenced, proximal delta front-mouth bar setting.

Dark-Gray Silty Mudstone (F-6)

Sedimentology: This facies is composed of organic mudstone interbedded with siltstone and sandstone. Sandstone and siltstone may be present less than 5% by volume of this facies. The mudstone has a planar parallel structure and may be lenticular or massive. Faint planar, pinstripe, wavy and discontinuous sandstone laminae may occur (Figure 2.9). The mudstone can be sparsely or intensely bioturbated and forms an upward fining succession (Figure 2.9). No defined physical sedimentary structures exist where bioturbation is high (BI = 5–6). Lithological accessories include pyrite nodules, shell fragments, sand laminae, and quartz crystal. Sideritized zones up to 15 cm thick commonly occur near the contacts of this facies. The thickness of this facies varies from 1 to 3 meters. Lower and upper contacts with F-7 is gradational to sharp. This facies generally occurs at the top of upward fining succession in the middle to the upper part of the studied unit.

Ichnology: BI 2-6. This facies is intensely bioturbated with local sparsely bioturbated zones. Typical traces include *Chondrites* with subordinate *Phycosiphon / Helminthopsis* and *Cosmorhaphe*. Small *Teichichnus, Thalassinoides, Skolithos, Asterosoma, Planolites* and *Zoophycos* occur locally and are most common in sideritized zones along the upper and lower contacts (Figure 2.9).

Interpretation: The massive sandy, silty mudstone with planar laminae as the dominant sedimentary structure likely indicates deposition from suspension under low energy, calm water conditions. Pervasive bioturbation (BI:4-6), uniform distribution of trace fossils and high ichno-diversities indicate fair-weather conditions. The presence of faint planar, pinstripe sandstone laminae points to infrequent storm activity. The wavy, discontinuous and lenticular ripple laminae may also infer a process of current transport. The grazing/foraging, deposit-feeding, and passive carnivore traces belong to the distal *Cruziana* Ichnofacies (MacEachern et al., 2007). These observations suggest deposition in offshore environments with neither large trace-making organisms nor extended settlement periods.

In summary, the highly bioturbated low-energy mudstone with high ichno-diversity, and sparsely-bioturbated, parallel laminated sandstone deposits having low ichnodiversity points to sedimentation in a stormy lower offshore setting at depths well below the fair-weather wave base (MacEachern and Pemberton, 1992; MacEachern et al., 2007; Buatois and Mángano, 2011; Pemberton et al., 2012).

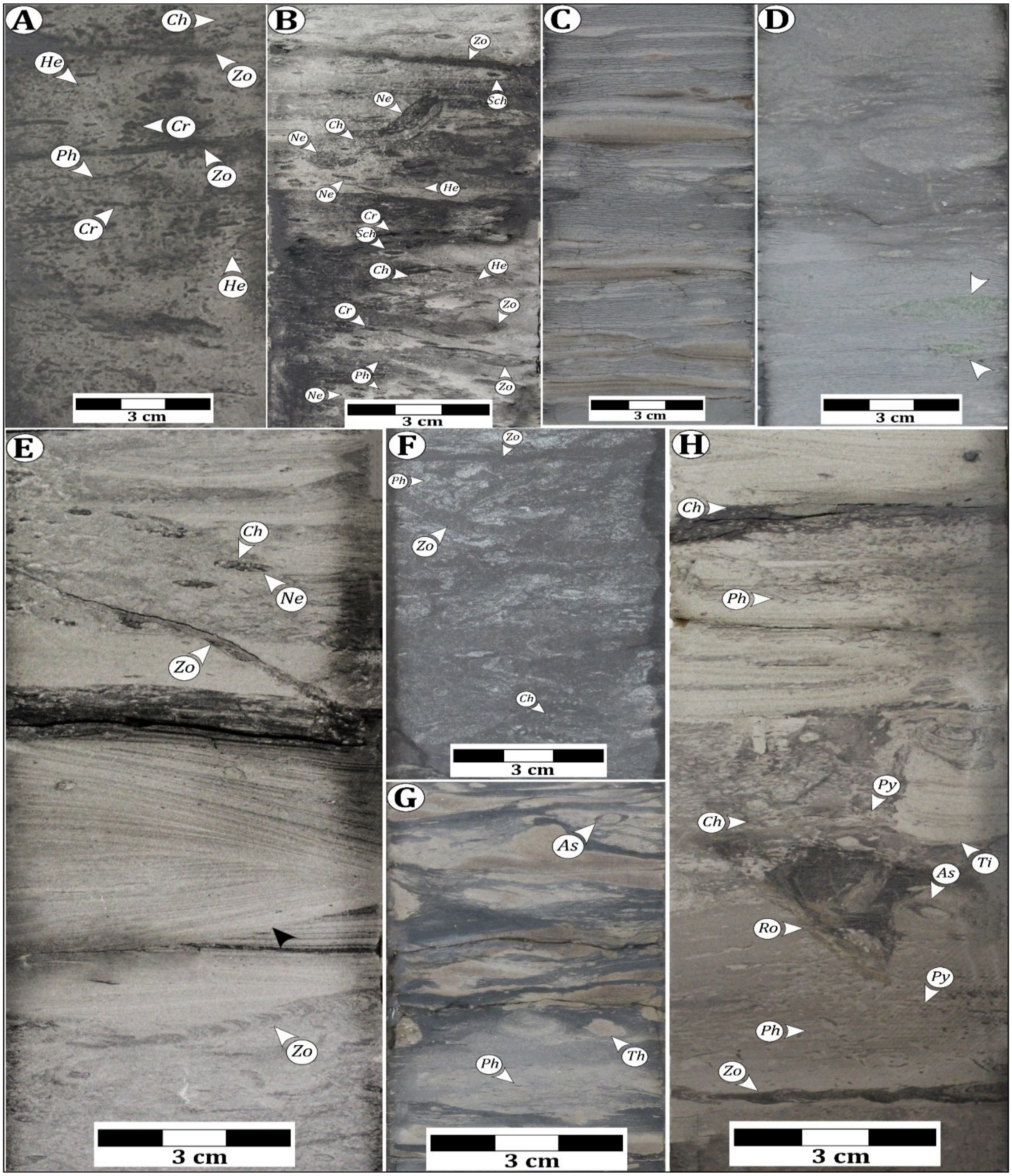


Figure 2. 9 The Wabiskaw Member core photographs of F-6 and F-7. A, B) Intense bioturbation has resulted in indistinct bedding (well AA-08-28-096-11W4M; depth: 57.21m). C) Storm-induced parallel laminated silt and sand interbed within F-6. D) Glauconite grains and laminae (white arrows) in F-6. G) Core photograph of facies F-7, indistinct bedding in bioturbated, glauconitic mudstone (well AA-04-07-096-12W4M; depth: 85m). E, F, G, H) Intensely bioturbated sandy mudstone and storm-induced, sparsely bioturbated, hummocky cross stratified and planar parallel laminated sandstone of F-7 (well AA-08-28-096-11W4M; depth: 53.92m, 53.21m, 53.10m).

Bioturbated Massive Sandy Glauconitic Mudstone (F-7)

Sedimentology: This facies is composed of light grey sandy-glauconitic and very fine-grained sandstone. High-intensity bioturbation homogenizes the sandstone and mudstone. Sedimentary structures, if preserved, may include low-angle planar and wavy to lenticular bedding. Oscillation-ripple cross-laminae occur where minimal bioturbation (Figure 2.9). Sandstone intervals are bitumen saturated. The sandstone is parallel laminated with a hummocky, wave and current-ripple cross-stratification. The bioturbation intensity is moderate to high. This facies is medium to light grey (Figure 2.9) or green grey due to glauconite laminae and grains. Other lithological accessories include pyrite and siderite. Sideriterized zone may occur along with the contacts. This facies is sandy at the bottom with a gradational upward decrease in grain size, forming a continuous upward fining succession. This facies gradually transitions into dark grey silty mudstones (F-6), but the contact between facies may also be sharp. Where F-7 occurs on top of F-8, the contact is gradational to sharp. This facies generally occurs in the middle to the upper part of the studied interval and vary in thickness from 1 to 3 meters.

Ichnology: (BI 3-5). Bioturbation in this facies is moderate to high and has partially obliterated the depositional fabric. Trace fossil suite includes *Phycosiphon*, *Rosselia*, *Cylindrichnus, Asterosoma*, *Scolicia*, *Teichichnus*, *Palaeophycus*, *Planolites, Skolithos*, *Zoophycos* and *Diplocraterion* (Figure. 7).

Interpretation: The bioturbated sandy glauconitic mudstone indicates deposition from suspension under low energy conditions. The interbedded bioturbated mudstone and un-bioturbated to sparsely bioturbated very fine-grained sandstone indicate low energy deposition from suspension punctuated by high energy storm events directly underneath the fair-weather wave base. Sand is deposited as tempestite during these high-energy storm events within the offshore (Leckie and Walker, 1982; Frey et al., 1990; Pemberton and MacEachern, 1995; Pemberton et al., 2012). Physical sedimentary structures are rare where moderate to high bioturbation (BI = 3–5). The ichnological suite belongs to the archetypal *Cruziana* Ichnofacies. *Cruziana* Ichnofacies indicate fully marine settings with well-oxygenated, lowered hydrodynamic energy and abundant food resources. The *Cruziana* Ichnofacies is characterized by high bioturbation intensity and diversity. The ichnological suite of *Cruziana* Ichnofacies consists mainly of horizontal traces with subordinate inclined and vertical traces of dominant deposit and detritus feeding behaviours (Seilacher, 1964, 1967; Howard and Frey, 1984; Frey and Pemberton, 1985; Frey et al., 1990; MacEachern and Pemberton, 1992; Maceachern et al., 1999; MacEachern et al., 2007c). The fair-weather, intensely bioturbated (BI = 5–6) silty mudstone with high ichno-diversity and storm-induced, sparsely bioturbated (BI=0–1), hummocky cross stratified and parallel laminated sandstone deposits with low ichno-diversity all points to deposition in a storm-influenced upper offshore at depths directly beneath the fair-weather wave base (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011; Pemberton et al., 2012).

Intensely Burrowed Muddy Sandstone (F-8)

Sedimentology: This facies consists of upper fine to fine-grained glauconitic sandstone. Sandy to silty wavy mud laminae and beds may occur at the base. These mud beds are bluish-gray and may occur interlaminated with glauconitic sandstone where not homogenized by bioturbation. The abundance of silt and mud decreases upward with a corresponding increase in the proportion of sandstone. Storm-induced sedimentary structures (tempestites or hummocky cross-stratification) may occur (Figure 2.10). The lower contact is erosional to sharp, whereas the upper contact is gradational. Bioturbation is intense and has obliterated sedimentary structures. Bioturbation is moderate, hummocky, thin trough cross-stratification, and oscillation ripple lamination occurs (Figure 2.10). Bitumen saturation in the sandstone is reasonably good. Glauconite grains and laminae, and pyrite nodules may occur as accessories. This facies occur at the base of upward fining succession. Thickness of F-8 is 3 to 6 m. The lower contact of this facies with underlying facies marks a major discontinuity and is generally sharp, bioturbated or erosional.

Ichnology: BI 3-6. Bioturbation in this facies is moderate to intense. A high abundance and high diversity suite of traces with moderate to complete bioturbation intensities include ichnogenera: *Asterosoma, Diplocraterion, Chondrites, Skolithos, Planolites, Scolicia Thalassinoides, and Teichichnus* (Figure 2.10). Robust *Asterosoma,* large *Diplocraterion, Scolicia* and *Teichichnus* typically occur in the sandstone. *Chondrites, Planolites, Skolithos,* and *Thalassinoides* dominantly occur in mudstone. Additionally, subordinate *Rosselia* and *Ophiomorpha* may occur locally in the sandstone.

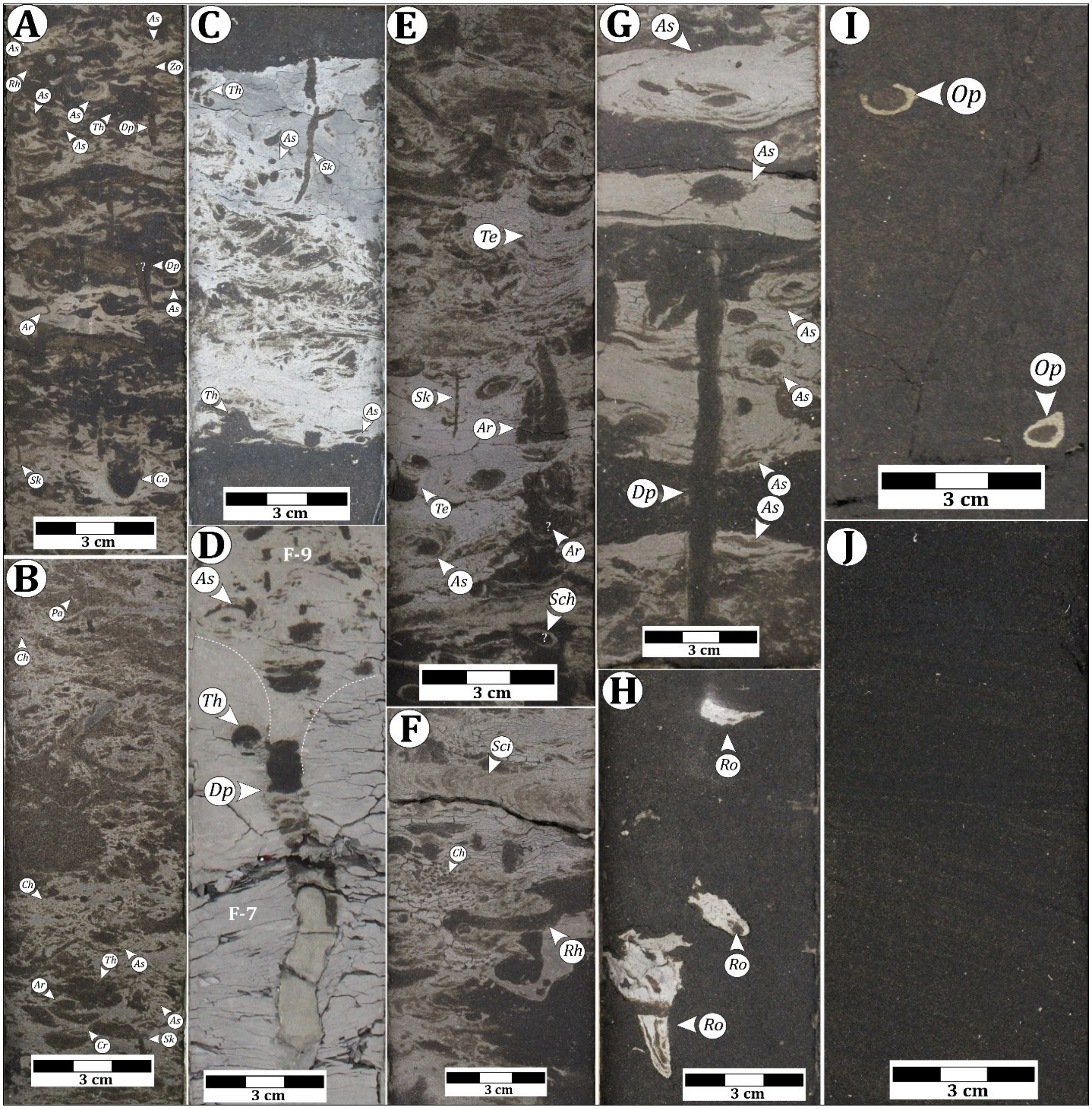


Figure 2. 10 The Wabiskaw Member core photographs of F-8, F-9, and F-10. A, B) Intensely bioturbated core expression of facies F-8 (well AA-11-14-096-14W4M; depth: 257.09 m). C) Fairweather bioturbated and unbioturbated storm deposits within F-8. D) Large *Diplocraterion* at the contact of F-7 and F-9 (well AA-15-03-097-12W4M; depth: 57.97 m). E, F, G) Robust trace fossils in F-9 (well AA-10-06-097-12W4M; depth: 114.34 m, well AA-07-11-096-13W4M; depth: 122.31 m, 122.20 m). H) Core expression of facies F-10, with robust *Rosselia* traces (well AA-10-12-098-14W4M; depth: 538.9m). I) Robust *Ophiomorpha* traces in the oil-saturated facies F-9 (well AA-08-07-098-13W4M; depth: 432.5m). J) Facies F-10 showing parallel to low angle cross-stratification (well AA-08-07-098-13W4M; depth: 434.1m).

Interpretation: Physical sedimentary structures are rare. The scarcity of sedimentary structures and high bioturbation intensity indicates that the infaunal reworking rate exceeded sedimentation. The occurrence of hummocky cross-stratification and the presence of low angle planar cross laminae may be associated with high energy storm deposition. Bioturbation is intense (BI 3-6) and uniform. Uniform bioturbation intensity, together with robust traces, points to a relatively low energy stable environment with homogenous food resources (MacEachern and Pemberton, 1992; Pemberton et al., 2012). The trace fossil suite represents a proximal expression of *Cruziana* ichnofacies (characteristic of lower shoreface with low to moderate hydrodynamic conditions in a fully marine environment). Uniform and intense bioturbation, robust fully marine trace fossils, plentiful food resources, low to moderate deposition rates, and moderate hydrodynamic energy in a shallow fully marine setting are all interpreted as evidence of deposition in the distal lower shoreface. In summary, this facies record sedimentation in a lower shoreface (distal) setting under fair-weather conditions punctuated by storm events.

Bioturbated Muddy Glauconitic Sandstone (F-9)

Sedimentology: This facies is composed of upper fine-grained glauconitic sandstone. The base part may contain light steel grey to blue mud beds. These bluish-grey mud beds may appear interlaminated with glauconitic sandstone when not homogenized by bioturbation. The abundance of silt and mud decreases upward with a corresponding increase in the proportion of sandstone. This facies thus form an overall upward coarsening and cleaning package, although the top may appear muddier where it grades into the overlying facies. Both the upper and lower contacts may be sharp to gradational and bioturbated. Bioturbation is intense and has obliterated sedimentary structures. Bioturbation is moderate, hummocky, thin trough, low angle, and wave ripple laminations may occur. Bitumen saturation in the sandstone is reasonably good. Glauconite and pyrite may be present as accessories minerals. This facies occurs at the top of upward coarsening succession. Thickness of F-9 varies from 2 to 5 m. The lower and upper contact of this facies with the bounding facies (F-6, F-7, F-10) is generally gradational to sharp.

Ichnology: BI 3-6. Bioturbation in this facies is moderate to intense. A high abundance and high diversity suite of traces with moderate to complete bioturbation intensities include ichnogenera: *Asterosoma, Teichichnus, Diplocraterion, Chondrites, Planolites, Skolithos, Scolicia and Thalassinoides* (Figure 2.10). Robust *Asterosoma,* large *Diplocraterion, Scolicia* and *Teichichnus* typically occur in the sandstone (Figure 2.10). *Chondrites, Planolites, Skolithos,* and *Thalassinoides* dominantly occur in mudstone. Additionally, subordinate *Rosselia* and *Ophiomorpha* may occur locally in the sandstone.

Interpretation: Physical sedimentary structures are rare. Intense biogenic reworking, high ichno-diversity, and uniform distribution of trace fossils indicate abundant food resources, low to moderate deposition rate, and moderate energy conditions. The observed tiering of the trace fossils indicates that the benthic community were responding to variable food resources, indicating a relatively unstressed environment (MacEachern et al., 2010). Uniform distribution, overprinting and tiering of trace fossils signifies slow and continuous deposition. Currents produce the preserved planar parallel and wavy to lenticular laminae under fair-weather conditions.

In contrast, low angle planar cross laminae are likely a product of low magnitude storm waves. Bioturbation is intense (BI 3-6). The trace fossil suite belongs to a proximal expression of *Cruziana* ichnofacies, characteristic of lower shoreface with low to moderate hydrodynamic conditions in a fully marine environment (MacEachern and Pemberton, 1992; Pemberton et al., 1997; Maceachern et al., 1999; Maceachern et al., 2007b; MacEachern et al., 2008; Pemberton et al., 2012). Intense bioturbation, high ichno-diversity, tiering, robust and fully marine trace fossil, slow continuous sedimentation indicate relatively low energy stable fully marine environment with homogenous food resources (MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1997; Pemberton et al., 2012).

In summary, this facies represents deposition in a lower shoreface environment under fair-weather conditions with occasional storm events.

Well-Sorted Fine-Grained Sandstone (F-10)

Sedimentology: This facies is composed of winnowed, bitumen-saturated, well-sorted sandstone. Rare mudstone laminae may occur with the fine to medium-grained sandstone. The occurrence of mud is limited to burrow fill and lining of burrows (Figure 2.10). The dominant physical sedimentary structures are hummocky cross-stratification and swaley, with some planar (parallel or low-angle) as well as massive beds. Minor rip-up clasts and thin mudstone laminae may occur throughout this facies as lithological accessories. Disseminated coal and carbonaceous material and fragments, rare shell fragments, pyrite and siderite, and the fault may also occur locally. This facies has an average thickness of 4 m. Lower contact is sharp to erosional with F-9, whereas upper contact with Clearwater Formation is gradational to sharp.

Ichnology: (BI 0-3). Bioturbation in this facies is sporadic and varies from low to moderate intensity. The bioturbation intensity in the lower part is moderate, with a gradual upward decrease. Trace fossil suite include Robust *Rosselia*, *Asterosoma, Cylindrichnus,* and *Ophiomorpha.* Other trace fossils include *Diplocraterion, Planolites, Skolithos, Schaubcylindrichnus,* and *Thalassinoides* (Figure 2.10).

Interpretation: Hummocky and swaley cross-stratification indicate storm-influenced sedimentation (Dumas and Arnott, 2006). The presence of rip-up clasts organic and coal fragments within the hummocky and swaley cross-stratified beds may indicate strong storm currents transporting near-shore material into more distal basin-ward settings. The un-bioturbated deposits may indicate either erosional removal of the bioturbated fair-weather beds or pervasive storm activity that prevented the benthic community from colonizing the substrate. Bioturbation is very low, and the substrate was colonized by opportunistic populations represented by *Rosselia*, *Ophiomorpha, Diplocraterion, Planolites, Skolithos, Schaubcylindrichnus,* and *Thalassinoides*. This opportunistic trace fossil colonization in conjunction with the presence of storm-generated hummocky and swaley cross-stratification and its stratigraphic position (i.e. on top of F-9) suggests deposition in proximal, middle shoreface environment (Dumas and Arnott, 2006; Pemberton and MacEachern, 1997; Pemberton et al., 2012).

In summary, this facies is interpreted to be deposited in storm-dominated middle shoreface environments under high energy, hydrodynamic conditions well above the fair-weather wave base.

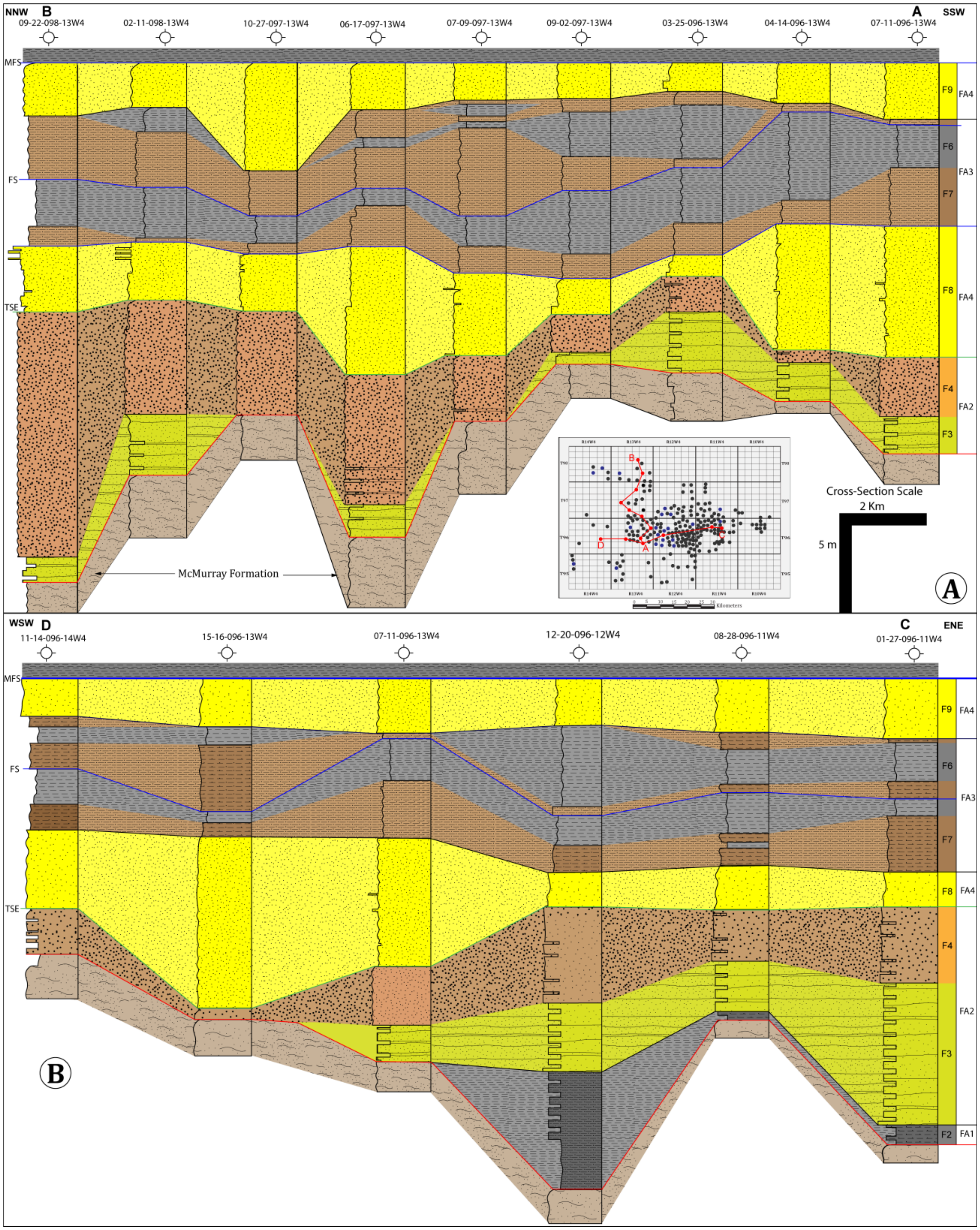


Figure 2. 11 Litholog cross-sections showing the distribution of facies and facies association. Cross-section A-B is dip oriented whereas cross-section C-D is strike oriented. No horizontal scale implied.

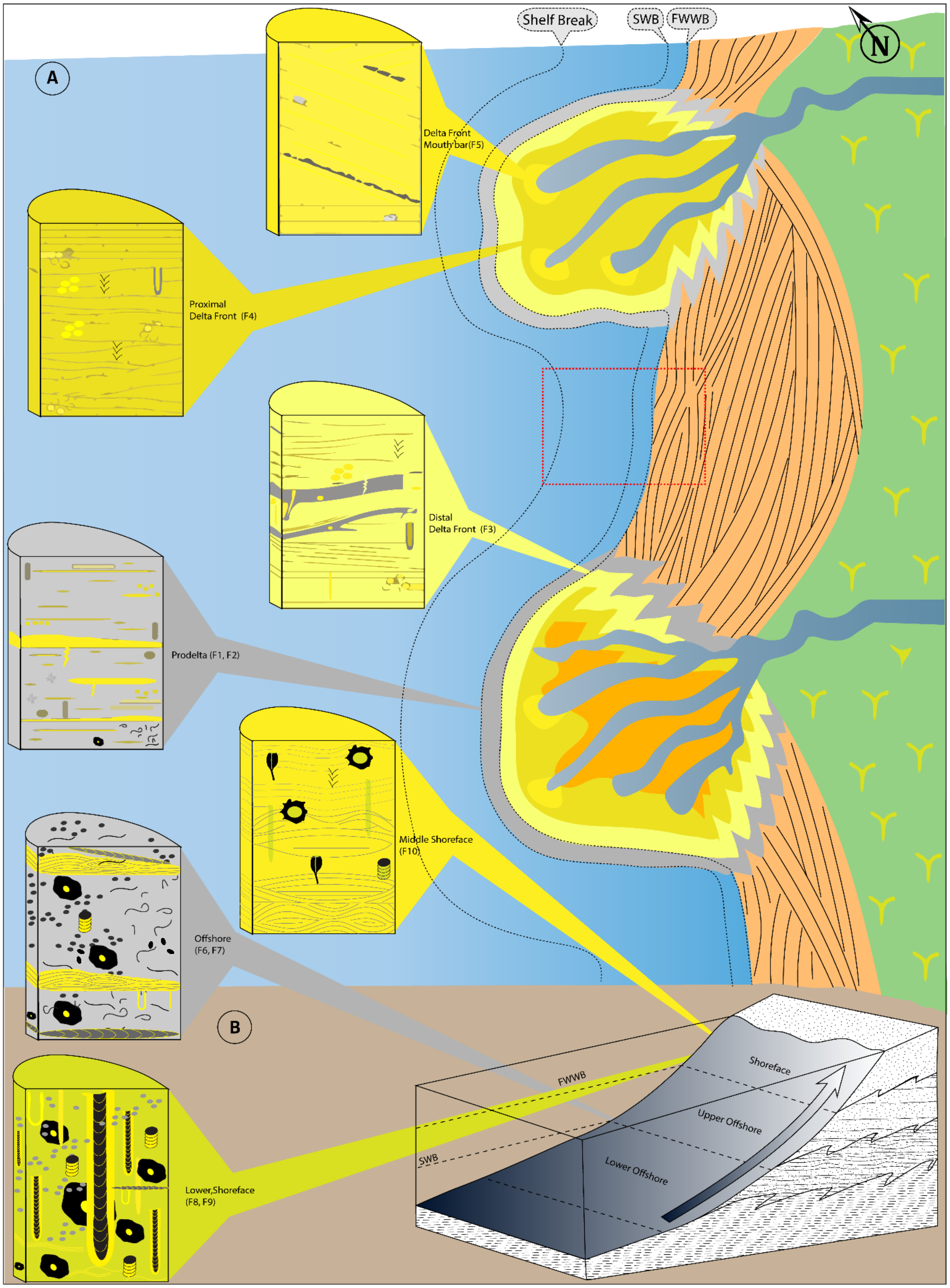
INTERPRETATION AND DISCUSSION

Geological Facies Model

Deltaic, strand plain shoreface, and offshore successions are the three main depositional systems recognized in the Wabiskaw Member strata. Four main facies associations (Figure 2.5, Figure 2.4-8) are recognized recording deposition in a shallow-marine setting. These facies associations reflect the depositional history of the basin over time. The trend of the paleo deltaic shoreline in the study area may have been in the east-northeast to south-southwest direction, as indicated by subsurface cross-section, during the Aptian time (Figure 2.11). In the south-southeastern portion of the study area, prodelta deposits predominate (F-1, F-2). In comparison, delta-front-to-mouth bar deposits occur further to the north-northwest and upward in the stratigraphic succession (F-3, F-4, F-5) (Figure 2.11-10). This deltaic system was flooded by a transgressive event (possibly regional) during the Aptian-Albian times (TSE in Figure 2.11), leading to its abandonment. An intricate interplay of wave and riverine processes with insignificant tidal processes may have shaped this deltaic shoreline (Figure 2.12).

The prodelta and delta-front deposits (FA-1, FA-2) show strong signatures of wave and riverine processes. These deposits are interpreted to have formed mainly in mixed energy (wave-river) influenced deltaic settings (Figure 2.12). The delta front deposits are wave-influenced and laterally extensive (F-3, F-4). Where wave processes are subordinate, lobate distributary mouth bar deposits are formed (F-5). The occurrence of abundant oscillatory sedimentary structures (Hummocky cross-stratification, combined flow ripples, symmetrical-nearly symmetrical ripples) in the deltaic deposits points to wave action. These waves-influenced deltaic deposits may be very similar to shoreface-offshore deposits. The presence of characteristic features (soft-sediment features, syneresis cracks and impoverished trace-fossil suites) distinguishes these deposits from their fully marine counterparts. The prodelta deposits (FA-1) of Wabiskaw Member occur in the south-southeast part of the study area and records progradational depositional geometry. The delta-front-to-mouth bar deposits (FA-2) are present throughout but dominate the north-northwestern part (Figure 2.11). The progradational deltaic lobes of FA-2 extend and becomes thick in the north-northwest direction (Figure 2.11).

Strand plain shoreface-offshore is developed in areas along-strike of the delta and upward in the stratigraphic succession (Figure 2.12). The strand plain shoreface-offshore sequence reflects deposition in offshore and lower-middle shoreface environments (Figure 2.9-2.10). Proximal depositional domains (upper shoreface, beach) are not observed in the core. Sedimentary structures (hummocky cross-stratification, parallel lamination) characteristic of storm waves and tempestites are not commonly observed but may occasionally occur within these deposits. This may indicate that storms were either not common (which is unlikely), or storm deposits may have been homogenized (highly likely) by bioturbators (burrowing organisms). High ichno-diversity and abundance, uniform bioturbation and high BI values point to wave-dominated settings with slow, continuous sedimentation (MacEachern et al., 1994; Gani et al., 2007). However, the parallel and HCS sandstone with low bioturbation intensity within these deposits may have resulted from deposition in the storm-influenced offshore-lower shoreface setting (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011; Pemberton et al., 2012). The strand plain shoreface-offshore deposits are present throughout the study area. The aggradational to retro-gradational offshore deposits (FA-3) tend to increase in thickness towards south-southeast and are present in the middle part of the studied unit (Figure 2.11). Shoreface deposits (FA-4) are present in the lower and upper parts of Wabiskaw Member and display general aggradational as well as retro-gradational depositional geometries with a south-southeast directed increase in thickness.



Shelf Break
SWB
FWWB
N
A
Delta Front
Mouth bar(F5)
Proximal
Delta Front (F4)
Distal
Delta Front (F3)
Prodelta (F1, F2)
Middle Shoreface
(F10)
Offshore
(F6, F7)
B
Lower,Shoreface
(F8, F9)
FWWB
SWB
Shoreface
Upper Offshore
Lower Offshore

Figure 2. 12 Proposed Wabiskaw Member depositional model within the study area. B) Represent the red, dotted rectangular area in A.

Ichnology and Elucidation of Physicochemical Stresses in Deltaic and Strandplain Shoreface-Offshore Complexes

The ichnology of shallow marine successions (deltas, estuaries, and shoreface) is becoming more popular due to trace fossils potential to discriminate diverse environmental stresses (river, wave, tidal) (Gingras et al., 1998; McIlroy, 2004; Bhattacharya and MacEachern, 2009; Buatois and Mángano, 2011; Ayranci et al., 2014; Bhattacharya et al., 2020). It is essential to identify these stresses accurately in order for environmental interpretations to be refined. Ichnology can significantly improve our ability to recognize these physicochemical stresses when used correctly. The deltaic and strand plain shoreface-offshore deposits of Lower Cretaceous (Aptian-Albian) Wabiskaw Member of Clearwater Formation of the northeast Alberta provide an excellent case study to evaluate the ichnological characteristics associated with laterally and vertically variable stresses. Based on the ichnological analysis, two main circumstances may be recognized in the studied area. These are (i) river and wave-influenced deltaic deposits; (ii) wave-dominated strand plain shoreface-offshore complexes.

Wave-Influenced Deltaic Deposits

Riverine processes influence the Wabiskaw Member prodelta (F-1,2) and delta-front (Facies 3,4,5) deposits and thus may exhibit extreme stress owing primarily to high river discharge, heightened deposition rate and water turbidity.

Prodelta Deposits

The prodelta deposits (FA-1) are variably bioturbated (BI=0-4). The lack of bioturbation (BI=0) and the massive nature of interbedded mudstones indicate that these may constitute fluid muds that hindered infaunal burrower colonization (MacEachern et al., 2005; MacEachern et al., 2008; Ayranci et al., 2014). Preserving biogenic structures of infaunal organisms in these substrates is unlikely because of the low shear stress (Ekdale and Bromley, 1984). The ichnological suite of moderately bioturbated prodelta deposits (FA-1) belongs to the *Phycosiphon* Ichnofacies (MacEachern and Bann, 2020). The ichnological signatures of FA-1 may indicate several stresses, such as 1) fluctuations in water salinity caused by riverine input, 2) freshets induced phytodetrital material and increase in water turbidity, 3) heightened deposition rates during storms (Gingras et al., 1998; Gingras et al., 2002; MacEachern et al., 2005; Gingras et al., 2007; MacEac hern et al., 2007b; Buatois et al., 2008; Buatois and Mángano, 2011).

In summary, the fine-grain nature, combined with high sedimentation rates, riverine influx, and *Phycosiphon* Ichnofacies, points to deposition in the prodelta environment.

Delta Front and Mouth bar Deposits

The Wabiskaw Member delta front ranges from wave-influenced to moderately storm-affected. In the storm-affected delta front, repeated storm waves impeded the preservation of the fair-weather trace-fossil suite, and only *Ophiomorpha* (deep burrow of decapod crustacean) is preserved. The fair-weather ichnological suite has been preserved partially in the moderately storm-affected delta front. As a result, these delta front deposits exhibit alternating laminated (storm) beds and bioturbated (fair-weather) beds, giving rise to the lam-scram pattern (Figure 2.8) (MacEachern and Pemberton, 1992). In wave-influenced environments, benthic organisms produce trace fossils suite belonging to the *Rosselia* Ichnofacies under predictable and relatively stable fair-weather conditions (MacEachern and Bann, 2020). The trace-fossil suite attributed to storm events (representing colonization following storm deposition) may establish under opportunistic community colonization (MacEachern and Pemberton, 1992; Pemberton et al., 2012). The trace fossils (bioturbation index, size and diversity) indicate physicochemical stress ("See Section 4.1.3, 4.1.4, and 4.1.5"). Persistently shifting substrates may be related to storm-wave action. The persistently shifting bedforms combined with heightened deposition rates and sporadically high current energies may limit animals (abundance and type) living on these substrates. Such substrates are inhabited only by decapod crustaceans (deep burrowers), forming *Ophiomorpha* to survive (Dashtgard and Gingras, 2012; Dashtgard et al., 2021). The occurrence of abundant *Macaronichnus* (tends to occur in high-energy, shallow water, nutrient-rich, siliciclastic conditions with high sedimentation rates) also supports such an interpretation (Clifton and Thompson, 1978; Saunders et al., 1990; Saunders et al., 1994; Pemberton et al., 2012). The presence of *Cylindrichnus, Diplocraterion, Rosselia*, and *Skolithos* (filter-feeding burrows) may indicate that waves winnowed fine-grained material as these trace fossils are rare in deltaic settings with heightened water turbidity (MacEachern et al., 2005). Fugichnia indicates that organisms were present in sediments, attempting to reach a new interface between sediment and water. The storm-generated oscillations resulted in erosion and amalgamation of tempestites which accounts for the lack of bioturbation (MacEachern and Pemberton, 1992; Gingras and

MacEachern, 2012; Pemberton et al., 2012). Opportunistic trace makers colonized storm deposits as evidenced by trace-fossil suite (cryptic bioturbation, *Ophiomorpha Palaeophycus, Skolithos, Diplocraterion*).

In conclusion, sandy nature, high hydrodynamic conditions, high sedimentation rate, proximity to a river, and *Rosselia* Ichnofacies may indicate deposition in a proximal delta front to mouth bar setting (Figure 2.12).

Wave-Dominated Strand Plain–Offshore Complexes

The Wabiskaw Member wave-dominated strand plain shoreface-offshore complexes exhibit ichnological characteristics, indicating fully marine conditions (fewer to no stresses) in the study area. These deposits occur on top of the delta front-mouth bar and represent deposition under normal marine aquatic conditions.

Offshore Deposits

The offshore deposits (FA-3) are highly bioturbated, resulting in complete homogenization of the background mudstone. Storm wave-generated deposits are not commonly observed in the lower offshore though they may occur locally. The scarcity of storm deposits in lower offshore may be due to intense bioturbation. However, sparsely bioturbated tempestites are present in the lower and upper offshore. Offshore deposits have higher trace fossil diversity compared to the coeval prodelta facies. The occurrence of fully marine trace fossils (*Asterosoma, Chondrites*, *Helminthopsis, Phycosiphon, Zoophycos)* and ichnodiversity of benthic fauna in these deposits points to slow, continuous deposition in near-normal marine (brackish) salinities, well-oxygenated, and nutrient-rich environmental conditions (MacEachern et al., 2005; Buatois and Mángano, 2011). On the other hand, variations in environmental conditions may have made intervals within F-7 uninhabitable for marine bioturbaters. *Cruziana* Ichnofacies indicate fully marine settings with well-oxygenated, lowered hydrodynamic conditions and abundant food resources (Seilacher, 1964, 1967; Frey and Seilacher, 1980; Howard and Frey, 1984; Pemberton and Frey, 1984; Frey and Pemberton, 1985; Frey et al., 1990; MacEachern and Pemberton, 1992; Maceachern et al., 1999). Reduced deposition rates are also inferred where the intensity of biogenic reworking is high due to an increased colonization window under fair weather (MacEachern et al., 2005; Campbell et al., 2016).

In summary, the intensely bioturbated fair weather silty mudstone and storm-induced, sparsely bioturbated sandstone deposits (hummocky cross stratified and planar parallel laminated) suggest sedimentation in a storm-influenced offshore environment.

Lower-Middle Shoreface Deposits

The shoreface deposits (F-8,9,10) are glauconitic sandstone (lower fine to fine-grained) with rare mudstone interbeds. Low sedimentation rates are suggested by the intense bioturbation (BI: 3-6), enhanced variety, and homogeneous ichnofossils distribution. *Asterosoma, Rhizocorallium*, and *Scolicia* (Fully marine trace fossils) suggest stable chemical conditions (MacEachern et al., 2010; Gingras and MacEachern, 2012; Gingras et al., 2012). The predominance of *Asterosoma, Chondrites, Arenicolites, Scolicia, Thalassinoides, Teichichnus, and Planolites* (deposit feeders) indicates a plentiful supply of food (MacEachern et al., 2010). The homogenous trace fossils distribution and the high diversity of trace suite suggest stable environmental conditions. In fair weather deposits, trace-fossil suites (produced by the benthic communities) may develop under stable, relatively predictable conditions. Trace-fossil suite of stormy conditions (colonization after storm deposition) may establish under opportunistic community colonization (*Skolithos* Ichnofacies) (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011). During storms, repeated storm-wave impeded the preservation of the trace-fossil suite, and only *Ophiomorpha* (deep burrow of decapod crustacean) is preserved. In the storm-influenced settings, the fair-weather ichnological suite is partially preserved. As a result, shoreface deposits exhibit a lam-scram pattern (MacEachern and Pemberton, 1992; Pemberton et al., 2012). The presence of marine suite (*Scolicia* and *Asterosoma)* indicates near marine salinities (Gingras et al., 2011; Gingras et al., 2012; Gingras and MacEachern, 2012). Large trace fossils (robust *Asterosoma* with a diameter of 25 mm and large *Diplocraterion* several centimetres in the vertical axis) provide additional evidence of stable conditions (Gingras et al., 2011; Gingras and MacEachern, 2012; Gingras et al., 2012). In summary, these deposits represent deposition in a fully marine (largely unstressed) setting where the hydrodynamic energy is moderate, chemical conditions are generally stable, and food resources are abundant: Lower to middle shoreface.

Sedimentology and Ichnology in Paleoenvironmental Reconstruction

The importance of integrating ichnological and sedimentological attributes to recognize physico-chemical stresses, lithofacies and palaeoenvironments of the rock record cannot be understated. The ichnological response to different stresses provides insight into depositional conditions that alone cannot be determined by sedimentological analysis. An integrated ichnological-sedimentologic approach can effectively recognize various paleodepositional environments, particularly shallow and marginal marine. In the studied succession, the ichnological characteristics indicate a trend wherein the depositional setting evolves from locally brackish, wave-influenced deltaic (prodelta-delta front) to fair-weather and storm-influenced offshore- shoreface. The Wabiskaw Member deltaic deposits (delta-front, prodelta), producing distinctive trace fossils characteristics, distinguishing these deposits from related shoreface deposits. In addition to obvious deltaic traits (syneresis, soft-sediment deformation structures, and fluid mud), the diversity of trace fossils is frequently low in these deposits. The bioturbation intensity is also low in these deposits than their coeval marine counterparts. Individual suites with low ichnodiversity are typical of *Phycosiphon* and *Rosselia* Ichnofacies and may suggest stress associated with salinity fluctuation. The occurrence of fully marine trace fossils (*Asterosoma, Chondrites*, *Phycosiphon,* and *Schaubcylindrichnus)* in these deltaic deposits (F-1, F-2) may indicate a normal marine salinity period within a river induced stress environment. The occurrence of fully marine ichnofossils with stressed suites (*Rosselia* Ichnofacies) characterizes wave-dominated distal delta-front and proximal-prodelta deposits (MacEachern et al., 2005; MacEachern et al., 2008; MacEachern and Bann 2020). The presence of fully marine trace fossils helps distinguish these deltaic deposits from inter-distributary bays and lagoons. On the other hand, entirely marine robust trace fossils characterize strand plain shoreface-offshore complexes with high ichno-diversity and intensity (*Cruziana*- *Skolithos* Ichnofacies). These ichnological signatures are consistent with the sedimentological characteristics and with previous studies on shallow and marginal marine settings (Bann et al., 2004; MacEachern et al., 2005; Coates et al., 2007; Hansen et al., 2007; Bann et al., 2008; Buatois et al., 2008; Dafoe et al., 2010; Dasgupta et al., 2016; Penn-Clarke et al., 2018; Buatois et al., 2019; Collins et al., 2020). Thus, it is crucial to integrate ichnological and sedimentological attributes to recognize physicochemical stresses, lithofacies, and palaeoenvironments within the rock record.

CONCLUSION

An integrated ichnologic-sedimentologic approach is used to investigate the depositional system of the Wabiskaw Member (Clearwater Formation). Two main depositional systems recognized in the studied area based on the ichnological and sedimentological analysis include (i) river and wave-influenced deltas; (ii) wave-dominated strand plain shoreface-offshore complexes. The Wabiskaw Member deltaic deposits (FA-1and FA-2) occur in the lower part. The deposits of FA-1 are shallow marine prodeltaic with *Phycosiphon* Ichnofacies. The ichnological signatures of FA-1 indicate several physicochemical stresses. These include fluctuation in water salinity, freshets induced phytodetrital material, and increased water turbidity. The deposits of FA-2 are river-dominated, storm-influenced delta-front-mouth bar. Ichnological suite belongs to a *Rosselia* Ichnofacies. The ichnological signatures of FA-2 point to high hydrodynamic conditions, high sedimentation rate, and fluvial influence. Following the deltaic depositional phase, wave-dominated strand plain shoreface-offshore complexes developed following the transgression. FA-3 record deposition in an offshore (lower, upper) setting with fully marine trace fossils belonging to *Cruziana* (distal to archetypal) Ichnofacies. The ichnological suite indicates fully marine settings with well-oxygenated, low energy conditions with abundant food. FA-4 records deposition in shoreface (Lower to middle) setting. Ichnologically, the intense bioturbation, high diversity and uniform distribution indicate low sedimentation rates, stable physio-chemical conditions and abundant marine food resources. Thus, integrating ichnology and sedimentology allows for a more accurate and robust determination of the depositional system and the presence of various physicochemical stresses during deposition.

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CHAPTER 3: INTEGRATING SEDIMENTOLOGY AND ICHNOLOGY WITH ROCK TYPING AND FLOW UNITS: IMPLICATIONS FOR CLASTIC RESERVOIR CHARACTERIZATION.

ABSTRACT

Shallow marine clastic reservoir facies prediction, correlation, distribution, thickness, and quality remains a challenge. This study integrates sedimentology and ichnology with reservoir rock typing and flow units to characterize the Lower Cretaceous Wabiskaw Member reservoir. An integrated geologic depositional model was erected using sedimentological data (rock types, sedimentary structures, grain size), ichnological data (trace fossils intensity, size, diversity), reservoir characteristics (porosity, permeability), and well log data. The Wabiskaw Member strata have been characterized using four facies associations (nine sedimentary facies). Facies association 1 (FA-1) comprises dark grey to blue-grey mudstone with a distinctly lenticular appearance (Facies 1, 2). Stressed archetypal Cruziana ichnofacies represent FA-1 ichnologically. Facies association 2 (FA-2) is fine-lower medium-grained sandstone with thin mudstone interbeds (Facies 3, 4). A stressed ichnological suite of mixed Skolithos-Cruziana ichnofacies is present in FA-2. Facies association 3 (FA-3) is dark grey to bluish-grey mudstone with minor sandstone interbeds (Facies 5, 6). Trace fossils of archetypal Cruziana ichnofacies are present in FA-3. Facies association 4 (FA-4) comprises upper fine to lower fine glauconitic sandstone (Facies 7, 8, 9) with high diversity, high-density trace fossil assemblage. FA-1 and FA-2 represent deposition in a wave-influenced prodelta to delta front settings, whereas FA-3 and FA-4 represent deposition in the offshore-shoreface environment. The reservoir quality of various reservoir facies (F-3, F-4, F-7, F-8) is evaluated by comparing facies reservoir characteristics (porosity, permeability, pore throat radii, flow-storage capacity, oil saturation, and thickness). F-4 is the best and most productive reservoir (pore throat radius > 20 µm, 18% flow, and 4 % storage capacity) in the study area. F-7 is ranked second-best in reservoir quality based on petrophysical characteristics (pore throat radius between 10 and 20 µm, 36% storage 47% flow capacity). F-8 is ranked third in reservoir quality with pore-throat radii ranging from 4 to 10 µm (mesoporous), 23% storage, and ≤ 5% flow capacity. F-3 is ranked last amongst the Wabiskaw Member reservoir facies. It is micro-porous (pore-throat radii ranging from 2 to 4 µm) with 37% storage and ≤ 5% capacity flow.

The reservoir characteristics are effectively constrained by the range of values recorded within each facies, demonstrating that a geological model (based upon detailed facies and wireline analyses) allows assessing how lateral facies changes affect the reservoir quality.

Keywords: Sedimentology, Ichnology, Pore throat radii, Storage-flow capacity, Reservoir

INTRODUCTION

Clastic reservoir facies quality, prediction, correlation, distribution, thickness, and lateral changes significantly impact hydrocarbon accumulation. Geological processes (Tectonic, sedimentation, deposition, and diagenesis) affect clastic sediments (size, sorting) and mineral composition, which control the reservoir characteristics of a rock unite (Morad et al., 2010; Xi et al., 2015; Cao et al., 2021). Lateral and vertical facies variations affect reservoir characteristics (storage and flow capacity) due to changes in rock types, mineralogy, and pore network (Fitch et al., 2015; Cao et al., 2017). Bioturbation also plays a crucial role in altering sediment grain distribution and may affect reservoir proprieties (Gingras et al., 2012a). The most significant aspect of characterizing a reservoir is rock typing and flow units, which efficiently unravels heterogeneities in the reservoir (Sfidari et al., 2014; Aliyev et al., 2016; Cao et al., 2017; Mehrabi et al., 2019; Cao et al., 2021). The Lower Cretaceous Wabiskaw Member of Clearwater Formation is a significant bitumen producer in northeast Alberta, Canada. Case studies dealing with the depositional environment of the Wabiskaw Member are scarce, and there is no detailed depositional model. This study integrates sedimentology and ichnology with rock typing and flow units to characterize the depositional environment and reservoir units of the Wabiskaw Member strata in northeast Alberta. This study uses detailed core logging data (documenting sedimentary structures, trace fossils distribution, and the various lithologies present), core analysis data (Porosity, Permeability), and geophysical well logs. This data set allowed us to identify the depositional system, processes of deposition, and reservoir quality. In particular, the primary significance of this study is to: (i) Document different lithofacies and facies associations; (ii) to determine the reservoir properties of the observed lithofacies and (iii) Propose an integrated geological model, that can be used to predict the reservoir units in the study area.

This integrated study effectively addresses the gaps in our geological knowledge of the area and contributes to the prediction and correlation of reservoir distribution, shape, and thickness with greater confidence.

REGIONAL GEOLOGICAL FRAMEWORK

The study area is a part of the Athabasca Oil Sands Deposit (AOSD) and is situated in the Alberta foreland basin in northeast Alberta, Canada. The Alberta foreland basin developed due to tectonic loading (induced by the collision of terranes against North American craton) during the Late Jurassic to Early Palaeocene time (Porter et al., 1982). This lithosphere flexure and subsidence resulted in three major paleo valley systems (Spirit River Valley, Edmonton Valley, and Assiniboia Valley) in the foreland basin. In Assiniboia Valley (McMurray sub-basin in Alberta), the regional salt-dissolution, which resulted in the partial collapse of the strata, most likely created the initial accommodation space before developing the foreland basin. Karstification of Devonian-aged strata (Prairie Evaporite Formation) and subsequent subsidence of overlying rocks (Beaverhill Lake Group) in the McMurray sub-basin modified the paleo topography and impacted sediment distribution during McMurray and Wabiskaw Member deposition (Crerar and Arnott, 2007; Broughton, 2013; Hauck et al., 2017; Schneider and Cotterill, 2017).

The Athabasca Oil Sands Deposit (AOSD) of Canada (northeastern Alberta) has the world's most extensive natural bitumen resources (1.7 trillion barrels estimated oil-in-place) (Energy Resources Conservation Board, 2013). The Lower Cretaceous Mannville group (McMurray Formation and Wabiskaw Member) clastic deposits host the bitumen in northeast Alberta (Figure 3.1. C).

Study Area

The Athabasca Oil Sands (largest), the Peace River Oil Sands, and the Cold Lake Oil Sands are the three significant oil sand deposits of north-central Alberta, Canada (Figure. 1 A). The study area is located in northeast Alberta, in the north-western portion of Athabasca Oil Sands, between Ranges 10 , 14W4 and Townships 95-98 (Figure 3.1 A-B). The Wabiskaw Member (the focus of this study) overlies the McMurray Formation and is overlain by the shale of Clearwater Formation (Figure 3.1 C).

The Wabiskaw Member has received the least attention in the AOSA as it is a secondary reservoir to the McMurray Formation. The Wabiskaw Member has been described mainly as four overlapping, discrete, fine-grained marginal to shallow marine sandstone with basal and partially inter-bedded marine mudstone(Wightman et al., 1997). Various depositional environments are suggested for the Wabiskaw Member in the southern AOSA, which include estuarine tidal channel and valley fill (Wightman et al., 1997), shoreface-attached marine bars (Ranger et al., 1988), barrier bars (Jackson and Masters, 1984), and offshore bars (Bayliss and Levinson, 1976).

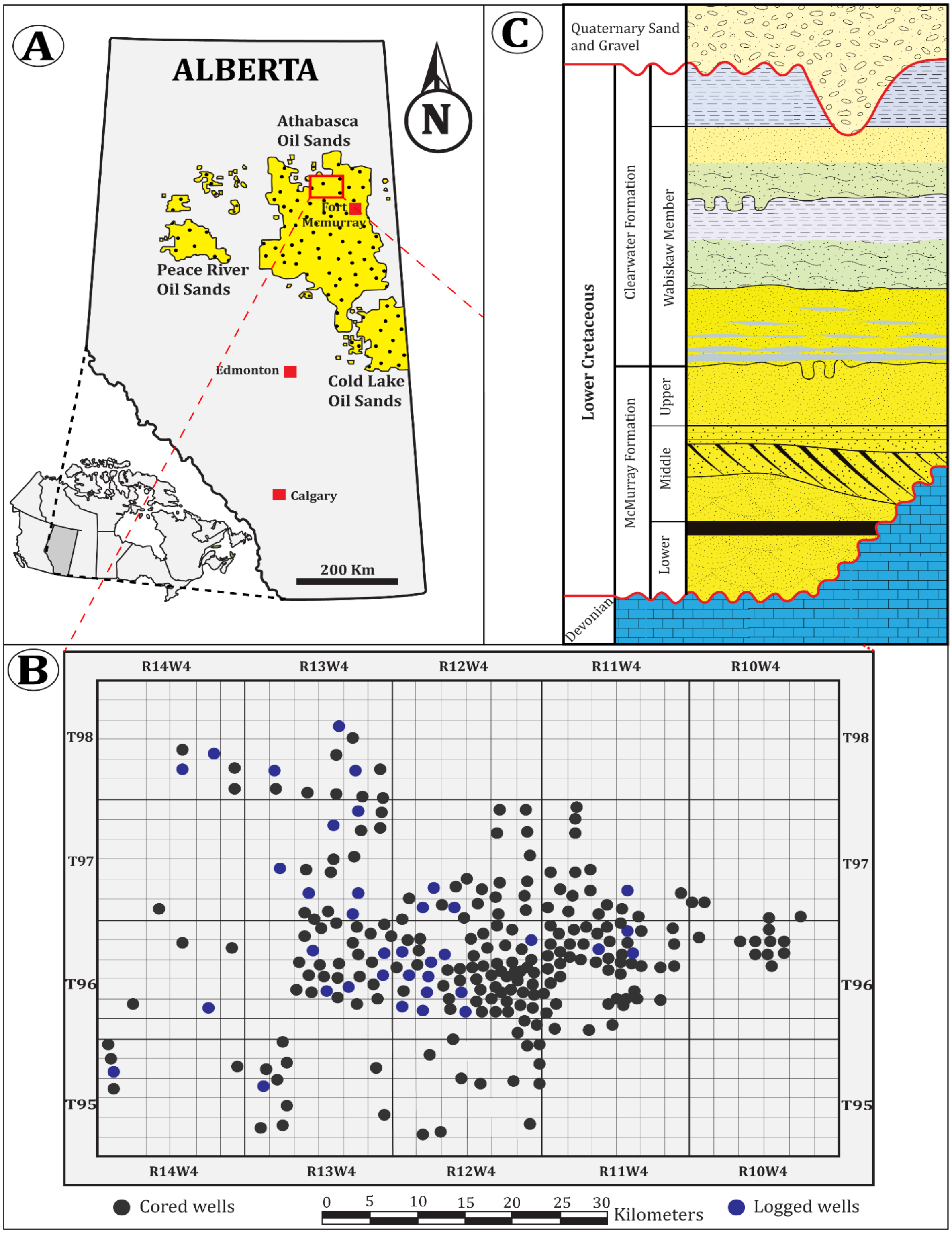


Figure 3. 1 Location Map. A) Geographic location of oil sand deposits of Alberta, Canada. B) Location map showing wells logged within the study and their relation to significant oil sand deposits in Alberta. C) Schematic stratigraphic column of Wabiskaw Member and related strata. The Wabiskaw Member overlies the McMurray Formation and underlies the Clearwater Formation strata. Modified from (Hayes et al., 2017).

DATABASE AND METHODOLOGY

The dataset for this research is primarily core and subsurface wireline. All observations and interpretations of this research come from detailed core logging and integration with petrophysical wireline and core analysis data. The sedimentary facies analysis is based on examining 40 cored wells of Wabiskaw Member in the Athabasca oil sand area in Northeast Alberta, Canada. Litho facies were characterized and classified using dominant rock type, sedimentary structures, contacts, and grain size data (Figure 3.2). Based on sedimentological and ichnological characteristics, a facies and facies associations scheme were erected, leading to paleoenvironmental interpretations (Table 3.1).

We used a petrophysical Winland plot and a graphical Stratigraphic Modified Lorenz Plot (SMLP) method to characterize the Wabiskaw Member reservoir units. Winland established an empirical formula for reservoir properties (porosity-permeability) and pore throat radius using curves (mercury injection-capillary pressure) of various sandstone (316 samples). The Winland plot is a semilog cross-plot that illustrates permeability (mD) verse porosity (%), derived from core analysis, with iso-pore throat lines. Winland showed that the 35th percentile of the mercury injection curve gives the best correlation with rock permeability. (Kolodzie Jr, 1980) published this equation as:

$$\text{Port Radius} = \text{Log } R_{35} = 0.732 + 0.588 \text{ Log } (K) - 0.864 \text{Log } (\varphi)$$

Whereas R_{35} is the pore-throat radius (μm) at the 35th percentile of mercury saturation, K is (permeability in millidarcy), and φ is (porosity in percent). The R_{35} port radius was classified into five flow units (varying in reservoir properties) corresponding to different values of R_{35} (Martin et al., 1997). These flow units are Mega-porous (pore throat radii large than ten μm), Macro-porous (throat radii 2.5-10 μm), Meso-porous (throat radii 0.5-2.5 μm), Micro-porous (throat radii 0.2-0.5 μm) and Nano-porous (throat radii 0.1-0.01 μm). The porosity-permeability data used in the Winland plot is obtained from routine core analysis. The core data set is classified into various rock types using the 35th percentile of the mercury injection curve (R_{35}).

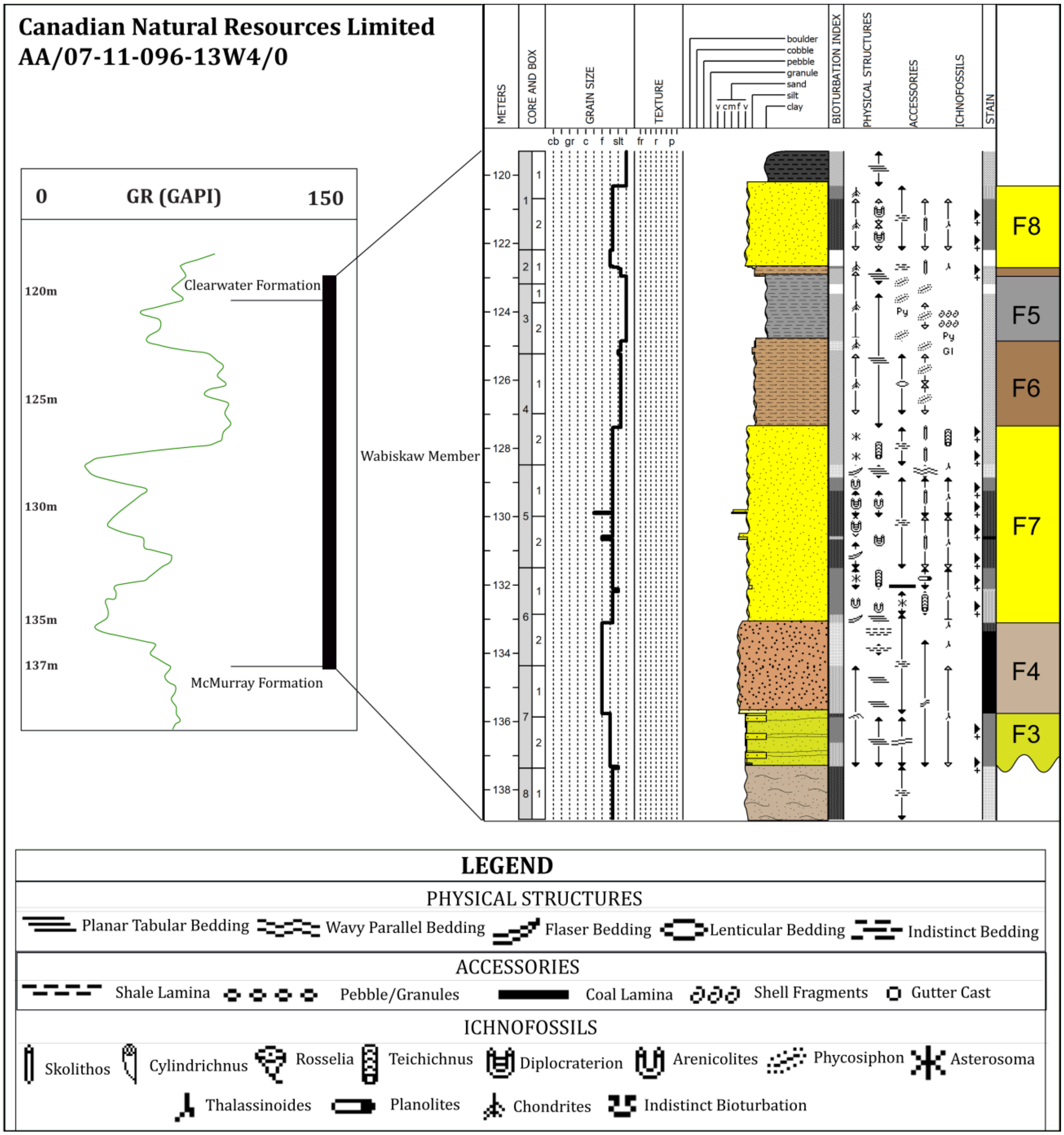
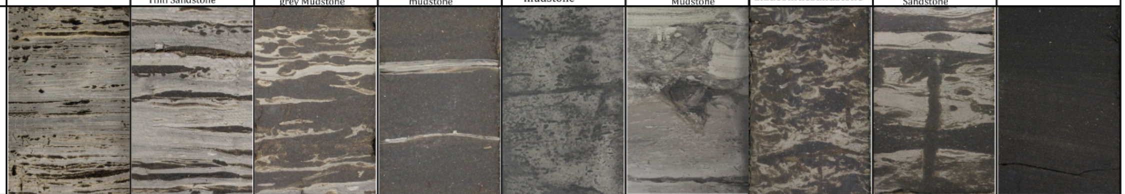


Figure 3. 2 AppleCore© log for well 07-11-096-113W4M, showing the details at which sedimentological and ichnological characteristics were recorded.

SMLP is a graphical tool used to determine reservoir flow units (Gunter et al., 1997). This method plots cumulative flow versus cumulative storage capacity in the stratigraphic sequence (ordered in depth). The porosity-permeability data used in the SMLP is obtained from routine core analysis.

Table 3.1. Summary of lithologic, ichnologic, and sedimentologic attributes of sedimentary facies

Facies	Facies 1(F1) Bioturbated Lenticular Mudstone	Facies 2(F2) Interbedded Blush grey Mudstone and Thin Sandstone	Facies 3 (F3)Heterolith Fine-Grain Sandstone Interbeddedwith blush grey Mudstone	Facies 4 (F4) Fine to medium grained sandstone with thin mudstone	Facies 5 (F5) Dark grey silty mudstone	Facies 6 (F6) Bioturbated Massive Sandyglauconitic Mudstone	Facies 7(F7) Intensly Bioturbated Muddy GlauconiticSandstone	Facies 8 (F8) Bioturbated Silty-Muddy Glauconitic Sandstone	Facies 9 (F9) Massive to planar parallel well sorted sandstone
Typical Core Ecxpression									
Sedimentological Characteristics	Mudstone is laminated to massive. Laminated mudstone is wavy to planar parallel. Sandstone and siltstone is sharp-based and less than 5cm thick. wavy, planar parallel with oscillation and current ripples.Synaeresis cracks soft-sediment deformation.	The mudstone beds are structureless to laminated. Thick mudstone is massive unlaminated. Laminated mudstone beds have thin laminations. Synaeresis cracks, soft-sediment deformation, mudstone drapes. Sandstone is planar to lowangle planar to wavy with some current ripples.	Sandstone and mudstone show rhythmic sedimentation. Mudstone is structureless to laminated. Sandstone is thin (< 5 cm), planar parallel to low-angle planar to paralle wavy bedded. Combined flow ripples and current ripples load and flame structures and synaeresis cracks	Sandstone is massive, wavy, planar parallel to low angle cross stratified. Low angle planar bedding, hummocky cross-stratification, current ripples and climbing ripples. Soft sediment deformation.Thin mudstone laminae. High bitumen saturation	Dark grey to bluish grey mudstone with minor siltstone to fine grained sandstone interbeds. Sandstone and siltstone comprise less than 5% by volume. Mudstone is planar parallel, massive to lenticular. Faint planar, pinstripe, wavy and discontinuous laminae.	Light grey sandy glauconitic mudstone to very fine grained sandstone. Low angle planar to horizontal and wavy to lenticular bedding. Wave and current-ripple cross-laminations. Bitumen saturated. Sandstone is planar parallel, hummocky,wave ripple cross stratified.	Fne to very fine glauconitic sandstone, glauconite import a distinctive green blue color to this facies. Light steel grey to blue mudstone interbeds may occur at the base. The sandstone and mudstone are homogenized by high intensity bioturbation. low angle planar to horizontal and wavy to lenticular beds	Sandy to silty, wavy mud laminae of light steel grey to blue in color occur at the base. Silt and mud decrease, while sand incrase upward. Upward coarsening and cleaning package. wave ripple lamination, thin trough, and hummocky cross-stratification. good bitumen saturation.	Well sorted, fine to medium grained sandstone moderately to strongly saturated with bitumen. Mudstone laminae are rare occur as filling and lining of burrows. Sandstone appears is massive, planar horizontal laminated. Low angle planar, hummocky and swaley cross-stratified.
Ichnological Characteristics	BI: (1-4). Bioturbation is weak to moderate. impoverished trace-fossil suite. Traces include: *Ar, As, Ch, Cyl, Dp, Lo, Pl, Rhi, Sk, Te* and *Th*	BI: (0-2). Bioturbation is sporadic. Diversity of trace fossils is low to moderate. Traces present, include: *Ar, As,Cy, fu, Pa,Pl, Si, Sk,* and *Th.*	BI: (0-3). Bioturbation is sporadic. Diversity is moderate. Trace fossil suite include: *Ar, As,Cy, Dpl,fu,Pa,Pl, Ma, Si,Sk,Te,* and *Th.*	BI: (0-2). Bioturbation is very sporadic.Low abundance and low diversity trace fossil assemblage include :*Pl, Th, Op* and *fu.*	BI: (2-4). Common traces include: *Ch* with subordinate *Phy, He,* and *Co.* Small *Te, Th, Sk, As,Pl* and *Zo.*	BI: (3-5). Bioturbation moderate to high. Trace fossil suite includes: *Phy, Ro, Cyl, As, Sc Te,Pa, Pl, Sk, Zo* and *Dp.*	BI: (3-6). High diversity, high density trace assemblage. Traces include: *Ch, Di,Pl Sk,Ti,Tha,Zo, As* and *Ro.*	BI: (3-5). Hhigh abundance and high diversity traces. Traces are: *As,Ch, Dp,Pl, Sk Sc,Th,* and *Te.* subordinate *Ro* and *Op.*	BI: (0-3). Bioturbation is very sporadic. Trace fossil assemblage include: Robust *Ro,As, Cyl, Op, Dp, Pl Sk,* and *Th.*
Lithological Accessories	Lithological accessories are rare and include siderite, glaucony, organic fragments, pyrite	Pebbles, mudstone rip-up clasts, shell debris, phytodetrital material, coal laminae, pyrite nodules	Lithological accessories include mud rip-up clasts, carbonaceous material, granules and coal fragments.	Thin mud laminae, glauconite, coal and carbonaceous material, sideritized zones, scour surfaces and gutter cast.	Shell fragments, pyrite nodules, siderite sand laminae, quartz crystals and coal fragments.	Lithological accessories include: glauconite laminae and grains, pyrite and siderite.	Lithological accessories include glauconite and pyrite. Bitumen saturation is good	Lithological accessories include glauconite and pyrite.	Thin mudstone laminae and rip-up clasts. pyrite and siderite. Coal and carbonaceous fragments.
Environmental Stresses	Rapid deposition, periodic hyperpycnal flows, event bed deposition, salinity flucation.	Rapid deposition, periodic hyperpycnal flows, event bed deposition, periodic salinity flucation.	Shifting substrate,rapid deposition, hyperpycnal flows, event bed deposition, periodic salinity flucation, strom influence	Shifting substrate, high current energy, rapid deposition, flucating salinity, wave reworking, strom influence	Well-oxygenated fully marine settings, lowered hydrodynamic conditions. Abundant food resources normal marine salinities. Reduced deposition rates	Fully marine settings, Abundant food resources normal marine salinities. Reduced deposition rates strom influence, event bed deposition.	Moderate to high energy, Stable chemical conditions. Abundant food resources, low sedimentation rates.	Moderate to high energy, Stable chemical conditions. Abundant food resources, low sedimentation rates.	High current energy, rapid deposition, wave reworking, strom influence
Facies Association	FA1		FA2		FA3		FA4		
Environmental Interpretation	Distal Prodelta	Proximal Prodelta	Distal Delta Front	Proximal Delta Front	Lower Offshore	Upper Offshore	Distal Lower Shoreface	Lower Shoreface	Middle Shoreface

Abbreviation Key

Trace Fossils

Ar-Arenicolites
As-Asterosoma
Ch-Chondrites
Cy-Cylindrichnus
Di-Diplocraterion
Fu-Fugichnia
He-Helminthopsis
Lo-Lockeia
Ma-Macaronichnus
Op-Ophiomorpha
Pa-Palaeophycus
Ph-Phycosiphon
Pl-Planolites
Rh-Rhizocorallium
Ro-Rosselia
Sc-Scolicia
Si-Siphonichnus
Sk-Skolithos
Te-Teichichnus
Th-Thalassinoides
Zo-Zoophycos

Bioturbation Index

0- Bioturbation Absent
1-Saprse Bioturbation
2-Uncommon Bioturbation
3-Moderate Bioturbation
4-Common Bioturbation
5-Abundant Bioturbation
6-Complete Bioturbation

RESULTS

Sedimentary Facies Associations Description

Nine distinct lithofacies (F-1-F-9) were identified in cores (Figure 3.3-3.6). Table 3.1 shows the detailed description of each lithofacies with their depositional interpretation. Facies division is based on the observed sedimentological and ichnological characteristics. Four leading facies associations (Table 3.1, Figure 3.3-3.6) record deposition in shallow-marine depositional environments in the study area. The facies associations are FA-1- shallow marine (prodelta), FA-2- shallow marine (delta front and mouth bar), FA-3- shallow-marine (offshore), and FA-4- shallow marine (lower to middle shoreface).

Facies association 1 (FA-1) comprises dark grey to blue-grey mudstone with a distinctly lenticular appearance. FA-1 was formed in prodelta environments, comprising distal and proximal prodelta, and are ichnologically represented by stressed archetypal Cruziana ichnofacies. FA-1 was observed in the lower part of Wabiskaw Member. Its lower contact with McMurray Formation is sharp and erosional, but upper contact with FA-2 is gradational. FA-2 is present in the south-southeast part and records progradational depositional geometry.

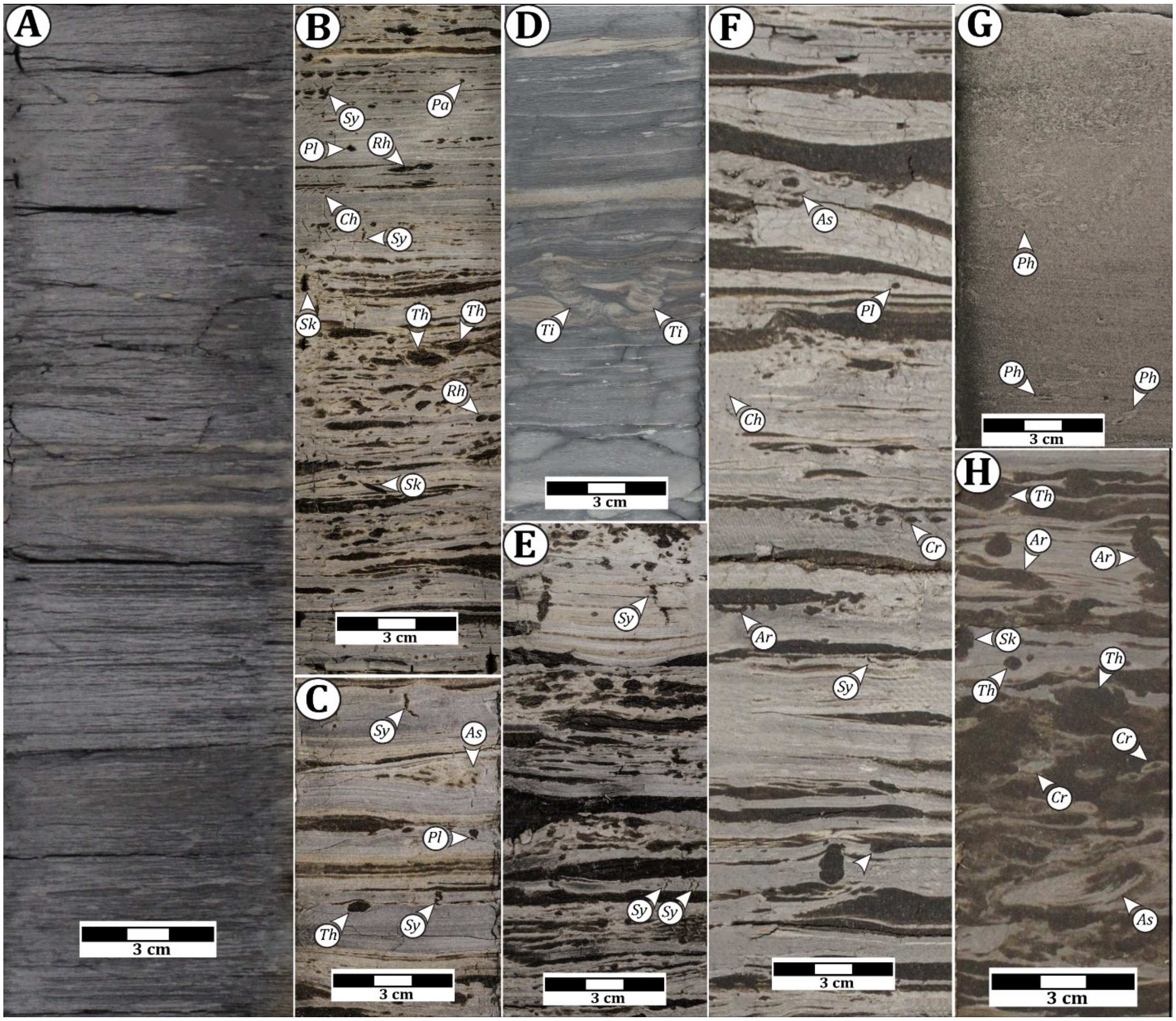


Figure 3. 3 Core photographs of Facies 1 and Facies 2 from the Wabiskaw Member. All depths represent core depths. A-D) Facies 1, bluish-grey mudstone with planar laminae and thin sand interbeds. A) Facies 1, bluish-grey mudstone (well 07-09-097W4M; 264.9 m). B. Facies 1, lenticular, bioturbated mudstone with fuzzy planar laminae due to bioturbation (well 12-20-096-12W4M; 115m). C) Facies 1 with syneresis cracks (well 10-17-096-12W4M; 73.10 m). D) Facies 1, bluish-grey mudstone with planar laminae and thin sand interbeds (well 07-09-097W4M; 262.30 m). E) Facies 2 with syneresis cracks (well 10-17-096-12W4M; 70.58m). F) Typical core expression of F-2 showing bioturbated lenticular mudstone with soft-sediment deformation features (arrow) (well 12-34-096-11W4M; 69m). G, H) Highly bioturbated expressions of Facies 2 (BI 3-4) (well 12-34-096-11W4M; 68.10m).

FA-2 consists of (F-3, F-4) of interbedded sandstone (fine to lower medium-grained) and thin mudstone. The proportion of mudstone decreases with a corresponding increase in sandstone upwards in FA-2. Sedimentary structures include wave, combined flow, and rare current ripples. Bioturbation intensity in FA-2 is low to moderately with low diversity and intensity trace fossil suite. Based on the observed attributes, FA-2 records deposition in a delta-front environment. FA-2 is observed in the basal part of the Wabiskaw Member. Its lower contact with FA-1 is gradational. Where FA-1 is not present, the lower contact of FA-2 with McMurray Formation is sharp and erosional, while its upper contact with FA-3 is also erosional (Figure 4). FA-2 can be found all over the study area and records progradational depositional geometry with delta lobes extending and thickening towards the north-northwest (Figure 3.9–3.10).

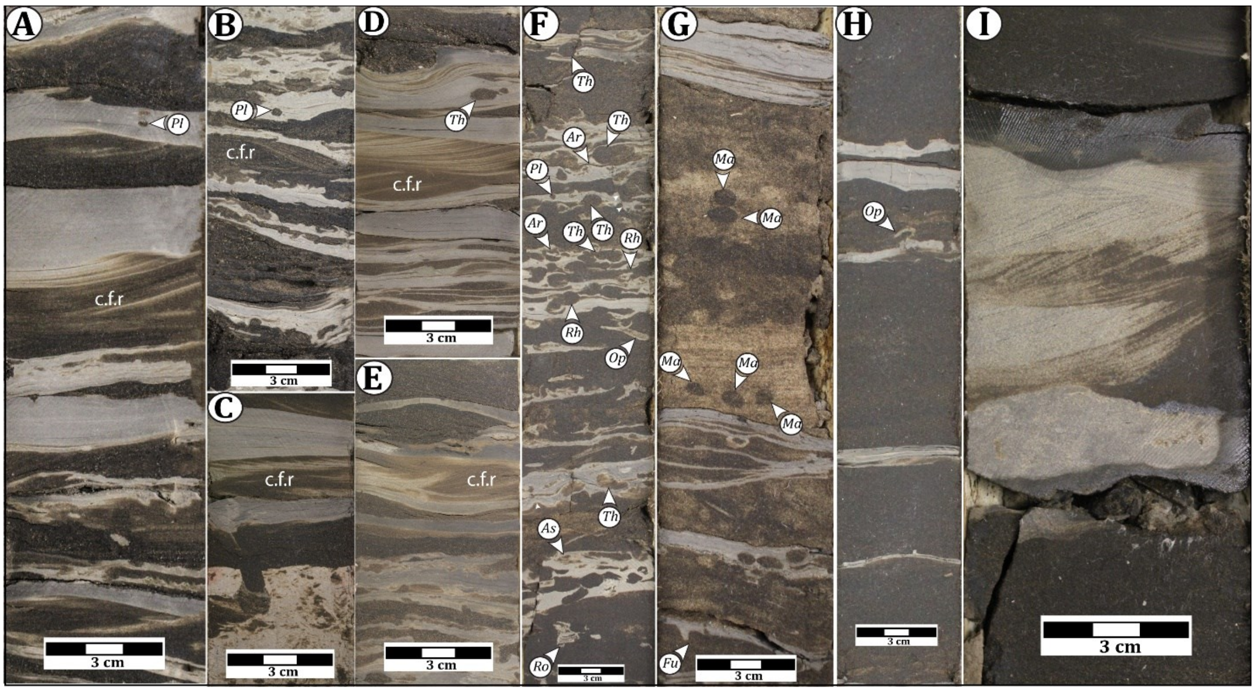


Figure 3. 4 Core photographs of Facies 3 and Facies 4 from the Wabiskaw Member. All depths represent core depths. A) Typical core expression of F-3 showing combined flow ripples (cfr), and Planolities Trace fossil (well 08-28-096-11W4M; 65.80m). B) Oil-stained F-3 sandstone with low-angle and combined flow ripples indicating wave-reworking. Trace fossil Planoloties and soft-sediment deformation features are also present (well 01-27-096-11W4M; 35.10m). C) Bioturbated contact of F-3 with underlying McMurray Formation (well 12-34-096-11W4M; 69.30m). D, E) Interbedded sandstone and mudstone of F-3. Note that the sandstone is combine flow rippled, oil-stained and bioturbated, whereas the mudstone is structureless with some thin internal laminations. (well 08-28-096-11W4M; 65.85m). F) Typical core expression of F-4 with moderate to high bioturbation. Well 12-34-096-11W4M; 60.40m. G) Cluster of Macaronichnus traces in clean sandstone of F-4. Fugichnia is also present (well 12-34-096-11W4M; 61.50). H) Low bioturbated (BI 0-2) expression of F-4 with mud drapes and ophiomorpha trace fossil (well 06-17-097-13W4M; depth 416m) I) Trough ripple fore sets and homogeneous wavy parallel bedding in F-4 (well 08-28-096-11W4M; 64.60m).

Facies association 3 (FA-3) is dark grey to bluish-grey mudstone with minor siltstone interbeds. The mudstone is planar parallel, massive to lenticular bedded. Occasional storm beds with hummocky stratification do occur. Sideritized zones commonly occur near the contact of FA-3. FA-3 is moderate to highly bioturbated. The ichnological suite represents archetypal Cruziana Ichnofacies. FA-3 consists of facies (F-5–F-6) and record deposition in the offshore environment. FA-3 is observed in the lower to the middle section of Wabiskaw Member and occurs uniformly throughout the study area. FA-3 is aggradational to retro-gradational in depositional geometry, increasing thickness and lateral distribution towards the south-southeast (Figure 3.9–3.10).

Facies association 4 (FA-4) comprises fine to lower fine glauconitic sandstone. Light steel grey to blue mudstone interbeds may occur. The sandstone and mudstone beds are homogenized by bioturbation. FA-4 is characterized by high diversity, high-density trace assemblage. This trace fossil suite represents aCruziana ichnofacies (proximal expression). FA-4 consists of facies (F-7–F-9) and record deposition in shoreface (distal lower to the middle) environment. FA-4 is observed in the lower and upper parts of Wabiskaw Member and occurs uniformly throughout the study area. Its lower contact with underlying facies associations is bioturbated and sharp, while its upper contact with clear water mudstone is transitional. This facies association also displays general aggradational and retro-gradational depositional geometry, increasing thickness and lateral distribution towards the south-southeast (Figure 3.9–3.10).

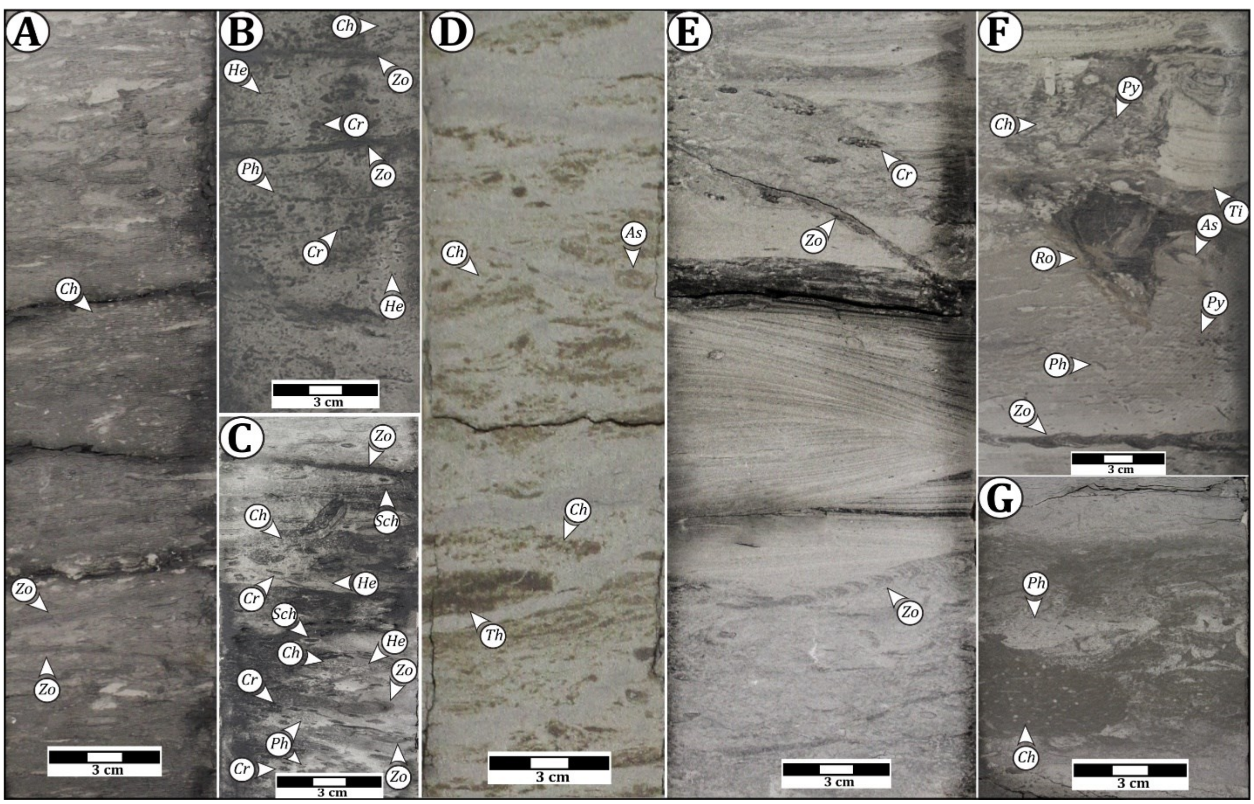


Figure 3. 5 Core photographs of Facies 5 and Facies 6 from the Wabiskaw Member. All depths represent core depths. A) Typical core expression of Facies 5, dark grey silty mudstone with indistinct laminae due to bioturbation (well 02-19-096-10W4M; 101m). B, C Intensely bioturbated (BI 5-6) Facies 5 with indistinct bedding due to bioturbation (well 08-28-096-11W4M; 57.21m). D) Typical core expression of Facies 6, bioturbated, massive sandy, glauconitic mudstone with indistinct bedding due to bioturbation (well 04-07-096-12W4M; 85m). E)

Intensely bioturbated (BI = 5–6) sandy mudstone and sparsely bioturbated (BI=0–1), hummocky cross stratified sandstone deposits (well 08-28-096-11W4M; 53.90m). F, G) Fairweather, intensely bioturbated (BI = 5–6) sandy mudstone with high ichnodiversity (well 08-28-096-11W4M; 53.50m).

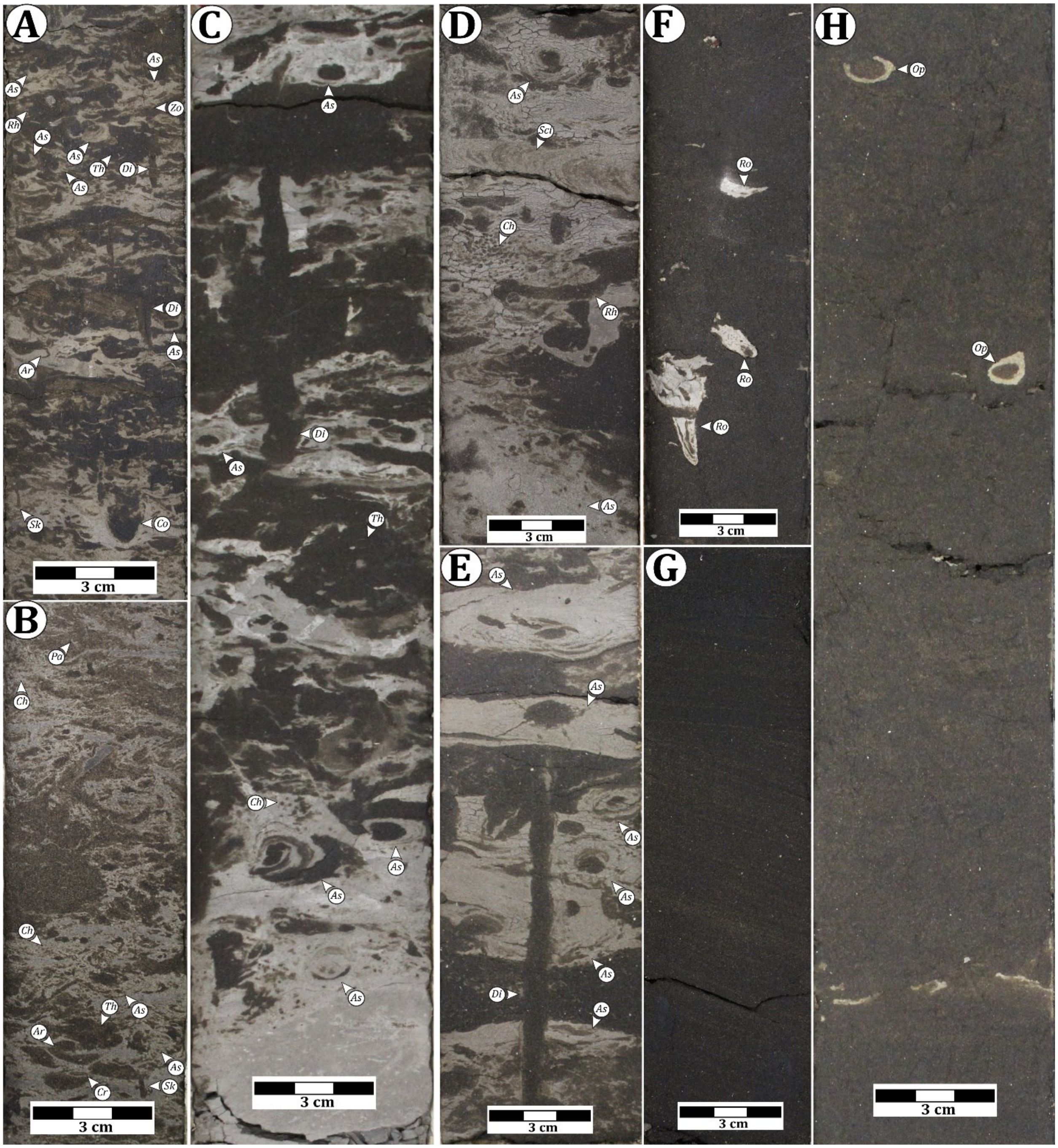


Figure 3. 6 Core photographs of Facies 7, Facies 8, and Facies 9 from the Wabiskaw Member. All depths represent core depths. A, B) Typical core expression of Facies 7, intensely bioturbated muddy glauconitic sandstone (well 11-14-096-14W4M; 257.09 m). C) Typical core expression of Facies 8, bioturbated silty, muddy glauconitic sandstone with robust common Asterosoma traces. Well 02-19-096-12W4M; 96.2m. D, E) Robust trace fossils (robust Asterosoma, Chondrites, Rhizocorallium, and Scolicia and Large Diplocreterian) in Facies 8 (well 07-11-096-13W4M; 122.20 m). F) Typical core expression of Facies 9, Massive to planar parallel well-sorted sandstone with robust Rossilia Traces (well 10-12-098-14W4M; 538.9m). G) Planar parallel to low angle cross-stratified sandstone

of F-9 (well 08-07-098-13W4M; 434.1m). H) Massive, oil-saturated sandstone of F-9 with robust Ophiomorpha traces (well 08-07-098-13W4M; 432.5m).

Reservoir Characteristics

Various facies of Wabiskaw Member are the reservoir, including F-3, F-4, F-7, and F-8 (Table 3.2, Figure 3.7-3.8). The reservoir facies are ranked based on petrophysical (porosity and permeability) data (derived from routine core analysis), oil saturation values (estimated in core logging), and reservoir thickness (derived from core logging and wireline log data) (Table 2). Statistical analysis of petrophysical data (permeability and porosity) have been summarized, which are the most valuable reservoir modeling and flow simulation parameters (Table 3.2). A petrophysical Winland plot and a graphical Stratigraphic Modified Lorenz Plot (SMLP) method characterize the Wabiskaw Member reservoir units.

Table 3. 1 Summary of permeability, porosity data, oil saturation, and reservoir thickness

<table>
<tr><th>Facies</th><th>Reservoir Properties</th><th colspan="9">Statistical Analysis</th></tr>
<tr><td rowspan="5">F-3</td><td rowspan="2">Permeability</td><td>Range</td><td>Mode</td><td>Median</td><td>Standard deviation</td><td>Arithmetic mean</td><td>Harmonic mean</td><td>Geometric mean</td><td>Max</td><td>Mini</td></tr>
<tr><td>203.8</td><td>104, 55</td><td>93.5</td><td>39.177</td><td>98.716</td><td>64.29711439</td><td>87.544</td><td>212</td><td>8.2</td></tr>
<tr><td>Porosity</td><td>23.1</td><td>28.2</td><td>28.2</td><td>4.555</td><td>27.333</td><td>26.14712386</td><td>26.835</td><td>34.9</td><td>11.8</td></tr>
<tr><td>Oil Saturation</td><td colspan="9">Low and patchy oil saturation (~10%).</td></tr>
<tr><td>Effective Thickness</td><td colspan="9">Maximum effective thickness is up to 6.16m.</td></tr>
<tr><td rowspan="4">F-4</td><td>Permeability</td><td>3506</td><td>2974, 2689,3754, 3178, 2784</td><td>2765</td><td>1021.907</td><td>2576.418</td><td>1919.55973</td><td>2287.599</td><td>4240</td><td>734</td></tr>
<tr><td>Porosity</td><td>12.1</td><td>31.2</td><td>31.9</td><td>2.992</td><td>31.990</td><td>31.71225631</td><td>31.851</td><td>38.1</td><td>26</td></tr>
<tr><td>Oil Saturation</td><td colspan="9">Very high oil saturation (saturation > 60%)</td></tr>
<tr><td>Effective Thickness</td><td colspan="9">Effective thickness of the reservoir can reach 11.01m.</td></tr>
<tr><td>F-7</td><td>Permeability</td><td>905</td><td>821</td><td>821</td><td>259.029</td><td>720.107</td><td>496.475008</td><td>636.110</td><td>1000</td><td>95</td></tr>
</table>

	Porosity	11.9	36.5, 37.9	32.45	3.258	32.860	32.54425385	32.701	39	27.1
	Oil Saturation	high (~30–60%) oil saturation								
	Effective Thickness	Effective reservoir facies thickness may reach up to 7.24m.								
F-8	Permeability	99	69, 11.7, 65,	72.5	26.567	65.876	17.0921014	52.085	100	1
	Porosity	14.7	29, 35.2, 32.3	31.5	3.753	30.615	30.10532127	30.369	35.8	21.1
	Oil Saturation	Medium oil saturation (~10–30%)								
	Effective Thickness	Effective reservoir facies thickness may reach up to 4.64m.								

Windland plot

The Windland plot, core analysis (porosity and permeability) data overlap slightly and do not show complete segregation into groups. Despite overlapping, the petrophysical (porosity and permeability) data is classified into four groups (Figure 3.1). The Windland plot indicates that large (Mega, Macro) pores decrease from RT-I to RT-IV.

Rock type 1 (RT-I) on Winland plot (Facie 4) is mega-porous (throat radii large than 20 µm), upper-medium to fine-grained sandstone with high oil saturation (very high saturation > 60%). F-4s reservoir characteristics (porosity and permeability) vary from 26-38.1 (%) and 734–4240 mD, respectively (Figure 3.2). The effective thickness of the lithofacies may reach 11.01 m. Rock type 2 (RT-II) on Winland (Facie 7) is macro-porous (throat radii 10-20 µm), is upper fine-grained sandstone with high (~30–60%) oil saturation. Petrophysical characteristics (porosity and permeability) of RT-II vary from 27.1-39 (%) and 95–1000 mD, respectively (Figure 3.3). Effective reservoir facies thickness may reach up to 7.24m. Rock type 3 (RT-III) on Winland plot (Facies F-8) is mesoporous (throat radii 4-10 µm), upper to lower fine-grained sandstone with medium oil saturation (~10–30%). Reservoir properties (porosity and permeability) of RT-III vary from 11.8-34.9 (%) and 8.2-212 mD, respectively (Figure 3.4). Effective reservoir facies thickness may reach up to 4.64m. Rock type 4 (RT-IV) on the Winland plot (Facies 3) is micro-porous (throat radii 2-4 μm). RT-IV mainly comprises thick, typically sharp-based mudstone interbedded with lower fine-grained sandstone with patchy oil saturation (~10%). Reservoir properties (porosity and permeability) of RT-IV vary from 21.1-35.8 % and 1-100 mD (Figure 3.5).

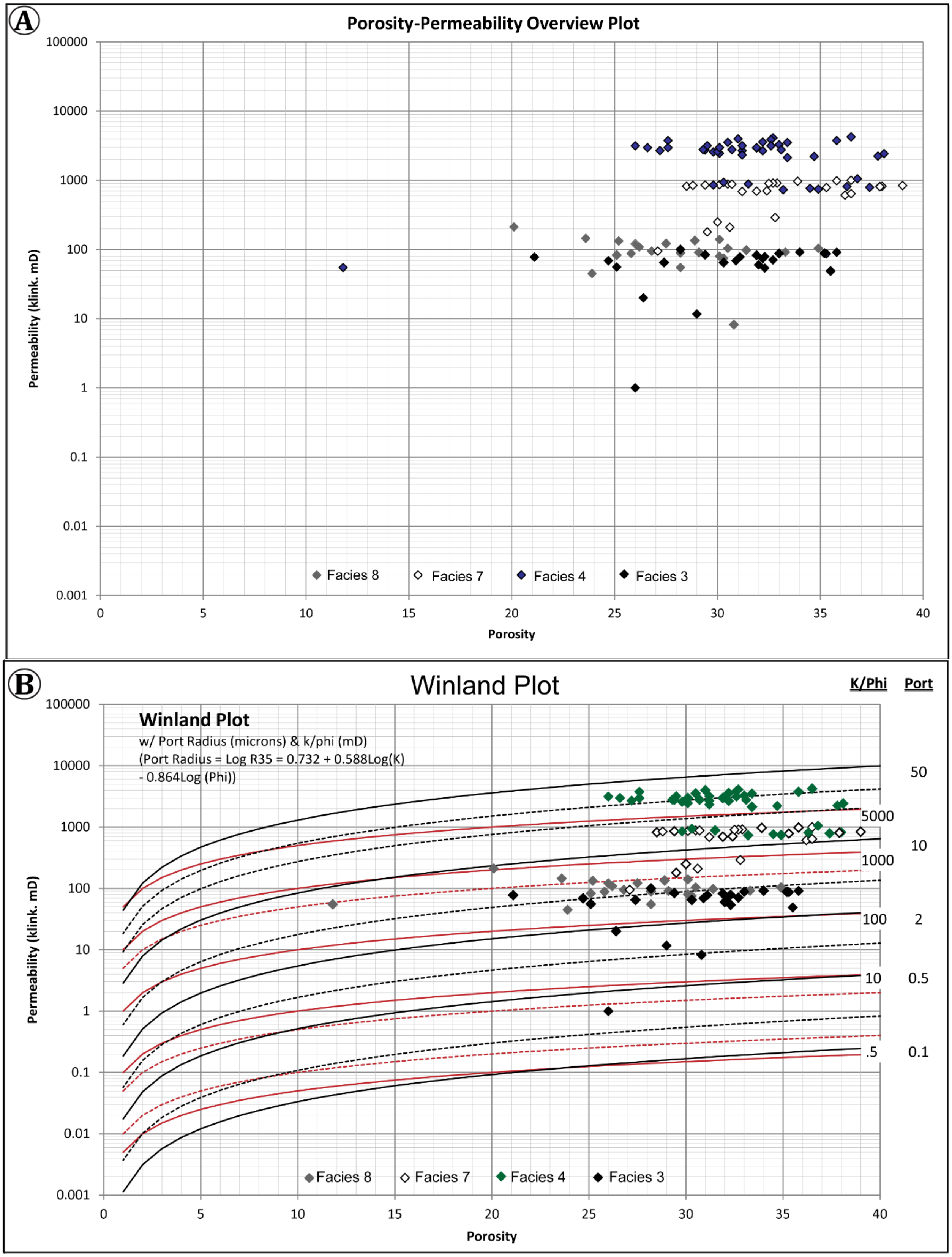


Figure 3. 7 A) Core permeability vs. core porosity of lithofacies. B) Reservoir rock types resulted from the Winland R35 rock typing method

Stratigraphic Modified Lorenz plot (SMLP)

In the SMLP, the key to describing a flow unit is to recognize the flow unit via its slop. The portion of the plot with steep slopes has greater reservoir flow capacity. Consequently, these segments are the conduits (speed zones). The flat, horizontal section of the plot has storage capacity but little flow capacity. These horizontal segments are baffles (zones that strangle fluid movement). The plot portion that has no flow or storage capacity is barriers (seal to flow). The steps used to construct SMLP are:

1. Data was depth sorted. Parts with a steep slope have more flow capacity than storage capacity, resulting in a faster reservoir process (fast reservoir zones).
2. The storage (Porosity thickness) and flow capacity (Permeability thickness) were calculated for each porosity permeability data in the routine core analysis on a foot-foot basis.
3. The SMLP plotted the storage capacity (percent) versus the flow capacity (percent).
4. Each flow unit was validated with the Winland method and core logging in the entire reservoir column in each well.
5. Each inflection points indicate initial flow units, leading to the assessment of reservoir flow. Steep slopes show faster flow, whereas gentle to no slope segments point to little or no flow. The constant 45-degree slope of the storage capacity means the uniform distribution of the storage capacity throughout the reservoir. Equal contribution from all pores to the flow (Inter-particle porosity) is inferred when the two lines overlap or plot closely. Unequal contribution from pores to the flow (intra-particle porosity) assumes that the two lines do not overlap and plot separately.

The SMLP was constructed for three wells in the study area. Figure 3.8 displays SMLP for wells (well_05-21-96-13w4, well_09-16-96-13w4, well_09-04-97-12w4). Four distinct flow units were distinguished in two wells (well_05-21-96-13w4, well_09-16-96-13w4), whereas five flow units were identified in one well (well_09-04-97-12w4) based on the inflection points in SMLP curves. Flow unite 3 on SMLP (Facies 4) has 18% flow and 4 % storage capacity and is the most productive (Figure 3.8). This unit (3), with very little to no variation in slop, is the speed zones and includes 45% of flow capacity and 25% storage capacity (Figure 3.8). Flow unit 2 on SMLP (Facie 7) has a constant 45-degree trend, with 47% flow capacity and 36% storage capacity (Figure 3.8). Flow Unit 4 on SMLP (Facies 8) is baffle (Tight zone) with 23% of storage and less than 5% flow capacity (Figure 9 B). Flow Unit 1 on SMLP (Facies 3) also baffle (Tight zone) with 37% of storage and less than 5% flow capacity (Figure 3.8 B).

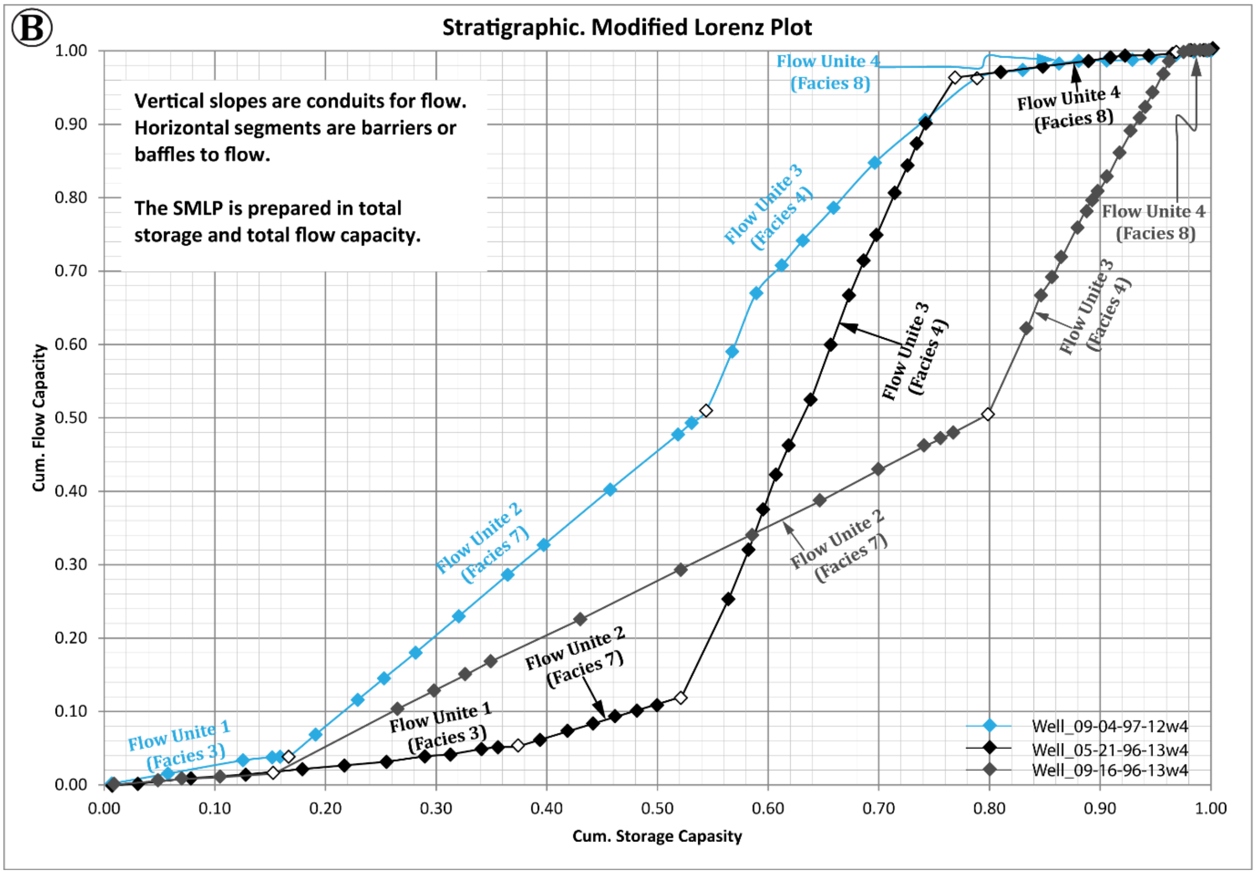


Figure 3. 8 SMLP showing various flow units in wells (well_05-21-96-13w4, well_09-16-96-13w4, and well_09-04-97-12w4).

INTERPRETATION AND DISCUSSION

Ichnologic-Sedimentologic Facies Model

The integrated ichnologic-sedimentologic approach allows for a more robust and accurate determination of the depositional system. Shallow marine prodelta deposition is represented by facies association1 (FA-1). FA-1 is comprised of dark grey to blue-grey mudstone with a distinctly lenticular appearance. Ichnologically, FA-1 is represented by stressed archetypal Cruziana ichnofacies. The ichnological suite includes mainly grazing and deposit-feeding traces and rare suspension-feeding traces, representing moderately stressed archetypal *Cruziana* ichnofacies. The impoverished *Cruziana* ichnofacies assemblage with diminutive trace fossil points to heightened deposition rate, water turbidity, and fluctuating salinity (Maceachern et al., 2005; Buatois et al., 2008). These stresses (Physico-chemical) were affecting the benthic community resulting in low bioturbation intensities and small traces (Gingras et al., 1998; Gingras et al., 2002; MacEachern et al., 2005; Gingras et al., 2007; MacEachern et al., 2007a; MacEachern et al., 2007b; Buatois et al., 2008; Buatois and Mángano, 2011). In conjunction with heightened deposition rate, fluvial influx, and moderately stressed archetypal Cruziana Ichnofacies, the fine-grain nature points to deposition in the prodelta environment (Figure 3.9).

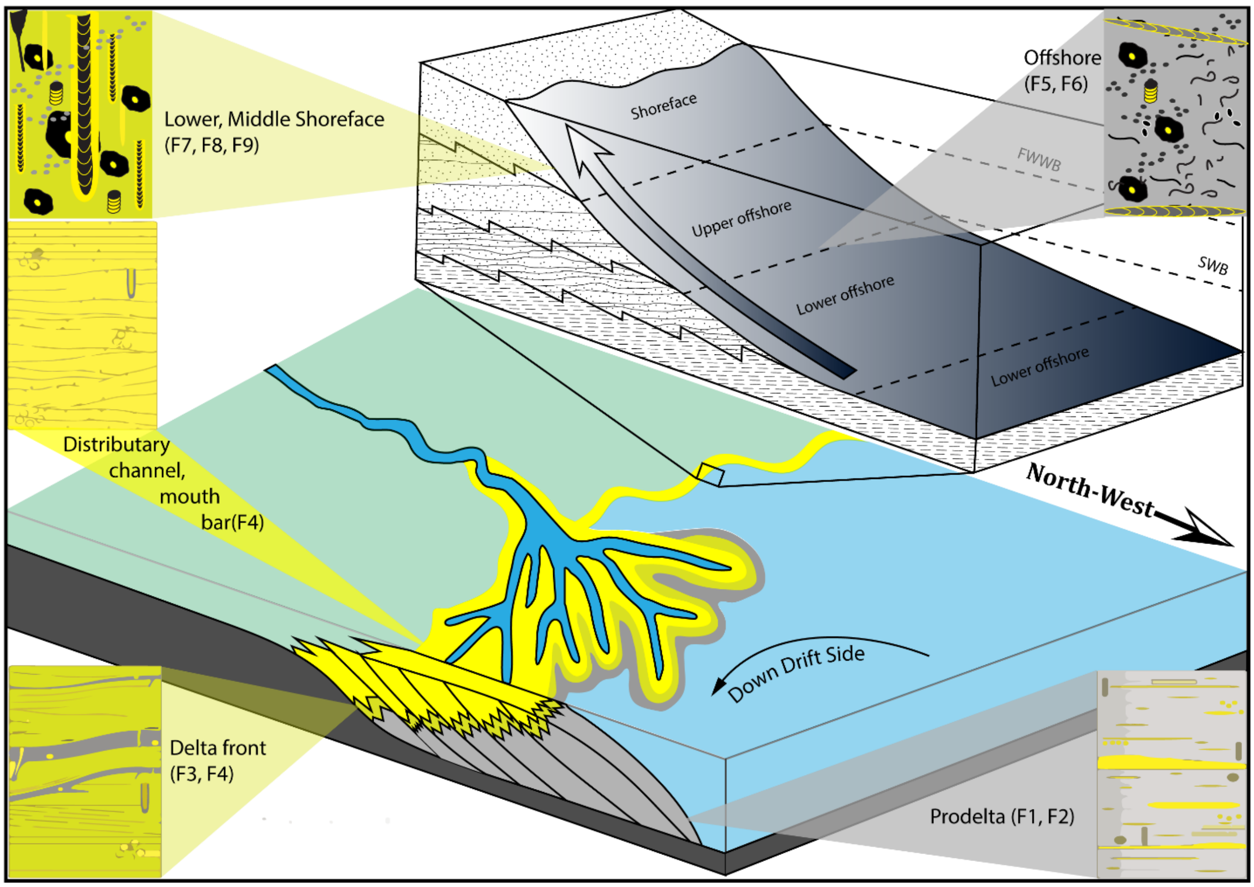


Figure 3. 9 The proposed geological model for the Wabiskaw Member strata.

The FA-2 represents Wabiskaw Member wave-influenced delta front and mouth bar deposits. FA-2 consists of fine to lower medium-grained sandstone interbedded with thin mudstone (1-15%). The stressed ichnological suite of mixed Skolithos-Cruziana ichnofacies (*Arenicolites*, *Cylindrichnus,* *Diplocraterion*, *Palaeophycus,* *Planolites,* *Macaronichnus*, *Ophiomorpha,* *Siphonichnus,* *Skolithos,* *Teichichnus*, and *Thalassinoides*) is present. Low bioturbation intensities (0-3) and low ichno-diversity are interpreted to reflect environmental stress. The presence of profuse deposit-feeding traces and few suspension-feeding traces indicates a stressed *Cruziana (*proximal expression) and the *Skolithos* Ichnofacies (Pemberton et al., 1995; MacEachern et al., 1999). Diminutive trace fossils (*Ophiomorpha*) indicate reduced salinity (Pemberton, 1992; Buatois and Mángano, 2011). Proximal delta front and mouth bar (F-4) show low ichno-diversity, the abundance of *Skolithos* like simple deposit feeders, and the dominance of *Skolithos* Ichnofacies with elements of the depauperate *Cruziana* Ichnofacies. The ichnological characteristics (bioturbation index, trace fossil size, ichnodiversity) indicate moderate physicochemical stress. The presence of abundant *Macaronichnus* indicates high-energy, shallow water conditions with abundant food resources and high deposition rates (Saunders et al., 1994; Pemberton et al., 2012; Shchepetkina et al., 2020), also point to deposition in a delta front setting. High-energy conditions, heightened deposition, proximity to a fluvial source, sandy nature, evidence of fluvial influx, and a stressed trace fossils suite of mixed *Skolithos*-*Cruziana* ichnofacies all point to deposition in the delta front environment (Figure 3.9). FA-3 is dark grey to bluish-grey glauconitic mudstone with minor sandstone interbeds. The mudstone is unbioturbated to highly bioturbated and forms a continuous upward fining succession. This lithofacies association represents low energy offshore deposits with continuous deposition under quiescent, fully marine conditions with periodic storm influence. Bioturbation intensity and ichnodiversity are low to high. Trace fossils include trophic generalist traces of grazing/foraging (*Helminthopsis*), deposit-feeding (*Asterosoma, Chondrites, Cosmoraphe Teichichnus, Phycosiphon, Planolites, Skolithos, Thalassinoides,* and *Zoophycos*), and passive carnivores (*Palaeophycus*). This ichnological assemblage is associated with the distal to an archetypal expression of *Cruziana* Ichnofacies (MacEachern et al., 2008). These observations support deposition in the offshore environment. The fair weather, intensely bioturbated (BI = 5–6) mudstone and storm-generated, hummocky and planar parallel laminated sandstone deposits (sparsely bioturbated BI=0–1), all point to deposition in a storm-affected offshore environment at depths above storm wave base (Figure 9) (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011; Pemberton et al., 2012; Baniak et al., 2014).

FA-4 comprises fine to lower fine glauconitic sandstone with light steel grey to blue mudstone interbeds at the base. The sandstone and mudstone beds are homogenized by bioturbation. FA-4 records deposition in a moderate to high energy environment, relatively stable chemical conditions with abundant food resources (Lower to middle shoreface). Ichnologically, the increased diversity, high-density trace assemblage (BI: 3-6), and homogenous distribution of trace fossils suggest low sedimentation rates. The presence of fully marine trace fossils (Asterosoma, Rhizocorallium, and Scolicia) indicates stable chemical conditions (MacEachern et al., 2010; Gingras et al., 2012b). The dominance of deposit feeders (*Arenicolites, Asterosoma, Chondrites, Teichichnus, Planolites*, *Scolicia,* and *Thalassinoides*) points to abundant marine food resources (MacEachern et al., 2010). Stable environmental conditions are inferred based on the homogeneous distribution of traces and high diversity trace assemblage (*Arenicolites, Asterosoma, Chondrites, Diplocraterion, Ophiomorpha, Planolites, Rosselia, Skolithos Scolicia, Thalassinoides, and Teichichnus*). In summary, FA-4 represents largely unstressed, fully marine stable physical and chemical conditions (Figure 3.9).

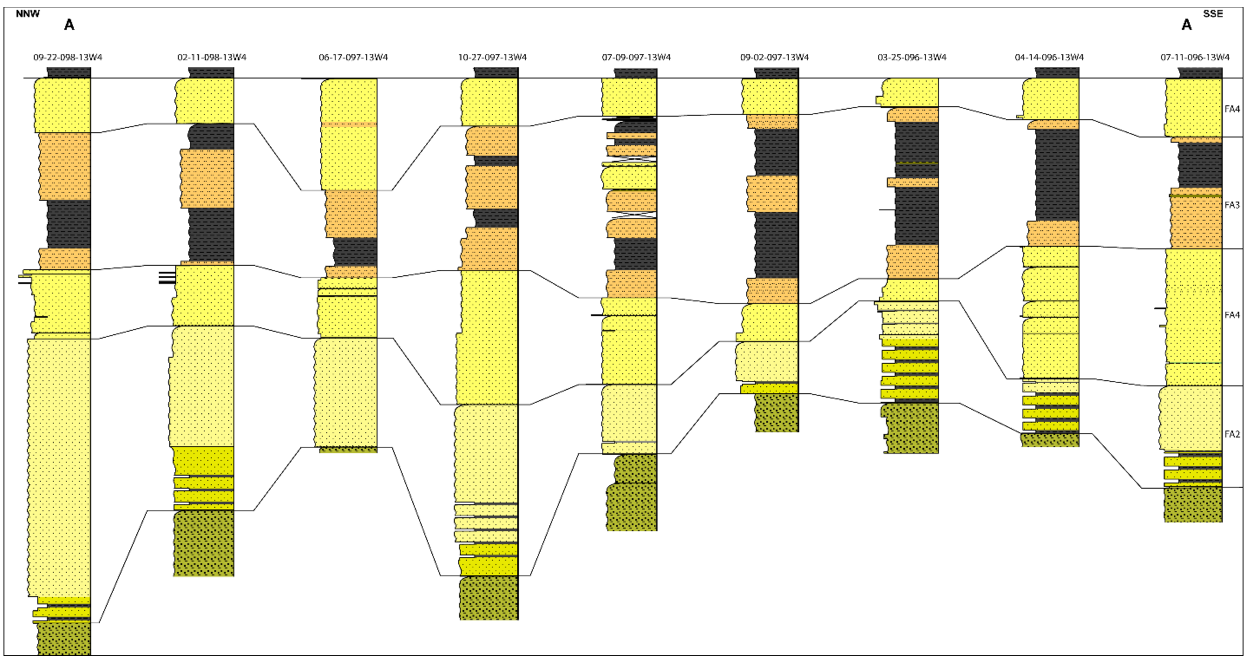
Implications on Reservoir Quality

The integrated ichnological-sedimentological approach allows for reconstructing a robust depositional model for the Wabiskaw Member. This depositional model (based upon detailed facies and wireline analyses) can characterize the reservoir by predicting reservoir distribution, shape, and thickness. Sedimentary facies combined with rock typing and flow units were used to describe the reservoir units of Wabiskaw Member in the study area. This integrated approach resulted in the determination of the most prospective reservoirs in the study area. Various facies of Wabiskaw Member are the reservoir, including F-3 (Distal delta front), F-4 (Proximal delta front and mouth bar), F-7 (Lower shoreface), and F-8 (Lower to middle shoreface) (Table 3.2, Figure 3.7-3.8). The reservoir facies are ranked based on petrophysical (porosity and permeability) data (derived from routine core analysis), oil saturation values (estimated in core logging), pore throat radii (derived from Winland plot), flow and storage capacity (derived from SMLP) and reservoir thickness (derived from core logging and wireline log data) (Figure 3.7, 3.8, 3.10) (Table 3.2).

Facies (F-4), corresponding to rock type 1 (RT-I) on Winland and flow-unite III on SMLP, is the best and most productive reservoir. It is mega-porous, with high oil saturation, high porosity (26-38.1 %), and permeability (734-4240 mD. Effective thickness may reach up to 11.01. It has 45% of flow and 25% storage capacity are the speed zones (Figure 3.7-3.8). Facies mapping shows that F-4 is likely deposited in the delta front-to-mouth bar setting (Figure 3.9). F-4 is present in the lower part of Wabiskaw Member, stretching from south-southeast to north-

northwest across to the paleodepositional strike (east-northeast to west-southwest) (Figure 3.9-3.10).

Facie (F-7), corresponding to rock type 2 (RT-II) on Winland and flow unite 2 (on SMLP) (Figure 3.7-3.8), is ranked second best in terms of reservoir quality based on its petrophysical characteristics (macro-porous, 27.1-39 (%) and 95-1000 mD), high (~30-60%) oil saturation, effective reservoir facies thickness (up to 7.24m). Facie (F-7), storage capacity (36%), and flow capacity (47%). Facies mapping demonstrates that F-7 reservoir facies constitute distal lower shoreface sandstone, oriented in a north-northwest to south-southeast direction (Figure 3.9-3.10).



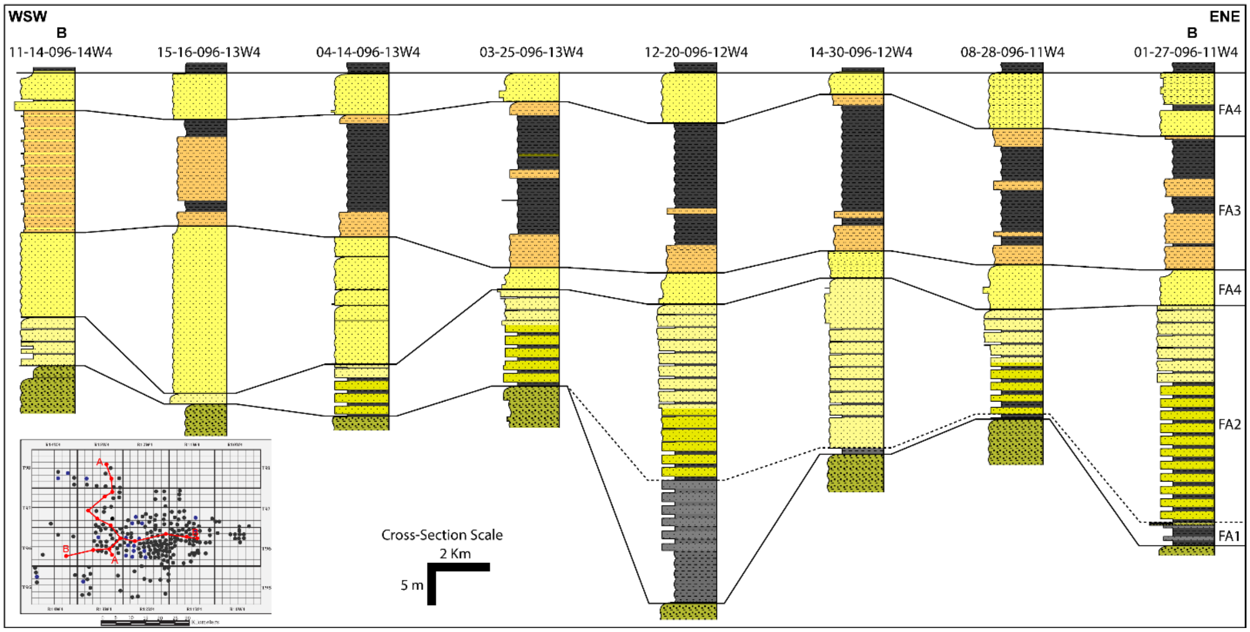


Figure 3. 10 Litho-log cross-sections of the Wabiskaw Member showing vertical and lateral facies distribution. Cross-section A-A′ is perpendicular to the paleo shoreline, whereas cross-section B-B′ runs parallel to the paleo shoreline. No horizontal scale implied.

Facies (F-8) corresponding to rock type 3 (RT-III) and flow-unite 4 (on SMLP) is ranked third in reservoir quality. RT-III is mesoporous with medium oil saturation (~10-30%). Reservoir properties (porosity and permeability) of RT-III vary from 11.8-34.9 (%) and 8.2-212 mD, respectively (Figure11). Effective reservoir facies thickness may reach up to 4.64m, Facies (F-8), Flow Unit 4 (on SMLP), is baffle (Tight zone) with 23% of storage capacity and less than 5% flow capacity (Figure 8). Facies mapping shows that F-8 is likely deposited in shoreface (lower to the middle) setting (Figure 9). F-8 has been observed within the upper part of Wabiskaw Member, stretching from south-southeast to north-northwest (Figure 3.9-3.10).

Facies (F-3), corresponding to rock type 4 (RT-IV) on Winland, and flow-unite 1 on SMLP, has the lowest reservoir properties. Rock type 4 (RT-IV) is micro-porous with low and patchy oil saturation (~10%). Reservoir properties (porosity and permeability) of RT-IV vary from 21.1-35.8 % and 1-100 mD (Figure 3.8). Despite its maximum effective thickness (up to 6.16m) and porosity, this facies is ranked last in the reservoir quality (low and patchy oil saturation and low permeability. Facies (F-3), flow Unit 1 (on SMLP), is also baffle (Tight zone) with 37% of storage capacity and less than 5% flow capacity (Figure 3.8). Facies mapping shows that this facies represents deposition in a distal delta front environment (Figure 3.9). F-3 has been observed within the lower part of Wabiskaw Member, stretching from south-southeast to north-northwest (Figure 3.9-3.10).

In summary, this ranking of lithofacies according to the reservoir quality in clastic reservoirs is related to the inherent environmental conditions (hydraulic sorting, energy). However, it also demonstrates the importance of detailed facies analyses in reservoir characterization.

CONCLUSION

The Wabiskaw Member (Lower Cretaceous) of the Clearwater Formation has been investigated through detailed ichnological and sedimentological data sets, well-logs, and routine core analyses. The sedimentary succession is divided into four distinct lithofacies associations, which provide information about the depositional system. Deltaic depositional system (FA-1, FA-2) is recognized in the lower part of the Wabiskaw Member. FA-1 represents deposition in a shallow marine prodelta environment with stressed archetypal Cruziana ichnofacies. The FA-2 represents Wabiskaw Member river-dominated, wave and storm-influenced delta front, distributary channels, and mouth bar deposits with a stressed ichnological suite of mixed Skolithos-Cruziana ichnofacies. After the deposition of FA-1 and FA-2, offshore (FA-3) and lower to middle shoreface (FA-4) covered the studied area after the transgression. FA-3 is deposited in an offshore (lower, upper) environment with a distal to an archetypal expression of *Cruziana* Ichnofacies. FA-4 records an environment of moderate to high energy, relatively stable chemical conditions, with abundant food resources (Lower to middle shoreface).

Various facies of Wabiskaw Member are the reservoir, including F-3, F-4, F-7, and F-8. F-4 (Proximal delta front, distributary channels, and mouth bar) represent the most prospective reservoir, whereas F-3 (Distal delta front) is ranked last in reservoir quality amongst the reservoir facies Wabiskaw Member. The reservoir characteristics of each lithofacies prove that a geological model (based on extensive facies and wireline analysis) permits how lateral facies changes affect reservoir quality.

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CHAPTER 4: TIDE-DOMINATED ESTUARINE OR DELTAIC DEPOSITS? SEDIMENTOLOGICAL AND ICHNOLOGICAL ANALYSIS OF LOWER PERMIAN DANDOT FORMATION, NORTH PAKISTAN.

ABSTRACT

The lower Permian Dandot Formation (Salt range, north-west Pakistan) contains a 35-40 m thick tide-dominated estuarine and tide-dominated deltaic, sand-dominated, heterolithic succession. Sedimentologic and ichnologic datasets have been integrated to characterize the depositional system of the Dandot strata. The integrated facies analysis allows recognizing a tide-dominated estuarine (estuarine tidal bar, intertidal mud to mixed flat and supratidal deposits) and tide-influenced deltaic succession (prodelta, delta front, distributary mouth bar, and channels). Depositional processes and sedimentary facies in the studied tide-dominated estuaries and deltas are remarkably similar. Common sedimentological characteristics (spring- neap cycle, single and double mud and mica drapes, soft-sediment deformation structures, syneresis cracks, rare wave ripples, bidirectional paleocurrent, coal seams, and fragments) and ichnological signatures (sporadic bioturbation, low diversity-low intensity impoverished trace fossils suite, the dominance of deposit-feeding traces, and rare occurrence of suspension-feeding traces) indicate several physicochemical stresses, such as fluctuations in hydrodynamic energy, fluctuations in water salinity, turbid water conditions and heightened depositional rates affecting the benthic communities of these tide-impacted settings. Despite similarities in sedimentary facies, there are significant differences in longer-term processes. These include regressive vs. transgressive conditions. This results in substantially different facies associations as well as stratigraphic architecture. The Lower Dandot tide-dominated estuarine succession shows a fining-upward trend in vertical profiles, whereas the Upper Dandot tide-dominated delta forms a coarsening-upward sequence. Typically the estuarine deposits are much cleaner and have better sorting than deltaic successions. The ichnological trend (regular heterogenous trace fossils distribution, variable bioturbation intensity, low diversity, diminutive traces, and characteristic traces fossils) points to several physiochemical stresses (seasonal fluctuations in sedimentary conditions, shifting substrates, turbid water, and anisotropic resources) that affected deposition in the estuarine setting. Trace fossils in the deltaic deposits are sporadically heterogeneously distributed. The dataset shows an overall upward decreasing trend in bioturbation intensity and ichnological diversity in deltaic deposits. The trace fossil assemblage typically displays

comparably more diversity in contrast to estuarine deposits. These may serve as valuable and distinct criteria for differentiating tide-dominated deltas from tide-dominated estuaries.

INTRODUCTION

Tidal, fluvial, and wave processes generally coexist and simultaneously impact a coastline's sedimentary dynamics (Bhattacharya and Giosan, 2003; Buatois and Mángano, 2011; Buatois et al., 2012; Bhattacharya et al., 2020; Dashtgard et al., 2021). Tide-dominated settings produce the most complex coastal facies associations and are the least understood. This has a significant economic impact because these facies are increasingly recognized in important petroleum reservoirs (Martinius et al., 2001; Cummings et al., 2006; Tanavsuu-Milkeviciene and Plink-Bjorklund, 2009; Nardin et al., 2013). Tidal depositional systems result from sedimentary environments influenced or dominated by tides (Nio and Yang, 1991; Longhitano et al., 2012; Plink-Björklund, 2012). The sediments deposited in tidal hydrodynamics are arranged into sedimentary facies that preserve strong tidal components that influence a particular coastal area (Dalrymple and Choi, 2007; Pontén and Plink-Björklund, 2009; Tanavsuu-Milkeviciene and Plink-Bjorklund, 2009; Longhitano et al., 2012; Plink-Björklund, 2012). Tidal depositional systems (deposits of tidal estuaries and tidal deltas) in the rock record remain comparatively poorly known. Modern tide-dominated estuaries and deltas are perhaps better understood than their rock-record counterparts, but there is still too little known about the deposits and ichnology of these systems. The physical characteristics of tidal deposits are affected by several factors. The primary physical process is the periodic waning and waxing of hydraulic currents (at diurnal, neap, and semidiurnal cycles), the mixing of fresh and marine water in estuaries and deltas (expanding the brackish water zone), and delivering marine plankton and terrestrial organics in heterogeneous quantities to nearshore locations (Gingras and MacEachern, 2012). These physical processes are likely to play an important role in determining the distribution and character of physical sedimentary structures. Also physicochemical stresses (i.e., current velocity, shifting substrate, sedimentation rate, turbidity, salinity, temperature, oxygenation) influence trace-making (benthic) animal activities in tidal settings. Ichnology is thus often used to provide sedimentological insight into the depositional environment. (Gingras et al., 1998; Gingras et al., 2002; Maceachern et al., 2005; MacEachern et al., 2008; Bhattacharya and MacEachern, 2009; Carmona et al., 2009; Gingras et al., 2009; Buatois and

Mángano, 2011; Gingras et al., 2011; Gingras and MacEachern, 2012; Pemberton et al., 2012; Dasgupta et al., 2016; Buatois et al., 2019; Shchepetkina et al., 2020a; Zheng et al., 2021). The sedimentologic-ichnologic expressions of these factors is not fully understood at present (Gingras and MacEachern, 2012). In particular differentiating the deposits of tide-dominated estuaries from tide-dominated deltas can be challenging. Although physical sedimentary structures and associated facies may help establish tidal influence, it can be challenging to determine if these facies formed in an estuary, delta, or open-marine environment because these facies can occur in multiple depositional environments. To better understand the origins of a tidal deposit, tidal sedimentology must be integrated with ichnology to refine the depositional interpretation. This study systematically documents facies and facies associations for the deltaic and estuarine systems in the Dandot Formation (Lower Permian), north Pakistan. The Dandot strata show distinct tidal estuarine and tidal deltaic characteristics. However, a detailed geological model for Dandot Formation in the study area has not yet been developed. In this study an integrated sedimentological-ichnological approach is employed to propose a geological interpretation for Dandot strata. The aims of this study are to (1) better predict the stratigraphic arrangement of tide-dominated or tide-influenced deltaic and estuarine facies. To (2) describe and interpret the sedimentologic and ichnologic signatures of these estuarine and deltaic deposits. And, to (3) highlight, contrast, and differentiate tidal estuarine deposits (formed during transgression) from tidal deltaic deposits (formed during regression) in the context of a general facies model for Dandot Formation tide-dominated deltas and estuaries.

GEOLOGICAL SETTING

The Lower Permian Dandot Formation (Nilawahan Group) is exposed in the Salt Range in the sub-Himalayas, Pakistan (Figure 4.1). The study area spans the eastern and central Salt Range and is a part of an active Himalayan foreland fold and thrust belt. The Himalayan fold and thrust belt formed because of a collision (Tertiary aged) between the Indian and Eurasian Plate (Searle and Tirrul, 1991; DiPietro and Pogue, 2004). The sub-Himalayas of Pakistan is bound to the north by Main Boundary Thrust (MBT) and to the south by Salt Range Thrust (SRT). Along SRT, the Precambrian to Pliocene strata is thrusted over the Quaternary of the Punjab plains (Ghani et al., 2018). The basin fill at the salt range consists of Precambrian to Pliocene strata punctuated by four significant unconformities (Figure 4.2) (Gee and Gee, 1989).

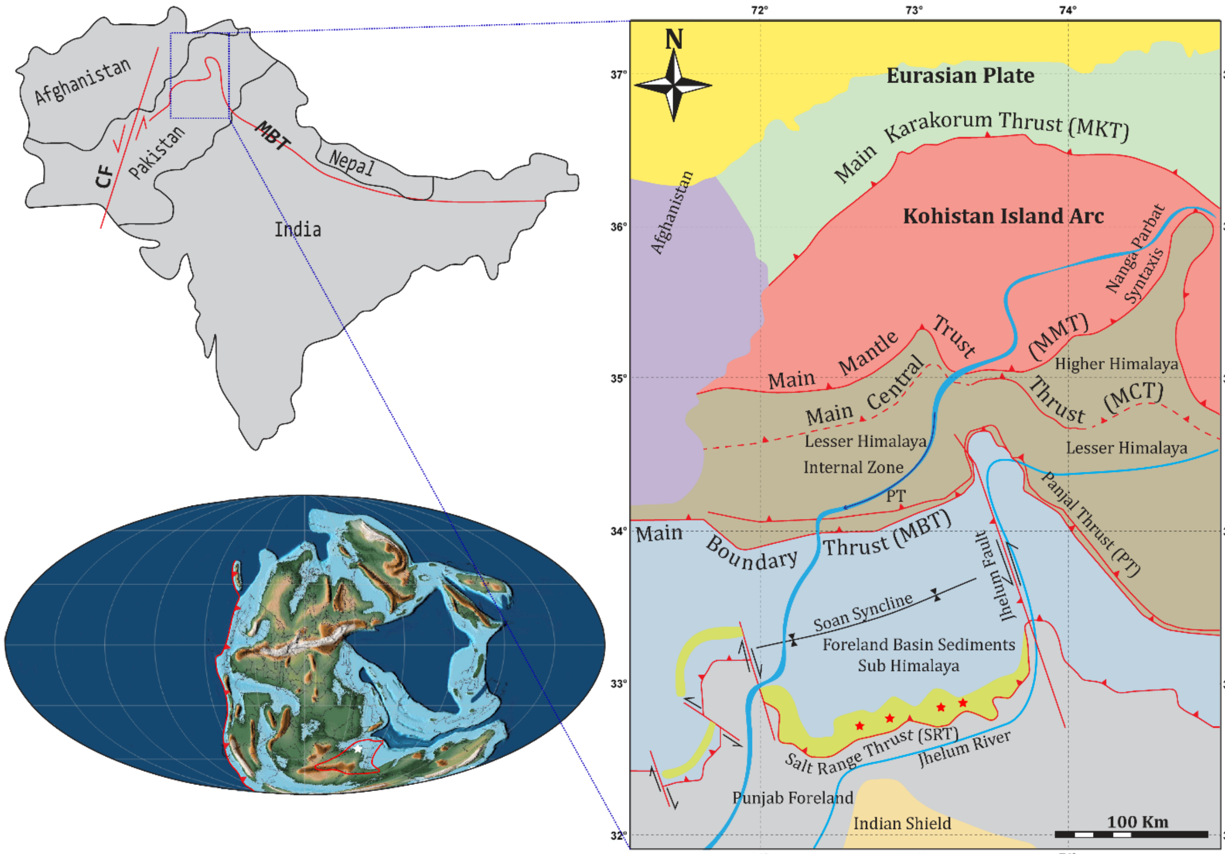

Figure 4. 1 Map of NW Himalayas in North Pakistan. The Lower Permian Dandot Formation is exposed in the salt range in the sub-Himalayas, Pakistan denoted by red stars. The paleogeographic map showing the location of the study area in the Paleozoic (white star).

Paleozoic basin history and paleogeography of NW margin of Gondwana supercontinent in Pakistan

In the Paleozoic time, the Upper Indus Basin (UIB) formed part of the northeastern wide, gently subsiding platform margin surrounding Gondwana (Pogue et al., 1992; Garzanti et al., 1996; Muttoni et al., 2009; Sciunnach and Garzanti, 2012; Angiolini et al., 2013). It was linked to neighboring Cimmerian microcontinents, and is now separated by major sutures and great distances (Pogue et al., 1992; Garzanti et al., 1996). The Ordovician to Carboniferous strata are absent in the Salt Range of UIB, and the Permian Nilawahan Group strata disconformably overlie the Cambrian Jhelum Group in the Eastern and Central Salt Range. However, the Cambrian strata are not preserved in the Western Salt Range, and the Permian strata rest directly on the Precambrian Salt Range Formation (Figure 4.2). This hiatus between Cambrian Jhelum Group and Permian Nilawahan Group strata in the Salt Range relates to a major episode of uplifting and erosion that co-occurs alongside Late Palaeozoic glacial erosion and rifting (Pogue et al., 1992; Garzanti et al., 1996; Sciunnach and Garzanti, 2012).

The stratigraphic successions from the adjacent basins (Peshawar basin, the Kashmir, and Zanskar areas) show evidence of Paleozoic rifting (Pogue et al., 1992; Garzanti et al., 1996). The opening of the Neo Tethys Ocean was possibly due to this continental rifting (Muttoni et al., 2009). Thermal uplifting and extension caused the formation of normal faults (northeast-trending) and alkaline magmatism. These normal faults are reported from the pre-Permian sedimentary sequence and crystalline basement rocks of the Indian plate (Baker et al., 1988; Qayyum et al., 2015). The lower Permian sequence of the salt range and trans-Indus ranges represent the syn-rift deposition in the half-graben basin on the southern side of the Permian rift system (Wardlaw and Pogue, 1995; Ghani et al., 2018).

The Nilawahan Group represents deposition in the Gondwana realm and disconformably overlies Cambrian or Precambrian strata (Gee and Gee, 1989; Wardlaw and Pogue, 1995). The glacio-fluvial Tobra Formation, the marginal marine Dandot Formation, the fluvial Warcha sandstone, and marine Sardhai Formation are the four Formations comprising this group (Wardlaw and Pogue, 1995). Nilawahan Group rocks are unconformably overlain by the Permian Amb Formation or Paleocene units. The Early Permian (Sakmarian) Dandot Formation (the focus of this study) of the Nilawahan group comprises interbedded sandstone, mudstone, and carbonaceous, fine-grained sandstone. Previous workers have proposed various depositional environments for Dandot Formation, including shallow marine to marginal marine (Ghazi et al., 2012; Jan et al., 2016), shoreface, inner shelf, tidal flat and estuarine (Jan et al., 2016).

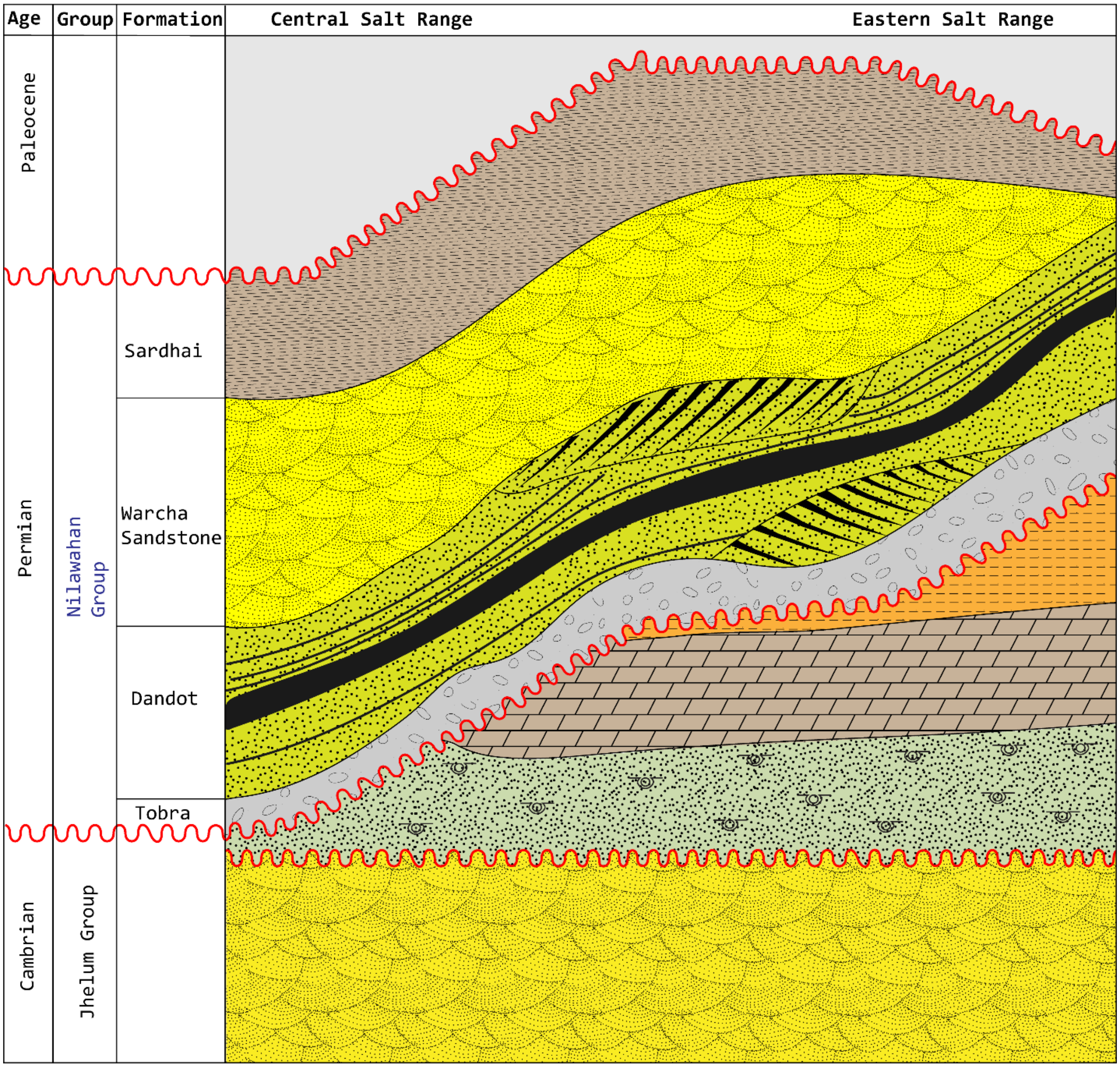

Figure 4. 2 Stratigraphic Column of the study Area. The Nilawahan Group represents deposition in the Gondwana regime and disconformably overlies Cambrian rocks.

METHODS

The Lower Permian Nilawahan Group (Dandot Formation) rocks are exposed in the salt range in the upper Indus basin, Pakistan (Fig. 2). This study area spans eastern and central salt ranges and is primarily based on outcrop analysis. Four outcrops with six measured sections were used to study the tidal deposits of the Lower Permian succession. Detailed (mm-cm scale) sedimentological attributes of the strata including thickness, lithology, grain size, sedimentary structures, and nature of contacts were recorded. The ichnological analysis included documentation of size, lining, diversity and abundance of trace fossils. A bioturbation index (BI) scale (0-6) is used following Taylor and Goldring, (1993) and Taylor et al., (2003). Detailed lithologs were constructed.

RESULTS

Sedimentary Facies Associations

Thirteen (13) lithofacies are recognized in the Dandot Formation based on detailed sedimentological and ichnological analyses of four outcrops and six measured sections (Figure 4.3). The physical attributes, ichnological characteristics and interpreted depositional environment are summarized in Table 4.1. These lithofacies occur in eight facies associations that are presented below.

Facies association 1 (FA-1): Fluvial Channel Deposits

Sedimentology: Facies association 1 (FA-1) occurs both in the lower and upper part of Dandot Formation. In the lower Dandot Formation, FA-1 is observed at two outcrop sections (Tobar Road Section and Motor Way Section). FA-1 is observed at all studied sections in the upper Dandot Formation. FA-1 in the lower part comprises 3-7m thick tabular bodies of coarse to medium-grained, massive to trough cross-bedded, and compound to low angle planar sandstone that can be traced laterally along the outcrops. Granule conglomerates and erosion surfaces are common. These erosional surfaces are channel-like in shape with irregular downcutting. In most cases, the thickness of the sandstone bodies is usually equal to the amount of downcutting, i.e., 3-7 m. In the upper part, FA-1 forms tabular bodies of coarse to medium-grained, massive to trough cross-bedded, and compound to low angle planar sandstone. Lateral accretion surfaces are common (Figure 4.4). Conglomerates and coal fragments are often found above the internal erosion surfaces. Paleocurrent direction from cross-strata in both the lower and upper part is unidirectional (towards the NW) and can vary between sandstone bodies by as much as 80° but typically only 40°-50°. The palaeocurrent direction is between 280°NW to 350°NW. Lithogical accessories include coal fragments, mud clasts, granules, and wood fragments. The lower contact with the underlying facies is erosional, whereas the upper contact is gradational to sharp.

Interpretation

Conglomeratic beds, coarse-grained sandstone, unidirectional (towards the NW) paleocurrents, tabular sandstone bodies, erosion surfaces, coal debris, wood fragments, plant material, and root horizons with the absence of marine trace fossils indicate riverine deposition in fluvial channels (Allen, 1991; Shanley et al., 1992; Plink-Björklund, 2005). Sandstone with abundant trough-cross-stratified beds indicates deposition in dunes. This further suggests flow energy sufficient for the generation of dunes. The conglomeratic lag deposits at the base of sandstone unit may indicate channel thalweg and migration of dunes. The low-angle planar cross-laminated and planar parallel-bedded sandstone suggests deposition in dunes, under upper flow conditions (Allen, 1991; Shanley et al., 1992; Plink-Björklund, 2005). The erosion surfaces indicate multiple channel incision and infill episodes (Plink-Björklund, 2005). The laterally accreting surfaces indicate deposition in the point bar (Thomas et al., 1987; Choi et al., 2004; Johnson and Dashtgard, 2014). The dominantly consistent paleocurrents, the coarse-grained nature, absent to uncommon overbank strata and uncommon lateral accreting strata indicate a comparably less sinuous (braided) channel system for the lower part whereas the common lateral accretion and overbank strata in the upper part indicate deposition in a point bar of a sinuous channel.

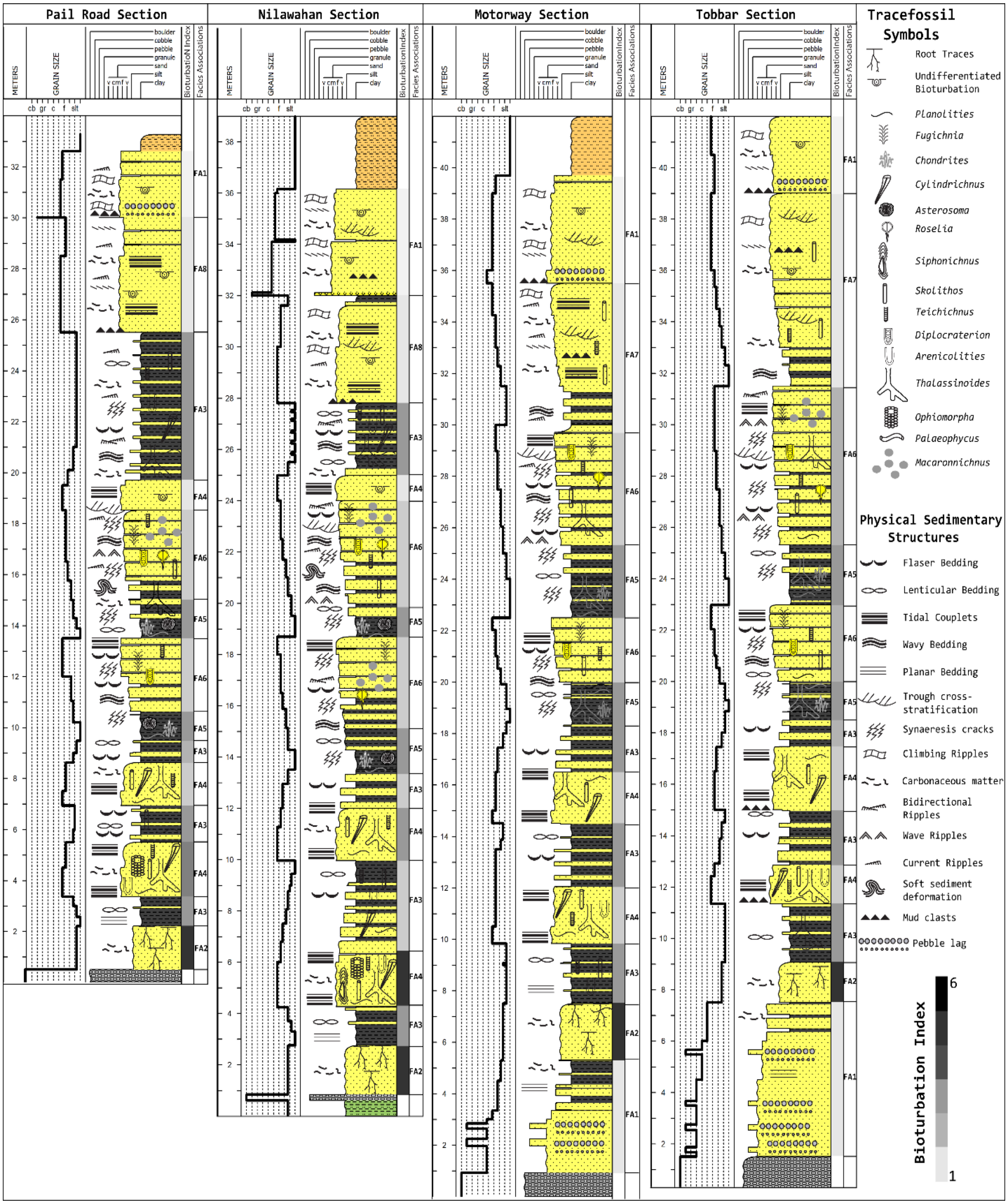

Figure 4.3 Detailed (mm-cm scale) strip logs showing sedimentological ichnological attributes.

Table 4.1 Summary of ichnologic, and sedimentologic attributes of sedimentary facies in the Lower Permian Dandot Formation, east-central Salt Range

Facies	Occurrence / Contacts	Sedimentological Characteristics / Lithological Accessories	Ichnological Characteristics	Inferred process Interpretation	Environment
F-1: Massive to trough cross-bedded sandstone	Present in the eastern Salt Ranges. Occur in the lower part of the measured sections. Lower contact with Tobra Formation is erosional and upper contact with bounding facies (F-2) is gradational.	Coarse to medium-grained, massive to trough cross-bedded, and compound to low angle planar sandstone. Multiple basal or internal erosion surfaces are common. Lithological accessories include coal fragments, mud clasts, granules, and wood fragments.	BI: (0). Unbioturbated	Multiple basal erosional scour surfaces indicate channel base. Compound to low angle planar sandstone and granules indicate high energy current-dominated setting. Coal and wood fragments indicate continental source. No bioturbation indicate physico-chemical conditions not affording colonization.	Riverine deposition in dunes in a fluvial channel.
F-2: Massive eluviated sandstone	Present in the eastern and central Salt Ranges. Occur in the lower part of the measured sections. Contact with Tobra Formation is erosional. Lower and upper contacts with bounding facies (F-1 and F-3) are gradational.	Massive eluviated, structureless sandstone Coalified plant fragments and coal balls are common. Scattered carbonaceous material and ferric minerals occur as accessories.	BI: (0-1). *Ps, Sc, Ta* and *No.*	Massive eluviated, structureless intervals indicate paleosol formation during nondeposition. Coalified plant fragments, coal balls, scattered carbonaceous material and ferric minerals indicate proximity to a continental source. Low BI suggest stressed physico-chemical conditions.	Paleosol formation in Supratidal Flat setting
F-3: Muddy Rhizoturbated sandstone	Occur in the eastern and central Salt Ranges. Occur in the lower part of the measured sections. Lower contact with F-2 is gradational whereas upper contact with bounding facies (F-4, F-5) is gradational.	Muddy sandstone with abundant rhizoliths. Burrow-mottled texture due to abundant root traces. Plant fragments and coal balls. Lithological accessories include scattered carbonaceous material and ferric minerals	BI: (0-5). Rhizoturbation is generally variable. Root traces	Rooted sandstone indicates subaerial exposure and proximity to the water table. Abundant rhizolith and scattered carbonaceous material indicate proximity to a continental source. Rhizoturbation indicate chemical conditions affording floral colonization.	Deposition in low-energy peat swamps under humid conditions- Supratidal Flat
F-4: Biotubated Mudstone	Present in both the eastern and central Salt Ranges. Occur in the lower, middle and upper part of the measured sections. Lower contacts with bounding facies (F-3, F-5, F-6, F-7) are gradational. Upper contacts with bounding facies (F-6, F-7, F-8, F9,) are erosional.	Massive to faintly parallel-aminated. The mudstone is dark in color and rich in organics. Occasional thin coals may be present as accessories.	BI: (1-3). *Cy, Pl*	The thinly laminated mudstone likely represents deposition from suspension and clay flocculation. Thin coal and organics suggest proximity to a fluvial source. Low sedimentation. Stable substrate. Low stress physicochemical conditions affording colonization by infauna	Deposition from suspension in the Intertidal Mud Flat
F-5: Heterolithic sandstone-mudstone	Present in both the eastern and central Salt Ranges. Occur in the lower, middle and upper part of the measured sections. Lower contacts with bounding facies (F-4, F-6, F-7) are gradational. Upper contacts with bounding facies (F-6, F-7, F-8, F9,) are erosional.	Faintly parallel, flaser, wavy and lenticular bedding is common.	BI: (1-2). *Cy, Pl, Te, Th, Si, Sk*, and *Ar.*	Heterolithic deposits indicate variations in sediment caliber. Massive mudstone likely points to fluid mud. Sandstone deposition was from traction. The bidirectional current reversal, and heterolithic nature suggest tides. Variable BI (high in muddy organic rich portions) likely indicate anisotropic exploitation of resource by the infauna.	Intertidal Mixed Flat
F-6: Inclined heterolithic stratified sandstone	Present in both the eastern and central Salt Ranges. Occur in the lower part of the measured sections. Lower contacts with bounding facies (F-4, F-5) are erosional to sharp. Upper contacts with bounding facies (F-4, F-5) are gradational.	Fine to medium-grained. sharp-based, cross-stratified sandstone. Reactivation surfaces and drapes of mudstone and mica are common. Lithological accessories include occasional thin coal seams and fragments.	BI: (0-1). Biogenic reworking is absent to uncommon.	IHS show oblique migration of the tidal bar into the adjacent channel through time. Flaser, wavy, and lenticular bedding, and bidirectional cross and sigmoidal bedding, reactivation surfaces, and drapes (mud, mica) indicate tidal currents. Low BI suggest stressed physico-chemical conditions.	Lateral accretion of tidal bar deposits- Tidal Bar
F-7: Bioturbated sandstone	Present in both the eastern and central Salt Ranges. Occur in the lower part of the measured sections. Lower contact with F-6 is gradational. Upper contacts with bounding facies (F-4, F-5) are also gradational.	Bioturbated fine-grained planar, wavy and current laminated sandstone with lenticular siltstone and mudstone. Dispersed mud clast, conglomerates (mud-clast), and organic matter are the accessories	BI: (3-5). Regular heterogenous bioturbation by *Sk, Ar, Op, Pl, Cy, Si, Th,* and *Te*.	High BI suggest relatively un-stressed physico-chemical conditions affording colonization. Flaser, wavy, and lenticular bedding, and bidirectional cross and sigmoidal bedding, reactivation surfaces, and drapes (mud, mica) indicate tidal currents.	Lateral accretion of tidal bar deposits- Tidal Bar
F-8: Dark carbonaceous mudstone	Present in both the eastern and central Salt Ranges. Occur in the middle part of the measured sections. Lower contact with F-6 and F-9 is sharp to erosional. Upper contacts with bounding facies (F-9, F-10) are gradational.	Organic-rich mudstone. Structureless (massive) to planar parallel laminated.	BI: (0-2). sparsely bioturbated by *Pl, Ch*	Thic, unbioturbated, massive-faintly laminated mudstone suggest hyperpycnal fluid mud. Load-and-flame structures, synaeresis cracks and low BI indicate a high deposition rate under turbid water conditions with fluctuating salinity. Rare oscillations indicates some wave action.	Distal Prodelta
F-9: mudstone-dominated heterolithics	Present in both the eastern and central Salt Ranges. Occur in the middle part of the measured sections. Lower contact with F-8 is gradational. Upper contact with bounding facies (F-10) is also gradational.	Thin (mm-scale) to thick (cm-scale) mudstone drapes. Sandstone occurs as thin streaks. Pinstripe lamination, lenticular and wavy bedding. Mud drapes, syneresis cracks, and load and flame occur as accessories.	BI: (1-3). Sparsely to moderately bioturbated by *Pl, As, Ch,* and *Tes, Sk* and *Th.*	Thin mudstone indicate deposition from suspension. Thick mudstone indicate fluid mud. Rippled sandstone show deposition from traction. Moderate BI, synaeresis cracks, and load-and-flame structures indicate physico-chemical stresses	Proximal Prodelta
F-10: Thin Heterolithic sandstone and mudstone	Present in both the eastern and central Salt Ranges. Occur in the middle to upper part of the measured sections. Lower contact with F-9 is gradational. Upper contacts with bounding facies (F-11, F-12) are gradational to sharp.	Couplets (mm-cm scale) of very fine sandstone, siltstone, and mudstone. flaser to wavy bedded and planar laminated. Spring- neap cycle, mica and mud drapes are common. Lithological accessories include mud rip-up clasts, carbonaceous material, granules, and coal fragments	BI: (1-3). Sparsely to moderately bioturbated by *Ro, Be, Pa Co, Sk, Pl, and Te.*	Low BI, sporadic distribution and lined trace fossils indicate shifting substrates and high-energy conditions. Fugichnia and soft-sediment deformation structures indicate high deposition rates. Unburrowed, thick mudstone indicate hyperpycnal fluid mud. Flaser to wavy bedding, spring- neap cycle, mica and mud drapes indicate tidal influence.	Distal Delta Front
F-11: Sandstone-dominated heterolithics	Present in both the eastern and central Salt Ranges. Occur in the middle to upper part of the measured sections. Lower contact with F-10 is gradational. Upper contact with F-12 is gradational to sharp.	Sandstone is thin (mm-scale) to thick (cm-scale). Mudstone occurs as thin drapes (mm scale). Wavy parallel to lenticular bedding with symmetrical and asymmetrical ripple cross-laminations. Syneresis cracks, abundant mud and mica drapes, flame and load structures, neap-spring cycles, and reactivation surfaces are common. Carbonaceous material, granules, and coal fragments.	BI: (1-3). Sparsely to moderately bioturbated by *Ma, Ro, Be, Pa, Co, Sk, Pl, and Te.*	Heterolithic strata, an abundance of carbonaceous detritus, climbing current ripples, and soft-sediment deformation indicate strong fluvial influx, high-energy conditions, and high deposition rate. low BI indicate high sedimentation rates, high energy conditions, water turbidity, and fluctuation in water salinity. Rhythmic bundling, mud, mica drapes, reactivation surfaces, and bi-directional cross-strata reflect tidal conditions.	Tidally influenced proximal delta-front to distributary mouth-bar region
F-12: Combine flow rippled sandstone	Present in both the eastern and central Salt Ranges. Occur in the middle to upper part of the measured sections. Lower contact with F-11 is gradational to sharp. Upper contact with F-4, F-5 is gradational to sharp.	Hummock and swaley cross-stratified sandstone. Wavy parallel to lenticular bedding with symmetrical and asymmetrical ripple laminae. Syneresis cracks, abundant mud and mica drapes, flame and load structures, and neap-springe cycles, are common. Carbonaceous material, granules, coal fragments, and siderite grains are the common accessories.	BI: (1-2). Sparsely bioturbated by, *Pa, Sk, Pl, Di, Te* and *Fu.*	Hummocky cross-strata and combine flow ripples indicate storm activity. Flame and load structures, and fugichnia indicate a high deposition rate. Carbonaceous material, and coal fragments indicate proximity to a fluvial source. The presence of trace fossils *Macaronichnus* and *Rosselia* and the paucity of suspension-feeding trace fossils indicate turbid water conditions	Storm-influenced delta front
F-13: Cross stratified sandstone	Present in both the eastern and central Salt Ranges. Occur in the upper part of the measured sections. Lower contact with F-4, F-5 is ersoional. Upper contact is gradational.	Sharp-based, planar parallel to bidirectional ripple cross-laminated. Asymmetric ripples and single-double mud and mica drapes are common. Rip-up clasts, laterally accreting surfaces and reactivation surfaces are common. Coal seams, and fragments are present as accessories.	BI: (1-2). Bioturbation is uncommon to low. The trace fossils include *Sk, Ar, Be, Pa, and Di.*	Coal debris, wood fragments, plant material and root horizons with the absence of marine trace fossils indicate riverine deposition. Sandstone with abundant trough-cross-stratified beds indicate deposition in dunes. The laterally accreting surfaces indicate deposition in the point bar. Low BI indicate stressed physico-chemical conditions.	Channel deposits

Key

Trace Fossils
Ar-Arenicolites; As-Asterosoma; Ch-Chondrites; Cy-Cylindrichnus; Di-Diplocraterion; Fu-Fugichnia; He-Helminthopsis; Lo-Lockeia; Ma-Macaronichnus; Op-Ophiomorpha; Pa-Palaeophycus; Ph-Phycosiphon; Pl-Planolites; Rh-Rhizocorallium; Ro-Rosselia; Sc-Scolicia; Si-Siphonichnus; Sk-Skolithos; Te-Teichichnus; Th-Thalassinoides; Zo-Zoophycos; Ps-Psilonichnus, Sc-Scoyenia, Ta-Taenidium and *No-Noktodermois.*

Bioturbation Index
0- Bioturbation Absent
1-Sparse Bioturbation
2-Uncommon Bioturbation
3-Moderate Bioturbation
4-Common Bioturbation
5-Abundant Bioturbation
6-Complete Bioturbation

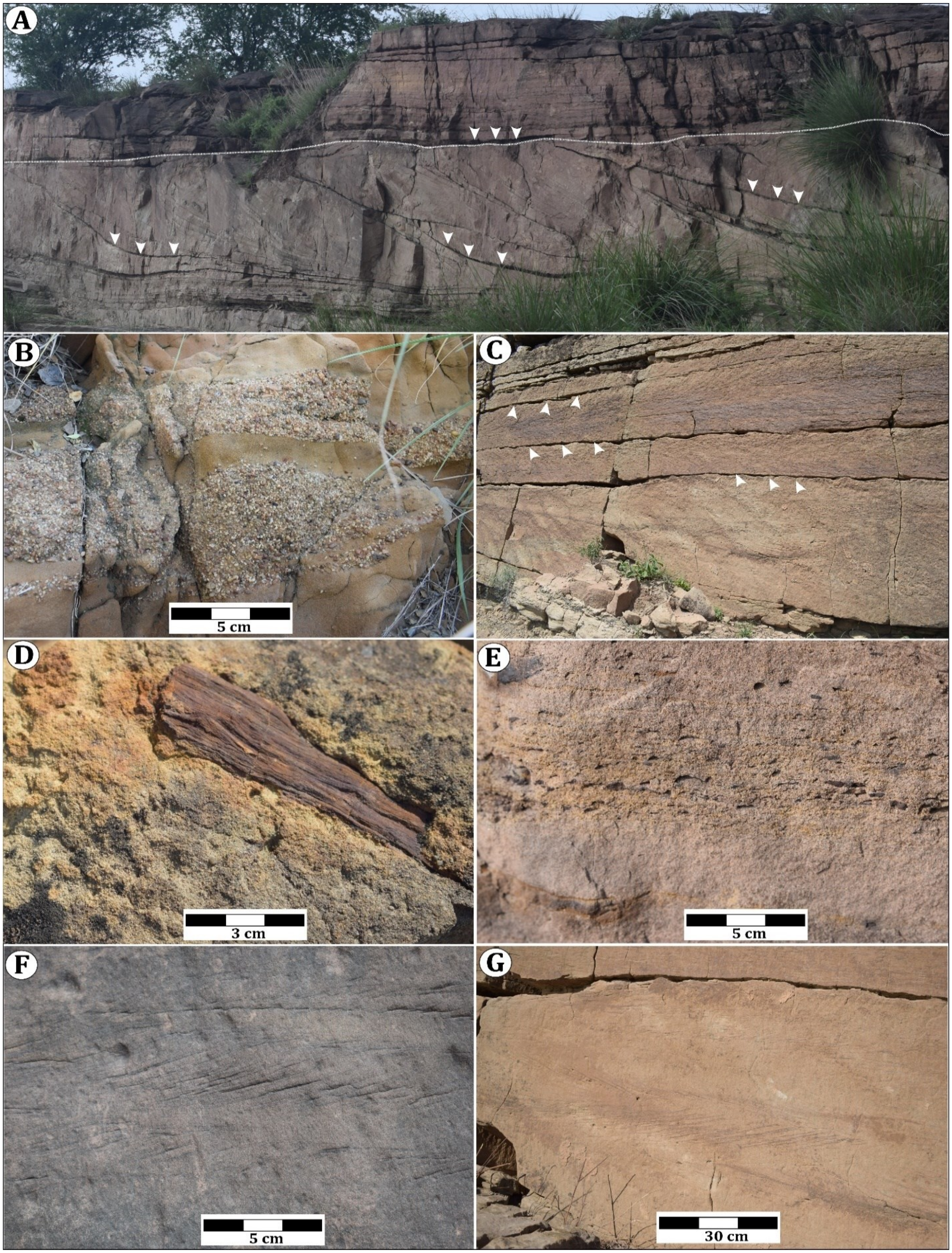

Figure 4.4 Facies association 1 (FA-1): Fluvial Channel Deposits. Fluvial Channel deposits with erosional surface (dashed line) and multiple lateral accretion surfaces (white arrows). B) Granule conglomerates in the lower part of

the channel deposits. C) Multiple erosional surfaces (white arrows) within channel deposits. D, E) Wood and lithic fragments. F, G) Cross-stratification in the sandstone.

Facies Association 2 (FA-2): Paleosol Deposits

Sedimentology: This facies association is commonly present above the glacio-fluvial Tobra Formation and represents the lower facies of Dandot Formation. These facies consist of massive eluviated, structureless sandstone and muddy sandstone with abundant rhizoliths. Sedimentary structures are obscured by rhizoturbation and eluviation. Locally present is a burrow-mottled texture due to abundant root traces. Coalified plant fragments and coal balls are common. Scattered carbonaceous material and ferric minerals occur as accessories. FA-2 is commonly 1 to 1.5 m thick. The lower contact with the Tobra Formation is sharp, whereas the upper contact with FA-3 is generally abrupt.

Ichnology: BI= 0-5. Rhizoturbation is generally variable. Some zones are completely rhizoturbated, whereas others are not. Where bioturbation is present, trace fossils may include rare *Psilonichnus, Scoyenia, Taenidium* and *Noktodermois.*

Interpretation: The presence of rooted sandstone (poorly sorted) indicates subaerial exposure and proximity to the water table, allowing plants to colonize the substrate (Retallack, 1997). Autochthonous coal balls, in-situ coal bed and fragments suggest accumulating plant material in low-energy peat swamps under humid conditions. Coal is formed by the alteration of peats buried in swamps or marshes near estuaries (Dashtgard and Gingras, 2005; Buatois and Mángano, 2011; Desjardins et al., 2012a). The massive eluviated, structureless intervals, bioturbated rooted intervals, and ferric mineral accumulations indicate paleosol formation during nondeposition when the landscape is stable and subaerially exposed (Retallack, 1997; Ruskin and Jordan, 2007; Gingras and MacEachern, 2012; Polo et al., 2018).

In summary, FA-2 represents deposition in swamps and peats, forming paleosols and accumulating organic matter (plant material), leading to coal formation in estuarine settings. (Retallack 1997; MacEachern and Gingras 2007; Gingras et al. 2012).

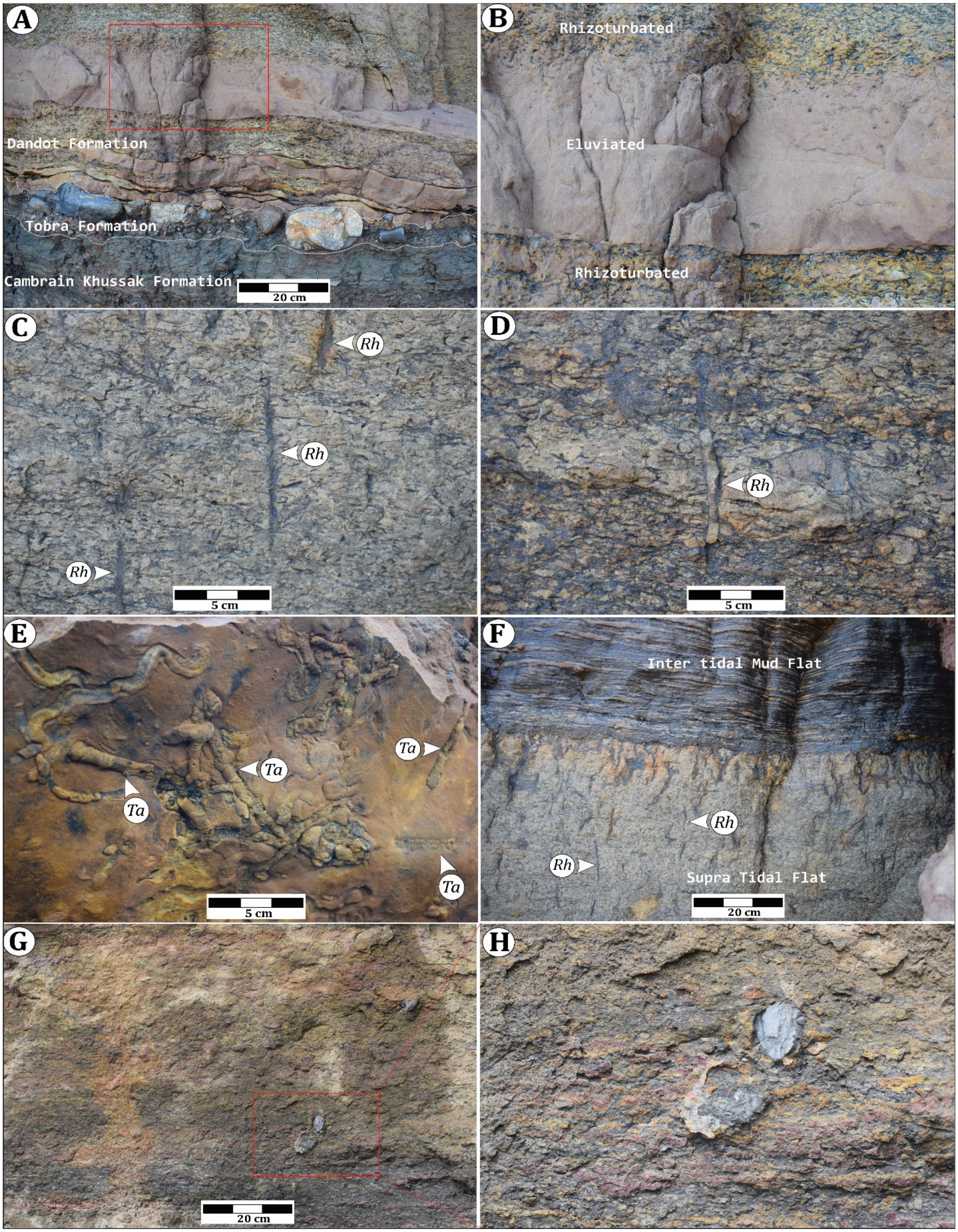

Figure 4.5 Supratidal deposits of Dandot Formation marking the contact with the underlying Tobra Formation. B) Mottled rhizoturbated and massive eluviated deposits. C, D Abundant rhizoliths obscuring physical sedimentary

structures. E) Trace fossils *Scoyenia*, *Taenidium* and *Noktodermois* at the sole of a sandstone bed. F) Sharp upper contact with FA-3. G, H) Coalified plant fragments and coal balls in FA-2

Facies association 3 (FA-3): Intertidal Mud-Flat to Mixed-Flat Deposits

Sedimentology: Facies association 3 (FA-3) occurs in the muddy levels above and below FA-4 estuary sand bars. FA-3 exhibits a characteristic generally muddy but upward-fining character. FA-3 consists of bioturbated mudstone to heterolithic sandstone and mudstones. If preserved, physical sedimentary structures include faint parallel, flaser, wavy and lenticular bedding. Bidirectional current ripples are observed. The mudstone is massive to laminated. Mud drapes and bidirectional paleocurrent directions are common in sand-rich intervals. The mudstone is dark in color and rich in organics. Occasional thin coals may also be present. The muddy portions are generally more bioturbated than the mixed hetrolithic part. Overall, these intervals present stacked, 3-5 m thick, weakly fining-upward successions. In the lower part of Dandot Formation, FA-3 gradationally overlies FA-2. The lower contact with bounding facies associations is gradational, whereas the upper contact is generally sharp and abrupt.

Ichnology: (BI= 1-3). Bioturbation in FA-3 is low to moderate. The moderately bioturbated heterolithic succession consists of dwelling and feeding structures of *Cylindrichnus*, *Planolites*, *Teichichnus*, *Thalassinoides*. *Siphonichnus*, *Skolithos*, and *Arenicolites*.

Interpretation: The lenticular mudstone and mudstone-dominated heterolithic deposits indicate variations in sediment caliber over time. The thinly laminated mudstone likely represents deposition from suspension and clay flocculation (Hovikoski et al., 2008; Mackay and Dalrymple, 2011). The apparently massive mudstone likely points to fluid mud deposition (Mackay and Dalrymple, 2011). The sandstone deposition was from traction. The bidirectional current reversal and heterolithic nature suggests variable currents such as tides. The variable BI (high in muddy organic rich portions and low in the sandy part) likely indicates anisotropic exploitation of heterogeneous food resource by the infauna (Gingras et al., 2011, 2012c). Heterogeneous food resource distribution generally results from tidal rhythmic bedding (Gingras et al., 2011). The low diversity, diminutive trace fossils exhibiting facies crossing generalist behaviors can be ascribed to brackish-water trace-fossil assemblages (Pemberton et al., 1982; Buatois et al., 2005; MacEachern and Gingras, 2007). The bioturbated, heterolithic deposits, variation in depositional energy, and common bidirectional paleocurrents indicate deposition in a low energy tidal setting. In summary, the heterolithic sandstone-mudstone, fluid muds, bidirectional current reversals, variable BI, anisotropic exploitation of heterogeneous food resource and brackish-water trace-fossil assemblages all indicate deposition in the intertidal mud to mixed flat setting. FA-3 (intertidal mud to mixed flat) is thought to occupy the space between the valley wall and the tidal channel. They generally flank the funnel-shaped estuary networks at their inner and middle parts (Dalrymple et al., 2012; Chen et al., 2014).

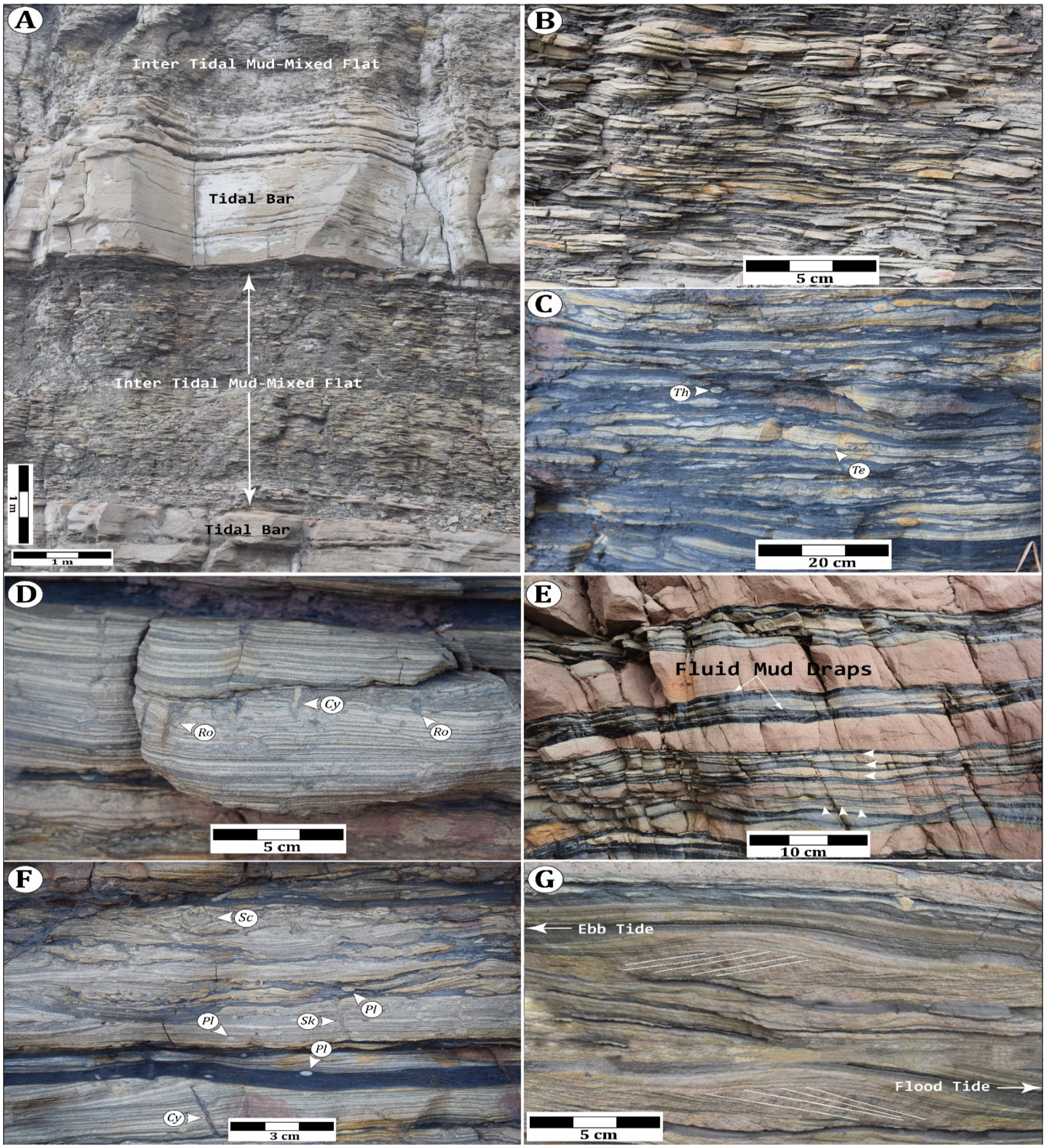

Figure 4. 6 A) Tidal flat deposits showing an upward-fining character. The lower contact with bounding facies associations is gradational, whereas the upper contact is sharp. B) Heterolithic sandstone and mudstones. C)

bioturbated mudstone D, F) Bioturbated sandstone to heterolithic sandstone with *Planolites*, *Teichichnus*, *Thalassinoides*, *Siphonichnus*, *Skolithos* traces. E) Fluid mud drapes in the sand-rich intervals. White arrows point to current ripples G) Bidirectional ripple cross laminae in the sand-rich intervals.

Facies Associations 4(FA-4): Estuarine Tidal Bars

Sedimentology: FA-3 occurs in all studied outcrop sections (Figs. 6, 8, 9). This facies association represents sand-dominated, inclined heterolithic stratification (IHS). The sandstone is fine to medium-grained, sharp-based, cross stratified with bidirectional cross sets. Reactivation surfaces and drapes (single-double) of mudstone and mica are common. The sandstone is rippled with some soft sediment deformation features. Dispersed mud clast conglomerates and organic matter occur as accessories. A medium-grained, planar, trough to sigmoidal, cross-bedded sandstone dominates the lower part of this facies association. The average bed thickness is 1.2 meters with some large cross-beds. Large mud clast (5cm diameter) and mud pebbles along the basal surface of the cross sets do occur. Bioturbation is absent to rare in the lower part, whereas the middle to the upper part is sparsely to moderately bioturbated. This FA has alternation of bioturbated and laminated beds. The thickness of burrowed beds is between 7 and 65 cm. The thickness of laminated units is between 8 and 70 cm, with a decrease in thickness at the top. The beds are generally sharp-based and crinkled locally. Locally the bioturbation is extending down somewhat into the top of the laminated bed (figure 4.8 (A, B, C). The bedding dip is between 10 and 12 degrees with small variance (less than 2 degrees) throughout the outcrops. Laminated beds are characterized by low-angle, planar laminated sedimentary couplets (Fig. 7A). Individual laminae housed within couplets show only slight variations in their thickness: the silty portion of the couplet commonly reaches thicknesses of 1 cm, whereas the sandy part rarely exceeds 2 mm. Laminae thicknesses are cyclically variable (Fig. 7A). Sandy laminae are fine-grained, well-sorted, and show no grading. This facies association forms an upward-fining package.

The upper part is fine-grained planar, wavy and current laminated sandstone with lenticular siltstone and mudstone. Siltstone and mudstone occur in the upper part. Paleoflow analysis of cross laminations and ripples indicates a bidirectional flow with the dominant current in the south-southeast (130-170) direction (flood dominated).

Ichnology: BI=0-5. These deposit shows regular heterogenous bioturbation. Bioturbation in the lower part is sparse. However, the medial parts have nonuniform regular heterogeneous trace fossil distributions. The succession consists of bioturbated beds and laminated (unbioturbated) beds. The trace fossil suite present includes *Skolithos, Arenicolites, Ophiomorpha, Planolites, Cylindrichnus, Siphonichnus, Thalassinoides,* and *Teichichnus*.

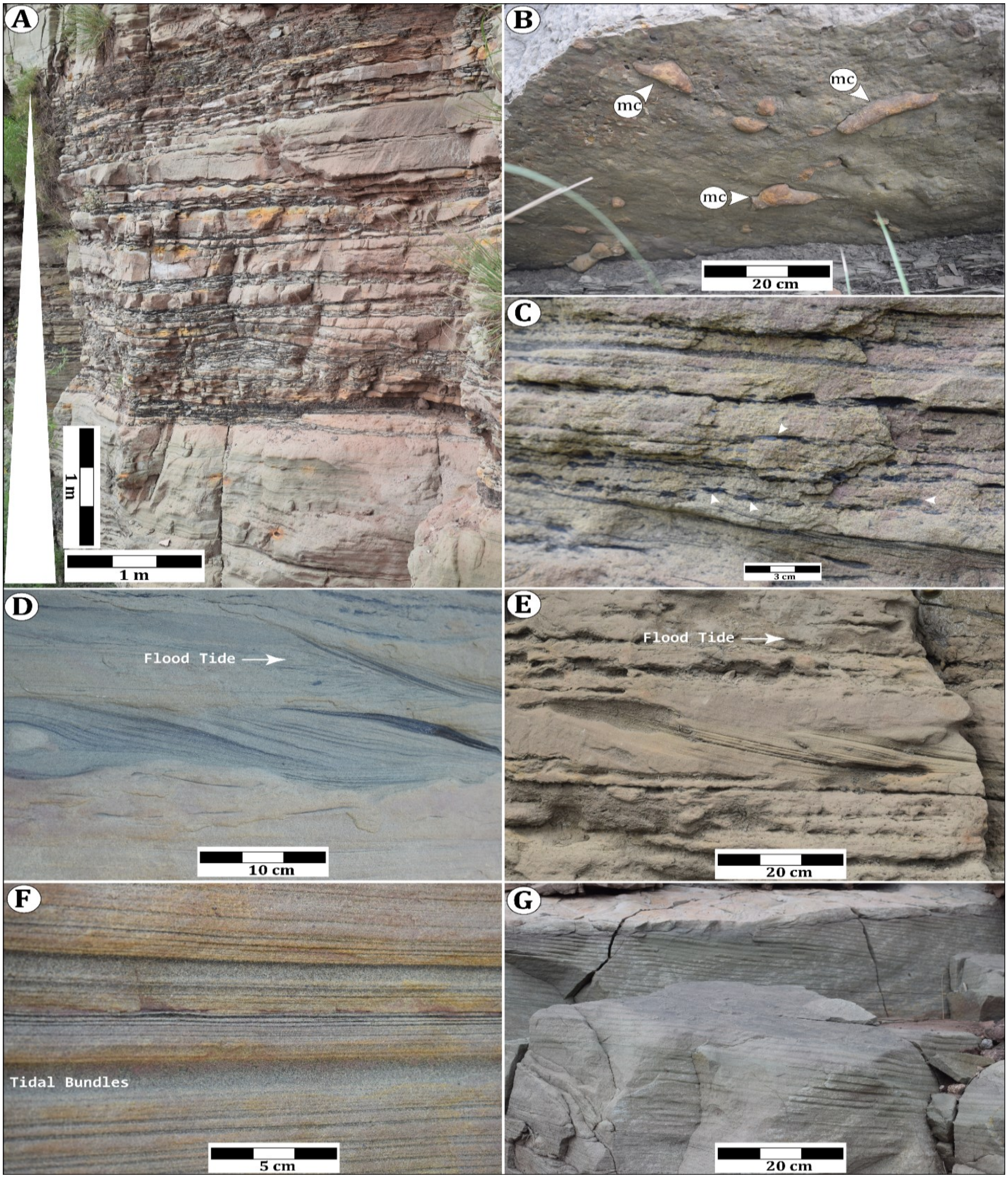

Figure 4.7 Tidal Bars deposits showing an upward-fining character. B) The lower contact with bounding facies associations is erosional to sharp with common mud clasts (mc). C) Mud clasts (arrows) in the tidal bar deposits. D,

E) Flood dominated cross-beds in the tidal bar deposits F, G) Tidal bundles in the tidal bar deposits at the Nilawahan gorge section.

Interpretation: The presence of flaser, wavy, and lenticular bedding, and bidirectional cross and sigmoidal bedding, reactivation surfaces, and drapes (mud, mica) are together good indicators of tidal currents during deposition (Reineck and Wunderlich, 1968; Nio and Yang, 1991; Willis et al., 2005). Forests show cyclic thickening or thinning within the cross-beds forming tidal bundles. This suggests rhythmic changes in neap and spring tides (Nio and Yang, 1991). The reactivation surfaces with cross strata superimposed points to deposition in large macro forms. The dip direction of the foresets and the bounding reactivation surfaces are not the same. This indicates lateral accretion instead of forwarding accretion and deposition within the tidal bar (Olariu et al., 2012). The basal surface is erosional. IHS shows oblique migration of the tidal bar into the adjacent channel through time (Dalrymple and Choi, 2007). These tidal channels have basal mud clasts as a common feature. The succession consists of bioturbated beds and laminated (unbioturbated) beds. The laminated-bioturbated alternation of the deposits results from markedly different summer-winter depositional conditions (Dalrymple et al., 1991; Gingras et al., 1999; Pearson and Gingras, 2006; Hauck et al., 2009). Laminated sediment accumulates in the early winter through to the early spring months. At these times infaunal population densities are too low to rework the sediment significantly (Dalrymple et al., 1991). The heterolithic sandstone with lenticular siltstone and mudstone with flood-dominated paleoflow indicates lower-energy conditions in the upper part. This facies association can be summarized as tidal bar deposits because of the abundance of tidal signatures (flaser, wavy, lenticular bedding), bidirectional cross and sigmoidal bedding, reactivation surfaces, and drapes.

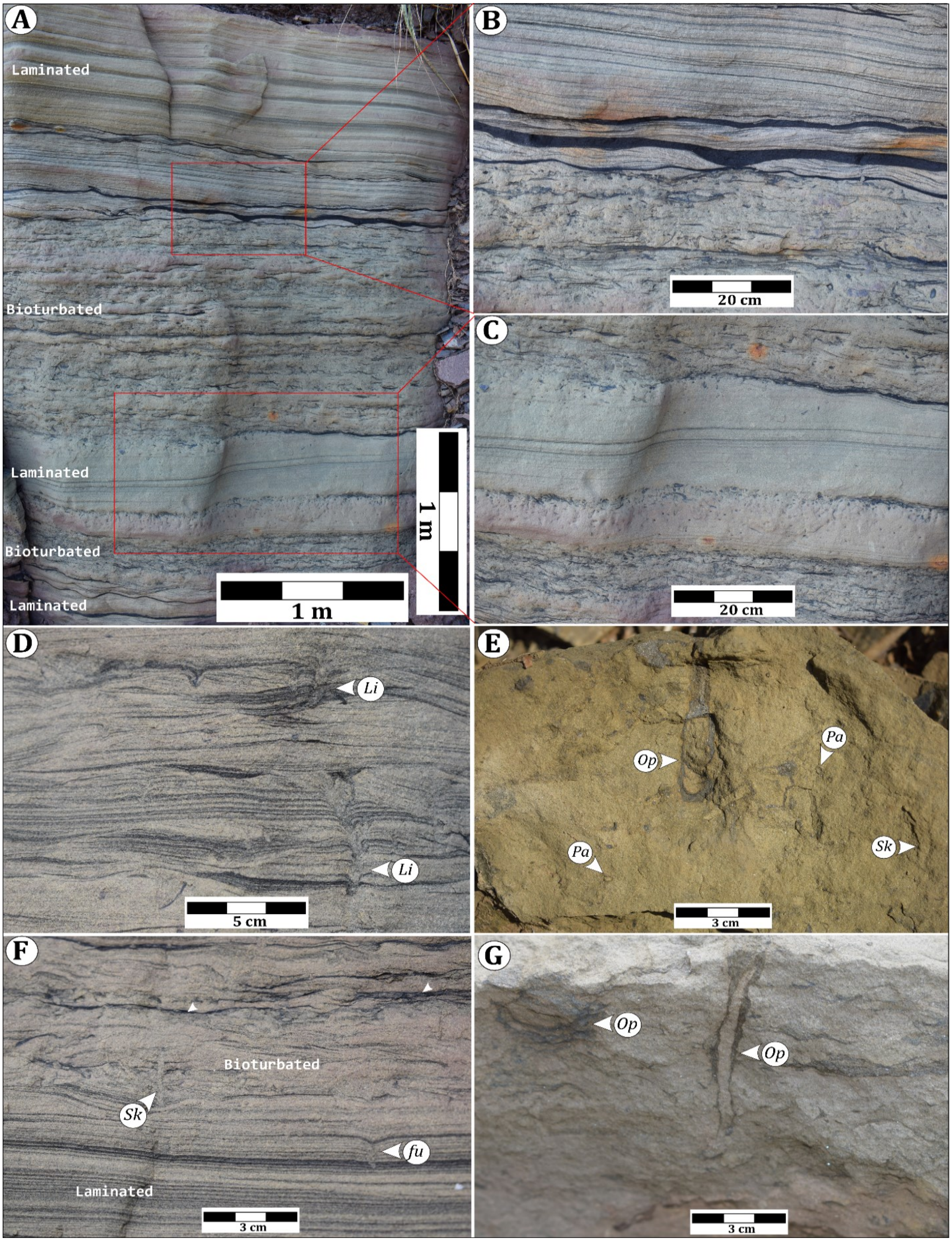
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Figure 4.8 Facies Associations 4 (FA-4): Estuarine Tidal Bars deposits. A) Laminated to bioturbated deposits. The laminated deposits indicate winter-spring deposition with little or no bioturbation (BI=0). The bioturbated deposits (BI=5) indicate summer and fall deposition. B, C) Zoom in view of parts of A. D,E, F, G) Various recognized trace fossils in the bioturbated tidal bar deposits.

Facies Association 5 (FA-5) Prodelta Deposits

Sedimentology: Facies Association 5 (FA-5) is comprised of dark carbonaceous mudstone and mudstone dominated (60 to 80 % mudstone) heterolithic strata. The lower part of this FA is dominated by organic-rich mudstone. This mudstone is structureless (massive) to planar-parallel laminated and may be sharp based. In the mud-rich heterolithic strata, the mudstone drapes are mm- to cm- scale thick. In contrast, the sandstone occurs as mm-scale, locally discontinuous leading to pinstripe lamination. Rhythmic alternations of mudstone and sandstone, lenticular and wavy bedding, asymmetrical current and rare wave ripple laminae are the main physical attributes observed in this FA. Laterally persistent bed sets may occur, though individual lenticular beds commonly display lateral variation in thickness. Paleocurrent analysis indicates bipolar flow (northwest-southeast). Mud drapes, syneresis cracks, and small soft sediment deformation structures are common. This facies association forms 1-3 m thick upward coarsening and thickening successions. Lower and upper contacts with FA-3 and FA-6 are gradational.

Ichnology: BI (1-3), This FA is sparsely to moderately bioturbated. Trace fossils present include *Planolites*, *Cylindrichnus*, *Chondrites, Helminthopsis, Phycosiphon,* and *Teichichnus.* Subordinate traces include *Skolithos* and *Thalassinodies.*

Interpretation: Rhythmic interbedded mudstone and sandstone indicate variable energy conditions during deposition. The mm- to cm- scale thick massive appearing mudstone likely represent hyperpycnal fluid mud deposits (Coates and Maceachern, 2009; Ichaso and Dalrymple, 2009; Mackay and Dalrymple, 2011). This is also evidenced by the rare bioturbation (BI=0-1) within these mudstone as bioturbation in fluid mud deposits is low to absent (Maceachern et al., 2005; Bhattacharya and MacEachern, 2009). The rippled sandstone beds and laminae show deposition from traction (high energy). Mud drapes, lenticular bedding, and bipolar current direction indicate tidal influence in a shallow marine setting (Reineck and Wunderlich, 1968). The rare occurrence of symmetrical oscillation ripples indicates some wave reworking. The presence of fluid mud, load-and-flame structures, and synaeresis cracks indicate a high deposition rate under turbid water conditions with fluctuating water salinity (Gingras et al., 1998;

Gingras et al., 2002; Maceachern et al., 2005; Gingras et al., 2007; Maceachern et al., 2007b; Buatois et al., 2008). Intervals with low bioturbation intensity (BI: 1) point to several physio-chemical stresses such as salinity, turbidity, and higher depositional rates (Gingras et al., 1998; Gingras et al., 2002; Gingras et al., 2007; Maceachern et al., 2007b). However, moderately bioturbated intervals may indicate periods of higher salinities with comparatively low sedimentation rates (Maceachern et al., 2007b). Therefore, the fluctuating energy conditions, tidal influence, high deposition rate from turbid water with fluctuating salinity and exposure to wave reworking in a shallow marine setting are interpreted to record deposition in a tide-influenced prodelta setting.

Facies Association 6 (FA 6): Delta Front Deposits

Sedimentology: This Facies Association contains thin heterolithic sandstone-mudstone in the lower part, which coarsens upwards into fine-grained sandstone. The distal delta front heterolithic strata in the lower part is flaser to wavy bedded, wavy parallel laminated, and planar laminated and occur in couplets (mm-cm scale) of very fine sandstones, siltstones and mudstones. Rhythmic laminae, single and double mica and mud drapes, rare wave ripples, and bidirectional paleocurrent are common in these heterolithic strata. The heterolithic strata coarsen upward into fine to medium-grained sandstones. In the sandstone-rich facies, the sandstone may be thin (mm-scale) to thickly bedded (cm-scale), whereas the mudstone may occur as thin drapes (mm-scale discontinuous or continuous). The sandstone has a prevalent wavy parallel to lenticular bedding with symmetrical and asymmetrical ripple cross-laminations and internal flaser bedding. Cross-stratification (sigmoidal, low angle, and tangential) is observed and the cross laminae dip in two opposite directions (dominantly to the northwest). Current and oscillation ripples may be observed. Synaeresis cracks, abundant mud and mica drapes, flame and load structures, neap-spring cycles, tidal bundles, and reactivation surfaces are commonly observed. Lithological accessories include mud rip-up clasts, carbonaceous material, granules, and coal fragments. The lower contact at the base and upper contact at the top of this facies is sharp/erosional. This facies association forms 2-5 m thick upward coarsening successions.

Ichnology:_The FA is sparsely burrowed (BI 1–2). Trace fossils include *Macaronichnus, Rosselia, Bergaueria, Paleophycus, Conichnus, Skolithos, Planolites, and Teichichnus*

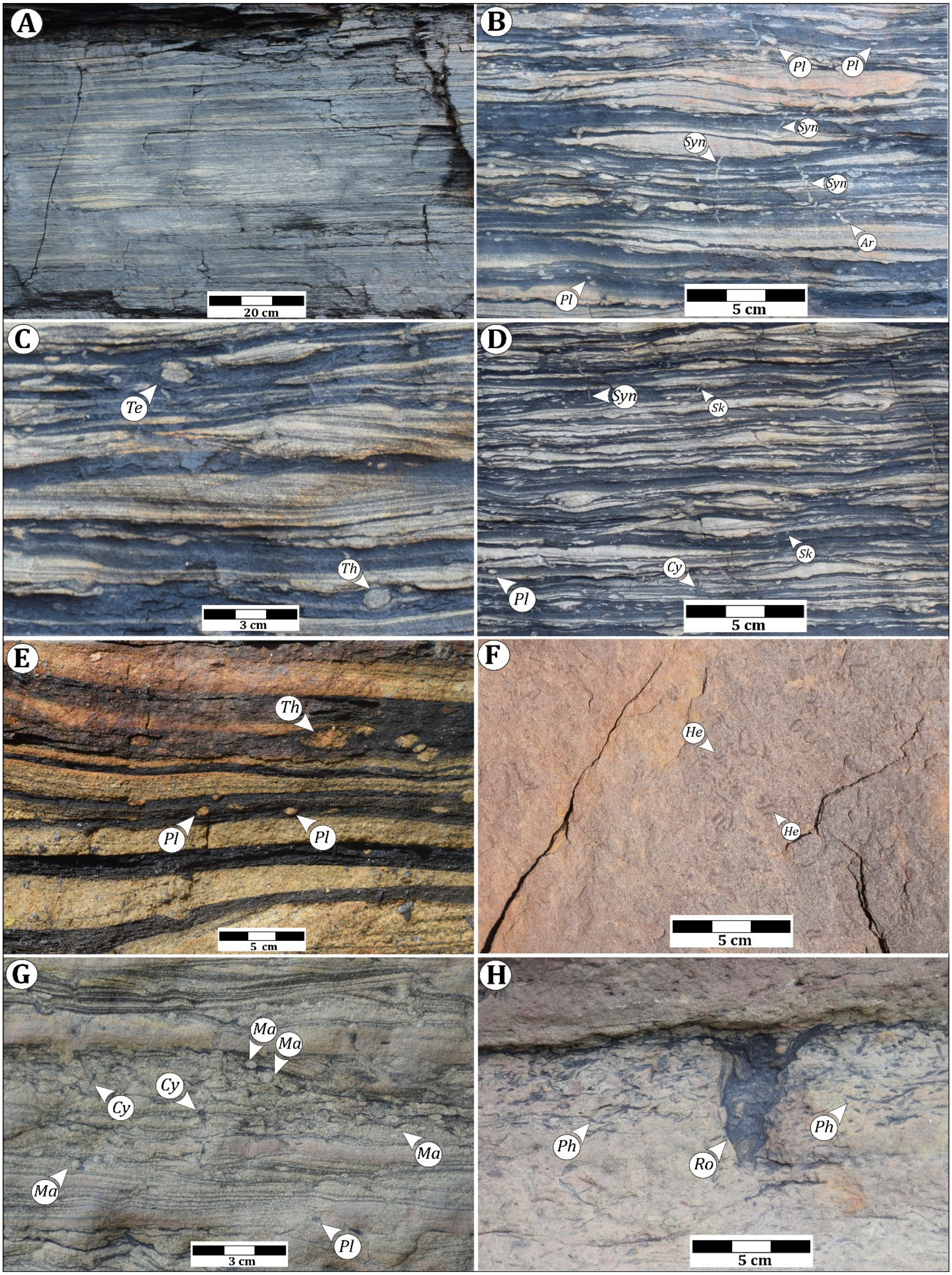
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Figure 4. 9 Facies Association 5 (FA-5) Prodelta Deposits. A) Faint parallel laminated mudstone. B, C, D, E, F) Sharp based massive mudstone represent fluid mud deposits. Mud drapes and syneresis cracks, are common. *Planolites*, *Cylindrichnus, Helminthopsis, Phycosiphon, Teichichnus, Skolithos* and *Thalassinodies* are commonly present. G, H) Bioturbated distal delta front deposits. *Macaronichnus, Rosselia*, and *Phycosiphon* are common.

Interpretation

The occurrence of mica and mud drapes (single and double) and bidirectional cross-stratification result from fluctuations in flow velocity and binary sediment transport direction (de Vries Klein, 1977; Dalrymple et al., 1991; Willis et al., 2005; Dalrymple and Choi, 2007; Dalrymple et al., 2012; Shchepetkina et al., 2019). Potential neap-spring bundles, double mud drapes, bidirectional paleocurrent, and reactivation surfaces indicate tidal influence in a shallow marine setting (Vakarelov et al., 2012; Gugliotta et al., 2017). Syneresis cracks indicate freshet-induced salinity fluctuations (Plummer and Gostin, 1981; Bhattacharya and MacEachern, 2009). Flame and load structures, and fugichnia indicate a high deposition rate (Maceachern et al., 2005; Bhattacharya and MacEachern, 2009; Coates and Maceachern, 2009). Carbonaceous material and coal fragments indicate proximity to a fluvial source (Maceachern et al., 2005; Coates and Maceachern, 2009; Dasgupta et al., 2016). The asymmetrical to symmetrical oscillation ripples point to subordinate wave reworking. The presence of trace fossils *Macaronichnus* and *Rosselia* and the paucity of suspension-feeding trace fossils indicate turbid water conditions (Gingras et al., 1998; Maceachern et al., 2005; Gingras et al., 2007; MacEachern and Gingras, 2007). The massive, unbioturbated mudstone likely represent fluid mud deposits (Bhattacharya and MacEachern, 2009; Ichaso and Dalrymple, 2009; Mackay and Dalrymple, 2011). Local hummocky cross-strata and combine flow ripples indicate minor storm activity (Dumas and Arnott, 2006).

In summary, FA-6 represents the river and tide-influenced delta front lobes that prograded and shifted laterally, likely within an embayed coastline.

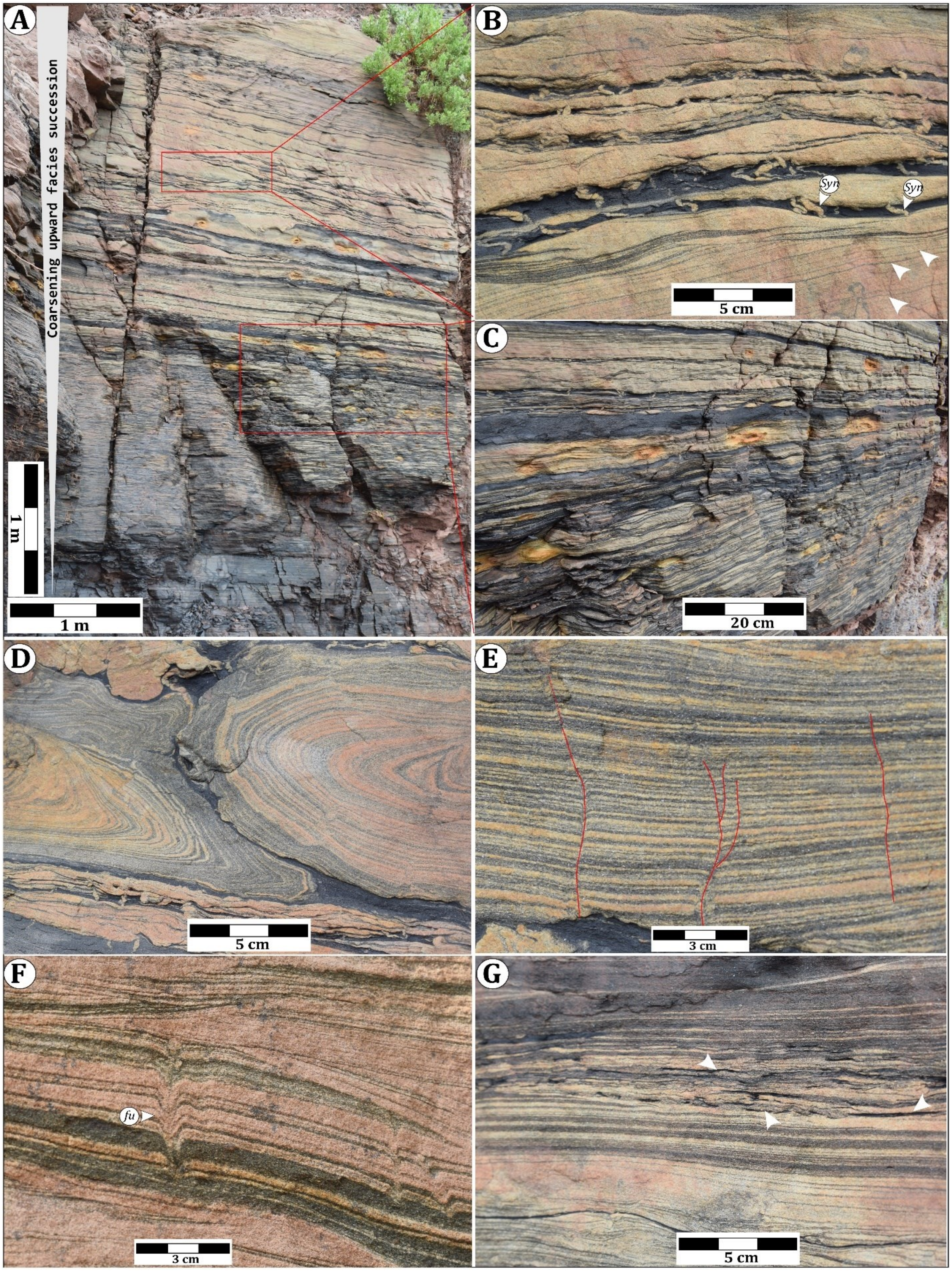
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Figure 4. 10 Facies Association 6 (FA-6): Delta Front Deposits. A) Delta front deposits showing an upward-coarsening character. B) Zoom in view of a part of A, showing mud drapes (arrow) and syneresis cracks (Syn). C) Zoom in view of a part of A, showing fluid mud deposits and heterolithic nature of distal delta front deposits. D, E) Large scale soft-sediment deformation structures and syn-depositional normal faults. F, G) Fugichnia (fu) carbonaceous matter (arrow) in the delta front deposits at the Pail Road section.

Facies association 7 (FA-7): Proximal Delta Front-Mouth Bar

Sedimentology: Facies association 7 (FA-7) forms an upward coarsening and thickening succession. This FA shares many characteristics with FA-6 (tide dominated delta front). However, the sandstone is less well sorted and carbonaceous (organic) detritus is very abundant (Figure 4.10 G). The lower part comprises interbedded sandstone and mudstone. The mudstone is dark, structureless and sharp-based fluid-mud layers. The sandstone is sharp-based, planar parallel to bidirectional ripple cross-laminated. Asymmetric ripples and single-double mud and mica drapes are common. The sandstone in the upper part is fine to lower medium-grained, massive, planar parallel to cross-stratified. Current ripples (asymmetric, symmetric, and climbing), rip-up clasts, and reactivation surfaces are common. Rhythmic bundling, mud and mica drapes, coal seams, and carbonaceous fragments are present. Paleocurrent direction derived from current ripples and cross-beds is bimodal (northwest to southeast) with overall northwest dominated current direction.

Ichnology: BI 1-2. Bioturbation is rare. The low diversity trace fossils suite includes *Skolithos, Arenicolites*, *Berguaeria*, *Paleophycus and Diplocraterion.*

Interpretation: The heterolithic strata (poorly sorted), an abundance of carbonaceous (organic) detritus, climbing current ripples, and soft-sediment deformation indicate strong fluvial influx (Maceachern et al., 2005; Coates and Maceachern, 2009; Dasgupta et al., 2016). Rock units with abundant cross-stratification show high-energy conditions in current-dominated depositional conditions. These cross-beds indicate the migration of dunes and ripples. The single-double mud and mica drapes, interbedded sandstone and mudstone, presence of rare oscillation ripples, flaser bedding, and minor wave reworking indicate fluctuation in flow conditions and discharge. The low diversity trace fossils with low bioturbation intensity indicate several physio-chemical stresses such as high sedimentation rates, high energy conditions, water turbidity, and fluctuation in water salinity (Gingras et al., 1998; Buatois et al., 2005; Maceachern et al., 2005; MacEachern and Gingras, 2007; Maceachern et al., 2007b; Buatois et al., 2008; Buatois and Mángano, 2011). Suspension settling results in thin mud drapes that indicate slack-water deposition (Mackay and

Dalrymple, 2011). The presence of thick, massive-appearing, unbioturbated mud beds is evidence of dynamic mud deposit in a tidally-influenced environment (Dalrymple and Choi, 2007; Mackay and Dalrymple, 2011). Rhythmic bundling, mud, mica drapes, reactivation surfaces, and bi-directional cross-strata reflect tidal conditions (de Vries Klein, 1977; Nio and Yang, 1991; Longhitano et al., 2012; Plink-Björklund, 2012). The upward coarsening-cleaning succession with persistent current and tidal-generated structures, rare wave influence, and low diversity trace assemblage is interpreted to record deposition in a tidally influenced proximal delta-front to distributary mouth-bar region exposed to minor wave action.

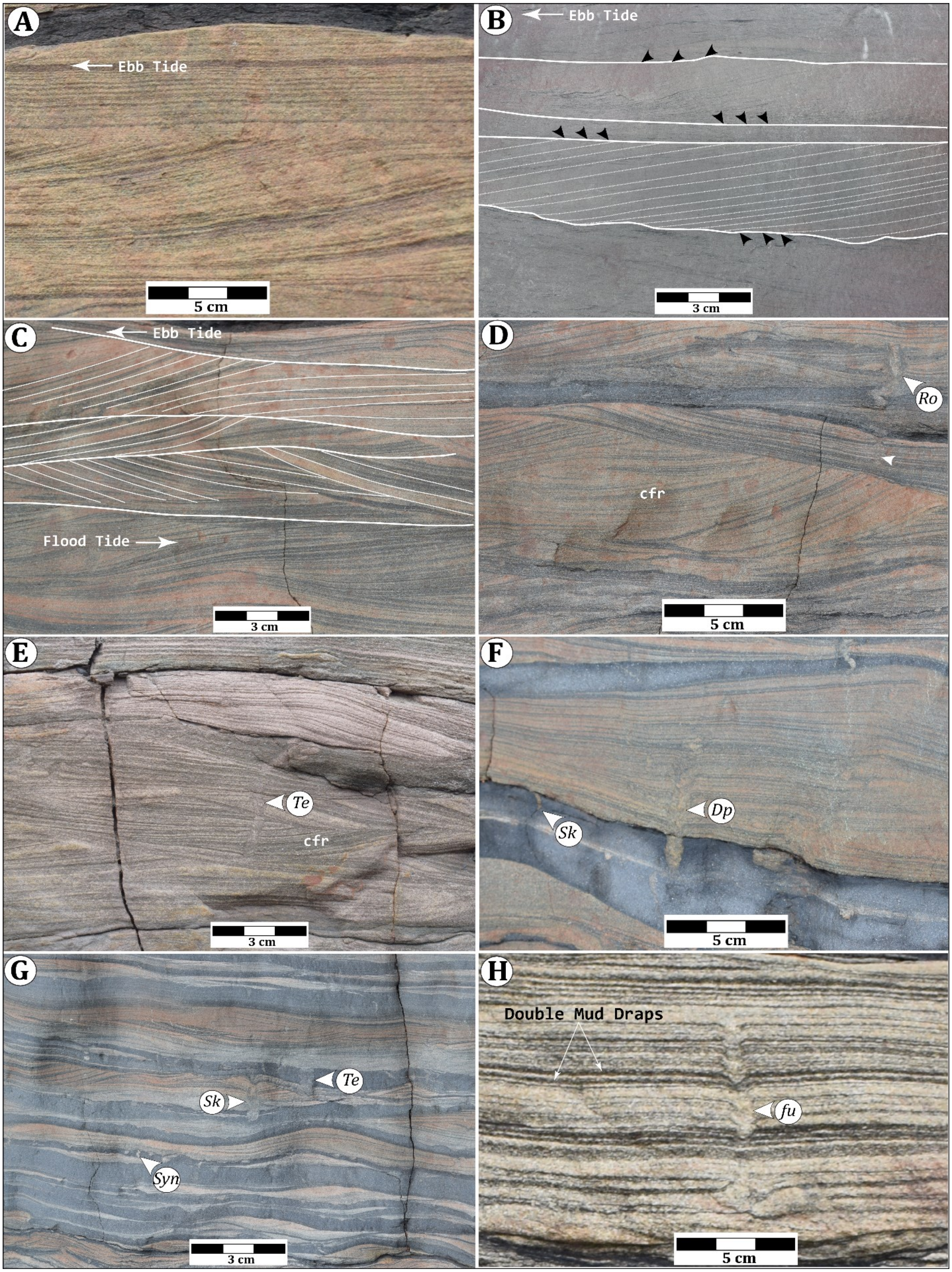
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Figure 4. 11 Facies Association 6 (FA 6): Delta Front Deposits. A, B) Ebb- dominated cross-beds in the delta front to mouth bar deposits with common reactivation surfaces (arrows) C) Flood and ebb- oriented cross-beds in the delta front deposits. D, E) Hummocky cross-beds and combine flow ripples in the delta front deposits. Water escape structure is indicated by white arrow. F) Skolithos and Diplocraterion in the delta front deposits. G) Skolithos and syneresis crack in the delta front deposits. G) Tidal bundles and fugichnia in the delta front deposits.

Facies association 8 (FA-8): Tidal Influenced Channel

Sedimentology: Facies association 8 (FA-8) is characterized by coarse to fine-grained, planar to trough cross-bedded, compound to low angle planar, and bidirectional cross-stratified sandstone with well developed rhythmites in the lower part that passes vertically into planar-laminated silty mudstones and very fine-grained sandstones. Abundant mudstone and mica drapes occur on foresets (Figure 4.12). Laterally accreted inclined heterolithic stratification is common. Sandstone units of this association are laterally discontinuous (a few meters wide) to continuous and not confined to the studied outcrops. Mud clasts are common along the basal surface. The dominant direction of paleocurrent is basinward. These bodies form 2 to 5 m thick upward-fining successions. The base of this facies association is made up of coarse-grained, cross-bedded sandstones (erosionally-based) containing large rip-up clast and fluid mud layers. On generally seaward-directed cross-beds, there are abundant mudstone drapes. Reactivation surfaces are common and are commonly covered with mud drapes. The inclined heterolithic strata occurs in sets of 0.6–2.1 m thickness. The IHS consist of 1-6 cm thick, low-angle (5–10°) inclined beds. Each IHS bed is composed of couplets (sandstone-mudstone). These couplets can be laterally traced (few to tens of meters). The IHS dip in a direction normal to the palaeocurrent direction (derived from ripples and cross-strata). Foreset dip directions can be divided into two groups: the northwest and southeast. Although the northwesterly paleocurrent can vary by as much as 90 degrees within individual sandstone bodies, they are generally between 40-50 degrees. The average north-westerly direction of the paleocurrent is between 304 to 332-degree NW. Although the south-easterly paleocurrent can vary by as much as 100 degrees within individual sandstone bodies, they are generally between 30-40 degrees with average between 80-150 degree SE.

Ichnology: BI 0-1. Bioturbation is rare to absent. Trace fossils present include *Skolithos*, *Planolites,* and *Scoyenia.*

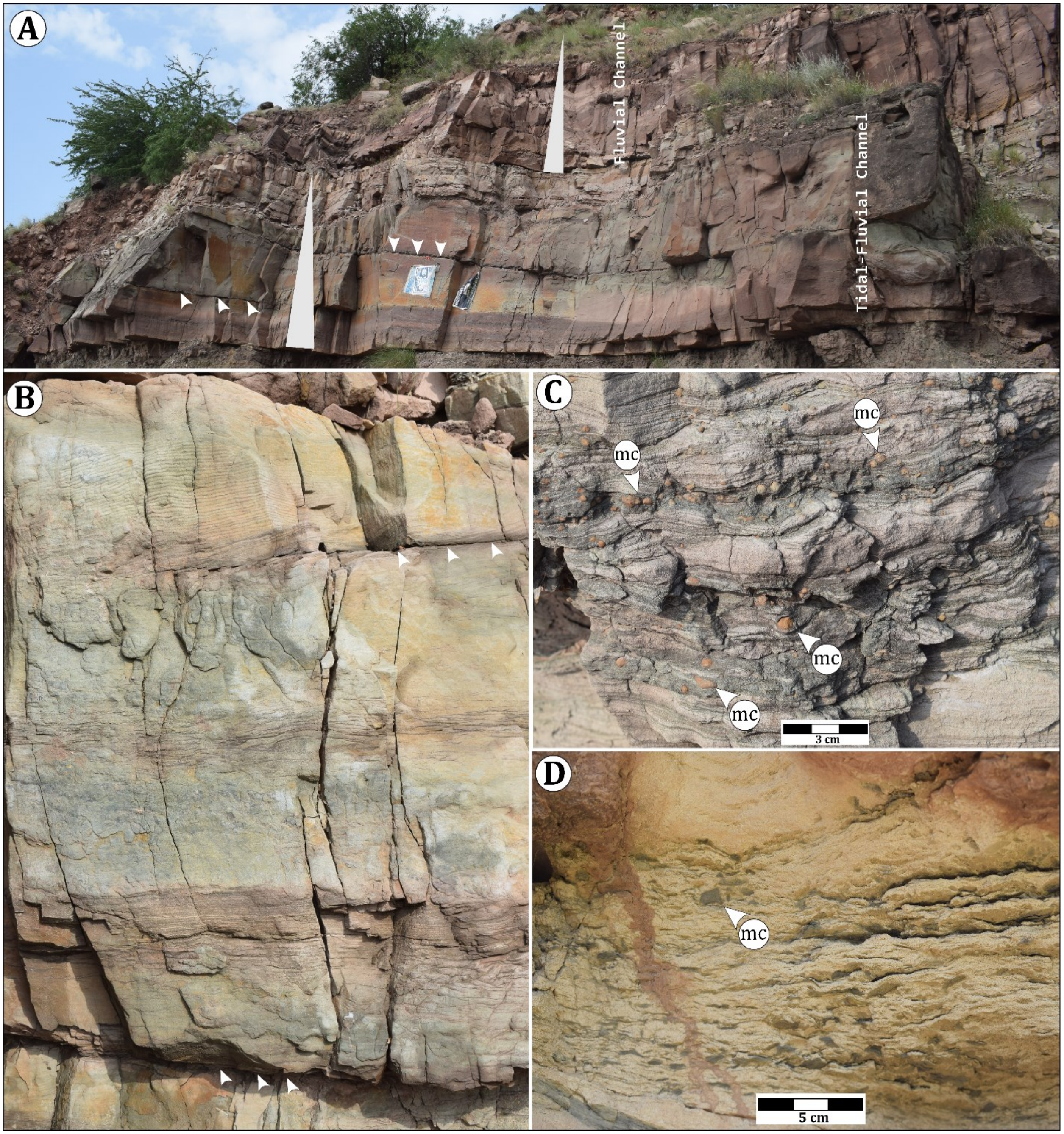

Figure 4. 12 Facies association 8 (FA-8): Tidal influenced channel deposits. A) Tidal influenced channel deposits showing an upward-fining character. Arrows indicate internal erosional surfaces. B) IHS and well-developed tidal bundles in the tidal influenced channel deposits at the Pail Road section. Arrows point to internal erosion surfaces. C, D) The lower contact with bounding facies associations is erosional to sharp with common mud clasts (mc).

Interpretation

The sharp erosional base, the presence of mud chips and lag, general fining upward trend, the presence of well-developed rhythmites and their occurrence within the lower bounding facies association (delta front, intertidal flat) suggest deposition from currents (high energy) in tidally influenced channels (de Vries Klein, 1977; Dalrymple et al., 1991; Nio and Yang, 1991; Choi et al., 2004; Dalrymple and Choi, 2007). Cross strata that are orientated predominantly northwestward (ebb tide direction) and occasionally orienting southeastward suggest some tidal impact in the channels. Mudstone drapes and climbing ripples occasionally occurring on cross-beds (seaward-directed) suggest ebb-dominant tidal flows, slack water periods, and a relatively weaker flood-directed current. The IHS can be interpreted as laterally accreting deposits, suggesting deposition on a tidal point bar surfaces in a sinuous tidal channel (Thomas et al., 1987; Choi et al., 2004; Dalrymple and Choi, 2007; Johnson and Dashtgard, 2014). Cross beds together with low-intensity simple burrows indicate a highly energetic, stressed environment (de Vries Klein, 1977; Dalrymple et al., 1991; Nio and Yang, 1991; MacEachern and Gingras, 2007; Buatois and Mángano, 2011; Buatois et al., 2012). The large widths are thought to suggest that the channels were extremely wide and extensively migrated, as reported in many modern and ancient tide-dominated settings (Gugliotta et al., 2017; Shchepetkina et al., 2019).

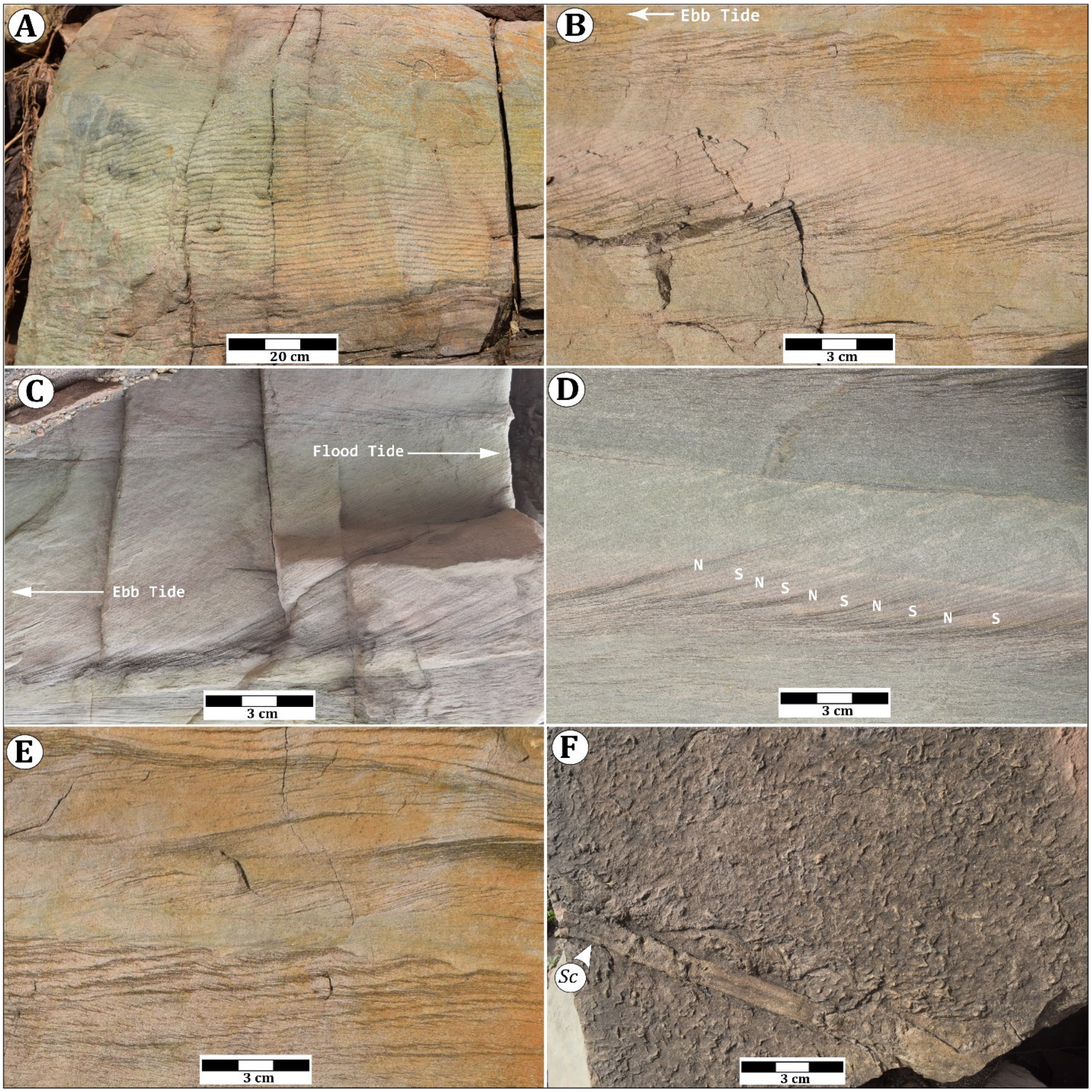

Figure 4. 13 Facies association 8 (FA-8): Tidal influenced channel deposits. A) Excellent tidal rhythmites. B, C, D) Sigmoidal bedding, tidal bundles, reactivation surface and neap-spring bundles within cross-stratified sandstone. E) Climbing asymmetrical ripples in the sandstone. F) Bioturbated sandstone with Scoyenia and burrow mottled surface.

INTERPRETATION AND DISCUSSION

Evidence of tidal influences

The deposits formed under strong tidal impact have characteristic tidal signatures such as bidirectional paleocurrent, ubiquitous fluid mud layers, spring-neap bundles, ubiquitous mica and mud drapes on cross-strata for-sets, and lenticular, wavy, and flaser bedding (de Vries Klein, 1977; Dalrymple et al., 1991; Willis et al., 2005; Dalrymple and Choi, 2007; Carmona et al., 2009; Dalrymple et al., 2012; Plink-Björklund, 2012; Vakarelov et al., 2012; Gugliotta et al., 2017; Shchepetkina et al., 2019). Multiple observations suggest that the studied Dandot succession was formed under strong tidal conditions. (1) The entire succession is characterized by bidirectional ripple cross-laminations and dune cross-stratification, with both flood and ebb-oriented ripples, oriented in opposing directions. 2) The succession has ubiquitous rhythmites. These rhythmites have mm and cm thick, sub-horizontal laminations of sandy and muddy alternations (rhythm in grain size and thickness). These rhythmic alternations are related to variations in the velocity of tidal currents (spring-neap or semidiurnal/diurnal). 3) The succession is strongly heterolithic with lenticular mudstone, wavy interbedded sand-mudstone, and flaser sandstone. A spectrum of rippled, heterolithic bedding can be formed in subaqueous environments depending on the sediment supply. This is possible through periodic and repeated alternations of ebb-flood cycles. These can be found in many subaqueous settings but they are most common in tidally-dominated settings where daily changes in the flow conditions occur. 4) The succession has ubiquitous fluid mud deposits. The presence of abundant fluid mud deposits (turbidites or hyperpycnites) in the studied succession likely indicate dynamic deposition of mud in a tide-dominated setting (Mackay and Dalrymple, 2011). (5) The studied succession has abundant mud drapes mantling ripples and forests of crossbeds. Mud drapes on ripples, and mantling dune foresets are indicative of fluctuations in current velocity and mud falling out during slack water conditions. Mud is deposited through suspension during slack water periods between the dominant and subordinate currents in tidal settings. (6) The studied succession has ubiquitous sigmoidal cross-stratification. Cross-stratification with sigmoidal contacts is a characteristic sandstone feature typical for tidal bodies (Willis, 2005). (7) Mud pebbles and clasts are abundant in the sandstone bed and considered common in tidal settings (Dalrymple , Choi, 2007).

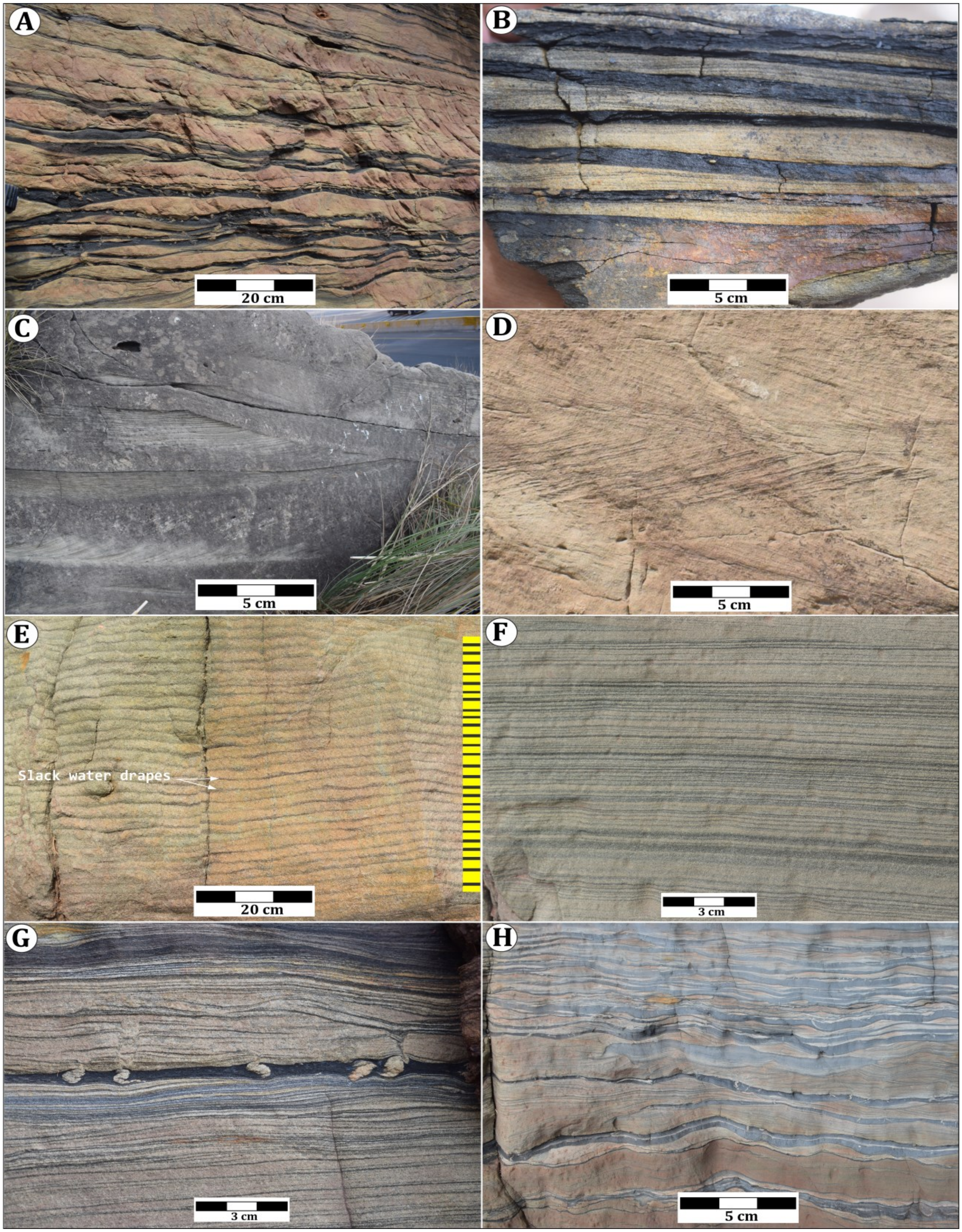

Figure 4. 14 A, B) Strongly heterolithic succession with lenticular mudstone, wavy interbedded sand-mudstone, and flaser sandstone. C, D) Characteristic bidirectional ripple cross-laminations and dune cross-stratification, with both

flood and ebb ripples, oriented in opposing directions. The dominant tidal current is right to left. C) Sigmoidal and trough cross-stratification D) Herringbone cross-stratification. E, F) Tidal rhythmites (thinly laminated) showing well-developed tidal couplets indicating repeated tidal cycles (asymmetric), with dominant tidal current forming thick sand layers (yellow), followed by mud and mica drapes (slack-water) and subordinate tidal current forming thin sand layer. G, H) Abundant mud drapes indicative of fluctuations in current velocity and mud falling out during slack water conditions.

Evidence of estuarine deposits

Differentiating the deposits of tide-dominated estuarine settings from tide-dominated deltaic settings can be challenging. However, estuaries (including tide-dominated) are fundamentally different from deltas. The lower Dandot succession demonstrates some fundamental characteristics pointing to deposition in a tide-dominated estuary setting as opposed to other tidal scenarios. The ichnological signatures of the lower Dandot Formation is consistent with brackish-water sedimentation. The fundamental characteristics of the brackish-water model were developed by (Pemberton et al., 1982) and refined by (MacEachern and Gingras, 2007; Maceachern et al., 2007b; Hauck et al., 2009). Suites of brackish water trace fossils are generally diminutive, have heterogeneous distribution trends, low diversities and characteristic combinations of ichnogenera. The observed trace fossil suite is of low diversity and comparably low-intensity trophic generalist behaviours (*Planolites, Thalassinoides, Skolithos, Cylindrichnus, Arenicolites, and Siphonichnus*).

Paleocurrent directions in the lower Dandot strata are flood-dominated (landward). The lower Dandot strata also display a strong tidal impact. The lower Dandot strata typically overlies either a sequence boundary or fluvial deposits (Tobra Formation), which are underlain by a sequence boundary, indicating that the lower Dandot Formation is trangressive. The studied lower Dandot succession is composed of upward fining successions (Figure 4.15) that indicate a characteristic backstepping pattern, which is typical of transgressive estuarine deposits (Gingras et al., 2012a).

In summary, we suggest the overall upward fining, overall flood-dominated paleocurrent directions, and brackish water ichnofossils in concert with their overall transgressive vs. regressive character, all suggest deposition in a tide-dominated estuary for the lower Dandot strata.

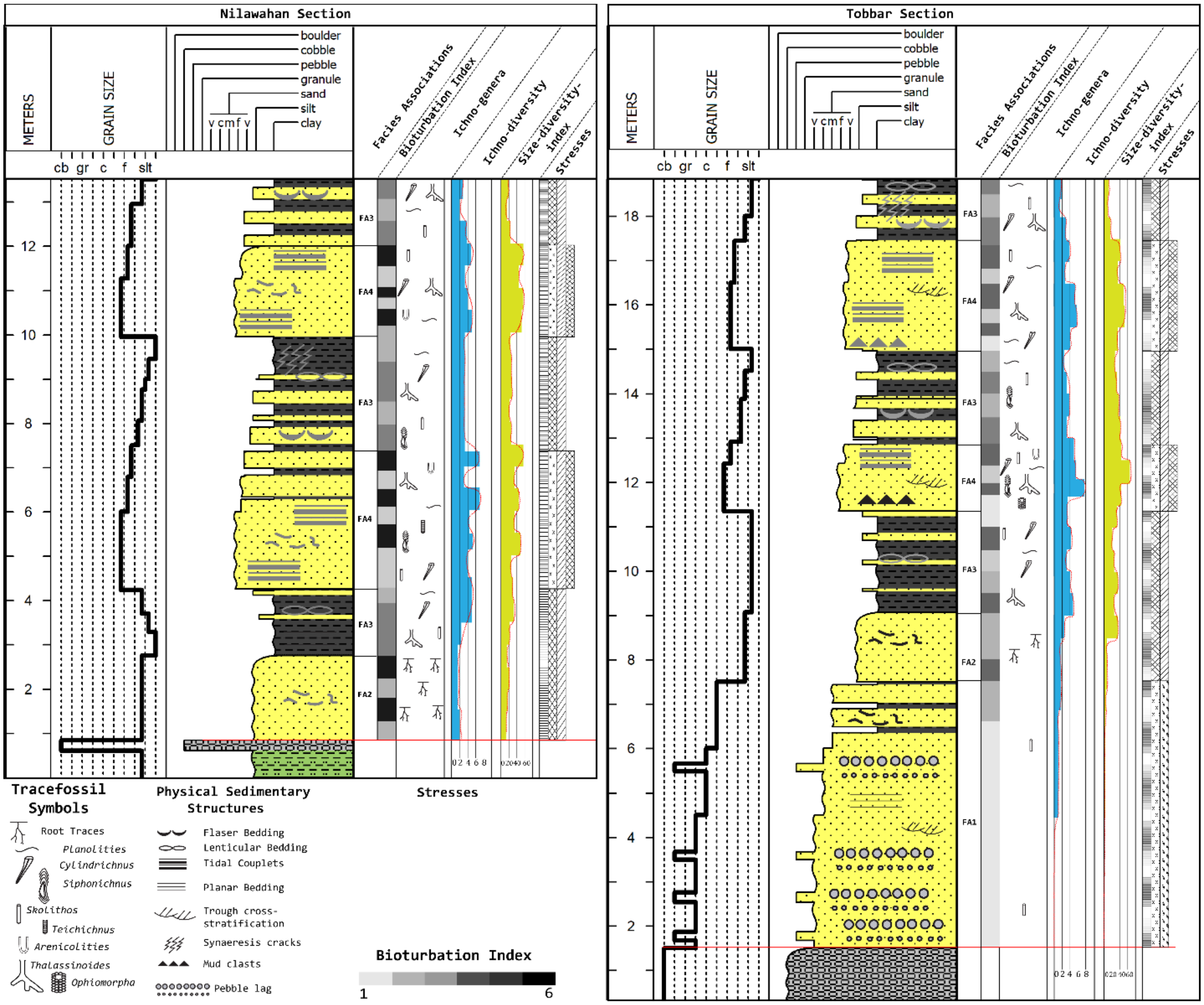

Figure 4. 15 Vertical section summarizing the trends in SDI, BI, ichnological diversity and proposed physical and chemical stresses in the lower Dandot Formation estuarine succession.

Evidence of deltaic deposits

Although physical sedimentary structures and associated facies may help establish tidal influence, it can be challenging to determine if these facies formed in an estuary, delta, or open-marine environment because these facies can occur in multiple depositional environments. The tide-dominated deltas are very similar to the estuaries, and they are often very difficult to differentiate from estuarine. However, estuaries and deltas (including tide-dominated ones) are fundamentally different. For the studied upper Dandot succession, a tide-influenced Delta is preferable to other tidal dominated settings like an estuary and open marine environment.

The studied upper Dandot succession exhibits bidirectional paleoflow directions. The dominant paleocurrent directions, however, are ebb-oriented. In a tidal-dominated estuarine setting, flood and ebb dominance would be nearly equally favored (Dalrymple et al., 1992; Gingras et al., 2012a).

The studied succession contains trace fossils demonstrating very stressed conditions. Biogenic reworking is not uniform. The trace fossil suite is of very low diversity and BI is low. However, stressed brackish water conditions can also be found in other depositional settings (estuaries, bays, and lagoons) affected by freshwater input (Gingras et al., 2002; Buatois et al., 2005; Maceachern et al., 2005; Gingras et al., 2007; MacEachern and Gingras, 2007; Maceachern et al., 2007b; MacEachern et al., 2008; Buatois and Mángano, 2011; Gingras et al., 2012c). Although the studied ichnofossils are comparably depauperate to their fully marine members, they indicate some departure from classic brackish water ichnofacies such as those found in estuaries and inter-distributary bays. The presence of *Helminthopsis. Phycosiphon*, and *Chondrites* (fully marine trace fossils) in these deposits may indicate a normal marine salinity period within a stressed environment (prodelta-distal delta front) (Maceachern et al., 2005; Gingras et al., 2007; MacEachern and Gingras, 2007; Buatois et al., 2008; Buatois and Mángano, 2011; Bhattacharya et al., 2020). These marine trace fossils help distinguish these deposits from estuaries, bays and lagoons.

The studied succession is composed of upward coarsening units indicating characteristic deltaic progradation (Bhattacharya and MacEachern, 2009). The upper Dandot strata lack any backstepping pattern, which is typical of transgressive estuarine deposits. Estuarine valleys can also show progradational stacking patterns when the bay-head delta progrades during the highstand (Dalrymple et al., 1992). However, the upper Dandot strata trace fossils are comparably more diverse than the bayhead delta (Buatois et al., 2005; MacEachern and Gingras, 2007).

In summary, we suggest the overall upward coarsening (basinward fining), general ebb tide-dominated paleocurrents, moderately stressed ichnofossils, and upward cleaning from prodeltaic mudstone to sandy delta front-tidal bars along with their overall regressive vs. transgressive character, all suggest deposition in a tide-dominated delta. These may serve as valuable and distinct criteria in differentiating tide-dominated estuaries from tide-dominated deltas.

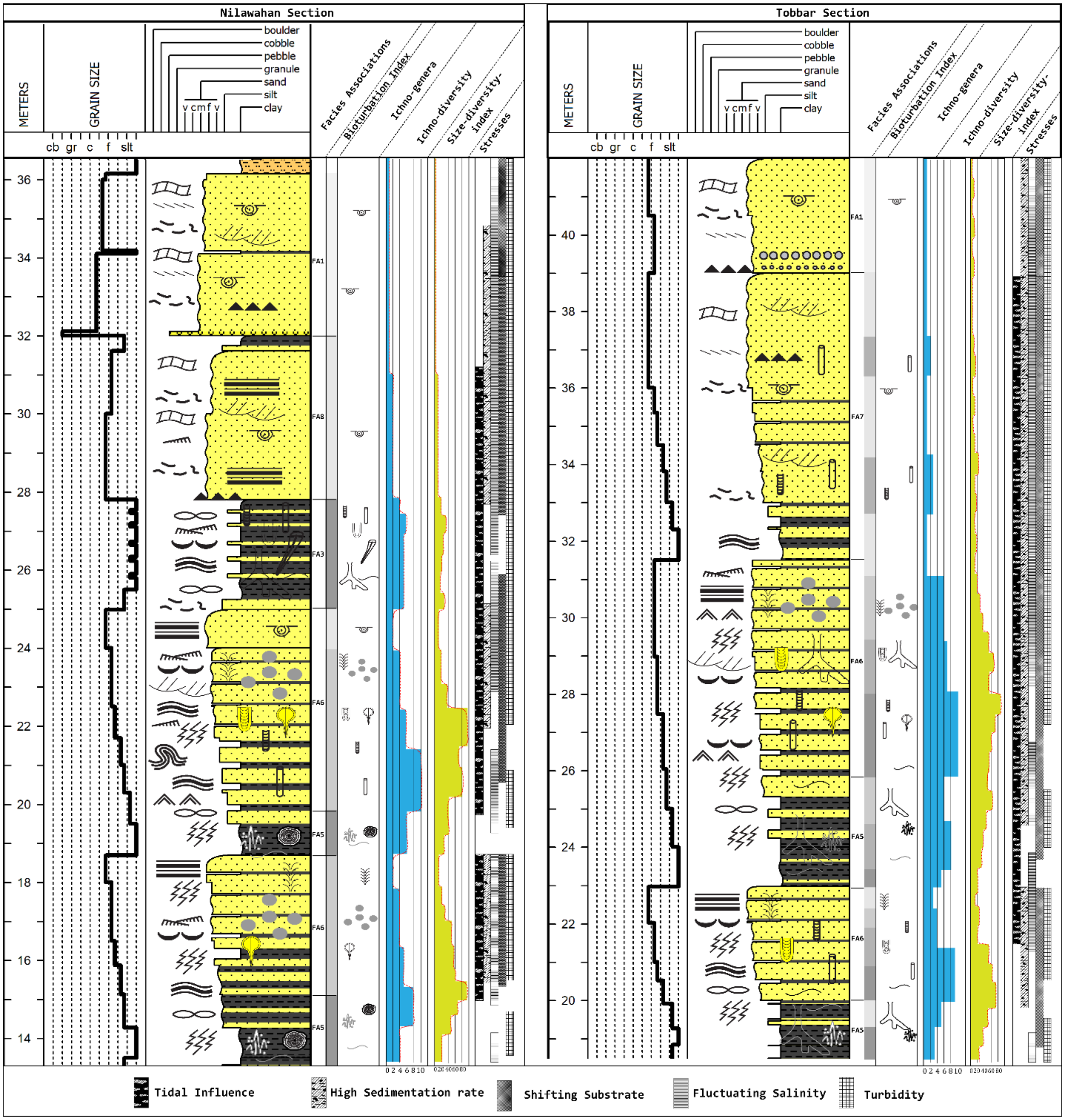

Figure 4. 16 vertical section summarizing the trends in SDI, BI, ichnological diversity and proposed physical and chemical stresses in upper Dandot Formation deltaic succession.

Ichnological trends in Estuarine and Deltaic deposits

Bioturbation indicates physicochemical conditions during deposition. Burrow distribution in a data set may primarily demonstrate stable conditions and temporal persistence of stresses (physiochemical conditions) in a sedimentary setting (Gingras et al., 2011; Botterill et al., 2015). Size selection and physiological duress lead to morphologic adaptations that result in diminution (Gingras et al., 2011). In marine environments, chemical stresses (fluctuating salinities, low dissolved oxygen) may lead to burrow diminution (Pemberton et al., 1982; Gingras et al., 1999; Hauck et al., 2009; Gingras et al., 2011). The degree of physicochemical stress is often reflected in trace fossil diversity. Highly diverse suites are characterized by optimal conditions, while low-diversity ones indicate environmental stress. The distribution of ichnofossils in the studied litho-facies association is regular heterogeneous to sporadic heterogeneous. These heterogeneous, sporadically bioturbated intervals indicate persistent temporal variability in physicochemical conditions such as rapid sedimentation, heightened water turbidity, persistently shifting substrates, and salinity fluctuations (Gingras et al., 1998; Maceachern et al., 2005; Gingras et al., 2007; Buatois et al., 2008; Dafoe et al., 2010; Buatois and Mángano, 2011; Gingras et al., 2011; Botterill et al., 2015; Dasgupta et al., 2016). These physicochemical stresses are common in settings where tides, waves, and fluvial processes impact deposition.

Estuarine Deposits

The estuarine tidal bar deposit shows regular heterogenous bioturbation. Bioturbation in the lower part of the bar is uncommonly sparse. However, the medial bars have nonuniform heterogeneous regular trace fossil distributions. The succession consists of bioturbated beds and laminated (unbioturbated) beds. The trace fossil suite present includes *Skolithos, Cylindrichnus, Arenicolites, Ophiomorpha, Polykladichnus* (vertical traces), and *Planolites, Thalassinoides, Teichichnus* (horizontal traces). These bioturbated and laminated (tidal bundle) inclined heterolithic strata (IHS) of tidal bars may indicate seasonal colonization (Dalrymple et al., 1991; Gingras et al., 1999; Pearson and Gingras, 2006). Seasonal fluctuations in sedimentary conditions are prevalent in marginal-marine environments (Dalrymple et al., 1991; Gingras et al., 1999; Pearson and Gingras, 2006). They are strongly linked to regular, heterogeneous trace fossil distributions (Gingras et al., 2011; Botterill et al., 2015).

Tidal organisms are known to concentrate fine-grained sediment (rich in refractory organic matter) near their burrows due to selective ingestion (Konhauser and Gingras, 2007), resulting in burrows that have thickened linings made of mud (Gingras and MacEachern, 2012; Gingras et al., 2012c). Predominantly thick-lined burrows in estuarine deposits (*Ophiomorpha* and *Cylindrichnus*) can infer ichnological characteristics related to the rhythmic availability of organic-rich mud. Burrow linings help recognize shifting substrates or turbid water conditions (Gingras et al., 2007; Gingras et al., 2011). Trace fossils in the estuarine setting include *Skolithos, Planolites, Thalassinoides, Teichichnus, Arenicolites,* and *Siphonichnus*. Traces with intrastratal deposit-feeding ethologies (*Planolites, Teichichnus*) indicate a benthic community bioturbating the deposit using varying levels of thoroughness and relatively rapid exploitation for intastratal foods (Gingras and MacEachern, 2012; Gingras et al., 2012c). Traces with interface deposit-feeding ethologies (*Skolithos, Arenicolites,*and *Siphonichnus*) reflect organisms that rapidly exploited food resources settled on the sediment-water interface (Gingras and MacEachern, 2012). Tidal environments can lead to food distribution that is both spatially and temporally heterogeneous. Substratal and surface deposit-feeding are both common (Gingras and MacEachern, 2012; Gingras et al., 2012c).

In summary, the ichnological trend (regular heterogenous trace fossils distribution, variable bioturbation intensity, low diversity, diminutive traces, and characteristic traces fossils) points to several physiochemical stresses (seasonal fluctuations in sedimentary conditions, shifting substracts, turbid water, and anisotropic resources) that affected deposition in the estuarine setting.

Deltaic Deposits

Trace fossils in the deltaic deposits are sporadically heterogeneously distributed. The dataset shows an overall upward decreasing trend in bioturbation intensity and ichnological diversity in deltaic deposits. Trace fossils typically display comparably more diversity in contrast to estuarine deposits. Prodelta deposits show salinity fluctuations as evidenced by the alternation of moderately bioturbated and unbioturbated units. The occurrence of synaeresis cracks in these deposits also indicates fluctuations in marine salinity. The low to moderate bioturbation intensity and sporadic distribution of traces together with the presence of fugichnia indicate high sedimentation rates (Maceachern et al., 2005). The dominance of *Macaronichnus* and the presence of *Rosselia* may indicate moderate to high hydrodynamic energy conditions in a delta front setting (Clifton and Thompson, 1978; Dafoe et al., 2010; Pemberton et al., 2012). In deltaic deposits, the dominance of lined burrows can infer persistently shifting substrates. These linings stabilize the burrow walls and prevent the collapse of the central shaft (Gingras et al., 2011). Additionally, a general paucity of filter feeding traces and the presence of *Rosselia* and *Diplocraterion*, which contain linings (*Rosselia*) and linings with spreite (*Diplocraterion*), can be used to infer pronounced water turbidity (Gingras et al., 2011). This interpretation assumes that trace makers most likely collected the mud at the sediment-water interface or in the water column. The ichnological characteristics suggest turbid conditions during deposition combined with hyperpycnal mud beds within deltaic deposits.

The low ichnodiversity with a low bioturbation index reflects several physicochemical stresses such as heightened depositional rate, high hydrodynamic conditions, and salinity fluctuations.

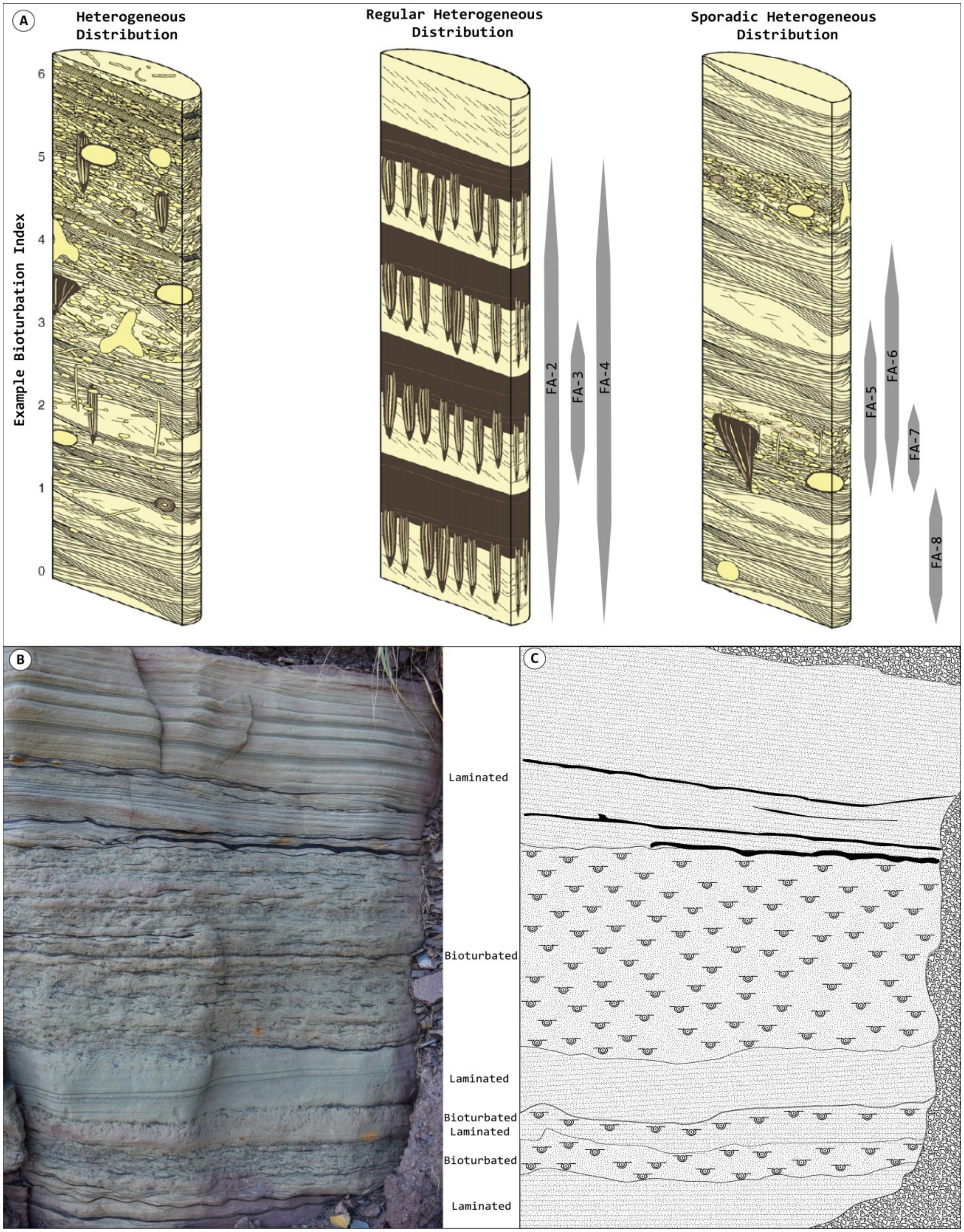

Figure 4. 17 A) Schematic of bioturbation distribution types and the approximate range of occurrence in individual facies association. Modified after Gingras et al. (2011). B, C) Field photograph and sketch showing regular heterogeneous trace fossil distribution.

Depositional Model

The sequence studied is retrogradational then progradational in nature. It represents one of the transgressive-regressive events that occurred within an overall transgressive pattern in the basin. Tidal dominance is typically seen in regions with an extensive tidal range and the absence of wave influence and is often associated with transgressive intervals. However, significant tidal amplification can also occur in a tectonically confined basin irrespective of the variations in sea level. High tidal ranges with absent to low wave energy were likely to have been present in a structurally controlled basin during the deposition of the Dandot Formation. The Dandot Formation is divided into transgressive estuarine deposits (FA-1, FA-2, FA-3 and FA-4) and regressive deltaic deposits (FA-5, FA-6, FA-7, FA-8). FA-4 sandstone bodies (cross-stratified and laterally accreting) with the evidence of tidal influence (mud and mica drapes, neap-spring bundles, bi-directional paleocurrents), characteristic bioturbation, and overall upward fining nature are interpreted as tidal bar deposits. During continuous transgression, the estuaries can infill their margins by the muddier supratidal or intertidal facies, resulting in an upward fining to muddier succession.

FA-2 and FA-3 represent deposition in a supratidal to intertidal (mud and mixed) flat setting. FA-3 commonly overlies FA-4 forming a fining-upward succession in the study area. This indicates the shift from tidal bar deposits (subtidal) to intertidal regions with decreasing tidal energy as the valley margins approach.

FA-3 widespread expansion across FA-4 suggests that the valley was infilled laterally by the expansion of intertidal zones towards its center. FA-3 can also be eroded by FA-4 at times. This could signify multiple episodes of the estuary being submerged, abandoned and incised. FA-3 (intertidal mud to mixed flat and supratidal mashes) are thought to occupy the space between the valley wall and the tidal channel. They generally flank the funnel-shaped estuary networks at their inner and middle parts (Chen et al., 2014; Dalrymple et al., 2012). These successions are often repeated in the lower portion of the succession, suggesting fluctuations in sedimentary conditions (subtidal-intertidal). The estuarine deposits indicate that the whole system was submerged and forced to move landward due to transgression and the expansion of a marine shelf during the pre to early syn-rift phase following climate amelioration during the late Carboniferous early Permian glacial maximum (after Tobra Formation deposition).

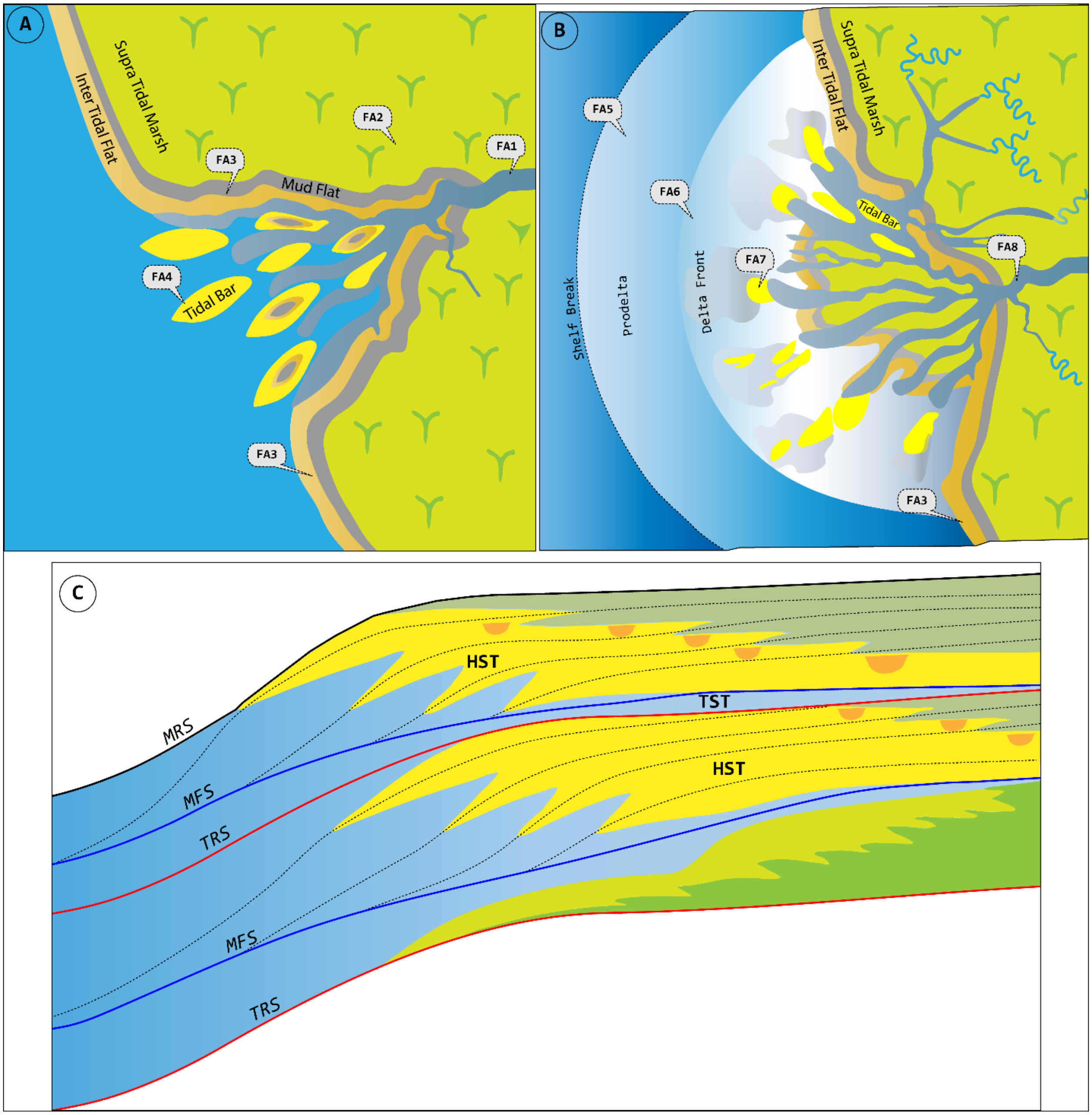

Figure 4. 18 Proposed depositional model for the Lower Permian Dandot Formation. A) The lower Dandot represents deposition in a tide dominated estuary. B) The upper Dandot Formation represent deposition in a tide dominated delta. C) Cross-section of the proposed depositional models.

The estuarine deposits are overlain by deltaic deposits (FA-5, FA-6, FA-7, FA-8). These deltaic deposits forms an overall upward coarsening and shallowing succession strongly indicating coastline progradation. The rhythmically interbedded mudstone and sandstone indicate variable energy conditions (suspension fallout and high energy traction). FA-6 is characterized by moderate bioturbation, fluid mud, load and flame structures, and synaeresis cracks indicating turbid water conditions with fluctuating salinity and a high deposition rate. FA-5 is thus deposited in a relatively calm prodeltaic setting. FA-6 and FA-7 are hetrolithic and become sandier upward. Substantial fluvial influx is inferred based on the abundance of carbonaceous (organic) detritus, climbing current ripples, and soft-sediment deformation. Mica and mud drapes, interbedded sandstone and mudstone, rare oscillation ripples, flaser bedding, and minor wave reworking indicate flow conditions and discharge fluctuations. Bioturbation is of low diversity and intensity. The succession of upward coarsening/cleaning with persistent current and tide-generated structures, rare wave influences, and low diversity trace assemblage of *Cruziana-Skolithos* Ichnofacies is thought to record deposition in the tidally influenced delta-front to a mouth bar region with little wave action. FA-6 is overlain by FA-3 (intertidal mud and mixed flat) deposits. FA-8 caps these deltaic deposits. This FA is characterized by fine to coarse-grained, trough cross-bedded sandstone with abundant mudstone and mica drapes on foresets. The basal surface is erosional with lag, mud, and extra formational clasts. The sharp erosional base, mud chips and lag, the general fining upward trend, and their underlying delta front facies indicate deposition from currents (high energy) in distributary channels. Cross-strata that are predominantly northwestward oriented (ebb tide direction) and occasionally orienting southeastward suggest some tidal impact in the channels. The deltaic succession represents lateral shifting and progradation of tide-dominated lobes, possibly within an embayed coast. The regressive deltaic deposits are often very muddy and silty but can be subdivided into upward coarsening units. These units measure 4-9 meters in thickness. These units possibly represent delta lobes shifting laterally when the delta gradually switched position along the shelf.

In summary, the study of the succession revealed that the nature of the deposits was greatly affected by tidal currents, subsidence, and river discharge. The distinctive architectures of deltaic and estuarine deposits show that the interaction of rivers, tides, and accommodation directly influenced coastal depositional systems. During the Early Permian (pre to early syn-rift) time, the low fluvial discharge in the tide-dominated estuary allowed tidal currents to play an increased role in sediment transportation during transgression-dominated periods. Riverine processes were restrained in the coastal areas, allowing rapidly attenuating tidal currents to impact deposition in the estuarine area, resulting in a thick, sandy, backstepping, fining upward succession. In contrast, large sediment discharge during the Early Permian (syn-rift) with strong tides produced subaqueous deltaic deposits.

CONCLUSIONS

The lower Permian Dandot Formation outcropping in the Salt Range, north-west Pakistan, contains tide-dominated estuarine and tide-dominated deltaic deposits.

1. The integrated sedimentologic and ichnologic facies analysis allows recognizing a tide-dominated estuarine (estuarine tidal bar, intertidal mud to mixed flat and supratidal deposits) and tide-influenced deltaic succession (prodelta, delta front, distributary mouth bar, and channels).
2. Sedimentological characteristics (spring-neap cycle, single and double mud and mica drapes, soft-sediment deformation structures, synaeresis cracks, rare wave ripples, bidirectional paleocurrent, coal seams, and fragments) and ichnological signatures (sporadic bioturbation, low diversity-low intensity impoverished trace fossils suite, the dominance of deposit-feeding traces, and rare occurrence of suspension-feeding traces) are common in both the estuarine and deltaic deposits. These sedimentological and ichnological characteristics indicate several physicochemical stresses, such as fluctuations in hydrodynamic energy, fluctuations in water salinity, turbid water conditions, and heightened depositional rates that affected the benthic communities of these tide-impacted settings.
3. While there are similarities in sedimentary facies, there are many differences in long-term processes. These differences include transgressive and regressive conditions, resulting in significantly different facies associations and stratigraphic architecture.
4. The lower Dandot tide-dominated estuarine succession shows a fining-upward trend in vertical profiles, whereas upper Dandot tide-dominated deltas form a coarsening-upward sequence. Typically the studied estuarine deposits are much cleaner and have better sorting than deltaic successions.
5. The ichnological trend (regular heterogenous trace fossils distribution, variable bioturbation intensity, low diversity, diminutive traces, and characteristic traces fossils) points to several physiochemical stresses (seasonal fluctuations in sedimentary conditions, shifting substracts, turbid water, and anisotropic resources) that affected deposition in the estuarine setting.

6. Trace fossils in the deltaic deposits are sporadically heterogeneously distributed. The dataset shows an overall upward decreasing trend in bioturbation intensity and ichnological diversity in deltaic deposits. Trace-fossil typically displays comparably more diversity in contrast to estuarine deposits.

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CHAPTER 5: DEPOSITIONAL SETTING AND TRACE FOSSIL SUITES OF THE EARLY CAMBRIAN KHUSSAK FORMATION, EAST-CENTRAL SALT RANGE, NORTH-WEST SUB-HIMALAYAS, PAKISTAN.

ABSTRACT

Understanding, establishing, and refining depositional models and the stratigraphic framework for a stratigraphic unit is essential to paleoenvironmental interpretations and depositional evolution. This is the first integrated ichnologic-sedimentologic study of the Khussak Formation at the Salt Range, Pakistan. In this study, the detailed integrated analysis is concentrated on identifying ichnological and sedimentological characteristics, leading to the identification of thirteen lithofacies and six recurring facies associations. Facies association 1 (FA-1) is made up of massive to parallel laminated mudstone with rare interbeds of sandstone. FA-1 is moderately bioturbated with trace fossils belonging to the *Cruziana* ichnofacies (*Cruziana*, *Rusophycus*, *Planolities*). FA-1 is interpreted to record deposition in the upper intertidal mud flat setting. Facies association 2 (FA-2) consists of thinly interbedded sandstone (wave-current ripple laminated) and mudstone (massive to parallel-laminated). The heterolithic wavy bedding is the dominant bedding type. FA-2 is variably bioturbated (BI=0-5). Trace fossils of moderate diversity of the *Cruziana* ichnofacies are present. FA-2 represents deposition in the middle intertidal mixed flat setting. Facies association 3 (FA-3) comprises gradational-based, laterally extensive, crudely bedded to massive, medium to lower fine-grained sandstone with thin (mm-scale) mudstone beds. FA-3 is intensely bioturbated (BI=3-5). Robust and diverse trace fossils belonging to the *Skolithos* ichnofacies are present (*Siphonichnus*, *Ophiomorpha, Thalassinoides, Planolites, Skolithos, Arenicolites*, *Diplocraterion Treptichnus pedum, Phycodes pedum,* and *Asteriacites).* FA-3 records deposition in the lower intertidal sand flat setting. Facies association 4 (FA-4) consists of muddy to silty lower-upper fine-grained sandstone with rare mudstone drapes. FA-4 is inclined heterolithically stratified (IHS). Tidal couplets (mud and mica drapes) and mud clasts are common. Bioturbation is uncommon to sparse (BI= 0-2) with low-diversity trace fossils of *Skolithos* ichnofacies (*Skolithos, Diplocraterion, Cylindrichnus Palaeophycus, Planolites,* and rare fugicnia*).* FA-4 is interpreted to represent deposition in an inter-tidal creek point bar. Facies association 5 (FA-5) consists of well sorted sandstone (upper medium to fine-grained). The sandstone is erosionally based, and laterally extensive. Planar parallel laminations, trough cross-stratification, reactivation surfaces, and mud drapes may be

present. The degree of biogenic reworking is low, and traces are sporadically distributed. Trace fossils present are of low diversity and abundance, including *Skolithos*, *Arenicolites*, *Diplocraterion*, *Siphonichnus, Cylindrichnus*, *Monocraterion*, *Planolites*, and *Palaeophycus*. FA-5 is interpreted as subtidal bar deposits. Facies association 6 (FA-6) is characterized by bioturbated muddy sandstone, heterolithic sandstone, and mudstone. Physical bedforms are commonly obliterated by bioturbation. Planar horizontal laminae, wavy laminae, small ripples, and synaeresis cracks may occur locally. FA-6 is moderate to intensely bioturbated (BI=3-6). The distribution of traces is heterogeneous (sporadically) to homogeneous (locally). Robust *Teichichnus, Ophiomorpha*, *Thalassinoides, Planolities*, *Siphonichnus, Phycosiphon, Rhizocorallium, Zoophycos, Bergauria,* and *Chondrities* are present. FA-6 record deposition in the subtidal bay region. The tidal flat deposits of the Khussak Formation show a unique ichnofacies trend. The *Cruziana* Ichnofacies characterize the lower energy proximal deposits (intertidal mixed and mud flat). In contrast, the high-energy distal deposits (lower intertidal sand flat and shallow subtidal) are characterized by *Skolithos* Ichnofacies. The ichnologic variation between the mud flat, mixed flat, sand flat, and sub-tidal deposits are gradational, but they can be used as facies edge indicators. Willapa Bay provides an excellent modern analog to explain the recognized lithofacies associations in the Khussak Formation. The deposits of the Khussak Formation and modern Willapa Bay show remarkable similarities suggesting that the Early Cambrian Khussak Formation represents tidal flat deposits reflecting similar, but not identical, depositional conditions operating at Willapa Bay.

Refining the geological model for the Khussak Formation will provide valuable insights into the distribution and occurrence of reservoir facies in addition to the basin's evolution and sea level history.

INTRODUCTION

Integrated geological analyses (sedimentologic-ichnologic) are required to reduce uncertainty in developing conventional oil and gas reservoirs, and they aid in predicting reservoir facies-dependent heterogeneities, distributions, and thicknesses better. The Khussak Formation is the second unit above the basal Khewra Sandstone of the Lower-middle Cambrian Jhelum Group and crops out in the eastern and central Salt Range of the north-west Himalayas. The Lower Cambrian Khussak Formation is a significant conventional petroleum reservoir in the Potwar

Basin and has produced oil and gas (Misa Kiswal Field) (Khan et al., 1986; Wandrey et al., 2004a, b) (Petroconsultants, 1996). Until now, production from the Khussak Formation has been limited. This is due to the uncertainty of reservoir distributions, thicknesses, and quality. However, previous facies analyses addressing the depositional environment of the Khussak Formation are scarce, and a comprehensive geological model has yet to be put forward. Ichnology provides a robust tool for aiding facies identification, depositional process, and refined paleoenvironmental interpretations when integrated with physical sedimentology (Ranger and Pemberton, 1991; MacEachern and Pemberton, 1994; McIlroy, 2004; Mackay and Dalrymple, 2011; Knaust and Bromley, 2012b; Botterill et al., 2016; Shchepetkina et al., 2020a). The prediction of reservoir distribution, shape, and size is largely dependent on using a geological model that, insofar as possible, addresses the depositional environment and stratigraphic framework, which are presently not established. This study's main theme is to develop an integrated geological model for the Khussak Formation in the study area. This study's primary focus is on the detailed sedimentology (observed physical attributes) and trace fossil assemblages of the Khussak Formation in the eastern and central Salt Range to help understand the depositional process, the distribution of facies, and the overall Early Cambrian depositional system. Developing an integrated geological model for Khussak Formation will also provide valuable insights into paleogeography, basin evolution, and sea level history, and contribute to understanding the distribution and occurrence of reservoir facies.

In this study, trace fossils analysis (suite, size, diversity, lining, and bioturbation intensity) is instrumental in detecting and differentiating various tidal-flat deposits formed under brackish-water or fully marine conditions providing the high resolution to propose a more robust facies model.

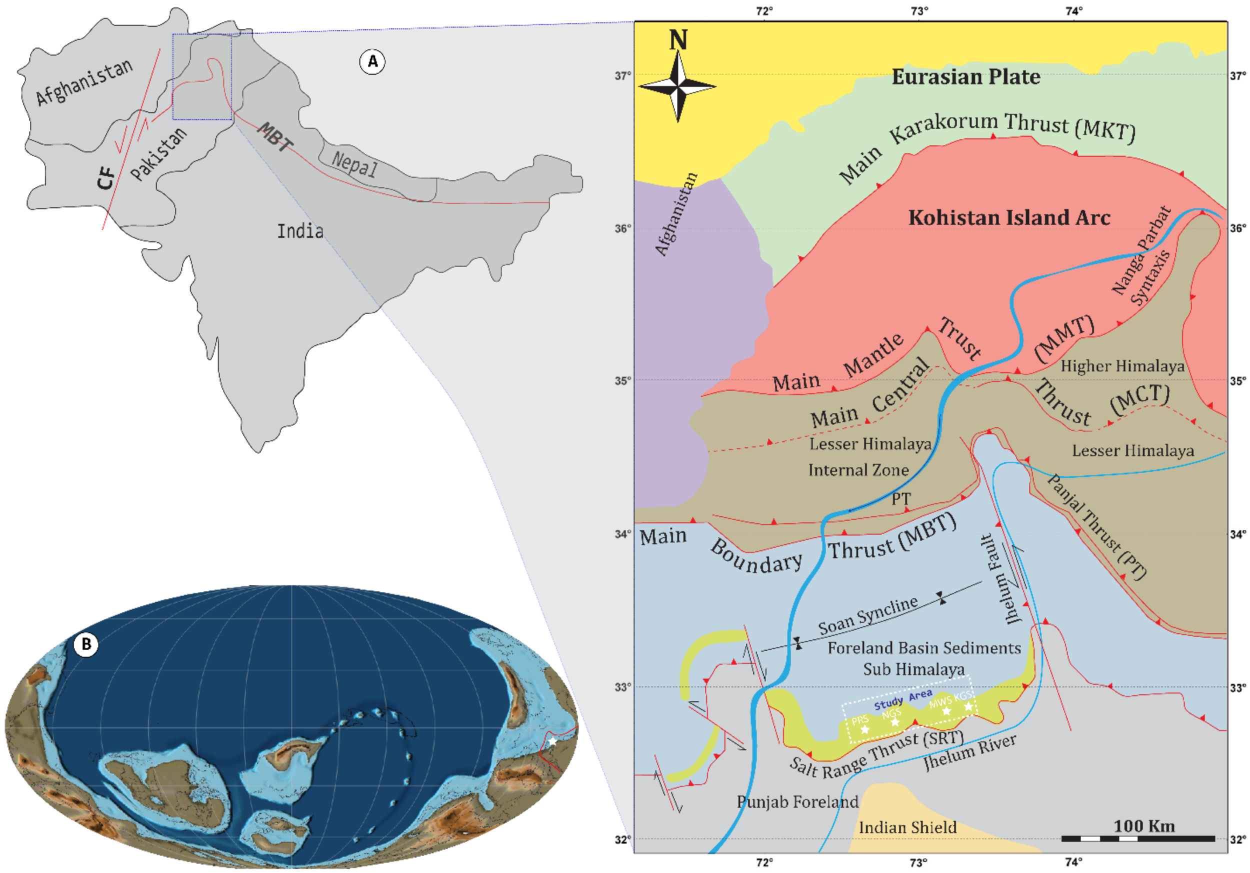

Figure 5. 1 Location maps of the study area. A) tectonic map of the northwest Himalayas showing the current location of the study area. The white doted rectangle showing the location of the study area (KGS= Khewra Gorge Section, MWS= Motor Way Section, NGS= Nilawahan Gorge Section, PRS= Pail Road Section). B) Early Cambrian paleogeographic map. The white star shows the study area.

GEOLOGICAL SETTING

The Salt Range of Pakistan (where Cambrian Jhelum Group rocks are exposed) is located in the sub-Himalayas (Figure 5.1 A). The Main Boundary Thrust (MBT) and Salt Range Thrust (SRT) mark the northern and southern limits of the sub-Himalayas, respectively (Figure 5.1 A) (Searle and Tirrul, 1991; DiPietro and Pogue, 2004). The Lower Cambrian Khussak Formation (the focus of this study) of the Jhelum group comprises bioturbated mudstone and sandstone, and dolomitic and glauconitic sandstone.

Jhelum Group

The Jhelum Group consists of four litho-stratigraphic units, including Khewra sandstone, Khussak Formation, Jutana Formation, and Bhaganwalla Formation (Figure 5.2) (Wynne, 1878;

Middlemiss, 1891; Gee, 1934; Fatmi, 1973; Shah, 1977; Gee and Gee, 1989). This Group has a laterally variable thickness due to regional erosion along the sub-Permian unconformity, with approximately 300-meter thickness in the eastern salt range (Shah, 1977). The Khewra sandstone is the lowermost unit that disconformably overlies the Pre-Cambrian Salt Range Formation (Shah, 1977). Furthermore, it consists of maroon, brick red, massive to laminated mudstone in the lower part, interbedded fine to medium-grained maroon sandstone and mudstone in the middle part, and massive to cross-bedded, medium to coarse-grained sandstone with minor granule conglomerate in the upper part (personal observations). Physical bedforms include planar laminae, tabular and trough cross-stratification, and soft sediment deformation structures. Seilacher, (1955) and Seilacher and Schindewolf, (1955) have reported *Rusophycus* in these deposits. The observed physical attributes and existing literature suggest deposition in a fluvio-deltaic setting (Khan et al., 2022). The Khussak Formation (lower Cambrian) overlies the Khewra Sandstone (Fatmi, 1973; Shah, 1980; Kadri, 1995; Bhargava, 2011). The contact between Khewra sandstone and Khussak Formation is disconformable, evidenced by a basal conglomerate lag and truncated strata, suggesting that this surface represents a sequence boundary (Hughes et al., 2019 and this study). The Lower Cambrian Khussak Formation of the Jhelum group comprises bioturbated mudstone and sandstone, and dolomitic and glauconitic sandstone. According to (Hughes et al., 2019), The Khussak Formation was deposited in a shallow marine environment. The Jutana Formation is the third unit overlying the Khussak Formation. It consists of massive to bedded dolomite, sandy dolomite, dolo-mudstone, dolo-grainstone, and bioturbated mudstone (Sajid et al., 2015; Hughes et al., 2019). The physical attributes, body fossils, and trace fossils indicate deposition in shallow marine settings (Schindewolf and Seilacher, 1955; Seilacher, 1955; Seilacher and Schindewolf, 1955; Teichert, 1964; Hughes et al., 2019). The Bhaganwalla Formation rests on Jutana Formation and consists of red to gray shale and very thin to medium-bedded limestone beds. In addition, the formation contains halite pseudomorphs indicating episodic hypersaline conditions (Hughes et al., 2019).

In summary, the Jhelum Group represents sedimentation in marginal to shallow-marine settings, including the fluvio-deltaic Khewra Sandstone, shallow to marginal marine Khussak Formation, shallow marine Jutana Formation and the lagoonal Bhaganwalla Formation.

Study Area

The Lower Cambrian marginal marine strata of the Khussak Formation at the Salt Range in the Upper Indus Basin, Pakistan, is the focus of this study. The Salt Range (the southernmost margin of sub-Himalayas) is located approximately 80 Km south of Islamabad. The Khussak strata were analyzed at four outcrop sections: Khewra Gorge, Nilawahan Gorge, Motorway, and Pail Road, to determine its sedimentological and ichnological characteristics. Measured sections were selected with no to minimal debris. The thickness of the Khussak strata in these sections is 66 m, 52 m, 58 m, and 14 m, respectively.

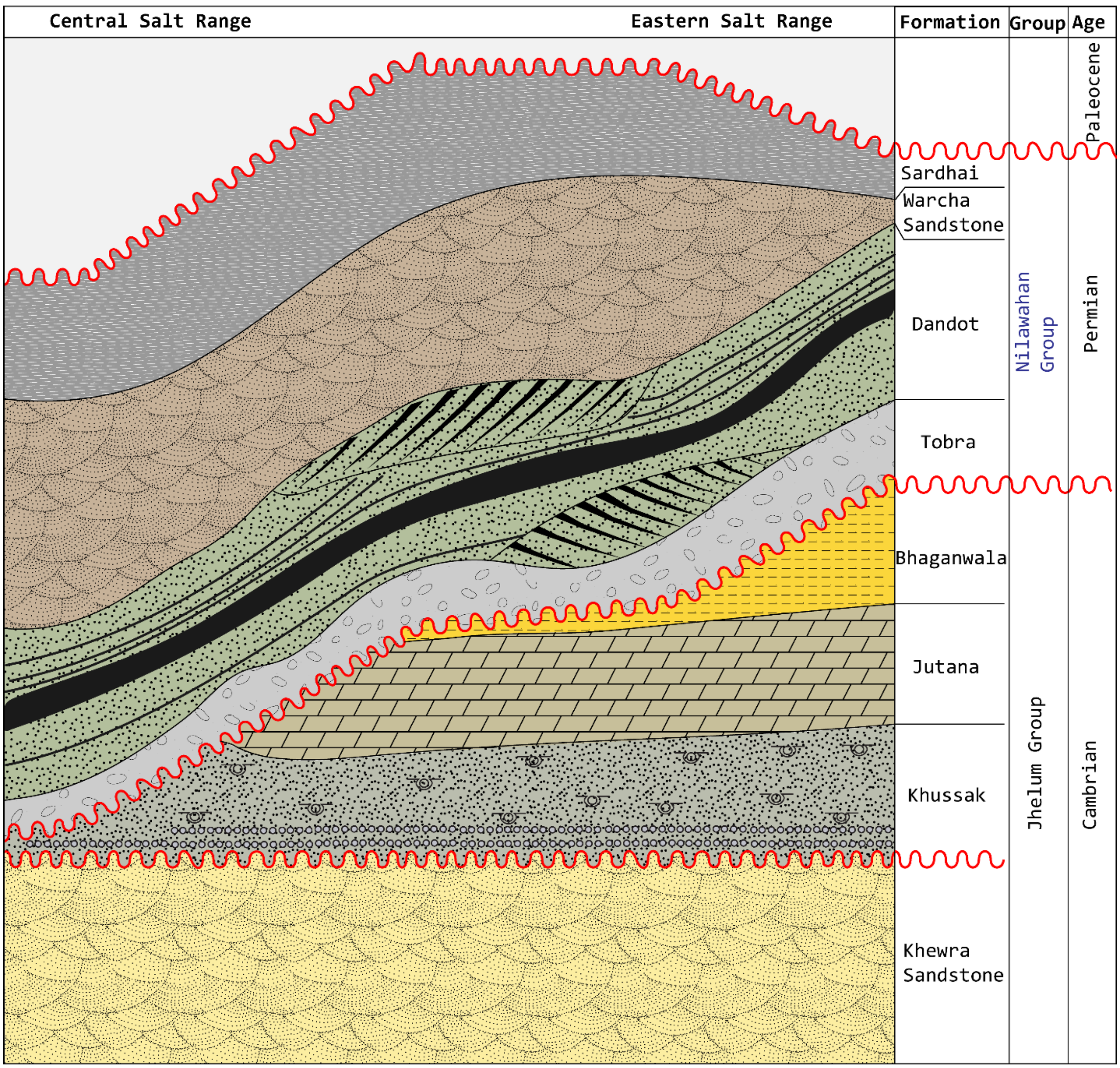

Figure 5. 2 Stratigraphic column of the eastern and central Salt Range.

METHODOLOGY

The detailed (mm-cm scale) sedimentological characteristics (thickness, lithology, grain size, sedimentary structures, and nature of contacts) and ichnological data (suite, size, ichnodiversity, lining, diversity, and bioturbation intensity) are documented. A bioturbation index (BI) scale (0-6) is adopted after (Taylor and Goldring, 1993; Taylor et al., 2003b). On this scale, a BI = 0 represent non-bioturbated strata, and a BI = 6 indicate completely bioturbated strata. This data set is presented as strip logs (1:100 scale) using AppleCore software. The khussak strata was divided into various lithofacies based on sedimentologic-ichnologic characteristics. These lithofacies are grouped into facies associations. The terminology of de Vries Klein, (1977) model of tide-dominated shallow to marginal marine setting is used in this paper, subdividing the tide-dominated shorelines into various zones, including supratidal, intertidal (upper, middle, and lower) and subtidal. According to this scheme, the subtidal zone lies below the mean low tide level. The intertidal zone includes the area between the mean low tide level to the mean high tide level, whereas the supratidal zone is above the mean high tide level (de Vries Klein, 1977).

RESULTS

Sedimentary Facies Associations

The integrated sedimentological and trace fossil analysis of Khussak strata at the Salt Range led to the recognition of thirteen (13) lithofacies (summarized in Table 5.1). These lithofacies are grouped into six facies associations representing the distinct depositional subenvirnments.

Facies Association 1 (FA-1) Mudflat

Sedimentology: Facies Association 1 deposits are laterally extensive. They are made up of massive-appearing to burrow mottled mudstone and laminated mudstone (Figure 5.5.4 B, C). Rare inter-laminae and interbeds of sandstone (lower fine-grained) and siltstone may be present. These deposits' sandstone /mudstone ratio is low (<1). The sandstone and siltstone interlaminae result in lenticular bedding (Figure 5.4, B). Other prominent features include desiccation cracks (Figure 5.4, G), erosive-based, graded beds of fine-grained sandstone, mudstone clasts, and symmetrical ripples. FA-1 is present in both the eastern and central Salt Ranges and varies in thickness from 50 centimeters to 6 meters. Lower and upper contacts with bounding facies are gradational (Figure 5.4, A)

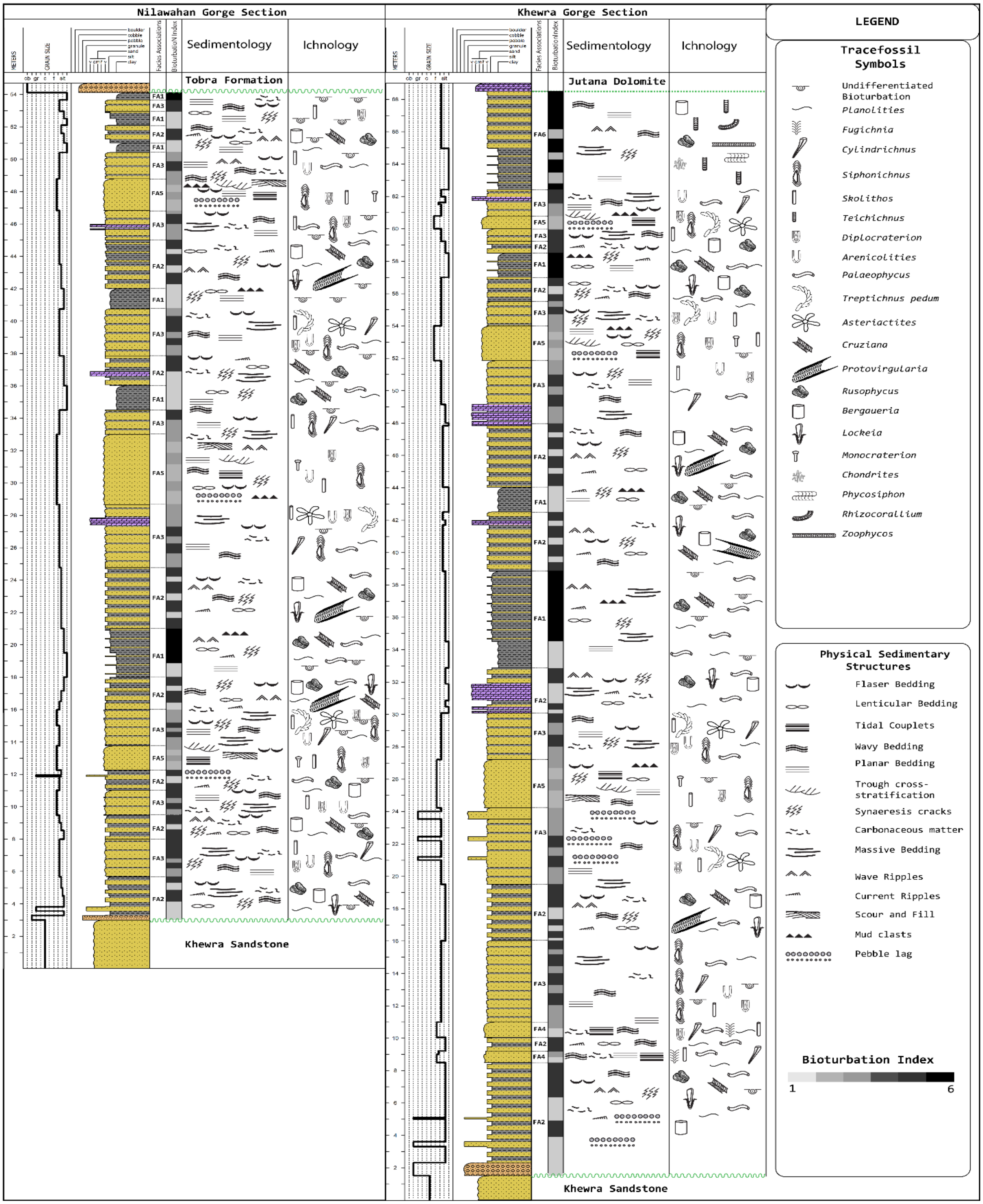

Figure 5. 3 Detailed (mm-cm scale) strip logs showing sedimentological ichnological attributes of the Khussak strata.

Ichnology: (BI=0-3) The deposits of FA-1 are moderately bioturbated. However, the scarcity of sandstone interlaminae often prevents the preservation of biogenic structures. It is, therefore, rare to find discrete trace fossils. Instead, a mottled texture (assigned to *Planolites, Teichichnus,* and *Skolithos*) (Figure 5.4, F) is common. Sporadic sandstone interlaminae locally displays *Cruziana*, and *Rusophycus*, which are assigned to the *Cruziana* ichnofacies (Figure 5.4, D, E). In addition, isolated vertical traces (*Skolithos*) may penetrate the mudstone from overlying sandstone beds.

Interpretation: The massive to planar laminated mudstone deposition generally occurs from suspension and clay flocculation (Buatois and Mángano, 2011; Flemming, 2012; De Boer, 2019). The mud-dominated heterolithic deposits indicate deposition from mixed traction and fallout from suspension. The presence of desiccation cracks indicates subaerial exposure (Reineck and Singh, 2012; Reise, 2012). Moderate bioturbation intensity and mottled texture suggest abundant food resources (Gingras et al., 1999; Dashtgard, 2011; Gingras and MacEachern, 2012). The presence of trace fossils suite of *Cruziana* Ichnofacies indicates comparatively low energy settings (Frey and Seilacher, 1980; Frey, 1984; Frey and Pemberton, 1985; McIlroy, 2004; MacEachern et al., 2007c). These sedimentological and ichnological attributes suggest that FA-1 likely records deposition in a low-energy upper intertidal mud flat setting. Mud flats are generally characterized by low hydrodynamic energy, abundant surface and intrastratal food resources, partial subaerial exposures, and sedimentation from traction and suspension (Dalrymple et al., 1992; Gingras et al., 1999; Mángano, 2002; Mángano and Buatois, 2004b; Dashtgard and Gingras, 2005; Buatois and Mángano, 2011; Desjardins et al., 2012a; Dashtgard et al., 2014).

Table 5. 1 Summary of ichnologic and sedimentologic attributes of sedimentary facies in the Lower Cambrian Khussak Formation, east-central Salt Range.

Facies Description	Occurrence / Contacts	Sedimentological Characteristics / Lithological Accessories	Ichnological Characteristics	Inferred process Interpretation	Environment
F-1: Lag Deposits	Occur at the contact of Khewra Sandstone and Khussak Formation. Gradational contact with F-4.	Conglomerate with pebble to cobble-sized rounded, subrounded, and angular clasts; 7–50 cm thick. Granules of various composition may occur as accessories.	No trace fossils are observed	Erosion and winnowing of underlying strata during sea level rise.	Transgressive Surface of Erosion
F-2: Massive to parallel laminated mudstone	Present in both the eastern and central Salt Ranges. Occur in the lower, middle and upper part of the measured sections. Lower and upper contacts with bounding facies (F-3, F-4) are gradational.	laterally extensive massive to parallel laminated mudstone. The mudstone is dark to purple in color and rich in organics. Occasional thin carbonaceous and sederitic laminae are present.	BI: (0-3). Mottled texture (most probably *Planolites*) is more common.	Deposition from suspension in a low energy setting; partial subaerial exposure indicated by desiccation cracks. Low sedimentation. Stable substrate. Stressed physicochemical conditions affording colonization by infauna.	Deposition from suspension in the upper Intertidal mud flat setting.
F-3: Lenticular Mudstone	Present in both the eastern and central Salt Ranges. Occur in the lower, middle and upper part of the measured sections. Lower and upper contacts with bounding facies (F-2, F-4, F-5) are gradational.	Mudstone with interlaminae of sandstone and siltstone. Sandstone /mudstone ratio is meager (<1). Scattered carbonaceous material and ferric minerals occur as accessories.	BI: (3-5). Trace fossils include *Cr, Ru, Ps, Pa, Lo, and Pv*.	Deposition primarily from suspension in a low energy setting punctuated by rare high energy events (sandstone lenses). Partial subaerial exposure indicated by desiccation cracks. Low sedimentation rate. Stable substrate. Stressed physicochemical conditions affording prolonged colonization by infauna	Suspension fall out with rare deposition from traction in the upper Intertidal mud flat setting.
F-4: Highly Bioturbated, heterolithic sandstone-mudstone	Present in both the eastern and central Salt Ranges. Occur in the lower, middle and upper part of the measured sections. Lower contacts with bounding facies (F-1, F-2, F-3) are gradational. Upper contacts with bounding facies (F-5, F-6, F-7, F-8) are gradational. Upper contact with F-9 is erosional.	Interbedded sandstone and mudstone with mottled texture due to abundant bioturbation. Mud pebbles may be present.	BI: (5). Trace fossils present include Cr, Ru, Ps, Pv, Lo, Pa, Pl, He, and Be	Alternate sand-mud deposition. Sand deposited from traction (by currents and local waves reworking). Mud deposited from suspension (fallout or as flocculation). Partial subaerial exposure indicated by desiccation cracks. Low sedimentation. Comparably stable substrate Relatively stable substrate. Physicochemical conditions affording prolonged colonization by infauna.	Alternate deposition from traction and suspension in the middle Intertidal mixed flat setting.
F-5: Bioturbated Heterolithic sandstone-mudstone	Present in both the eastern and central Salt Ranges. Occur in the lower, middle and upper part of the measured sections. Lower contacts with bounding facies (F-3, F-4) are gradational. Upper contacts with bounding facies (F-6, F-7, F-8) are gradational. Upper contact with F-9 is erosional.	Thinly interbedded sandstone (wave-current ripple laminated) and mudstone (massive to parallel-laminated with sand/mud ratio of about 1:1. Heterolithic wavy bedding is the dominant bedding type, however, flaser bedding is also present. Scattered carbonaceous material and ferric minerals occur as accessories.	BI: (0-3). Cr, Ru, Ps, Pv, Lo, Pa, Pl, He, and Be.	Deposition from mixed traction and fallout from suspension. Sand deposited from traction (by currents and local waves reworking). Mud deposited from suspension (fallout or as flocculation). Partial subaerial exposure indicated by desiccation cracks. Relatively stressed physicochemical conditions affording colonization by infauna.	Deposition from mixed traction and fallout from suspension in the middle Intertidal mixed flat setting.
F-6: Massive to laminated Dolomite	Present in both the eastern and central Salt Ranges. Occur in the middle and upper part of the measured sections. The Lower and upper contacts with bounding facies (F-4, F-5, F-7, F-8) are gradational.	Massive to planar wavy laminated dolomite. Dolomitic mudstone, siltstone, and sandstone laminae may also be present. Other sedimentary structures include birdseye structures and synaeresis cracks. Scattered granules may occur as accessories.	Bioturbation is absent; no trace fossils were observed in this dolomitic succession.	Seepage reflux and evaporation	Intertidal Lagoon
F-7: Bioturbated sandstone	Occur in the measured section's lower, middle and upper parts. The lower contact with F-4, F-5 and F-10, F-11 is gradational, whereas the upper contact with F-10, F11 is erosional to sharp.	light green to white, gradational based, laterally extensive, crudely bedded to massive, medium to lower fine-grained, bioturbated sandstone. Dispersed mud clast, organic matter, and ferric minerals occur as accessories	BI: (3-5). Homogeneous bioturbation by *Si, Op, Th, Pl, Sk, Ar, Dp, Tr, Phy and Ast.*	Deposition dominated by traction due to currents and local waves reworking. Low sedimentation rate. Shifting substrate. Relatively less stressful physicochemical conditions (desiccation, and fluctuating salinity), allowing prolonged biogenic modification of sand.	lower Intertidal Sand Flat.
F-8: Flaser Sandstone	Occur in the measured section's lower, middle and upper parts. The lower contact with F-4, F-5, F-7 and F-10, F-11 is gradational, whereas the upper contact with F-10, F11 is erosional to sharp.	Sandstone with interlaminae of mudstone and siltstone. The sandstone/mudstone ratio is high (>1). Dispersed mud clast, organic matter, and ferric minerals occur as accessories.	BI: (3). Homogeneous bioturbation by *Si, Op, Th, Pl, Sk, Ar, Dp, Tr, Phy and Ast.*	Sediment deposition from traction (by currents and waves). Relatively stressful physicochemical conditions (desiccation, shifting substrate, and fluctuating salinity), affording biogenic reworking.	Deposition in the lower Intertidal Sand Flat.
F-9: Cross stratified sandstone	Occur in the lower part of Khewra Gorge section. Lower erosional contact with F-5 and F-7. Upper contact with bounding facies is sharp to gradational.	Planar parallel to ripple cross-laminated sandstone with mud and mica drape, rip-up clasts, and reactivation surfaces. Organic debris and granules are present	BI: (0-1). Bioturbation is uncommon to absent. The trace fossils include *Sk, Cy, Pa, and Di.*	Sediment caliber indicates low to moderate energy. Lateral accretion indicates deposition in a point bar of a meandering channel. Grain size striping indicates tidal influence.	Inter Tidal creek
F-10: Bioturbated Inclined heterolithic stratified sandstone	Lower with F-11 and upper contact with F-7, F-8 is gradational. Upper contact with F-13 is sharp to erosional.	Bioturbated, upper medium to fine-grained sandstone, erosionally based, laterally extensive cross-stratified sandstone. Mud and mica drapes are common. Dispersed mud clast, and organic matter.	BI: (1-2). Bioturbation is uncommon to low and includes *Sk, Ar, Di, Si, Cy, Mo, Pl, and Pa.*	Erosional base, planar and trough cross-stratification, and reactivation surfaces indicate deposition in a moderate to high-energy setting. Mudstone and mica drapes, and grain size striping indicate tidal influence. BI indicate relatively stable bedforms, affording colonization.	Laterally accreting bar in a sub-Tidal environment
F-11: Inclined heterolithic stratified sandstone	Rip-up clasts and pebbly lags define the lower erosional contact F-7, F-8. The upper contact with F-7, F-8 is gradational.	Sharp-based, cross-stratified sandstone with common reactivation surfaces and mica-mud drapes. Dispersed mud clast, and organic matter	BI: (0-1). Biogenic reworking is absent to uncommon.	Sediment caliber, erosional base, planar and trough cross-stratification, and reactivation surfaces indicate deposition in a high-energy setting. Mudstone and mica drapes, flaser, wavy bedding, and reactivation surfaces indicate tidal influence. Low BI indicate actively shifting bedforms, with unfavorable conditions for colonization.	Laterally accreting bar in a sub-Tidal environment
F-12: Heterolithic sandstone and mudstone	Occur in the upper part of Khewra Gorge section. Lower contact with F-10 is sharp to erosional. Upper contact with F-13 is gradational	Interbedded sandstone and mudstone with planar parallel and wavy bedding. Flat mud pebbles and glauconite grains may be present.	BI: (3-4). Moderately bioturbated. Trace fossils include *Ch, Ph, Pl and Te.*	Suspension and traction under fair weather, near normal marine salinity with minor storm activity.	Subtidal Bay-Upper offshore
F-13: Bioturbated	Occur in the upper part of Khewra Gorge section. The lower contact with F-12 and the	Massive to crudely bedded bioturbated muddy sandstone. Planar horizontal	BI: (3-6). Intensely bioturbated. Trace	Deposition under low-hydrodynamic conditions and with abundant food resources. Normal	Subtidal Bay-Lower

muddy sandstone	upper contact with Jutana Dolomite is gradational	laminae, wavy laminae, and small ripples may be preserved. Glauconite grains may occur as accessories	fossils include *Ch, Ph, Pl and Te, Zo, Rh, Si.*	marine salinity. Stable physicochemical conditions with prolonged colonization by infauna	shoreface

Abbreviation Key

Trace Fossils

Ar-Arenicolites; Ch-Chondrites; Cy-Cylindrichnus; Di-Diplocraterion; Fu-Fugichnia; He-Helminthopsis; Lo-Lockeia; Ma-Macaronichnus; Op-Ophiomorpha; Pa-Palaeophycus; Ph-Phycosiphon; Pl-Planolites; Rh-Rhizocorallium;; Si-Siphonichnus; Sk-Skolithos; Te-Teichichnus; Th-Thalassinoides; Zo-Zoophycos

Bioturbation Index

0- Bioturbation Absent 1-Sparse Bioturbation 2-Uncommon Bioturbation 3-Moderate Bioturbation 4-Common Bioturbation 5-Abundant Bioturbation 6-Complete Bioturbation

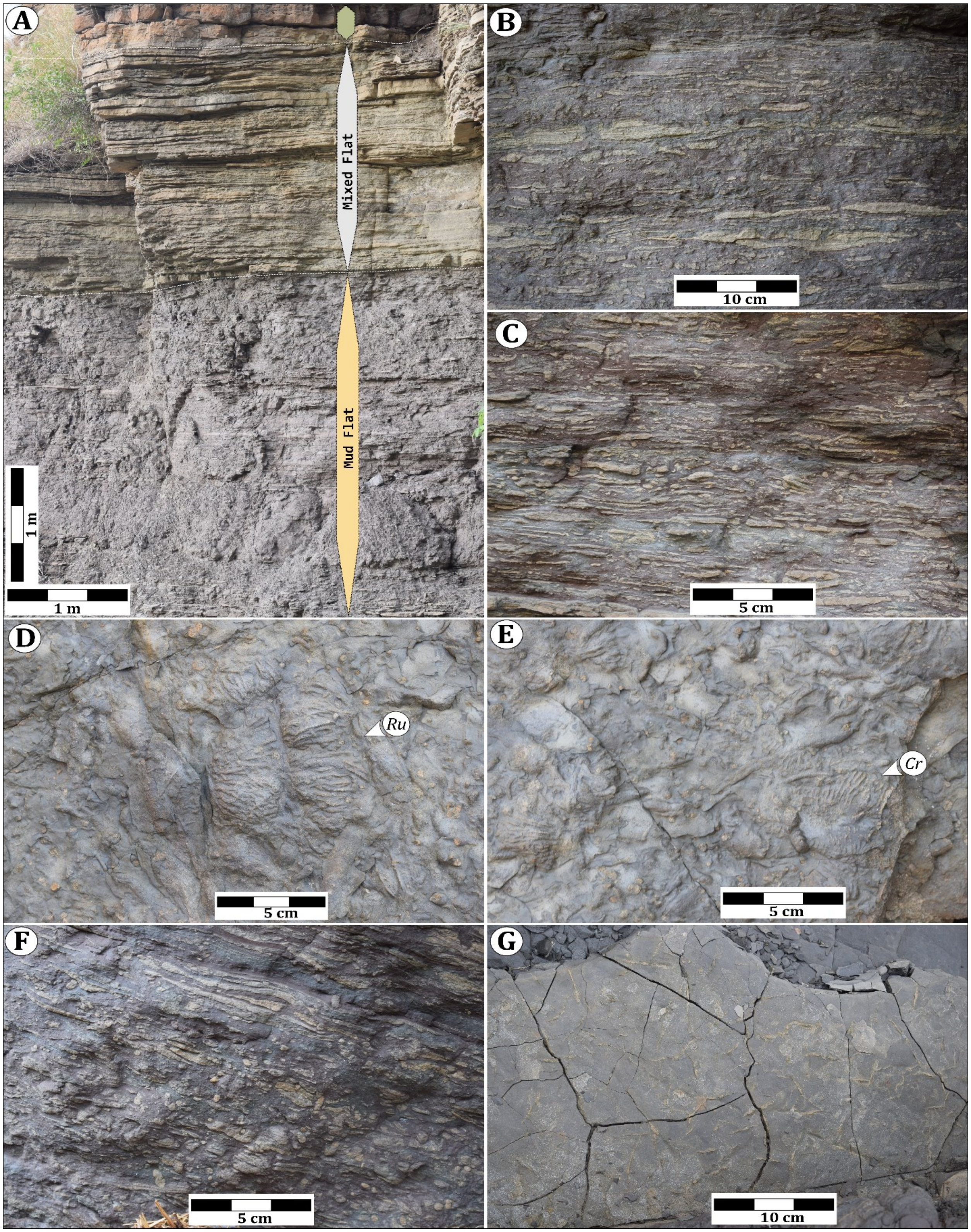

Figure 5. 4 Representative field photographs of the observed physical attributes and trace fossils in mud flat deposits. A) Field photograph showing the gradual transition from mudflat to mixed flat. B) Lenticular bedded mudstone of the mud flat. C) Bioturbated, planar laminated mudstone of the mud flat. D) Trace fossil Rusophycus in the mudstone of mud flat deposits. E) Trace fossil Cruziana in the mudstone of mud flat deposits. F) Highly

bioturbated mudstone with a mottled texture in the mud flat deposits. G) Desiccation cracks in mudstone of the mud flat deposits.

Facies Association 2 (FA-2) Mixed flat

Sedimentology: FA-2 consists of thinly interbedded lower fine-grained sandstone (wave and current ripple laminated) and mudstone (massive to parallel-laminated). The sandstone and mudstone are present in equal proportions with a sand/mud ratio of about 1:1. Individual laminae are 1–15 cm thick (Figure 5.5. A, B, C). The dominant bedding is heterolithic, manifested by flaser and wavy bedding. Wavy bedding is the dominant bedding type (Figure 5.5. A, B, C). Other sedimentary structures include ripple cross laminae, wrinkle marks, synaeresis cracks, and soft-sediment deformation. Bedding surfaces are undulated with symmetric and asymmetric ripples (Figure 5.5. E). Graded beds of erosively-based sandstone (coarse-lower fine-grained) with flat mud pebbles and ripples are locally observed. In places, this heterolithic facies is capped by massive to planar wavy laminated dolomite. Dolomitic mudstone, siltstone, and sandstone laminae may also be present. Other sedimentary structures include birdseye structures and synaeresis cracks. Bioturbation is absent; no trace fossils were observed in the dolomitic succession. FA-2 is 30 centimeters to 7.2 meters thick. The lower contact with underlying Khewra Sandstone and upper contact with FA-4 are erosional whereas the lower and upper contacts with other facies are gradational (Figure 5.5. A, B).

Ichnology: (BI=0-5) Bioturbation intensity in FA-2 is highly variable. Trace fossils include *Bergaueria, Cruziana*, *Helminthoidichnites, Lockeia, Palaeophycus*, *Planolites, Psammichnites*, *Protovirgularia, Rusophycus* and *Skolithos* (Figure 5.6). This assemblage is characteristic of the *Cruziana* Ichnofacies.

Interpretation: Flaser and wavy, heterolithic sandstone and mudstone indicate varying sediment caliber in a depositional setting characterized by variable hydraulic energy (Klein, 1970; Reineck et al., 1973; Dalrymple et al., 1990; Reineck and Singh, 2012). Mudstone deposition generally takes place from suspension and clay flocculation. The mud-dominated heterolithic deposits indicate deposition from mixed traction and fallout from suspension. The observed ripples indicate deposition in current dominated setting (Allen, 1969; Reineck et al., 1973; Allen, 1983). The presence of desiccation cracks indicate subaerial exposure. Erosive-based, graded beds of fine-grained sandstone with mudstone clasts evidence episodic storm deposition. The variable bioturbation intensity (*Cruziana* Ichnofacies suite) and mottled texture suggest heterogeneous food resources (Gingras et al., 1999; Gingras and MacEachern, 2012; Gingras et al., 2012c).

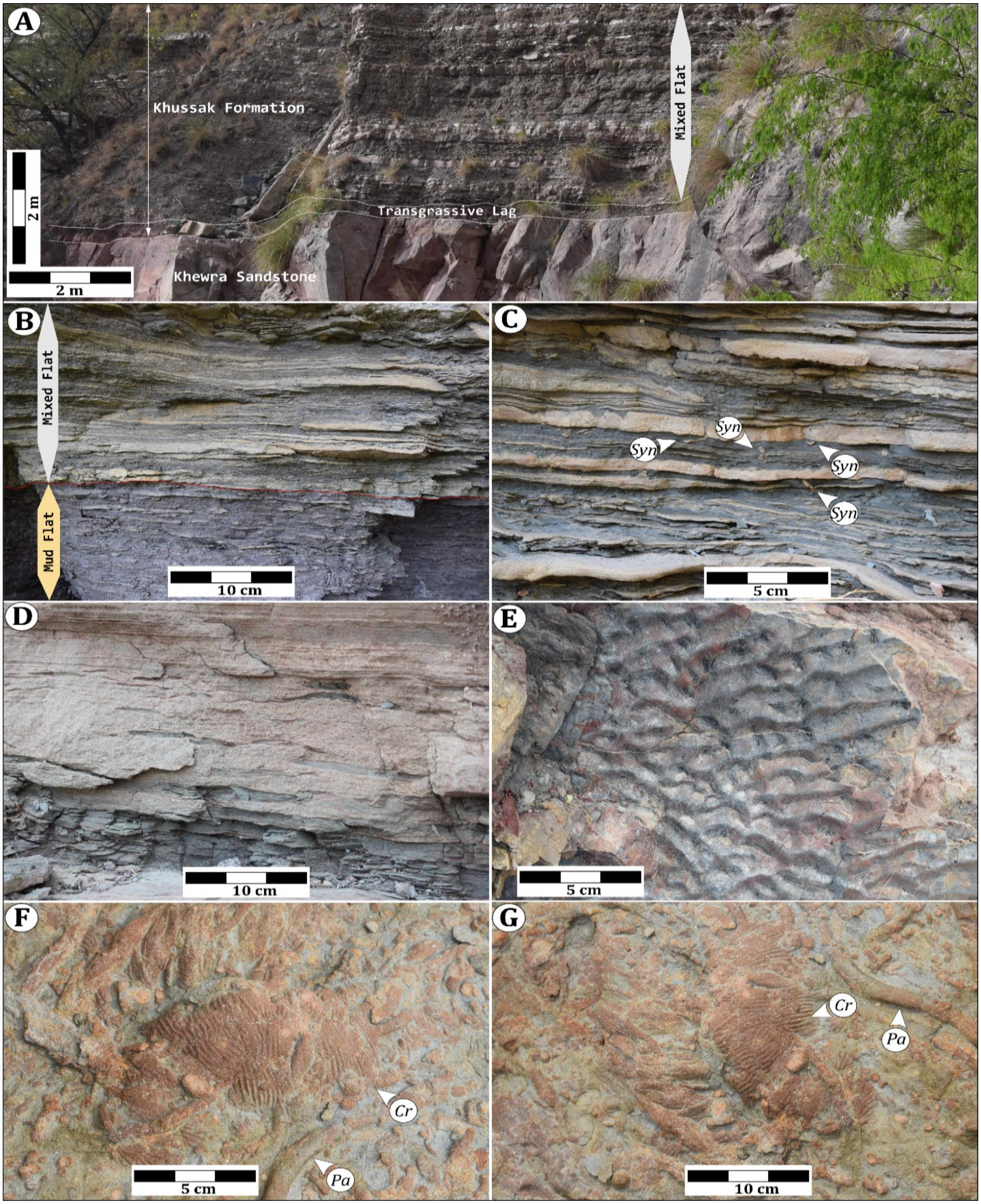

Figure 5. 5 Panoramic view and representative field photographs of the observed physical attributes in mixed flat deposits. A) Panoramic view showing the contact of Khussak Formation with the underlying Khewra sandstone.

Note the transgressive lag and mixed flat deposits above the contact at the Nilawahan section. B) Gradational contact between mud flat deposits below and mixed flat deposits above at the Khewra gorge section. C) Syneresis cracks in mixed flat deposits at the Khewra gorge section. D) flat mud pebbles in the mixed flat deposits at the Nilawahan section. E) Bedding plain view of interference ripples at the Motorway section. F, G) *Cruziana* trace fossils occurring at the base of beds in mixed flat deposits at the Nilawahan section.

The trace fossil suite of *Cruziana* Ichnofacies indicates generally low energy settings (Frey and Seilacher, 1980; Frey, 1984; Frey, 1987; MacEachern et al., 2007c; MacEachern et al., 2010). These sedimentological and ichnological attributes suggest that FA-2 likely represents deposition in a low moderate-energy middle intertidal mixed flat setting. Mixed flats are generally characterized by moderate hydrodynamic energy, abundant surface and intrastratal food resources, partial subaerial exposure, and sedimentation from traction and suspension (Mángano and Buatois, 2004b; Dashtgard and Gingras, 2005; Buatois and Mángano, 2011; Desjardins et al., 2012a).

Facies Association 3 (FA-3) Sand flat

Sedimentology: FA-3 comprises light green to white, gradationally based, laterally extensive, crudely bedded to massive, medium to lower fine-grained sandstone with rare thin (mm-scale) mudstone beds (Figure 5.7 A, B, C). The proportion of sandstone is more than 90% leading to a higher (>1) sandstone/mudstone ratio. Where preserved, the medium to lower fine-grained sandstone has planar parallel laminae (upper-flow regime) and rare ripples (wave and current) (Figure 5.7 D, E). The crudely bedded sandstone has flaser bedding with rare wavy bedding. Other bedforms and structures include mud drapes, gutter-pot casts, flat-topped ripples, washout structures, wrinkle marks, asymmetric ripples, interference ripples, and synaeresis cracks (Figure 5.7 F, G). FA-3 consists of rare through, and planar cross-bedded, coarse- to fine-grained, thick-bedded sandstone. Stratigraphically FA-3 is present in the measured section's lower, middle and upper parts, with thicknesses ranging from 30 centimeters to over 5 meters. The lower contact with FA-2 and FA-5 is gradational, whereas the upper contact with FA-5 is erosional to sharp.

Ichnology: (BI=3–5) Bioturbation in FA-3 is moderate to high. Trace fossils include medium- to large-sized *Siphonichnus*, medium-sized *Cylindrichnus* and *Paleophycus,* diminutive *Planolites, Skolithos, Arenicolites*, and *Diplocraterion* (Figure 5.8). In addition, horizontal trace fossils such as *Treptichnus pedum, Phycodes,* and *Asteriacites* are common in FA-3 (Figure 5.8).

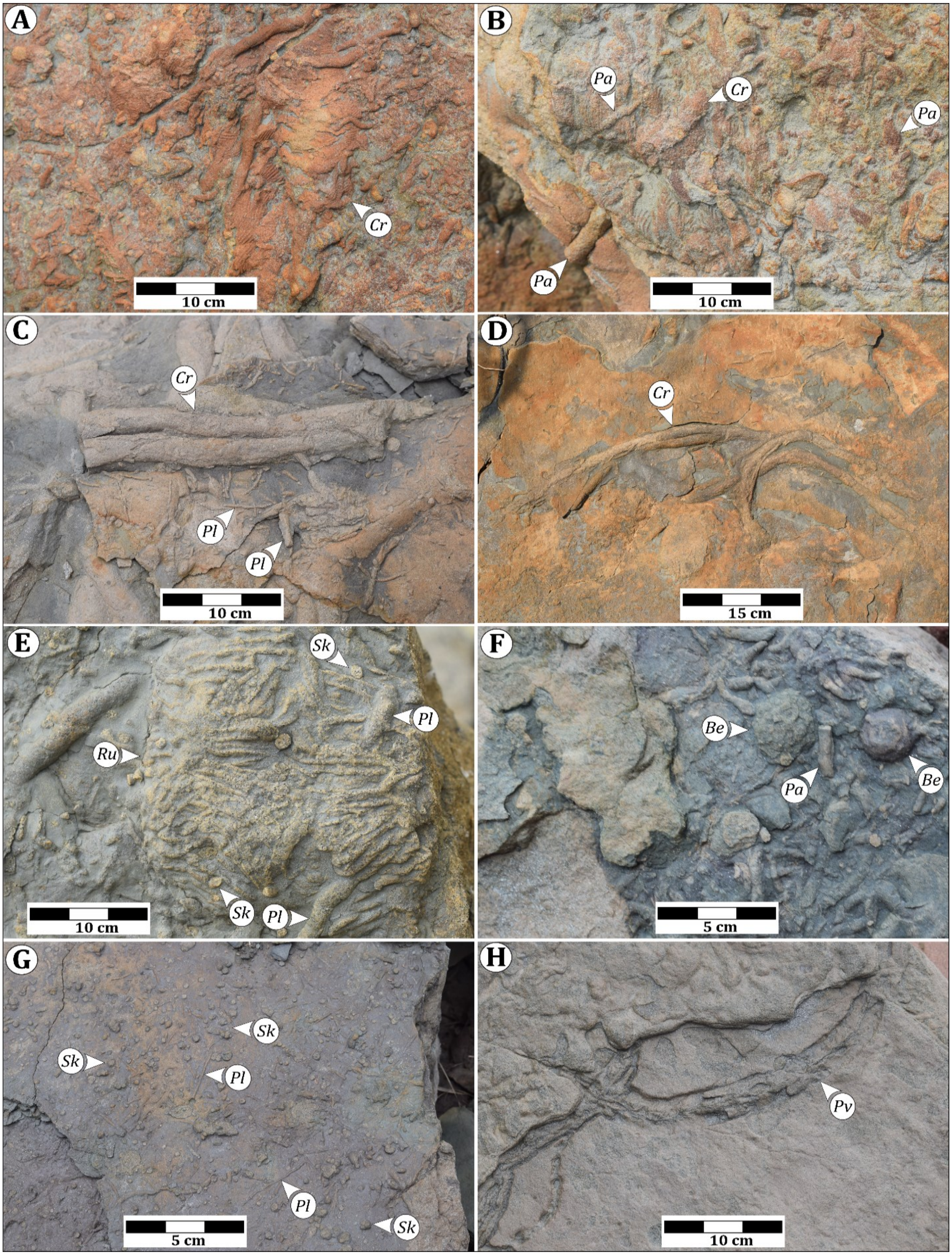

Figure 5. 6 Field photographs showing representative trace fossil suites in mixed flat deposits. A, B) *Cruziana* trace fossils occurring at the base of beds in mixed flat deposits at the Nilawahan section. C, D) *Cruziana* trace fossils

occurring at the base of beds in mixed flat deposits at the Khewra gorge section. E) *Rusophycus* in mixed flat deposits at the Nilawahan section. F) *Bergaueria* in mixed flat deposits at the Khewra gorge section. G) *Lockeia* in mixed flat deposits at the Nilawahan section. H) *Protovirgularia* in mixed flat deposits at the Nilawahan section.

Interpretation: The coarse sediment caliber (medium to lower fine-grained sand), the associated flaser bedding, and current and interference ripples reflect deposition dominated by traction under lower flow regime conditions. Thorough, uniform bioturbation in the sandy substrates indicates a high bioturbation rate and frequent colonization windows (Swinbanks and Luternauer, 1987; Gingras et al., 1999). The presence of ripples (flat-topped, interference, starved) indicates tidal currents (low- moderate energy) and wind-generated wave action. The presence of vertical and deep trace fossils of suspension feeders and passive predators (*Skolithos*, *Diplocraterion, Arenicolites, Siphonichnus)* belonging to the *Skolithos* Ichnofacies points to deposition in a comparably high-energy setting (Seilacher, 1967, 1978; Frey, 1984; Frey and Pemberton, 1985; Pemberton, 2001; MacEachern et al., 2007a). The caliber of the sediments, hydrodynamic conditions, bioturbation intensity, distribution, and trace fossil suite indicate deposition in a moderate to wave influenced lower intertidal sand flat setting. Compared to mud flats, sand flat have moderate to high hydrodynamic energy, reasonably high organic (food) resources (limited deposit and abundant suspension food resources), and sedimentation from traction (Gingras et al., 1999; Mángano and Buatois, 2004b; Dashtgard and Gingras, 2005; Buatois and Mángano, 2011; Desjardins et al., 2012a).

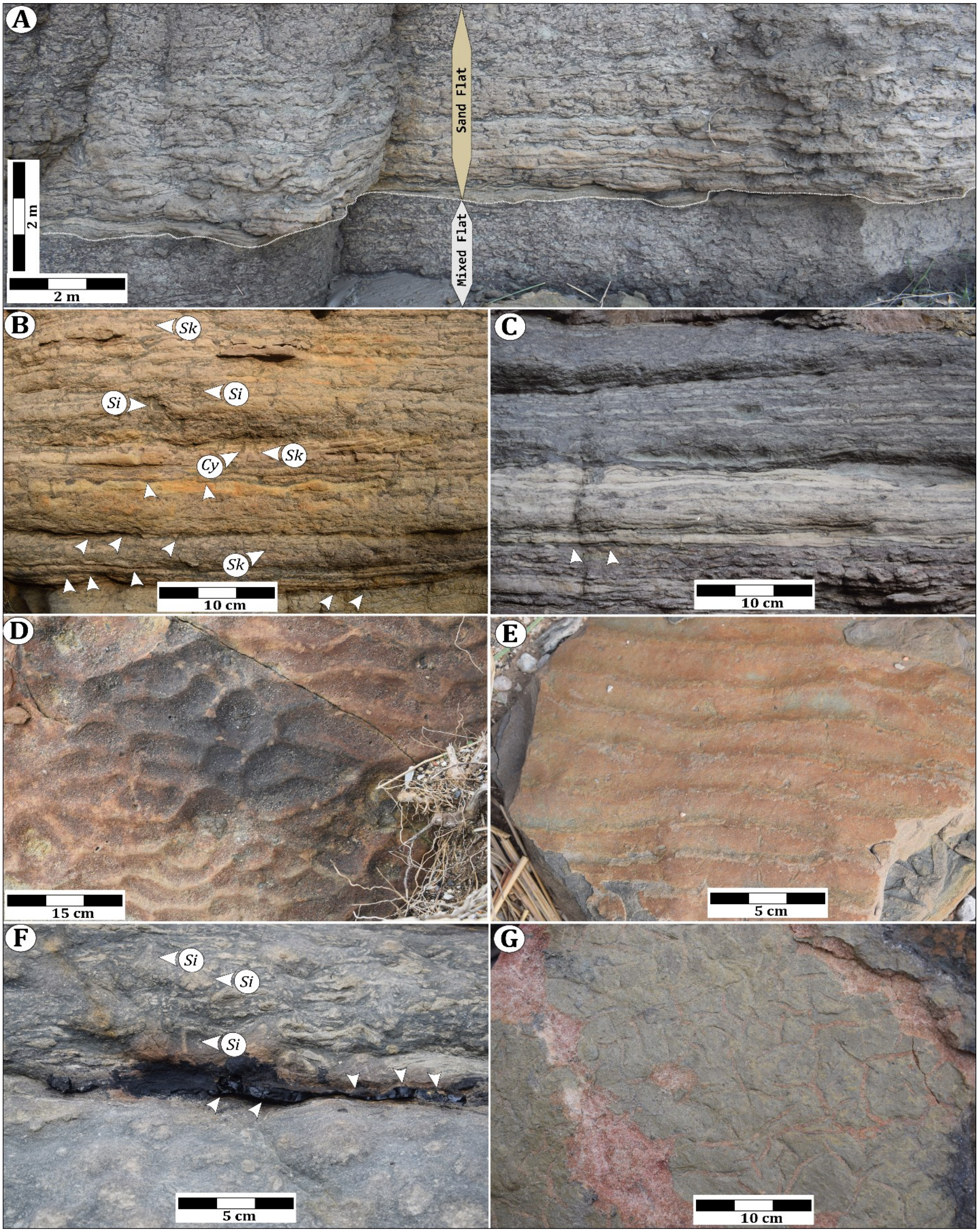

Figure 5. 7 Representative field photographs of the observed physical attributes in sand flat deposits. A) Contact between mixed and sand flats at the Khewra gorge section. B, C) Crudely bedded bioturbated sandstone with rare mudstone interbeds and drapes (white arrows). D, E) Bedding plain view ripples (current and wave) in the sandstone

at the Motorway and Khewra gorge section, respectively. F) Volcanic rock fragments in the bioturbated sandstone at the Khewra gorge section. G) Dessication cracks in sand flat sandstone at the Nilawahan gorge section.

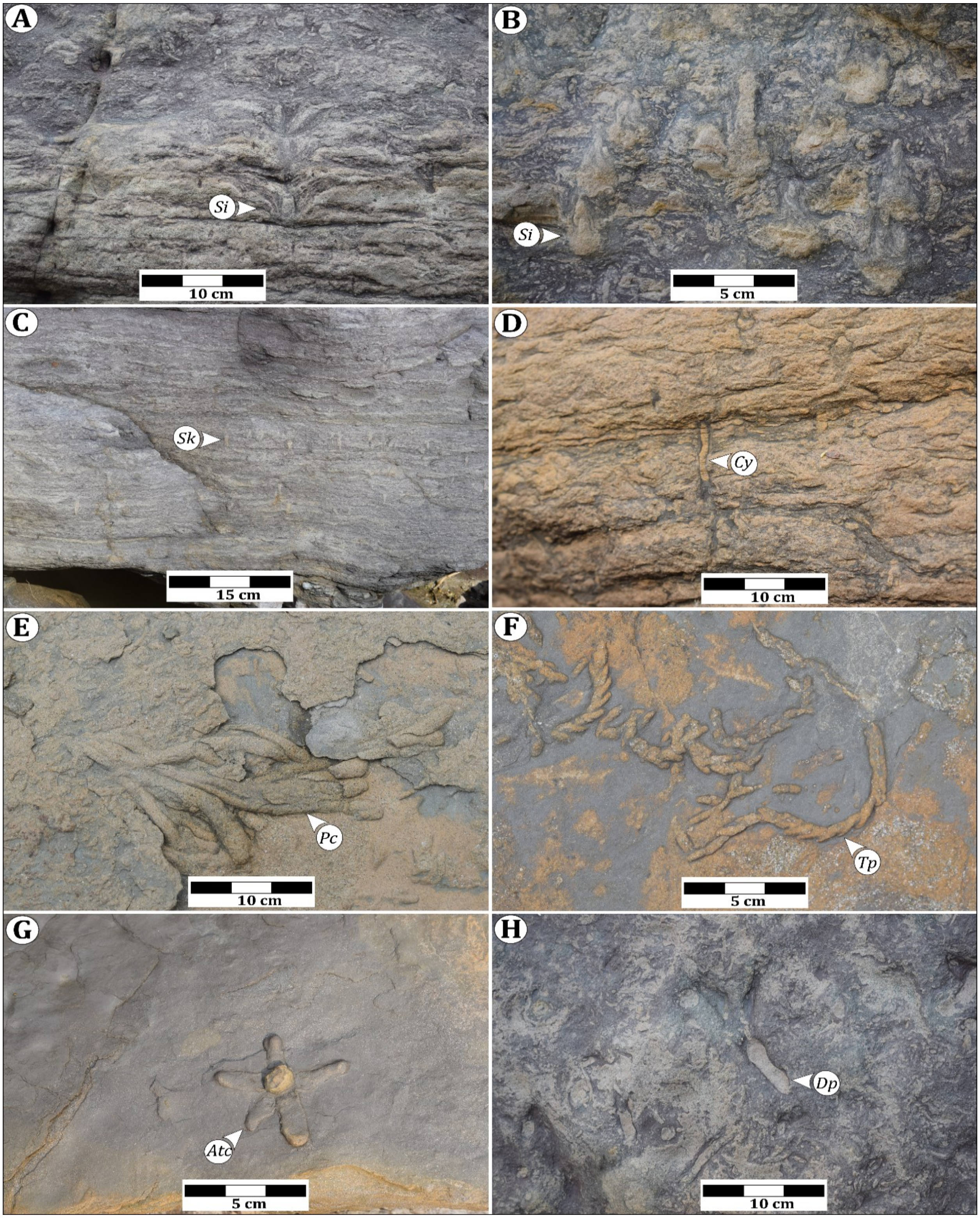

Figure 5. 8 Field photographs of the representative trace fossils observed in the sand flat deposits. A, B) *Siphonichnus* in the bioturbated sandstone of the intertidal flat deposits at the Khewra gorge section. C) *Skolithos*

dominated sand flat deposits at the Khewra gorge section. D) Trace fossil *Ophiomorpha* in the crudely bedded bioturbated sandstone at the Khewra gorge section. E, F) Trace fossil *Phycodes* pedum and *Treptichnus pedum* in the sandstone dominate heterolithic strata of sand flat at the Nilawahan gorge section. G, H) Trace fossil *Asteriacites* and *Diplocraterion* in the sand flat deposits at the Khewra gorge section respectively.

Facies Association 4 (FA-4) Inter Tidal Creek Point-bar Deposits

Sedimentology: FA-4 consists of muddy to silty lower-upper fine-grained sandstone with rare mudstone drapes. FA-4 is inclined heterolithically stratified (IHS) with some planar laminae (Figure 5.9, B, E). Sedimentological attributes include planar laminae, graded bedding, cross-bedding and current ripple lamination. Sedimentary couplets (mud and mica drapes) are common (Figure 5.9, C). Carbonaceous detritus may occur as accessories. FA-4 varies in thickness from 1 to 2.5 meters. Mud clasts are commonly present at the lower erosional contact. Upper contact with bounding facies is sharp to gradational (Figure 5.9 A, D).

Ichnology: (BI= 0-2) Biogenic reworking is uncommon to sparse with a low-diversity trace fossils (Figure 5.9 F, G). The observed low-diversity vertical and horizontal trace fossils include *Skolithos, Diplocraterion, Cylindrichnus Palaeophycus, Planolites,* and rare fugicnia.

Interpretation: Inclined heterolithic stratification (IHS) indicates lateral accretion in point bars (Thomas et al., 1987). A low degree of bioturbation suggests high sedimentation rates. Tidal influence is evidenced by the presence of sedimentary couplets (Dalrymple et al., 1990; Reineck and Singh, 2012). The presence of planar and trough cross-stratification indicate deposition in a high-energy setting (Dalrymple et al., 1990; Reineck and Singh, 2012). Trace fossil suite of stressed *Skolithos* Ichnofacies indicates moderate to high energy conditions (MacEachern et al., 2007a). Inclined heterolithic stratification, low bioturbation, tidal influence, and the associated trace fossils indicate the deposition of meandering tidal channels and creeks that cross-cut the intertidal flats and migrate across the intertidal zone reflecting higher rates of sedimentation along the unstable channel margins (Gingras et al., 1999).

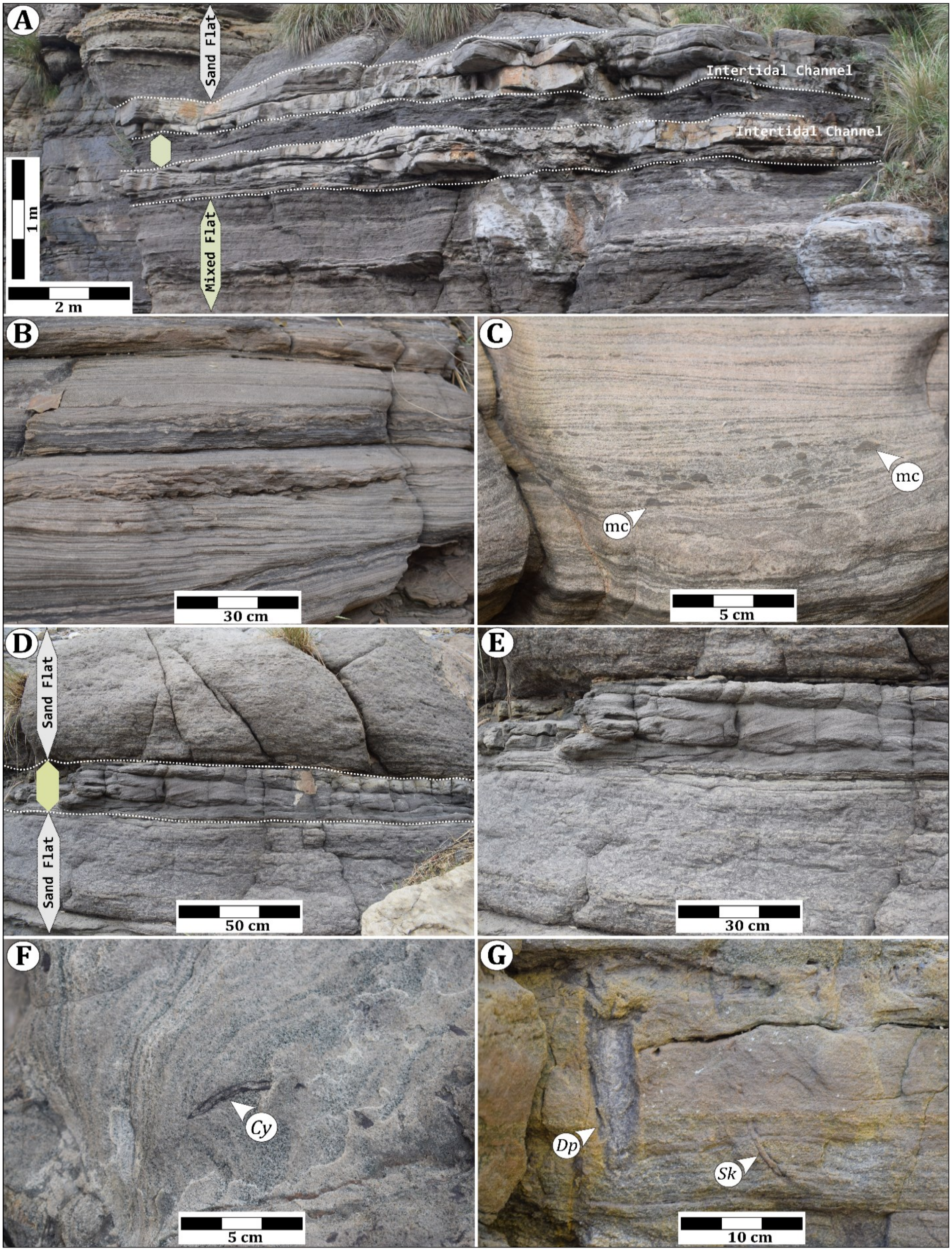

Figure 5. 9 Representative field photographs of the observed physical attributes and trace fossils in the intertidal creek point bar deposits. A) Field photograph showing two intertidal channels with associated mixed and sand flat

deposits at the Khewra gorge section. B, E) Laterally accreting inter-tidal channel at the Khewra gorge section. C) Tidal couplets and mud clast (mc) at the base of intertidal creek deposits at the Khewra gorge section. D) Intertidal creek deposits bounded below and above by sand flat deposits at the Khewra gorge section. F, G) Trace fossil *Cylindrichnus*, *Diplocraterion*, and *Skolithos* in the intertidal creek deposits at the Khewra gorge section, respectively.

Facies Association 5 (FA-5) Subtidal Bar deposits

Sedimentology: FA-5 consists of well-sorted sandstone (upper medium to fine-grained). The sandstone is erosionally based and laterally extensive. Planar parallel laminations, trough cross-stratification, reactivation surfaces, and mud drapes may be present (Figure 5.10 F, G; Figure 5.11 A). Synaeresis cracks may occur in the mud drapes (Figure 5.11 D). Other physical sedimentary structures include flaser and wavy bedding, planar lamination, graded bedding, and local current scours. Carbonaceous organic material is less abundant. Bedding plane structures are common, including ripple patches, and interference ripples. The thickness of FA-5 varies from 1.2 meters to 4 meters. Rip-up clasts and pebbly lags define the lower erosional contact of these deposits. The upper contact with FA-3 is gradational.

Ichnology: BI (1-3). The degree of biogenic reworking is low, and traces are sporadically distributed. Trace fossils present are low in diversity and abundance, including *Skolithos*, *Arenicolites*, *Diplocraterion*, *Siphonichnus, Cylindrichnus*, *Monocraterion*, *Planolites*, and *Palaeophycus* (Figure 5.11 F, G, H). Many beds present monospecific or paucispecific assemblages.

Interpretation: The sediment caliber and texture, erosional base, planar and trough cross-stratification, and reactivation surfaces indicate deposition in a high-energy setting (Dalrymple et al., 1990; Reineck and Singh, 2012). The presence of mudstone and mica drapes, flaser, wavy bedding, and reactivation surfaces indicate tidal influence (Dalrymple et al., 1990; Dalrymple et al., 1991; Dalrymple et al., 2012). Zones with low BI value may indicate actively shifting bedforms, with unfavorable conditions for colonization (Dalrymple et al., 1990; Gingras et al., 1999; Desjardins et al., 2012a). The presence of suspension feeding traces indicates a high-energy shallow subtidal setting where food is held in suspension (Gingras et al., 1998; Gingras et al., 2007; MacEachern et al., 2007a; Buatois and Mángano, 2011; Desjardins et al., 2012a).

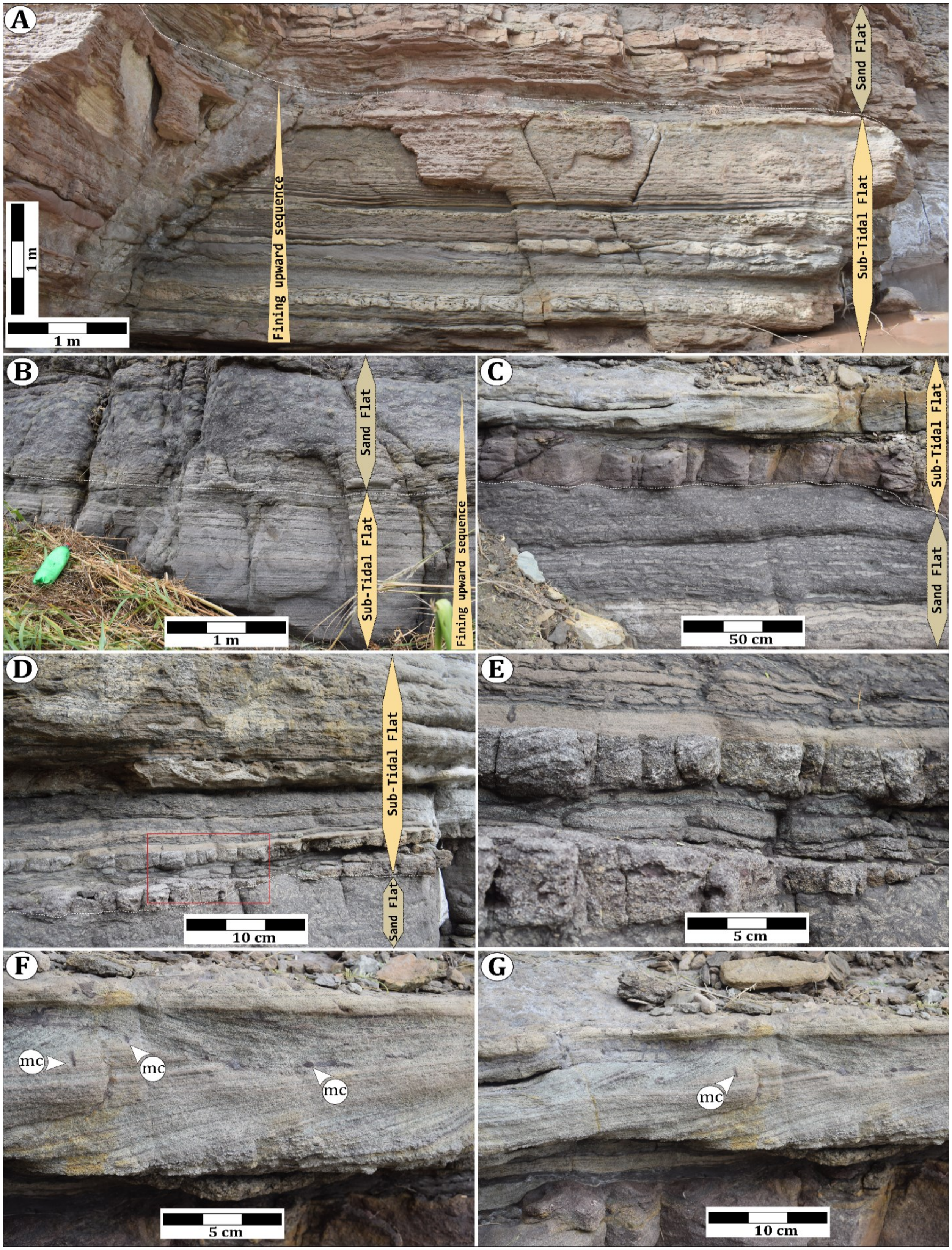

Figure 5. 10 Representative field photographs of the observed physical attributes in the subtidal deposits. A) Field photograph showing upward fining subtidal deposits having gradational contact with the overlying sand flat deposits

at the Nilawahan gorge section. B, C) Field photograph showing upward fining subtidal deposits having gradational contact with the overlying sand flat deposits at the Khewra gorge section. D, E) Transgressive lag-granules at the basal contact of subtidal flat deposits. F, G) Trough cross-stratification and bidirectional bedding in the subtidal deposits at the Khewra gorge section.

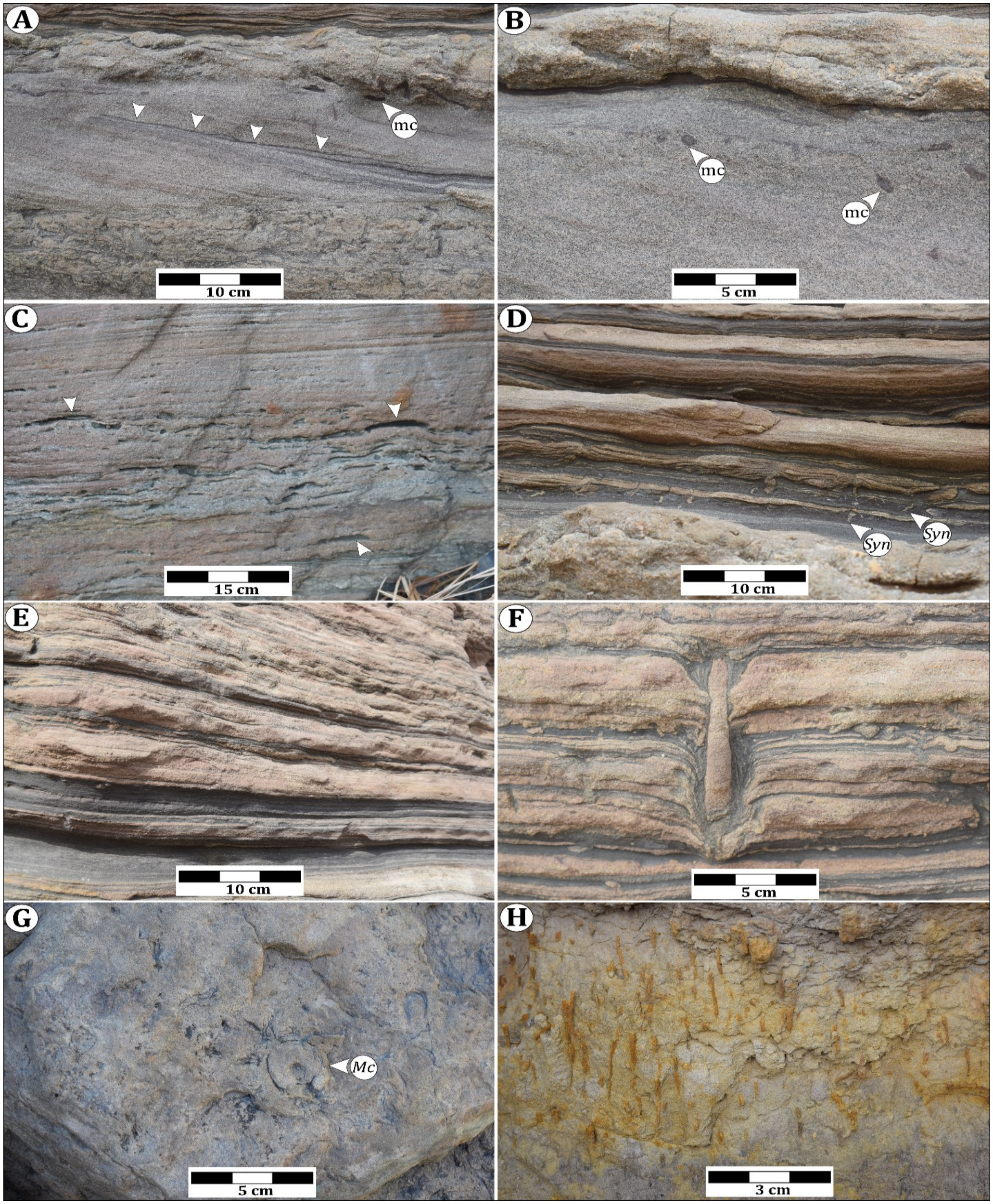

Figure 5. 11 Representative field photographs of the observed physical attributes and trace fossils in the subtidal bar deposits. A) Trough cross-stratification in the subtidal deposits at the Nilawahan gorge section. B, C) Mud clast

(arrows) at the base of subtidal deposits at the Nilawahan gorge section. D) Synaeresis cracks in the subtidal deposits at the Nilawahan gorge section. E) Heterolithic sandstone-mudstone with tidal couplets and mud drapes at the Nilawahan gorge section. F) Robust *Siphonichnus* in the subtidal deposits at the Nilawahan gorge section. G) Trace fossil *Monocraterion* in the subtidal deposits at the Khewra gorge section. H) Trace fossils *Skolithos* at the Khewra gorge section.

Facies Association 6 (FA-6) Subtidal Bay Deposits

Sedimentology: FA-6 is characterized by bioturbated muddy sandstone and heterolithic sandstone and mudstone (Figure 5.12 A). The degree of biogenic reworking is moderate to high. Physical bedforms are commonly obliterated by bioturbation (Figure 5.12 B). Planar horizontal laminae, wavy laminae, and small ripples are the bedforms where the physical sedimentary structures are preserved. Synaeresis cracks may occur locally. FA-6 is 6 meters thick in the eastern Salt Range, whereas it is not present in the central Salt Range due to erosion along the sub-Permian unconformity. Lower contact with underlying facies is erosional. Flat mud pebbles and glauconite grains are commonly present at the lower contact (Figure 5.12 E). Upper contact with oncoidal dolomite of Jutana Formation is gradational.

Ichnology: BI=3-6. FA-6 is moderate to intensely bioturbated. The distribution of traces is heterogeneous (sporadically) to homogeneous (locally). Robust *Teichichnus, Ophiomorpha,* and *Thalassinoides* are the most conspicuous trace fossils, overprinting a mottled fabric (*Planolities*, *Rosphycos*, *cruziana*) (Figure 5.13). *Siphonichnus, Phycosiphon, Rhizocorallium, Zoophycos, Bergauria, Chondrities,* and bivalve adjustment traces are sporadically distributed and may occur locally (Figure 5.12).

Interpretation: The fine-grain sediment caliber (lower fine sand-silt mud) and wavy parallel bedding indicate low energy conditions. The paucity of bedforms indicates low sedimentation rates. High BI points to abundant organics in the substrate and in the water column. The presence of glauconite suggests transgressive marine conditions (McRae, 1972; Stonecipher, 1999) The ichnological suite consists of fully marine trace fossils (*Rhizocorallium, Zoophycos, Chondrites,* and *Phycosiphon)* that indicate entirely or near fully marine conditions (Buatois and Mángano, 2011; Gingras et al., 2011). In addition, the trace fossils are robust and further indicate stable conditions (Pemberton et al., 1982; Buatois et al., 2005; Gingras et al., 2007; Maceachern et al., 2007b; Hauck et al., 2009). The stated sedimentological and ichnological evidence points to deposition in a sheltered setting (lower bay-margin shoreface) with relatively stable salinity.

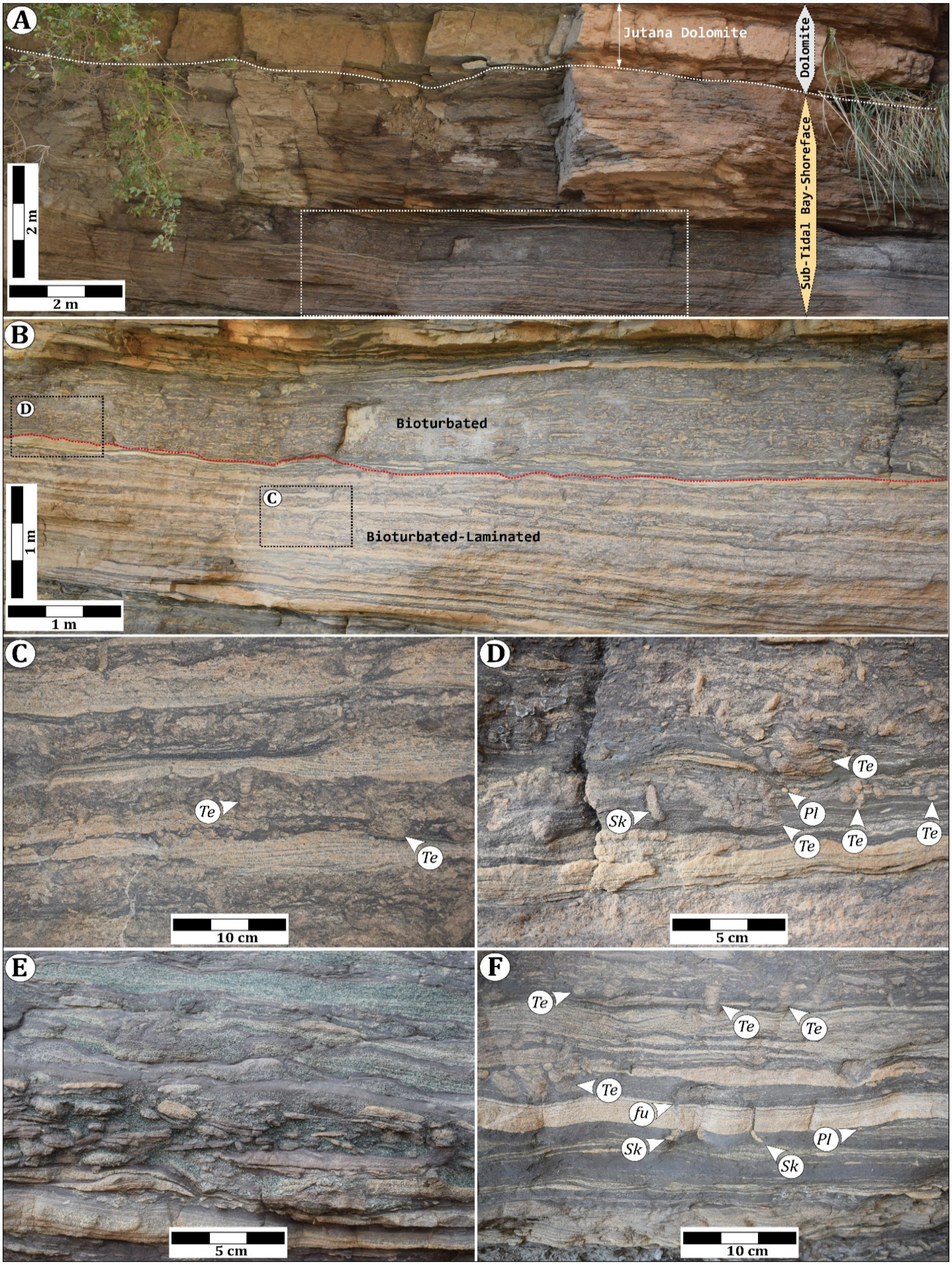

Figure 5. 12 Representative field photographs of the observed physical attributes in the subtidal bay deposits. A) Field photograph showing the bioturbated to laminated subtidal bay deposits having gradational contact with the

overlying Jutana Dolomite at the Khewra gorge section. B) Bioturbated and bioturbated to laminated subtidal bay deposits at the Khewra gorge section. C, D) Zoom in view of parts in (B). E) Mud pebbles and glauconite grains in subtidal bay deposits. F) Sharp based, graded, wavy parallel laminated subtidal bay deposits

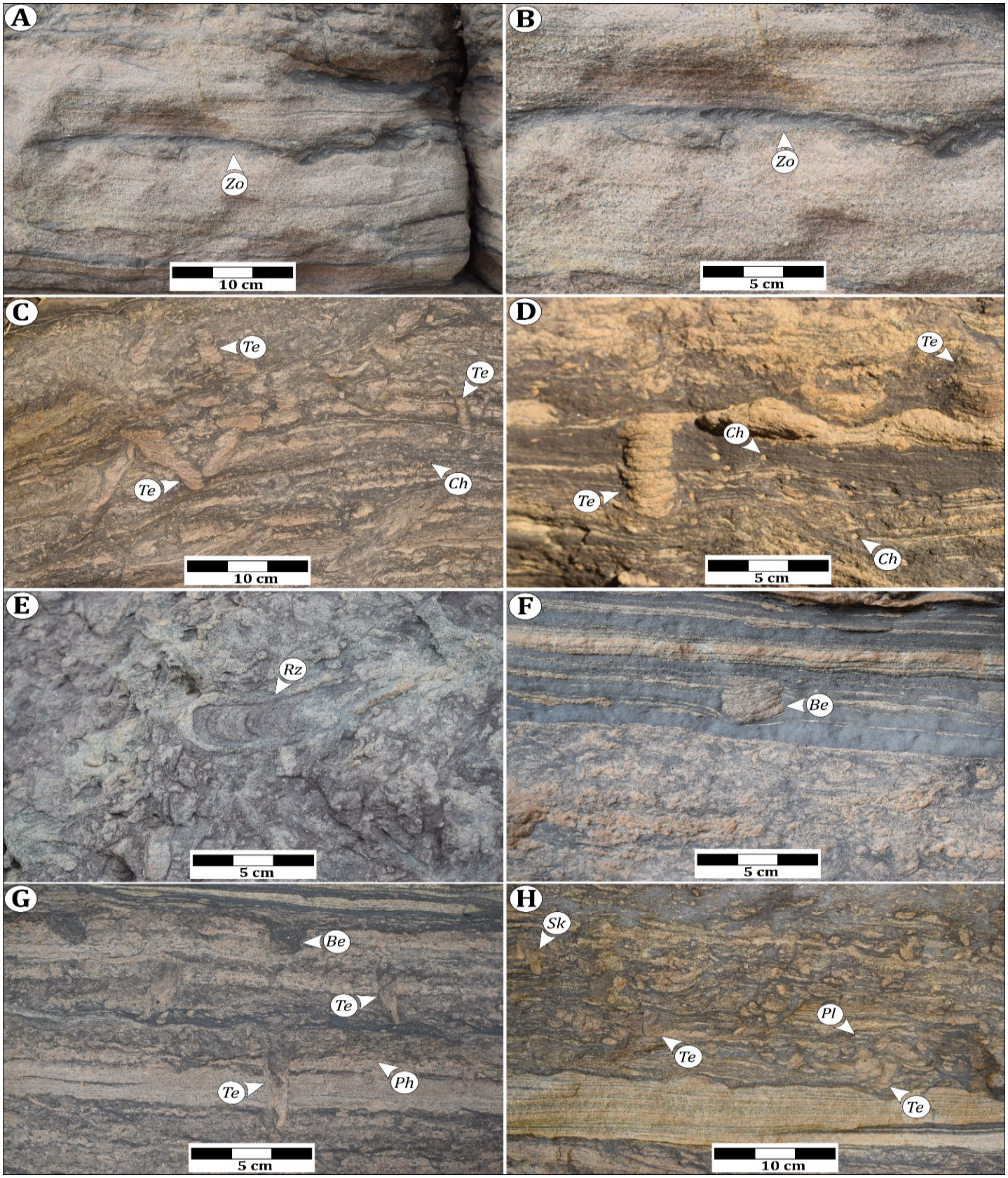

Figure 5. 13 Field photographs of the representative trace fossils observed in the subtidal bay deposits. A, B) *Zoophycos* in the subtidal bay deposits. C, D) *Teichichnus* and *Chondrites* in the subtidal bay deposits. E) *Rhizocorallium* in the subtidal bay deposits. F) *Bergauria* in the subtidal bay deposits. G, H) *Phycosiphon* and *Teichichnus* in the subtidal bay deposits.

INTERPRETATION AND DISCUSSION

Geological Facies Model

The laterally and vertically stacked lithofacies associations of the studied Khussak Formation are interpreted to represent a tidal-flat complex and subtidal bay (see section 5.1 to 5.6). The sedimentary environment of the underlying Early Cambrian Khewra Sandstone has been interpreted as fluvio-deltaic (Khan et al., 2022). The initiation of Early Cambrian transgression is recorded at the lower contact of the Khussak Formation, evidenced by a transgressive lag (Figure 5.14). This erosional contact between the Khewra Sandstone and the Khussak Formation (Figure 5.15) records an abrupt landward shift of sedimentary environments, characteristic of transgression (Catuneanu et al., 2009). The succession comprises two upward coarsening retrogradation cycles, including facies associations typical of subtidal to intertidal (sand, mixed, and mud) flat. Intertidal flat (mud flat, mixed flat, intertidal lagoon, sand flat, intertidal creek), subtidal bar, and subtidal bay are the main depositional systems recognized in the Khussak Formation strata. The various recognized facies associations (Figure 5.5.4-13) recorded deposition in a shallow-water tidal setting (Figure 5.14). Ichnodiversity in these subtidal-intertidal deposits (Table 5.1) is high, indicating sedimentation in a mesotidal setting (Zonneveld et al., 2001). Mesotidal settings are characterized by near-normal marine salinities (30– 35‰), leading to robust and diverse benthic communities (Zonneveld et al., 2001).

FA-1 to FA-3 record deposition in the intertidal zone. The intertidal flat setting is characterized by flow conditions that vary in strength and direction. Furthermore, the intertidal environment is very heterogeneous, with current flow velocity varying from zero (still-water conditions) at high tide to maximum (locally upper plane bed conditions) during ebb tide (Clifton and Phillips, 1980; Eisma, 1998; Zonneveld et al., 2001; De Boer, 2019). The sedimentological and ichnological characteristics of FA-1, FA-2, and FA-3 indicate deposition in various intertidal flat sub-environments. The subtle sedimentological and ichnological changes are consistent with the inherent heterogeneous nature of the intertidal flats. Intense bioturbation (BI= 5-6) and the scarcity of physical sedimentary structures indicate low deposition rates and high rates of biogenic reworking in intertidal mud (FA-1), mixed flats (FA-2), and sand flat (FA-3) (Gingras et al., 1999; Buatois and Mángano, 2011; Gingras and MacEachern, 2012; Gingras et al., 2012c). These intertidal flat deposits represent the retrogradation of the lower intertidal outer facies association (FA-3) over the middle-upper intertidal inner facies association (FA-1, FA-2). This basinward coarsening character has been documented in several ancient and recent intertidal flat deposits, including the lower Cambrian Gog Group of western Canada (Desjardins et al., 2010), Cambrian (Campanario Formation) in north-west Argentina (Mángano and Buatois, 2004b), Middle Triassic of British Columbia (Zonneveld et al., 2001), and Willapa Bay, Washington (Gingras et al., 1999).

FA-5 indicates deposition in a higher-energy setting with actively shifting bedforms, evidenced by the low BI values and sporadic traces of *Skolithos* Ichnofacies. The suspension-feeding traces indicate a higher energy shallow subtidal setting (Gingras et al., 1999; Buatois and Mángano, 2011; Desjardins et al., 2012a; Gingras and MacEachern, 2012; Gingras et al., 2012c). FA-6 is characterized by fully marine trace fossils (*Rhizocorallium, Zoophycos, Chondrites,* and *Phycosiphon)* that indicate marine conditions (Pemberton et al., 2012). The sediment caliber, physical attributes, and trace fossil content points to sedimentation in a low-energy setting (lower bay-margin shoreface) (Figure 5.14).

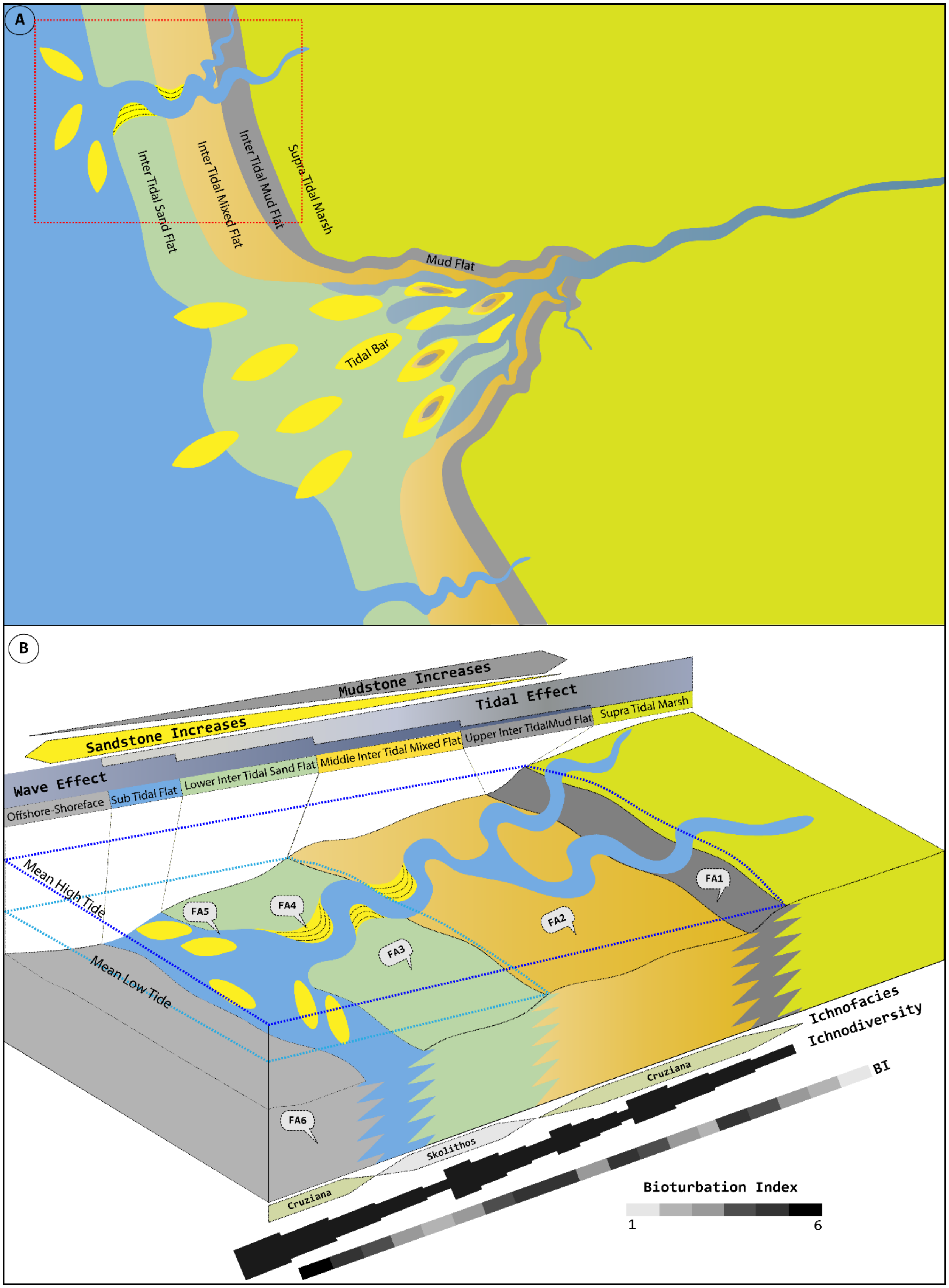

Figure 5. 14 Proposed depositional Model for the Lower Cambrian Khussak Formation.

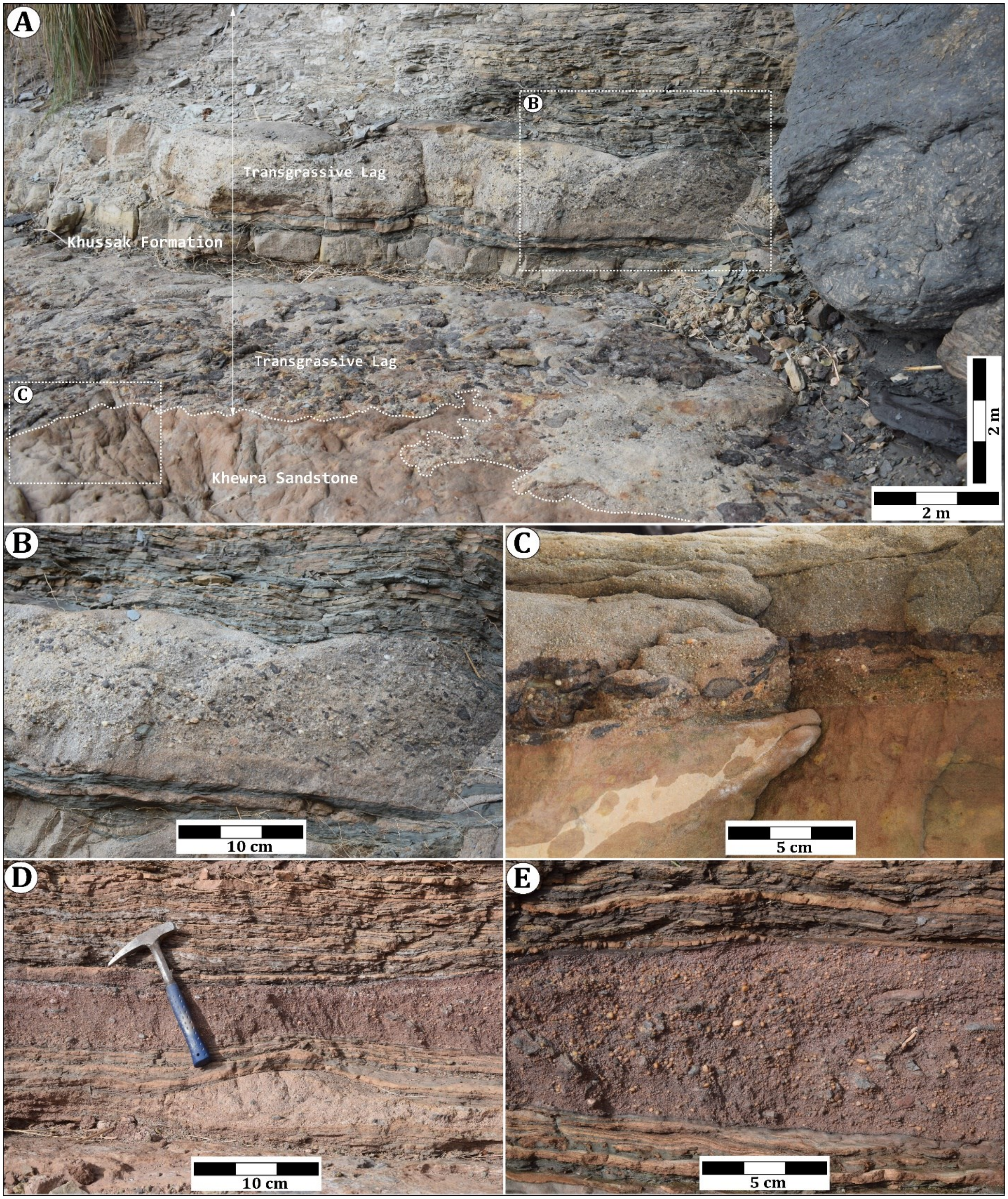

Figure 5. 15 Representative field photographs of transgressive lag deposits at the contact of the Khewra sandstone and Khussak Formation at different studied outcrop sections. A) Transgressive lag deposits at the base of Khussak Formation indicating a transgressive erosion surface at the Khewra gorge section. B, C) Zoom in view of parts of (A). D, E) Transgressive lag deposits at the base of Khussak Formation indicating the initiation of Early Cambrian transgression at the base of Khussak Formation at the Nilawahan gorge section.

Ichnological Trends in Tidal Flat Deposits

Ichnofacies Trends

The tidal flat deposits of the Khussak Formation show a unique Ichnofacie*s* trend. The *Cruziana* Ichnofacies characterize the lower energy proximal deposits (intertidal mixed and mudflat). In contrast, the high-energy distal deposits (lower intertidal sand flat and shallow subtidal) are characterized by *Skolithos* Ichnofacies. Intertidal mixed and mud flat regions have comparatively low tidal energy (caused by gradual landward dissipation of tidal energy and due to flood and ebb reversal), leading to low sand/mud ratio, low sediment oxygen (caused by a combination of factors including high levels of organic matter, microorganisms, evaporation and sediment compaction), persistently stable substrate, and more mud content and organics. Consequently, the mud and food deposits are highest in the mixed flat region (Gingras et al., 1999; Buatois and Mángano, 2011; Dashtgard, 2011; Flemming, 2012). Consequently, diverse trace fossil suites of the *Cruziana* Ichnofacies tend to dominate intertidal mixed flat deposits. The lower intertidal sand flat and shallow subtidal settings are variably bioturbated and influenced by high hydrodynamic energy, salinity, substrate, turbidity, and type of food (Frey, 1987; Gingras et al., 1999; Buatois and Mángano, 2011; Gingras and MacEachern, 2012; Gingras et al., 2012c). Food in high-energy tidal (upper subtidal-lower inter-tidal) settings is usually held in suspension (Gingras et al., 1999; Buatois and Mángano, 2011; Gingras and MacEachern, 2012). The suspension-feeding traces belonging to the *Skolithos* Ichnofacies tend to dominate these settings. This Ichnofacies trend is similar to the Ichnofacies trend reported by various authors from other tidal flat deposits (Zonneveld et al., 2001; Mángano and Buatois, 2004b; Buatois and Mángano, 2011; Desjardins et al., 2012b). The recognized ichnologic variation between the mud flat, mixed flat, sand flat, and sub-tidal deposits of the Khussak Formation are gradational (gradual transition from one sub-environment to another). Despite the gradational nature of these ichnologic variation, they can be used to distinguish between different types of sub-environments.

Controls on Trace Fossil Distributions in Tidal Flat Setting

Key environmental factors control the distribution of trace fossils in a sedimentary setting (Gingras et al., 1999; Buatois and Mángano, 2011; Desjardins et al., 2012a). The most important palaeoenvironmental factors affecting the benthic community in intertidal to subtidal settings are (1) hydrodynamic energy, (2) salinity, (3) substrate type, and (4) food supply.

Hydrodynamic Energy

Hydrodynamic energy plays a crucial role in marginal and shallow-marine environments. The high energetic tidal currents and waves impact the sedimentary dynamics of a coastline. Hydrodynamic energy controls the food (availability and distribution), sediment mobility, the nature of the substrate, and bedform development along a tidal-impacted coastline (Klein, 1970; Reineck et al., 1973; Dalrymple, 1984; Dalrymple et al., 1990; Desjardins et al., 2012a). This control determines the zones of benthic communities inhabiting different energy settings, leading to trace fossil distribution in these settings. Low diversity, vertical and deep trace fossils of suspension feeders and passive predators (*Skolithos*, *Diplocraterion, Arenicolites, Siphonichnus)* belonging to the *Skolithos* Ichnofacies tend to dominate the upper subtidal-lower intertidal (high-moderate energy) zones (Gingras et al., 1999; Mángano, 2002; Mángano and Buatois, 2004b; Buatois and Mángano, 2011; Dashtgard, 2011; Desjardins et al., 2012a). The burrows of these vertical and deep trace fossils may buffer the impact of energetic tidal currents (Mángano, 2002; Mángano and Buatois, 2004b). Trace fossils suite (*Skolithos*, *Diplocraterion, Arenicolites, Siphonichnus)* of the *Skolithos* Ichnofacies dominate the upper subtidal-lower intertidal zones in the Khussak Formation. Tides and storms generating repeated scouring events on the tidal flat may lead to erosional burrow truncation, as indicated by trace fossil *Siphonichnus* forming composite surfaces suggesting repeated bivalve colonization events. (Mangano et al., 1998) reported similar repeated bivalve colonization events from the Upper Carboniferous of Eastern Kansas. Unbioturbated subtidal deposits with rare bioturbated zones may indicate high hydrodynamic energy with occasional short-term colonization windows. Tidal currents in the subtidal region reach a maximum with rapidly migrating bedforms, precluding the establishment of both epifaunal and shallow infaunal fauna (Dalrymple et al., 1992). Ichnodiversity increases in the upper intertidal mixed to mud flat (moderate-low energy) deposits of the Khussak Formation, and the trace fossils suite is dominated by horizontal traces (deposit, detritus feeders, and grazers) of *Cruziana* Ichnofacies. This trace fossil suite may indicate lower hydrodynamic energy concomitant with high food abundance (Gingras et al., 1999; Mángano and Buatois, 2004a; Buatois and Mángano, 2011; Dashtgard, 2011; Desjardins et al., 2012a), although the occurrence of intraclast-filled scours may indicate occasional high-energy storm events.

Substrate

Substrate often exerts a control over the distribution of trace fossils in tidal deposits (Klein, 1970; Dalrymple, 1984; Dalrymple et al., 1990; Gingras et al., 2001). The substrate also plays a crucial role in the resulting trace fossil morphologies reflecting substrate cohesiveness (Mangano et al., 1998; Gingras et al., 2001; Mángano, 2002). The studied Khussak Formation has trace fossil zones reflecting substrate heterogeneity and texture. The trace fossils of the archetypal *Skolithos* Ichnofacies occur in relatively clean, medium to lower fine-grained sandstone. Trace fossils from the *Cruziana* Ichnofacies dominate the heterolithic lower fine-grained sandstone and mudstone. In addition, horizontal interface trace fossils are observed at the interface of sandstone/mudstone. This preferred interface occurrence may signify preservational bias and visibility of these trace fossils in homogeneous strata (Mángano, 2002). Shifting substrate resulting from bedform migration is crucial because it controls the colonization window (duration) (Dalrymple, 1984; Dalrymple et al., 1990; Pollard et al., 1993; Desjardins et al., 2012a). Under persistently shifting substrates, the colonization window is either closed or short-term, precluding bioturbation or allowing opportunistic colonization only under high energy conditions (Pemberton et al., 1997; Maceachern et al., 2005). Longer-term colonization takes place in the persistently stable substrate.

Food supply

Food supply is another critical parameter in controlling trace fossil distribution in a sedimentary setting. Food in high-energy tidal (upper subtidal-lower inter-tidal) settings is usually suspended (Gingras et al., 1999; Mángano, 2002; Mángano and Buatois, 2004a; Buatois and Mángano, 2011; Dashtgard, 2011; Desjardins et al., 2012a; Gingras and MacEachern, 2012). The suspension-feeding traces belonging to the *Skolithos* Ichnofacies in the subtidal-lower inter-tidal deposits of the Khussak Formation reflect the suspended nature of food particles in these settings. However, food in low energy tidal (intertidal mud to mixed flat) setting occurs as surface or inter-stratal deposit organic material (Gingras et al., 1999; Buatois and Mángano, 2011; Desjardins et al., 2012a; Gingras and MacEachern, 2012). The presence of deposit-feeding traces belonging to the *Cruziana* Ichnofacies in the intertidal (mud-mixed flat) deposits of the Khussak Formation is a clear manifestation of the substrates (organic-rich) exploited by the benthic community in these settings.

Salinity

Salinity is another factor that strongly influences bioturbation intensity, ichnodiversity and trace fossil size in flat tidal settings (Pemberton et al., 1982; Gingras et al., 1999; Mángano and Buatois, 2004b; Hauck et al., 2009; Buatois and Mángano, 2011; Gingras et al., 2011; Desjardins et al., 2012a; Gingras et al., 2012c). The comparatively low BI, low ichnodiversity, and relatively small trace fossils in the upper and middle intertidal (mud to mixed) flat of the Khussak Formation may suggest salinity stress associated with periodic submersions and exposure of the upper and middle intertidal zone and with the freshwater influx from the land and through seasonal rainfall (Gingras et al., 1999; Buatois and Mángano, 2011; Desjardins et al., 2012a; Gingras and MacEachern, 2012). Bioturbation intensity and ichnodiversity in the lower intertidal flat is comparatively high with robust trace fossils (Figure 5.7). This trend may suggest relatively stable, near marine salinity conditions together with the inundation period (which determines how much oxygen burrowing organisms have access to) (Gingras et al., 1999; Mángano and Buatois, 2004a; Buatois and Mángano, 2011; Desjardins et al., 2012a; Gingras and MacEachern, 2012). Trace fossils in the subtidal bar and subtidal bay are robust and fully marine, with high ichnodiversity indicating fully marine salinity conditions in these settings (Gingras et al., 1999; Mángano and Buatois, 2004a; Buatois and Mángano, 2011; Desjardins et al., 2012a; Gingras and MacEachern, 2012).

Comparison with a Modern Analogue: Willapa Bay, Washington

Willapa Bay provides an excellent modern analog to explain the recognized lithofacies associations (Table 5.1) in the Khussak Formation. The mesotidal Willapa Bay, Washington, on the Pacific coast, is sheltered from waves by a long spit (North Beach Peninsula) and Willapa Bar (Gingras et al., 1999). The vertically stacked facies associations of the Khussak Formation consisting of bioturbated mudstone, heterolithic sandstone and mudstone, sandstone-rich heterolihics, and bioturbated sandstone may record deposition in laterally adjacent settings, similar to modern intertidal flat deposits at the Willapa Bay described by Gingras et al. (1999). The deposits of the Khussak Formation and modern Willapa Bay show remarkable similarities. Bioturbation intensity in ancient and modern deposits is high, overprinting the physical sedimentary structures. Robust burrows characterize the intertidal sand flats in both cases. These deposits share many physical attributes such as massive to parallel laminated mudstone, lenticular bedding, heterolithic wavy bedding, ripple cross laminae, symmetric and asymmetric ripples, wrinkle marks, synaeresis cracks, soft-sediment deformation, mud drapes, gutter-pot casts, tidal couplets, flat-topped ripples, washout structures, and interference ripples. In addition to these similarities, there are some differences, including the occurrence of dolostone in the intertidal flat deposits of the Khussak Formation. The presence of dolomitic units may be related to the different climatic conditions and tectonic settings at the time of deposition of the Khussak Formation. Intertidal Creek Point-bar, subtidal bar, and subtidal bay deposits of the Khussak Formation display very similar sedimentological attributes and ichnologic signatures to their modern counterparts at Willapa Bay described by Gingras et al. (1999). Biogenic reworking in the intertidal creek point bar and subtidal bar deposits is generally low to moderate with a trace fossil suite of the *Skolithos* Ichnofacies. These deposits are characterized by inclined heterolithic stratification, mudstone and mica drapes, and reactivation surfaces. Bioturbation in subtidal bay deposits of both Khusssak Formation and Willapa Bay is moderate to intense, obliterating physical bedforms. In summary, the Early Cambrian Khussak Formation represents tidal flat deposits reflecting similar, but not identical, depositional conditions operating at the Willapa Bay.

CONCLUSIONS

The Early Cambrian Khussak Formation in the east-central Salt Range, north-west Sub-Himalayas, Pakistan, is studied through four outcrop sections. The studied Khussak Formation represents a tidal-flat complex with upward coarsening retrogradation cycles, including facies associations typical of subtidal to intertidal (sand to mixed and mud) flat. The initiation of Early Cambrian transgression is recorded at the lower contact of the Khussak Formation, evidenced by transgressive lag. Intertidal flat (mud flat, mixed flat, intertidal lagoon, sand flat, creek), subtidal bar, and subtidal bay are the main depositional systems recognized in the Khussak Formation strata. The tidal flat deposits of the Khussak Formation show a unique ichnofacies trend. Horizontal feeding, resting, and locomotion traces of the depauperate *Cruziana* ichnofacies characterize the lower energy proximal deposits (intertidal mixed and mudflat).

In contrast, the high-energy distal deposits (lower intertidal sand flat and shallow subtidal) are characterized by the vertical trace fossils (suspension feeders and passive predators) of the *Skolithos* Ichnofacies. The ichnological variation between the mud flat, mixed flat, sand flat, and sub-tidal deposits are subtle, but they can be facies edge indicators when integrated with physical sedimentology. Willapa Bay provides an excellent modern analog to explain the recognized lithofacies associations in the Khussak strata. The deposits of the Khussak Formation and modern Willapa Bay show remarkable similarities suggesting that the Early Cambrian Khussak Formation represents tidal flat deposits reflecting similar, but not identical, depositional conditions operating at the Willapa Bay.

Developing an integrated geological model for Khussak Formation provides valuable insights into the basin's evolution and sea level history, in addition to the distribution and occurrence of reservoir facies.

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CHAPTER 6: CONCLUSIONS

This thesis focuses on characterizing sedimentary successions in the rock record. The studied successions include the Lower Cretaceous Wabiskaw Member of Clearwater Formation north-east Alberta, Canada, the Lower Permian Dandot Formation of east-central Salt Range, Pakistan, and the Early Cambrian Khussak Formation of east-central Salt Range, Pakistan. A new holistic (integrated sedimentological-ichnological) approach is used to refine facies models and understands the depositional environments of these units. This study examines trace fossils assemblages and sedimentological features in the Lower Cretaceous Wabiskaw Member of Clearwater Formation, the Lower Permian Dandot Formation, and the Early Cambrian Khussak Formation, providing evidence for marginal and shallow marine environments' existence. This approach challenges traditional perspectives and introduces new models and processes for understanding sediment deposition during their respective time period.

This thesis has achieved four major goals. Firstly a sedimentological-ichnological framework for the Lower Cretaceous Wabiskaw Member (Clearwater Formation) north-east Alberta, Canada, is established in chapter 2. Secondly, the Lower Cretaceous Wabiskaw Member reservoir is characterized by integrating sedimentology, ichnology, reservoir rock typing, and flow units in chapter 3. Thirdly, the tide-dominated estuarine or deltaic nature of the Lower Permian Dandot Formation, north Pakistan, is determined using sedimentological and ichnological analysis in chapter 4.

Finally, Chapter 5 presents the depositional environment and trace fossil assemblages of the Early Cambrian Khussak Formation, east-central Salt Range, North-west Sub-Himalayas, Pakistan.

CHAPTER 2: ICHNOLOGY AND SEDIMENTOLOGY OF THE LOWER CRETACEOUS WABISKAW MEMBER (CLEARWATER FORMATION) ALBERTA, CANADA

The study utilized an integrated ichnologic-sedimentologic approach to investigate the depositional system of the Wabiskaw Member (Clearwater Formation). The analysis revealed two main depositional systems: deltas (influenced by both rivers and waves), and waves dominated shoreface and offshore deposits. The deltaic deposits (FA-1, FA-2) show features that indicate syn-depostitional physico-chemical stresses (fluctuating salinity, turbid water, fluvial influence, high sedimentation rate, and high hydrodynamic conditions). These deposits are characterized by an ichnological suite of *Phycosiphon* and *Rosselia* Ichnofacies. FA-3 and FA-4 records deposition in fully marine offshore and shoreface (Lower to the middle) settings, respectively. Stable physio-chemical conditions (well-oxygenated, low-energy conditions, low sedimentation rates), abundant marine food resources, and an ichnological suite of *Cruziana* (distal to archetypal) Ichnofacies characterize shoreface-offshore deposits. Integrating ichnology and sedimentology improved our ability to determine the depositional system of the Wabiskaw Member with greater precision and robustness. It also allowed us to identify the various physicochemical stresses during its deposition.

CHAPTER 3: INTEGRATING SEDIMENTOLOGY AND ICHNOLOGY WITH ROCK TYPING AND FLOW UNITS: IMPLICATIONS FOR CLASTIC RESERVOIR CHARACTERIZATION.

This study examined the Wabiskaw Member using a holistic approach. The ichnological and sedimentological data sets are integrated with routine core analysis data to characterize the Wabiskaw Member. The lower part of the Wabiskaw Member ((FA-1, FA-2) is recognized as a deltaic depositional system, while the upper part (FA-3, FA-4) indicates deposition in the offshore-shoreface setting. Different facies of the Wabiskaw Member were identified as potential reservoirs, with F-4 being the most prospective and F-3 being last in reservoir quality. This study proposes that a geological model utilizing comprehensive facies and wireline analysis could aid in predicting how lateral changes in facies impact reservoir quality.

CHAPTER 4: TIDE-DOMINATED ESTUARINE OR DELTAIC DEPOSITS? SEDIMENTOLOGICAL AND ICHNOLOGICAL ANALYSIS OF LOWER PERMIAN DANDOT FORMATION, NORTH PAKISTAN.

Through integrated sedimentologic and ichnologic facies analysis, this study has identified tide-dominated estuarine and tide-influenced deltaic deposits in the lower Permian Dandot Formation outcropping in the Salt Range, north-west Pakistan. The estuarine deposits consist of an estuarine tidal bar, intertidal mud to mixed flat and supratidal deposits, while the deltaic deposits include prodelta, delta front, distributary mouth bar, and channels. Both the estuarine and deltaic deposits in the lower Permian Dandot Formation exhibit similar sedimentological characteristics, such as bidirectional paleocurrent, coal seams, fragments, and features like spring-neap cycle, single and double mud and mica drapes, soft-sediment deformation structures, syneresis cracks, and rare wave ripples. Additionally, the ichnological signatures found in both deposits include sporadic bioturbation, low diversity-low intensity impoverished trace fossils suite, and dominance of deposit-feeding traces, with the rare occurrence of suspension-feeding traces. The sedimentological and ichnological characteristics found in both estuarine and deltaic deposits suggest that there were physicochemical stresses present, which affected the benthic communities in the tide-impacted settings. These stresses included fluctuations in hydrodynamic energy, water salinity, and turbid water conditions, as well as heightened depositional rates.

Although there are similarities in sedimentary facies between the estuarine and deltaic deposits, there are also significant differences in long-term processes due to transgressive and regressive conditions. These differences result in distinct facies associations and stratigraphic architecture. In the lower Dandot Formation, the tide-dominated estuarine succession exhibits a fining-upward trend in vertical profiles, whereas, in the upper Dandot Formation, the tide-dominated deltas form a coarsening-upward sequence. Furthermore, the studied estuarine deposits are typically cleaner and have better sorting than the deltaic successions. The ichnological trend, which is characterized by a regular heterogeneous distribution of trace fossils, variable bioturbation intensity, low diversity, diminutive traces, and characteristic trace fossils, suggests that several physiochemical stresses, such as seasonal fluctuations in sedimentary conditions, shifting substrates, turbid water, and anisotropic resources, affected the deposition in the estuarine setting. The distribution of trace fossils in deltaic deposits is sporadically heterogenous, and the dataset reveals an overall upward decreasing trend in bioturbation intensity and ichnological diversity in such deposits. Compared to estuarine deposits, deltaic deposits typically exhibit greater diversity of trace fossils.

CHAPTER 5: DEPOSITIONAL SETTING AND TRACE FOSSIL SUITES OF THE EARLY CAMBRIAN KHUSSAK FORMATION, EAST-CENTRAL SALT RANGE, NORTH-WEST SUB-HIMALAYAS, PAKISTAN.

The Early Cambrian Khussak Formation in the east-central Salt Range, North-west Sub-Himalayas, Pakistan, is studied through four outcrop sections. The Formation represents a tidal-flat complex exhibiting upward coarsening retrogradation cycles with typical subtidal to intertidal (sand to mixed and mud) flat facies associations. The Khussak Formation strata contain intertidal flat, subtidal bar, and subtidal bay depositional systems. A distinct ichnofacies trend is observed in the tidal flat deposits, with depauperate *Cruziana* Ichnofacies dominating lower energy proximal deposits (such as intertidal mixed and mudflat) with horizontal feeding, resting, and locomotion traces. The high-energy distal deposits of the Khussak Formation, including the lower intertidal sand flat and shallow subtidal, are characterized by the Skolithos Ichnofacies, which is marked by vertical trace fossils of suspension feeders and passive predators, in contrast to the depauperate Cruziana ichnofacies found in lower energy proximal deposits. The ichnological variation between the mud flat, mixed flat, sand flat, and sub-tidal deposits are subtle, but they can be facies edge indicators when integrated with physical sedimentology. The recognized lithofacies associations in the Khussak strata can be explained using modern Willapa Bay as an excellent analog. The similarity between the deposits of the Khussak Formation and modern Willapa Bay indicates that the Khussak Formation represents tidal flat deposits, which reflect similar but not identical depositional conditions in the Willapa Bay. The integrated geological model of the Khussak Formation provides valuable insights into the basin's evolution, sea level history, and the occurrence of reservoir facies.

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