SEDIMENTOLOGICAL AND ICHNOLOGICAL CHARACTERIZATION OF THE LATE CARBONIFEROUS–MIDDLE PERMIAN SUCCESSION IN THE SUBSURFACE OF CENTRAL SAUDI ARABIA

By

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ABSTRACT

The Late Carboniferous–Middle Permian Unayzah Group is a widespread sand-rich stratigraphic unit with equivalent deposits across the subsurface of the Arabian Peninsula. Historically, sediment deposition for this interval in the subsurface of Saudi Arabia has been ascribed to continental settings dominated by aeolian processes. Combining ichnology, sedimentology, and palynology; this study refines traditionally held views. By introducing new depositional models and sedimentary processes operating at the time of sediment deposition, this study confirms the presence of shallow-marine sedimentary environments.

Integration of ichnological and sedimentological observations in the Nuayyim Formation allowed the identification of marginal-marine, tidally influenced sedimentation (FA1), and shallow-marine, wave- and storm-dominated sedimentation with subordinate tidal and fluvial influence (FA2) in its basal Wudayhi Member. Colonization by bioturbating infauna exhibiting elements of an overall impoverished *Skolithos* and *Cruziana* Ichnofacies is interpreted to be related to sea-level rise, with regional transgression induced by the melting of glacier ice following the Late Carboniferous to Early Permian glaciation that affected southern Gondwana. Following climatic amelioration and continental drift of the Arabian Plate towards a more temperate paleolatitud, sediment deposition for the overlaying Tinat Member was characterized by aeolian and marginal-marine, tidally influenced interactions in two facies associations (FA1 and FA2) that are conformably interbedded. Therein, FA2 reflects sedimentation in shallow-marine, tidally influenced environments and includes punctuated occurrences of bioturbated tidal flats and sheltered shallow bay deposits interbedded with aeolian sediments. The ichnofossil assemblage exhibits a diminutive, highly stressed mixture with structures reflecting an impoverished *Skolithos* Ichnofacies and *Cruziana* Ichnofacies. It constitutes a model for marginal-marine and aeolian interactions and their resulting ichnofossil suite that can be used in similar successions in the rock record. Widespread paleosols characterize the upper part of the Tinat Member with burrowing that exhibits elements of the *Scoyenia* Ichnofacies. Therein, biogenic activity in the form of continental fauna and plants mark palimpsest surfaces. Progressive thermal updoming is interpreted to have occurred during the latest portion of the Unayzah Group sedimentation cycle in the Arabian Plate culminating in the regional “Pre-Khuff unconformity” at the top of this megacycle recognized in this study by biogenically-demarcated diastems. Thereby, providing an example of the utility of trace fossil analysis in genetic stratigraphy in continental settings.

PREFACE

This thesis is an original work by Camilo A. Polo. Chapter 2 of this thesis has been published as "C.A. Polo, J. Melvin, N.P. Hooker, A.J. Rees, M.K. Gingras, and S.G. Pemberton, (2018), The ichnological and sedimentological signature of a late-Palaeozoic, postglacial marginal-marine and shallow-marine, tidally influenced setting: The Wudayhi Member of the Nuayyim Formation (Unayzah Group in the subsurface of central and eastern Saudi Arabia" *Journal of Sedimentary Research*, vol. 88, 1-35. I was responsible for the data collection and analysis as well as the manuscript composition and figures drafting. I also served as the corresponding author during the publication process. J. Melvin assisted with the the data collection and analysis as well as the manuscript proof reading and composition. N.P. Hooker assisted with the palynological data collection, the palynotaxa identification and analysis. A.J. Rees assisted with the the data collection and analysis. M.K. Gingras was the co-supervisory author and assisted with the ichnotaxa identification and contributed to manuscript edits. S.G. Pemberton was the co-supervisory author and assisted with the the data collection, the ichnotaxa identification and analysis of its environmental significance.

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CHAPTER 1– INTRODUCTION

1.1 The Late Carboniferous–Middle Permian succession of Saudi Arabia

Across subsurface Saudi Arabia (Fig. 1.1), a sand-rich Paleozoic succession is widespread, with strata ranging from Cambrian through to Permian in age. It includes the Late Carboniferous–Middle Permian Unayzah Group (Fig. 1.2). The strata that make up the Unayzah Group consists of a series of sand-rich sediments deposited on, and infilling, the paleotopography of the Hercynian Unconformity ("Pre-Unayzah Unconformity", or so-called "PUU"), and is bounded at the top by the "Pre-Khuff Unconformity", or so-called "PKU" (Husseini 1992; Al-Husseini 2004; Faqira et al., 2009; Husain et al., 2013) (Fig. 1.2). In a regional context, the Unayzah Group is a ubiquitous, sand-dominated stratigraphic unit with age-equivalent deposits across the subsurface of the Arabian Peninsula including, Kuwait, Saudi Arabia, Bahrain, United Arabs Emirates (UAE), and south into Oman (Al-Laboun 1982; Levell 1988; Angiolini et al., 2003; Tanoli et al., 2008; Melvin and Norton 2013) (Fig. 1.1). In subsurface Saudi Arabia, this interval has been historically subdivided into three members: Unayzah A; Unayzah B and Unayzah C (Ferguson and Chambers 1991) (Fig. 1.2).

Price et al. (2008) presented a proposal for an entirely new stratigraphic framework within the Unayzah Group (Fig. 1.2). The rocks that occurred between

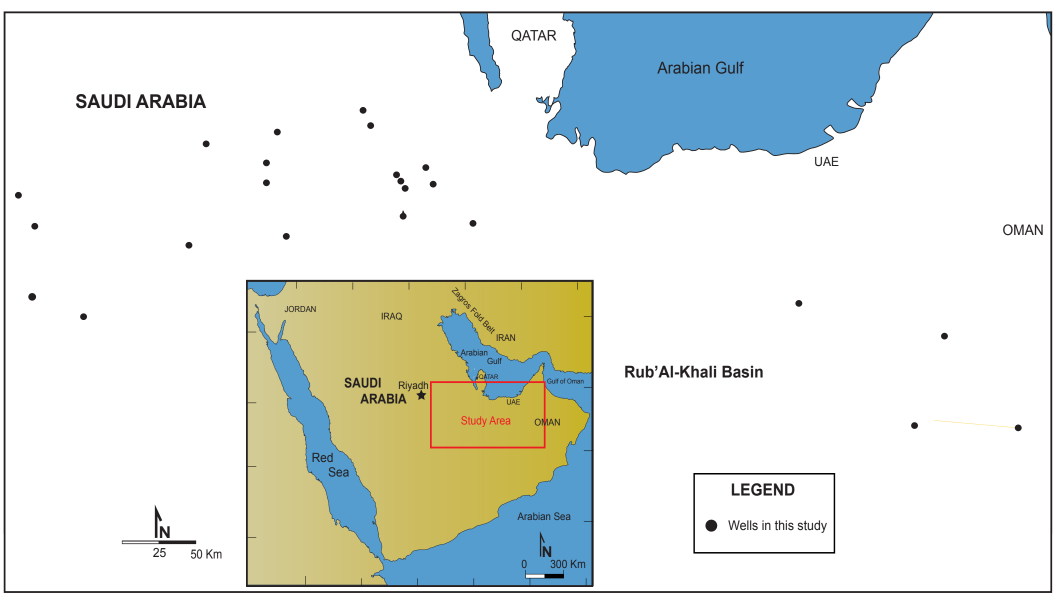

Figure 1.1. Location Map. Location map showing the Arabian Peninsula and the locations of the wells involved in this study. The study area is located in the subsurface of central eastern Saudi Arabia, southeast of Riyadh, and covers an area of approximately 70,000 km^2.

the pre-Unayzah (or "Hercynian") unconformity and the pre-Khuff unconformity were formally arranged by those authors into two formations, each of which was subdivided into two members (Fig. 1.2). The lower of these two formations was called the Juwayl Formation and represents the deposits laid down during the Late Paleozoic Ice Age (LPIA). Of its two members, the Ghazal Member (formerly the Unayzah C), where present, rests upon the pre-Unayzah unconformity and represents syn-glacial deposition and deformation. It is overlain by the Jawb Member (formerly the Unayzah B) which comprises the deposits associated with the terminal melting of the ice sheets. The Juwayl Formation is overlain by the Nuayyim Formation (formerly the Unayzah A), which is entirely post-glacial in its character. In its lower part it comprises the Wudayhi Member (formerly the un-named middle Unayzah member of Melvin et al., 2010a). This member is in turn overlain by the Tinat Member which is truncated at the top by the pre-Khuff

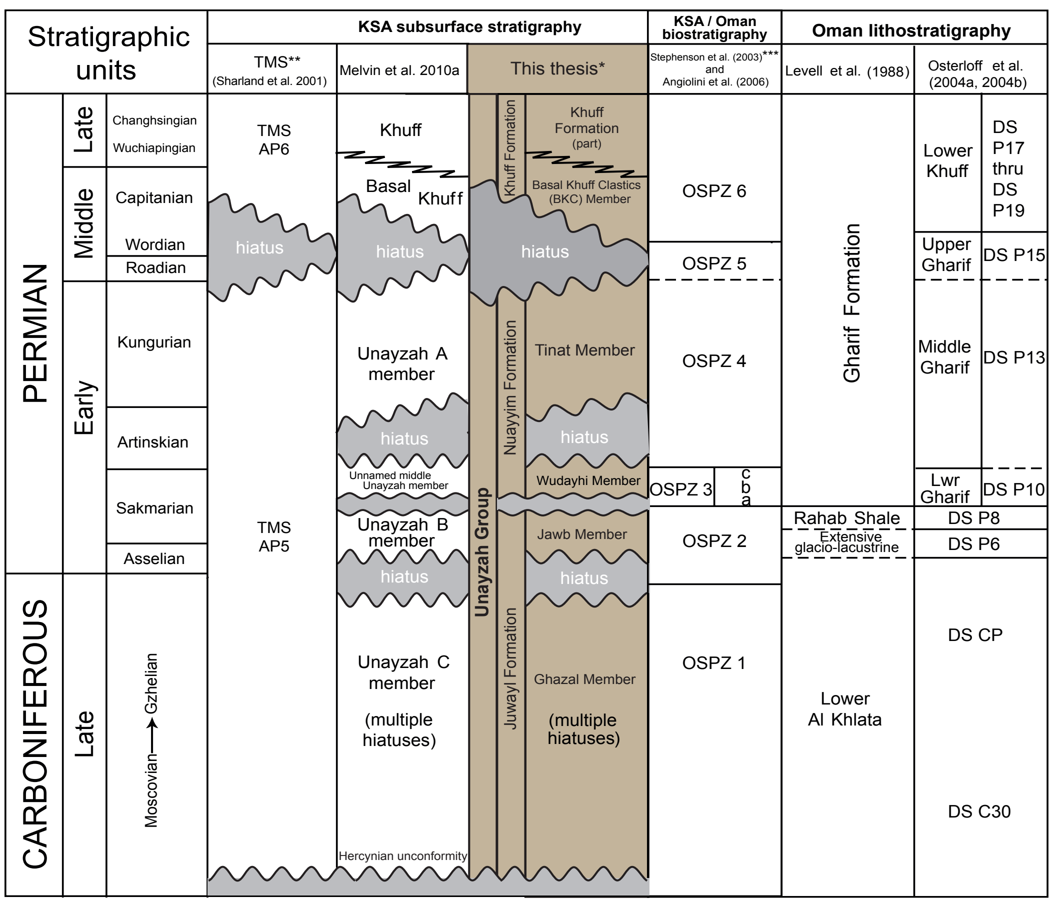

Figure 1.2. Late Carboniferous-Permian stratigraphic framework of Saudi Arabia (KSA) and Oman. (*) This thesis follows the stratigraphic nomenclature proposed by Price et al. (2008) for subsurface Saudi Arabia. (**) Tectonostratigraphic Megasequences (TMS) of Sharland et al. (2001) and (***) biostratigraphic zonation (OSPZ1-OSPZ6) of Stephenson et al., (2003) provide the regional context to compare age-equivalent successions across the Arabian Peninsula extending south into Oman.

unconformity. Studies carried out in the Unayzah Group include sedimentologic and biostratigraphic analyses at both local and regional scales (see Al-Laboun 1982, 1986, 1987; Ferguson and Chambers 1991; McGillivray and Husseini 1992; Senalp and Al-Duaiji 1995; Evans et al., 1997; Al-Hajri and Owens 2000; Melvin and Heine 2004; Melvin et al., 2005; Melvin and Sprague 2006; Price et al., 2008; Melvin et al., 2010a, 2010b). In spite of these efforts, facies successions and the depositional environments of the constituent formations and members remain a matter of continuous refinement. This stems from: 1) laterally variable facies distributions; 2) several internal discontinuities; 3) the lack of a unified nomenclatural framework; 4) the paucity of biostratigraphic markers; and 5) the absence of outcrops of equivalent age in central Saudi Arabia (Fig. 1.1).

A particular and recurrent topic is that sedimentation in the Nuayyim Formation (formerly the Unayzah A) across subsurface central and eastern Saudi Arabia has been chiefly ascribed to continental sedimentary environments. However, a number of levels in this formation, within both its Wudayhi Member and Tinat Member (Fig. 1.2) feauture evidence for marginal-marine and shallow-marine sedimentation. This study documents trace-fossil faunas and sedimentological characteristics from these facies, and presents a regional depositional model for the Nuayyim Formation and its constituent members that confirms the presence of shallow-marine sedimentary environments.

1.2 Trace fossils and their role in the Late Carboniferous–Middle Permian succession of Saudi Arabia

Ichnology is the science that study the traces left by the organisms within the environment they occupy. It can be subdivided into two sub-disciplines:
(1) paleoichnology, which deals with the study of preserved ancient traces in the rock record (i.e. trace fossils or ichnofossils), and (2) neoichnology, which deals with the study of modern animal-sediment relationships and its products. The resulting modifications of the original sedimentary fabric by organisms inhabiting the depositional environment are known as bioturbation.

Ichnology is a dynamic and evolving displine that has undergone a vibrant transformation since the first drawings of *Paleodictyon* by Leonardo da Vinci in the early 16th century (Baucon, 2010) and the notes from Charles Darwin on the effect of earthworms on a substrate trough time (Darwin, 1881). Subsequent developments that brought ichnofossils beyond their subordinate role as paleontological entities in facies analysis towards a more predominant role, being sedimetological entities

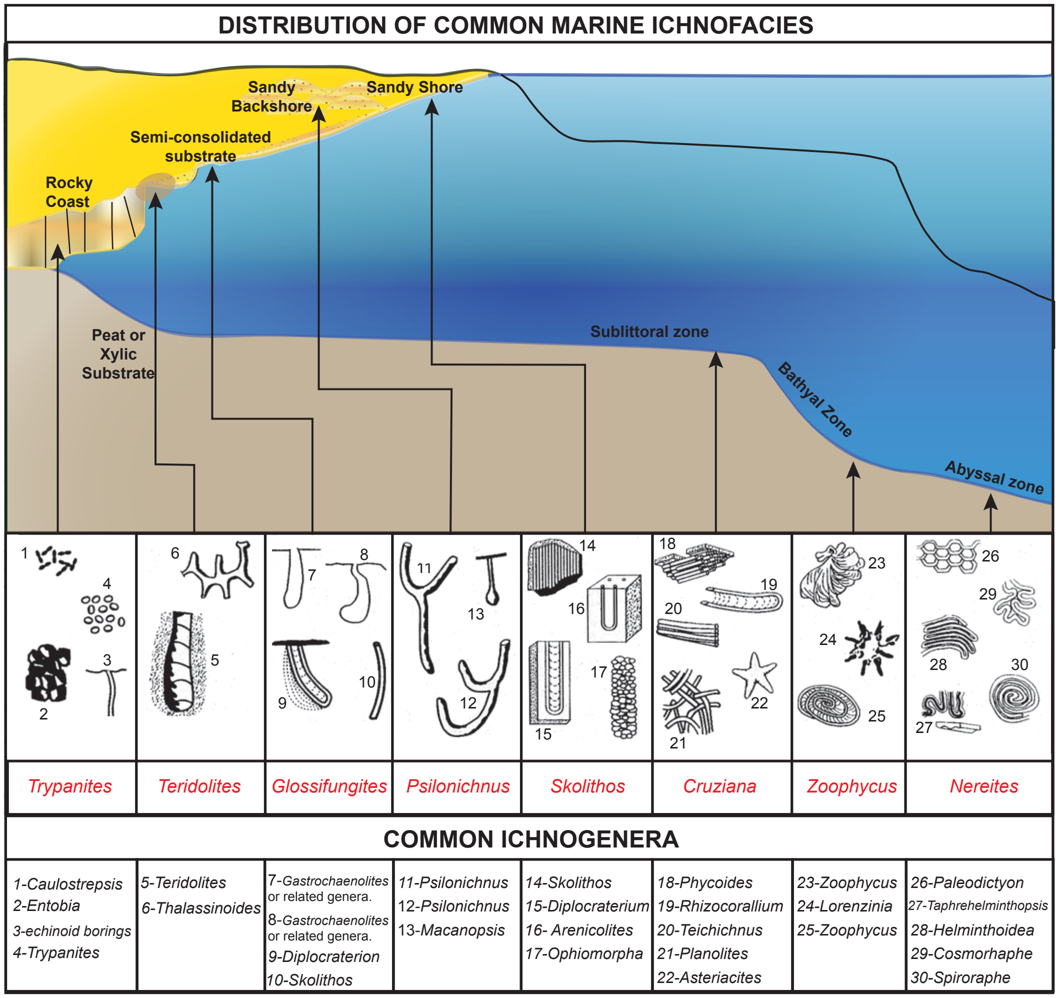

Figure 1.3. Idealized schematic bathymetric zonation of the recurring archetypal “Seilacherian” Ichnofacies framework (modified after Pemberton et al., 1992). Note how each Ichnofacies occupies a paticular place along and idealized depositional profile. Thus, organisms bear a passive relationship to their depostional environmnet and can reflect a wide range of environmnetal conditions.

include among others (i.e., not restricted to) the pioneer work of Rudolf Richter, Adolf Seilacher, Walter Häntzschel, Robert Frey and George Pemberton. A trip in time through the historical development of ichnoloy starting by ‘Age of Fucoids’ (1823–1881) will display a colorful evolution towards ‘The Modern Era’ (1953–Present). A particular example of this integral evolution can be drawn from the fact that since the inception of the original “Seilacherian” ichnofacies framework (Seilacher, 1964; Seilacher, 1967a,b), more ichnofacies have been included resulting in the mosaic that is used currently to characterize a variety of depositional environments. Following the seminal work by Adolf Seilacher, Frey and Seilacher (1980) added the *Trypanites* Ichnofacies, Bromley et al. (1984) introduced the *Teredolites* Ichnofacies, and Frey and Pemberton (1987) proposed the *Psilonichnus* Ichnofacies. More recently, Genise et al. (2000) proposed the *Coprinisphaera* Ichnofacies. This showcases a continuous refinement of the whole conceptual framework that underpins the Ichnofacies paradigm allowing it to play significant roles within new realms in the study of sedimentary successions such as genetic stratigraphy (MacEachern et al., 2007c; MacEachern and Bann., 2008). This dynamism continues to make ichnology an active discipline within the field of sedimentary geology that keeps luring young, enthusiastic geoscientists into its realms. Subsequently, the applications of trace fossils to facies analysis and the understanding of depositional environments have undergone significant advances in recent decades. As a tool, when combined with sedimentology, it can provide insights into sedimentary processes and paleoecological conditions at the time of sediment deposition. Ichnofossil assemblages often reflect factors such as energy, substrate consistency, water turbidity, availability and distribution of food

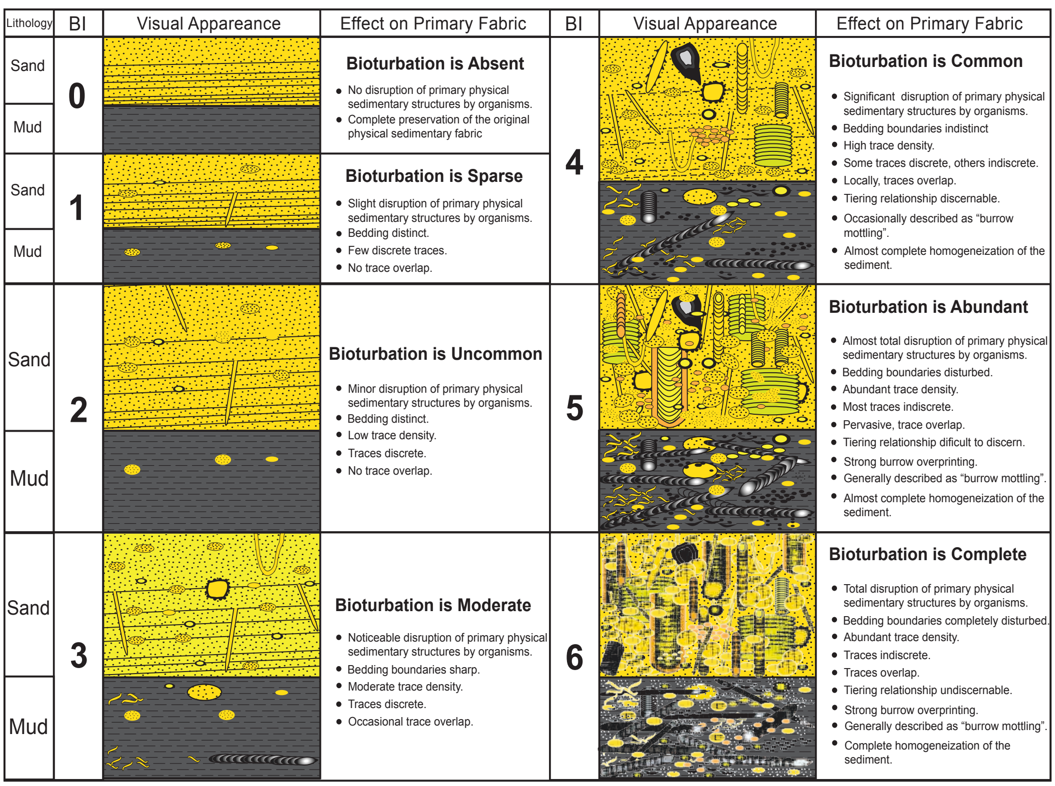

Figure 1.4. The Bioturbation Index (BI). It constitutes a useful tool to assess the degree of biogenic reworking in a given primary depositional fabric (Taylor and Goldring, 1993). Bioturbation intensity and descriptive criteria are based on (Bann et al., (2008) and MacEachern et al. (2010). In a practical sense, for studies carried out based on outcrop observations, or subsurface core samples, the scheme provides a semi-quatitative, flash-card approach to assess bioturbation that allows visual comparisons among datasets and sedimentary workers (MacEachern et al., 2010). The quantification of the degree of biogenic reworking has also evolved from the early efforts by Reineck, (1963), followed by Reineck and Singh, (1980) and iclude alternative frameworks such as the ichnofabric facies scheme provided by Droser and Bottjer, (1986).

resources, sediment rate, etc. (MacEachern et al., 2007b; MacEachern et al., 2010). This modern approach departs from the past wherein erroneous application of trace fossils analysis to the understanding of the stratigraphic record restricted their utility to bathymetry (Fig. 1.3), confining ichnology to a subordinate role.

A growing research body demonstrates that a diligent sedimentological assessment of lithofacies paired to trace fossils analysis allows reconstruction of the primary biotic content of the studied interval, which, in turn, enriches the interpretation of depositional environments. Trace fossils reflect *in situ* modifications of the sediment as a product of the activities of bioturbating infauna. The record of their activities within the environment they occupy chiefly reflects the behavior that infauna performed while making the trace (Gingras et al., 2010). This has led ichnologist and sedimentologists to classify trace fossils depending on the behaviours the tracemaker was performing. Seilacher (1964; 1967a,b) presented the unifying framework that allows environmental interpretations to be depicted from trace fossil interpretations. The so-called "Seilacherian ichnofacies" group specific behavioral patterns of benthic communities into distinctive archetypical association of traces (MacEachern et al., 2007a). These groupings are recurrent in the stratigraphic record as organisms respond in a similar manner to recurrent environmental conditions that can be repeated through time. They are also laterally continuous and can be mappable over significant areas. In this sense, ichnofacies follow Walter's Law and these archetypal designations occupy idealized positions within a continuum of environmental conditions along the depositional profile from sediment source to sink (MacEachern et al., 2007a) (Fig. 1.3).

1.3 Trace fossils and the Petroleum Industry

Since the second half of the past century, sedimentologists have realized that ichnology constitutes an important tool in the interpretation of ancient sedimentary successions. Currently, sedimentological and trace fossils analysis is commonly incorporated in any high-quality sedimentological study. In some instances, due to the degree of biogenic reworking (Fig. 1.4), the assemblage of primary physical sedimentary structures may be completely absent; thereby, augmenting the role that ichnofossil analysis can exert on the understanding of these particular intervals. With the increasingly challenging task to find hydrocarbons, some of the applications of trace-fossils in petroleum exploration and reservoir characterization include: 1) the ichnological model of brackish-water settings (Pemberton et al., 1982); 2) the integration of ichnology with sedimentology and genetic stratigraphy (Bromley, 1975; MacEachern et al., 1992; Gingras et al., 2001; 2004; MacEachern et al., 2007c); and 3) the detailed characterization of shoreface, delta, bay and estuary deposits (Moslow and Pemberton, 1988; MacEachern and Pemberton, 1992; Gingras et al., 2002; Baniak et al., 2014). More recently, ichnological analysis has been applied to reservoir characterization in both aquifer and hydrocarbon reservoirs. This deals with the fluid-flow modifications due to biogenically induced heterogeneities in the reservoir, and "reservoir ichnology" constitutes a growing field among ichnologist and sedimentologists working in the industry and other institutions (Pemberton and Gingras, 2005; Cunningham et al., 2012; Gingras et al., 2012). Thus, exemplifiying the multitude of ways in which ichnology can be integrated into the continually evolving analysis of sedimentary successions and their economic applications.

1.4 Organization and aim of this study

Sedimentation in the Unayzah Group across subsurface central and eastern Saudi Arabia has been chiefly ascribed to continental sedimentary environments (Ferguson and Chambers 1991; McGillivray and Husseini 1992; Senalp and Al-Duaiji 1995; Evans et al., 1997; Al-Hajri and Owens 2000; Melvin and Heine 2004; Melvin et al., 2005; Melvin and Sprague 2006; Price et al., 2008; Melvin et al., 2010a, 2010b). However, a number of levels in this formation show evidence for marginal-marine and shallow-marine sedimentation. This research project aims to formulate a multidisciplinary sedimentological, ichnological, and stratigraphic model of the Late Carboniferous–Middle Permian succession in the subsurface of central Saudi Arabia represented by the Unayzah Group. The main challenge with this interval has been the lack of geological studies with an integrated approach conductive to refine the facies and facies associations in the subsurface of central Saudi Arabia striving to place them into a proper genetic stratigraphic framework. This thesis is divided into five chapters (including introduction and conclusion) highlighting the value of the application of a multidisciplinary approach including ichnology, sedimentology, and palynology to ancient sedimentary successions. This thesis is written in a paper format with the final aim being to simplify it for publication of each chapter into peer-reviewed journals. As a consequence of this arrangement, more than one chapter may share large portions of the same document in order to provide the necessary context for each chapter. A brief summary of each chapter is provided below in order to assist the reading process.

Chapter 2 deals with the ichnology and sedimentology of the Wudayhi Member of the Nuayyim Formation (Unayzah Group) from a number of selected wells in the subsurface of central Saudi Arabia. Paired with sedimentological observations, the ichnofossil assemblages provide a basis for refinement of the sedimentary environment and depositional processes. This chapter documents trace-fossil faunas and sedimentological characteristics from these facies. It also presents a regional depositional model for the Wudayhi Member that confirms the presence of shallow-marine environments following the Late Paleozoic Ice Age.

Chapter 3 documents aeolian and shallow-marine, tidally-influenced interactions and describes their ichnofossil suites from the early Permian Tinat Member of the Nuayyim Formation of subsurface central Saudi Arabia. This study confirms marine sedimentation in an interval historically interpreted as being dominated by continental settings wherein aeolian processes prevailed. The main aim of the chapter is to characterize *in situ* animal-sediment interactions in coastal dune fields and erg margins in arid to semiarid settings where the description of organism-sediment relationships, until now, has been focused on the landward portion including fresh-water suites. Therein, sedimentological and ichnological assessments in the Tinat Member allowed the identification of aeolian and marginal-marine, tidally influenced interactions.

Chapter 4 deals with the facies, ichnofacies and palynological analysis from the early Permian Tinat Member of the Nuayyim Formation of subsurface central Saudi Arabia. Their integrated analysis suggest an arid to semi-arid setting with biogenic activity in the form of continental fauna and plants in deposits associated with pedogenetical alteration in paleosol horizons. Therein, burrowing exhibits elements of the *Scoyenia* Ichnofacies in beds with sparse to abundant bioturbation. This chapter outlines several soil-forming cycles that allowed the establishment of a trace fossil suite with continental affinities, thus demarcating the end of an entire sedimentation cycle. Thereby, resulting in biogenically-demarcated diastems.

Chapter 5 summarizes, the main findings and provides the conclusions of this project. The conclusions outlined in this chapter also serve as a basis for the establishment of a framework that can act as a reference model for future comparison, prediction and refining of similar successions in modern settings, and the rock record.

As a whole, the data presented in this thesis is intended to provide a more thorough examination of the existing dataset for the Late Carboniferous–Middle Permian from the subsurface Saudi Arabia (Fig. 1.1). By pairing sedimentology, ichnology and palynology, this study provides an example of an integrated approach that contributes to: (i) refine existing interpretations of the paleoenvironmental history in the study area incorporating ichnological analysis; (ii) identify marginal-marine, and shallow-marine sedimentary environments; (iii) characterize bioturbated aeolian and shallow-marine tidally influenced strata; (iv) document diastems marking breaks in sedimentation; and, (v) outline several soil-forming cycles that allowed the establishment of a trace fossil suite with continental affinities, thus demarcating the end of an entire sedimentation cycle. Thereby, drawing attention to the utility of ichnofossils in genetic stratigraphy in continental settings.

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CHAPTER 2 – THE ICHNOLOGICAL AND SEDIMENTOLOGICAL SIGNATURE OF A LATE PALEOZOIC, POSTGLACIAL MARGINAL-MARINE AND SHALLOW-MARINE, TIDALLY INFLUENCED SETTING: THE WUDAYHI MEMBER OF THE NUAYYIM FORMATION (UNAYZAH GROUP) IN THE SUBSURFACE OF CENTRAL AND EASTERN SAUDI ARABIA*

2.1 INTRODUCTION

The Late Carboniferous–Middle Permian Unayzah Group is a widespread sand-rich stratigraphic unit with equivalent deposits across the subsurface of the Arabian Peninsula, including Kuwait, Saudi Arabia, Bahrain, United Arab Emirates (UAE), and south into Oman (Al-Laboun 1982; Levell et al., 1988; Angiolini et al., 2003; Tanoli et al., 2008; Melvin and Norton 2013) (Fig. 2.1). In the subsurface of Saudi Arabia, this interval has been subdivided historically into three members: Unayzah A, Unayzah B, and Unayzah C (Ferguson and Chambers 1991) (Fig. 2.2). Studies carried out in this interval include sedimentologic and biostratigraphic analyses at both local and regional scales (see Al-Laboun 1982, 1986, 1987; Ferguson and Chambers 1991; McGillivray and Husseini 1992; Senalp and Al-Duaiji 1995; Evans et al., 1997; Al-Hajri and Owens 2000; Melvin and Heine 2004; Melvin et al., 2005; Melvin and Sprague 2006; Price et al., 2008; Melvin et al., 2010a, 2010b). Despite these efforts, facies successions and the depositional environments of the constituent formations (such as the Nuayyim Formation presented in this chapter) and members remain a matter of some debate. This stems from: 1) laterally variable facies distributions; 2) several internal discontinuities; 3) the lack of a unified nomenclatural framework; 4) the paucity of biostratigraphic markers; and 5) the absence of outcrops of equivalent age in central Saudi Arabia. Melvin and Sprague (2006) attributed the variability observed in the wireline signatures of Unayzah strata to an extreme lateral variation in thickness and facies among its members. A series of erosional and non-depositional unconformities throughout the succession contribute to its complexity and impose significant challenges in oil and gas exploration and reservoir characterization in this interval.

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This chapter deals with the ichnology and sedimentology of the Wudayhi Member of the Nuayyim Formation from a number of selected wells in the subsurface of central Saudi Arabia (Fig. 2.1). Paired with sedimentological observations, the ichnofossil assemblages provide a basis for refinement of the sedimentary environment.

2.2 STUDY AREA AND GEOLOGICAL SETTING

2.2.1 Location

The study area is located in the subsurface of central eastern Saudi Arabia, southeast of Riyadh, and covers an area of approximately 70,000 km^2 (Fig. 2.1). A sand-rich Paleozoic succession is widespread, with strata ranging from Cambrian through to Permian in age. It includes the Late Carboniferous–Middle Permian Unayzah Group (Fig. 2.2). In the subsurface of Saudi Arabia, the Unayzah Group consists of a series of sand-rich strata deposited on, and infilling, the paleotopography of the Hercynian Unconformity ("Pre-Unayzah Unconformity", or so-called "PUU"), and is bounded at the top by the "Pre-Khuff Unconformity", or so-called "PKU" (Husseini 1992; Al-Husseini 2004; Faqira et al., 2009; Husain et al., 2013) (Fig. 2.2).

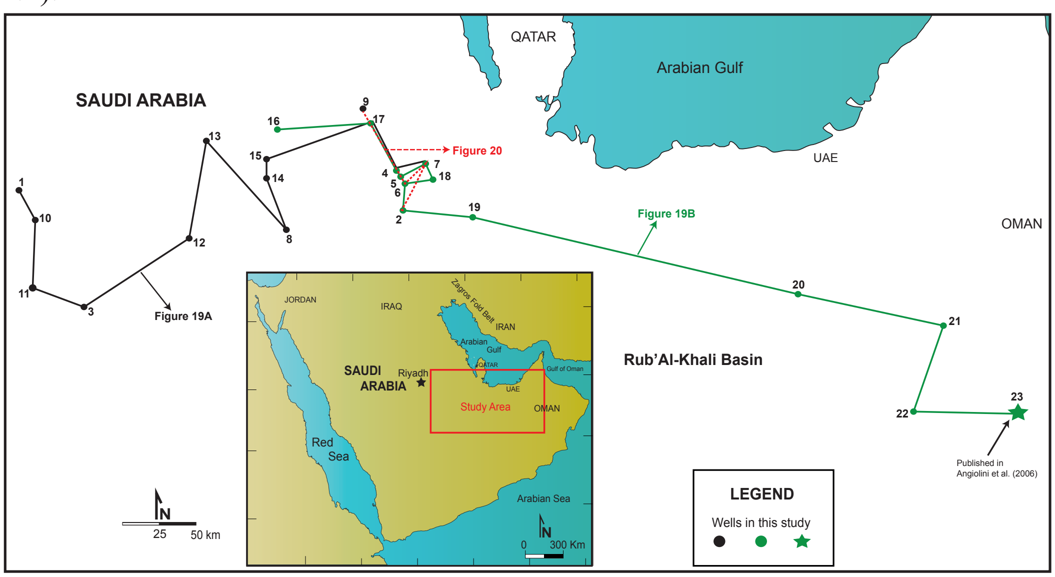


Figure 2.1. Location map showing the Arabian Peninsula, the locations of the wells involved in this study and the wells involved in the cross sections in Figure 2.19A (black well symbols connected by black lines), 2.19B (green well symbols connected by green lines), and Figure 2.20 (red dashed line). The Ghawar oil field (top center) is labeled for reference. Well 23 (green star) is used to complete the correlation with age-equivalent deposits in Oman.

2.2.2 Stratigraphy of the Late Carboniferous–Middle Permian in subsurface of Saudi Arabia

Ferguson and Chambers (1991) identified a lithostratigraphic succession, comprising an upper sand-prone Unayzah A Member that overlies sandstones of the Unayzah B Member, with a prominent red siltstone that commonly separates them. Based on subsurface core observations, they also recognized a basal unit they referred to as the Unayzah C Member, although this was not present everywhere (Fig. 2.2). Those authors described the Unayzah A Member as consisting of "a single prograding and coarsening upward clastic cycle, bounded on the base by the post Unayzah B Member flooding surface and on the top by the Khuff transgressive surface" (Ferguson and Chambers 1991). These rocks were described to consist of a thin transgressive lag followed by a regressive pulse of offshore marine siltstones (characteristically red, and unburrowed to moderately bioturbated), storm-influenced shoreface sandstones, and capped by coastal-plain sediments of mixed

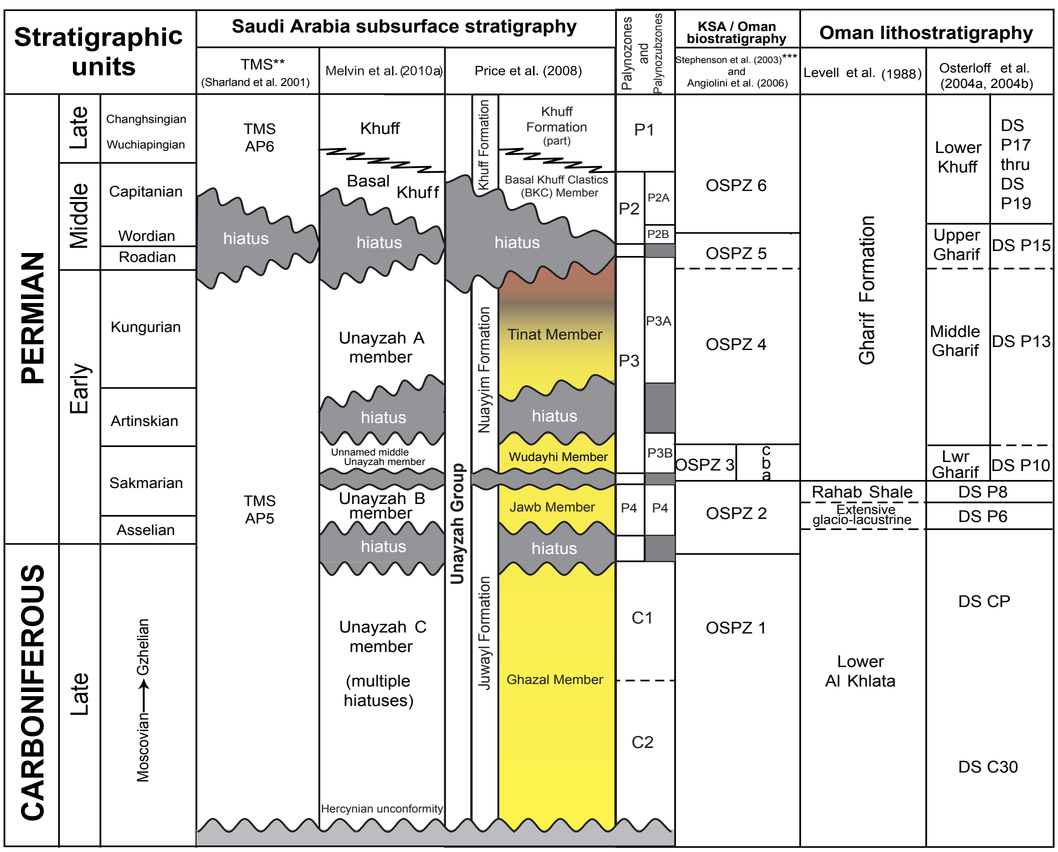


Figure 2.2. Late Carboniferous-Permian stratigraphic framework of Saudi Arabia (KSA) and Oman. (*) This study follows the stratigraphic nomenclature proposed by Price et al. (2008) for Saudi Arabia. (**) Tectonostratigraphic Megasequences (TMS) of Sharland et al. (2001), and (***) biostratigraphic zonation (OSPZ1-OSPZ6) of Stephenson et al. (2003) provide the regional context to compare age-equivalent successions across the Arabian Peninsula extending south into Oman.

clastic lithologies (Ferguson and Chambers 1991). The rocks of the Unayzah B Member were described by the same authors as fine-grained to pebbly sandstones, and interpreted to be of alluvial origin. This informal lithostratigraphy of the subsurface Unayzah Group was generally accepted by subsequent workers in the area (e.g., McGillivray and Husseini 1992; Senalp and Al-Duaiji 1995; Aktas et al., 2000; Al-Qassab et al., 2001; Wender et al., 1998; Al-Husseini 2004).

Sharland et al. (2001) published a sequence stratigraphic evaluation of the Phanerozoic rocks of the entire Arabian Plate. They identified a number of "Tectonostratigraphic Megasequences" (TMS) that provided the foundations of that sequence stratigraphic framework (Fig. 2.2). Specifically, their TMS AP5 megasequence comprises the Unayzah Group in its entirety. It is bounded at its base by the Hercynian Unconformity (Pre-Unayzah Unconformity of Al-Husseini 2004), representing the mid-Carboniferous "Hercynian tectonic event" in Arabia. The upper boundary of TMS AP5 is the "Pre-Khuff Unconformity" of Senalp and Al-Duaiji (1995).

Melvin and Sprague (2006) identified a new lithostratigraphic unit in the lowest part of the Unayzah A Member of Ferguson and Chambers (1991), which

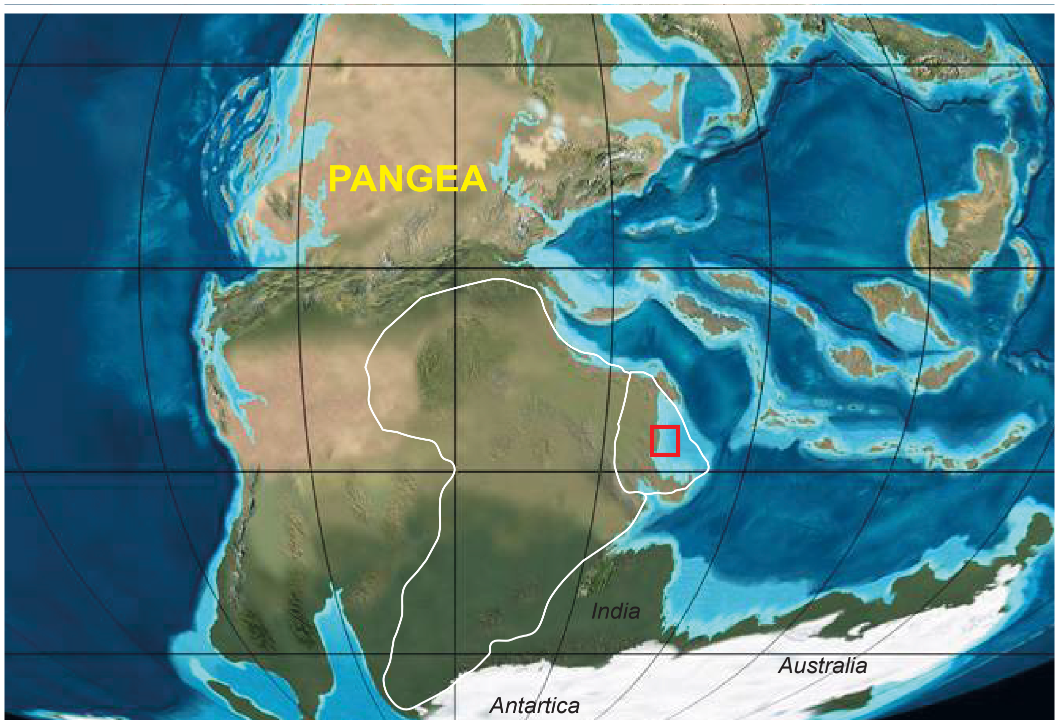


Figure 2.3. Molleweide projection of paleogeography during the Middle to Late Permian (Approx. late Sakmarian-early Artinskian). During this period, the area corresponding to the present-day Arabian Peninsula was located between 15° and 35° south of the equator in the temperate zone. Red square marks the study area for this paper and its relationship to present-day central Saudi Arabia (modified from Blakey, 2011).

they referred to as the “Un-named middle Unayzah member” (Fig. 2.2). This unit was described by Melvin and Sprague (2006) as being dominated by red siltstones that commonly pass upwards into red, very fine-grained, silty sandstones. These red beds were considered to be ephemeral (playa) lake deposits laid down in an arid continental setting. Coarser-grained sandstones showing fluvial and aeolian affinities, and which were thought to be relatively isolated, were also noted to occur sporadically throughout this member. It is commonly capped by a silty, rubbly paleosol that was interpreted by Melvin and Sprague (2006) to be indicative of a depositional hiatus at the top of the “Un-named middle Unayzah member”. Those authors proposed that the “Un-named middle Unayzah member” was equivalent to the Lower Gharif Member, which rests directly above the glaciogenic Al Khlata Formation in Oman.

Price et al. (2008) proposed an entirely new stratigraphic framework within the Unayzah. The rocks that occurred between the Hercynian Unconformity (Pre-Unayzah Unconformity) and the Pre-Khuff unconformity were placed into two formations, each of which was subdivided into two members (Fig. 2.2). The lower of these two formations was referred to the Juwayl Formation and represents sediments deposited during the Late Paleozoic Ice Age. Of its two members, the Ghazal Member (formerly the Unayzah C Member), where present, rests upon the Hercynian Unconformity (Pre-Unayzah Unconformity) and represents syn-glacial deposition and deformation. It is overlain by the Jawb Member (formerly the Unayzah B Member), which comprises the deposits associated with the terminal melting of the ice sheets. The Juwayl Formation is overlain by the Nuayyim Formation (formerly the Unayzah A Member), which is postglacial. In its lower part it comprises the Wudayhi Member (formerly the “Un-named middle Unayzah member”). This member is in turn overlain by the Tinat Member, which is truncated by the Pre-Khuff Unconformity.

2.2.3 Biostratigraphy

In terms of biostratigraphic control, palynology provides the only tool currently used to date and correlate the members of the Nuayyim Formation. Postglacial palynofloras in the Nuayyim Formation are assigned to the P3 Palynozone of Saudi Aramco (Fig. 2.4), which is in part equivalent to the *K. subcircularis* Assemblage of Love (1994). The P3 Palynozone is subdivided from older to younger into the P3B Palynosubzone (Wudayhi Member), which is overlain by P3A Palynosubzone (Tinat Member) (Fig. 2.4A). They are late Sakmarian-early Artinskian and late Artinskian-Kungurian in age, respectively (Price et al., 2008).

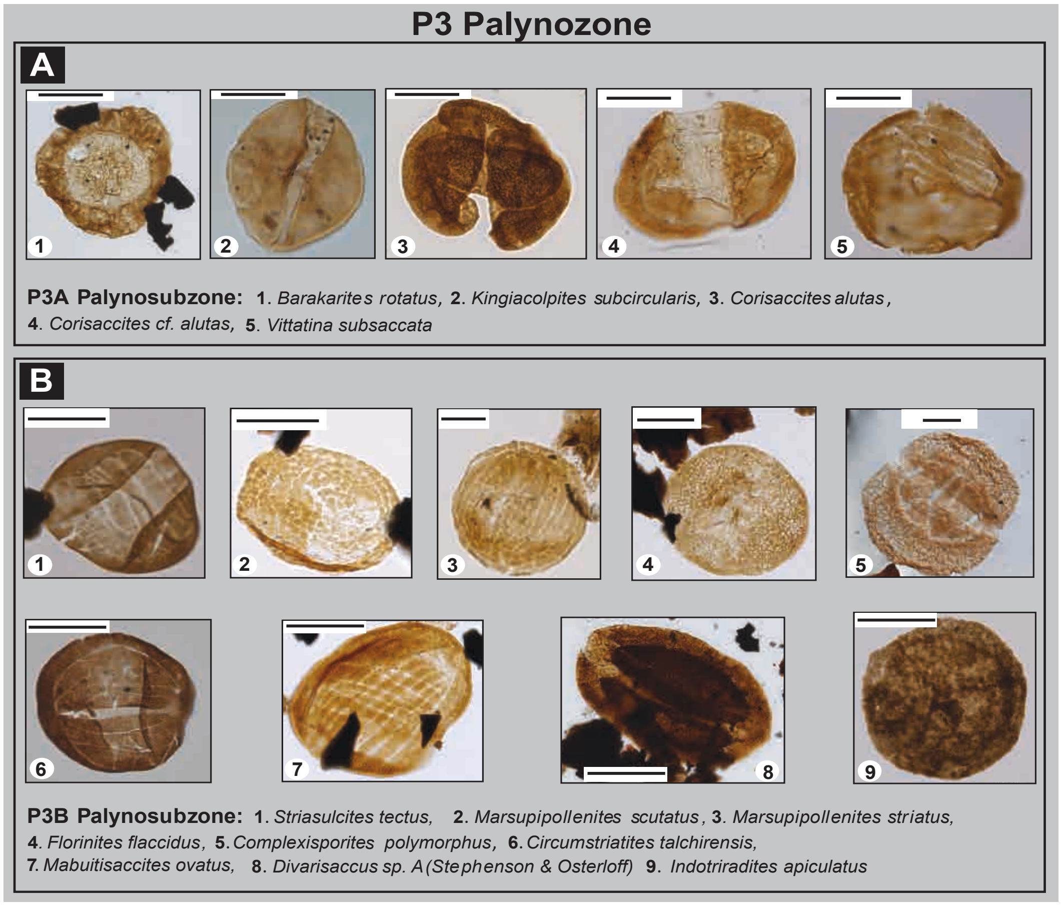


Figure 2.4. P3 Palynozone of Saudi Aramco and corresponding subdivisions for the Nuayyim Formation with representative palynological taxa. A) P3A Palynosubzone characterizes the Tinat Member and is Early Permian (late Artinskian-Kungurian) in age; B) P3B Palynosubzone characterizes the Wudayhi Member and is Early Permian (late Sakmarian-early Artinskian) in age.

The P3B Palynosubzone of Saudi Aramco contains persistent *Marsupipollenites* spp. (notably *M. scutatus* and *M. striatus*), and assemblages are generally pollen-dominated and characterized by taeniate sulcate (*Striasulcites*), taeniate bisaccate (*Protohaploxypinus*), pseudo-bisaccate (*Caheniasaccites*), taeniate monosaccate (*Striomonosaccites, Mabuitisaccites*), and large costate (*Vittatina*) forms (Fig. 2.4B). The earliest records of rare C. *alutas* and similar forms, (e.g., C. cf. *alutas* and *Lueckisporites* cf. *virkkiae*) occur in the upper part of P3B Palynosubzone (Appendices 1 and 2). Regionally, this equates to a level in OSPZ3 described by Stephenson et al. (2003), and it is probably equivalent to the base of the OSPZ3b-c interval, immediately above the P10 MFS of Sharland et al. (2001) (Fig. 2.2) (see Angiolini et al., 2006; Stephenson and Osterloff 2002). This implies that the P3B Palynosubzone equates to the OSPZ3 of Stephenson et al. (2003), which characterizes the Lower Gharif Member of the Gharif Formation in Oman, and that the Wudayhi Member in Saudi Arabia is broadly coeval with the Lower Gharif Member (Fig. 2.2). This strongly supports the introduction of the "Un-named middle Unayzah member" (herein the Wudayhi Member) of Melvin and Sprague (2006), who tentatively correlated it with the Lower Gharif Member in Oman. Locally, P3B Palynosubzone assemblages can be spore dominated, with influxes of *Densoisporites* spp., *Lundbladispora* spp. (including *L. gracilis*), *Indotriradites* spp. (including I. *apiculatus*), *Retusotriletes* spp., and *Calamospora* spp.

The P3A Palynosubzone assemblages are entirely pollen dominated, with forms that are very similar to those in the P3B Palynosubzone (Fig. 2.4). The absence of verrucate *Marsupipollenites* (*M. scutatus*) and a greater frequency and persistence of *C. alutas* and similar forms, however, differentiate the P3A from the P3B Palynosubzone (Fig. 2.4). P3A Palynosubzone assemblages are less commonly encountered than in the older P3B Palynosubzone, although they are still geographically widespread.

2.3 METHODS AND DATASET

A total of 46 slabbed cores (approximately 655 m of interval) covering the Nuayyim Formation were studied in detail to assess the sedimentological and ichnological character of their constituent lithofacies. Sedimentological analysis concentrated on characteristics such as grain size, sorting, bed thickness, bedding contacts, primary physical sedimentary structures, and syn-sedimentary deformation structures. Relative dominance and influences on depositional processes are discussed using the classification scheme for mixed-process paralic systems proposed by Ainsworth et al. (2011). In this study, each facies was analyzed in terms of the relative influence of the depositional processes (wave, tide, and fluvial) inferred to be responsible for the generation of the sedimentary structures. Therefore, a facies that displays a dominance of wave-generated sedimentary structures, with a subordinate percentage of tide-generated structures and even fewer river-generated structures would be classified as a wave-dominated, tide-influenced, fluvial-affected system (Wtf) (Table 2.1; Ainsworth et al., 2011; Vakarelov and Ainsworth 2013). Additional data derived from ichnological analysis included identification of ichnotaxa and their relative abundance, ichnofossil size, ethologic and trophic types, assemblage diversity, and intensity of bioturbation (Bioturbation Index (BI), sensu Taylor and Goldring 1993) was also utilized in the process classification.

Bioturbation intensity and descriptive criteria are based on MacEachern et al. (2010).

In addition to the logging of core samples, 61 core and ditch-cutting samples were collected for palynological analysis from Well 1 and Well 2 (Fig. 2.1), with the objectives being to: 1) constrain the age of the studied dataset; 2) gain insights to the palaeoclimatic setting; and 3) integrate the results of palynological assemblages with the depositional environments derived from ichnological and sedimentological assessments. Samples were processed using standard palynological extraction techniques and strew-mount slides, systematically analyzed to produce data on palynomorph range and abundance. Results of analyses are presented in Appendix 1 and Appendix 2 at the end of the paper. In most cases, core-logs, photos presented in figures and appendixes are devoid of depths, as permission was not granted to show this information.

2.4 RESULTS AND INTERPRETATION

2.4.1 Wudayhi Facies, Facies Associations and Depositional Environments

Six facies, grouped into two facies associations, were identified in core samples from the Wudayhi Member in subsurface southeastern Saudi Arabia (Table 2.1, Figs. 2.5, 2.7, 2.9, 2.11, 2.13, 2.15). Facies Association One (FA1) is marginal-marine and tidally influenced, and comprises the following facies: F1) coal deposits; F2) interbedded very fine- to fine-grained sandstone and mudstone; and F3) very fine- to medium-grained cross-bedded silty sandstone. Facies Association Two (FA2) is shallow-marine and tide- and storm-influenced, and comprises the following facies: F4) burrowed, fine- to medium-grained, sandstone; F5) burrowed, very fine- to fine-grained muddy sandstone; and F6) burrowed sandy mudstone.

2.4.1.1 Marginal-Marine, Tidally Influenced Facies Association (FA1)

Facies 1 (F1): Coal deposits. – Facies 1 consists of *in situ* coal deposits that commonly rest on top of poorly sorted, very fine- and fine-grained sandstones that display carbonaceous root traces. It is the least abundant facies in the studied dataset, being identified only in Wells 1 and 2 (Fig. 2.5). This is the first report of coal in the Unayzah Group. The coal beds are dark gray to black, and range in thickness from centimeter- to meter-scale beds in Well 2 (Fig. 2.6). Sandstone beds

LITHOFACIES	LITHOLOGY & MINERAL ACCESORIES	SEDIMENTARY STRUCTURES	ICHNOLOGY	ENVIRONMENTAL INTERPRETATION
Facies 1: **Coal Deposits.**	- Poorly sorted very-fine- and fine-grained sandstone with carbonaceous-rich root traces (i.e., Rhizoliths). - *in situ* coal beds. - Locally, Pyrite.	- Undiscernible in coal beds. - Sandstone beds are dominated by “rhizoliths-mottling” without any sing of relict sedimentary structures. - Contacts are commonly gradational or sharp but conformable surfaces.	- Variable: absent to uncommon bioturbation. - (BI = 0-2). - Evidence of biogenic activity in the form of plant root-traces (i.e., Rhizoliths). Locally, burrow-mottled texture due to abundant root traces.	- *in situ* coal beds suggest sedimentation in low-energy environments likely in standing water bodies that allowed establishment and subsequent preservation of abundant vegetable material (likely, coastal swamps). - Sandy paleosoils with root traces and scattered carbonaceous detritus suggest proximity to the shore/sediment source, likely associated to a fresh water input, or periodically flooded marsh lands in a setting with prolonged periods with low to none sedimentation prone to floral colonization. - Absence of bioturbation by organism suggest by burrowing organisms or unfavorable paleoecological conditions for animal colonization. - Conclusion: abundant vegetable material accumulated in standing water bodies that resulted in coal deposits and plant colonization in paleosoils within marginal marine settings, likely in swamps associated to estuaries.
Facies 2: **Interbedded very fine- to fine sandstone and mudstone.**	- Very fine- and fine-grained sandstone interbedded with mudstone.	- Common, reactivation surfaces. Lenticular bedding occurs throughout as well as current ripples. Abundant synaeresis cracks. - Some intervals display flaser bedding and mud drapes occur rhythmically. Parallel lamination, locally current ripple cross-lamination and single mud drapes. - Contacts are commonly gradational or sharp but conformable surfaces.	- Variable: absent to uncommon bioturbation. - (BI = 0-2). - Sparsely; *Skolithos*, *Planolites*, *Palaeophycus* and *Thalassinoides*.	- Interbedded very fine-, to fine-grained sand and mud suggest variable hydrodynamics at the time of sedimentation (i.e., tides) - Absent to uncommon bioturbation suggest that burrowing organisms developed under unfavorable paleoecological conditions (e.g., short termed salinity fluctuations). - Possible sediment transport mechanisms include tidal currents and riverine currents with subordinate input of wave currents. - Conclusion: Estuarine deposits. Highly stressed, low-diversity mixed expressions of the *Cruziana* ichnofacies with subordinate elements of the *Skolithos* ichnofacies.

Table 2.1. Lithological, sedimentological and ichnological characteristics of each facies identified for the Wudayhi Member of the Nuayyim Formation in the study area. Particular interpretations are expanded on the main body of the text for each facies.

Facies-3: **Very fine- to medium-grained cross-bedded silty sandstone.**	- Very fine- to medium-grained sandstone. - Single and double mud drapes. - Locally, small (cm-scale) siltstone beds. - Locally, carbonaceous-rich single and double mud drapes.	- Rhythmic single and double silt and mud drapes as inclined heterolithic stratification (IHS). - Rarely, planar and wavy-parallel lamination. Thin and thick alternations of lamina sets. - Contacts are commonly gradational or sharp bases but conformable surfaces. Locally, erosive bases.	- Absent bioturbation. - (BI = 0).	- Rhythmically interbedded very fine- to medium-grained sand and mud drapes as inclined heterolithic stratification (IHS) suggest variable hydrodynamics at the time of sedimentation with quiescencent periods that allowed mud deposition. - Mud drapes and sparse mud beds suggest mud dispersed in the water column with low-energy periods for mud to settle down from suspension. - Absent bioturbation suggest stressful conditions for bioturbating infauna (e.g., fluctuating salinity levels related to the tidal exchange and mixing of marine and fresh water) and/or constant migration of substrates by lateral and downstream accretion. - Possible sediment transport mechanisms include tidal currents as well as fluvial discharge. - Conclusion: Tidally influenced deposits such as fluvio-tidal tidal channels, subtidal 2D dunes and tidal flats.
Facies-4: **Burrowed fine- to medium-grained sandstone.**	- Fine- to medium-grained, sandstone. - Recurrent single and double silt laminae. - Scattered carbonaceous flakes. - Locally, deformed mudclasts/ pellets and pyrite specks.	- Abundant low-angle and horizontal lamination. - Commonly, planar, wavy, crinkly and wavy-parallel lamination. - Locally, tabular-, trough-cross bedding and trough cross lamination. - Rarely, wave ripples and low-angle cross lamination. - Contacts are commonly, gradational or sharp but conformable surfaces. Occasionally, abrupt.	- Variable: absent to moderate bioturbation. - (BI = 0-3). - Commonly, *Planolites*, *Thalassinoides*, *Ophiomorpha irregulaire*, *Palaeophycus* and *Bergaueria*. - *Sparsely*, *Teichichnus*, *Skolithos*, *Arenicolites*, *Ophiomorpha*, *Lockeia* and fugichnia. - Locally, beds display mono-ichnogeneric *Planolites* suites. - Some intervals display burrow-mottled texture. Therein, individual ichnotaxa are difficult to discern.	- Recurrent fine- to medium-grained sand with mud (e.g., low-angle mud laminae, tabular- and through-cross bedding and trough cross lamination) suggests subaqueous sedimentation with variable hydrodynamic levels. - Absent to moderate bioturbation suggest periods where burrowing organisms developed under favorable paleoecological conditions (e.g., substrate consistency and food resources) and/or low sedimentation rates allowing colonization. - Preponderance of vertical and inclined traces suggests food resources mostly but not exclusively suspended in the water column owing to frequent agitation. - Scattered carbonaceous flakes suggest proximity to the shore/sediment source. - Possible sediment transport mechanisms include tidal and wave currents. - Conclusion: Upper Shoreface deposits. Impoverished proximal *Skolithos* ichnofacies.

Table 1.1.– *Contined*.

Facies-5: **Burrowed very fine- to fine-grained muddy sandstone.**	- Very fine- to fine-grained muddy sandstone. - Commonly, mud laminae and centimeter-scale beds.	- Commonly, planar, wavy, crinkly and wavy-parallel lamination. - Locally, hummocky cross stratification (HCS) and subordinate swaley cross stratification (SCS). - Rarely, wave ripples and low-angle ripple cross lamination. - Contacts with other Facies are commonly, gradational or sharp but conformable surfaces. - Contacts between alternating fair-weather beds (laminated) and storm beds (hummocky cross stratified HCS with subordinate occurrences of swaley stratification SCS) are erosional.	- Highly variable as a whole: Absent to common bioturbation. (BI = 0-4). - Two types of ichnocenoses: 1) resident, fair-weather association (BI 0-4), and 2) opportunistic storm-bed association. **1)** resident, fair-weather association: *Planolites*, *Thalassinoides*, *Palaeophycus hiberti*, *Palaeophycus*, *Skolithos*, *Ophiomorpha*, *Ophiomorpha nodosa*, *Ophiomorpha irregulaire*, *Diplocraterium*, *Arenicolites*, *Helminthopsis*, *Lockeia*, *Cylindrichnus*, *Teichichnus* and *Bergaueria*. **2)** opportunistic, storm-bed association: *Ophiomorpha*, *Ophiomorpha irregulaire* and fugichnia that in places resemble laminated and scrambled, "lam-scram" bedding patterns resulting from the biogenic reworking between alternating fair-weather and storm episodes. - Some intervals display burrow-mottled texture. Individual ichnotaxa is difficult to discern or present cryptic bioturbation.	- Recurrent very fine- to fine-grained sand with clay/silt laminae suggest variable hydrodynamic levels within an overall moderate to low energy setting. - Locally, thin beds with erosional bases, hummocky cross stratification (HCS) and subordinate occurrences of swaley cross stratification (SCS) suggest episodic, high-energy events that alternate between background fair-weather conditions. - Absent to common bioturbation suggests periods where burrowing organisms developed under favorable paleoecological conditions (e.g., substrate consistency, food resources) and/or low sedimentation rates. - Thin, amalgamated hummocky sets typically unbioturbated to locally slightly bioturbated with Ophiomorpha being the only ichnogenus recorded. - Mixed association of vertical, inclined and horizontal traces suggest food resources both suspended in the water column and deposited on the substrate. - Possible sediment transport mechanisms include tidal and wave currents as well as storm- generated currents. - Conclusion: Storm-influenced, proximal lower shoreface deposits. Impoverished proximal *Cruziana* ichnofacies interbedded with elements of the distal *Skolithos* ichnofacies.
Facies-6: **Burrowed sandy mudstone**	- Sandy mudstone with very-fine grained sandstone. - Locally, homogeneous, structureless, silty mudstone.	- Commonly, planar, wavy, crinkly and wavy-parallel lamination. - Contacts are commonly, gradational or sharp but conformable surfaces. Occasionally, abrupt.	- Highly variable: absent to abundant bioturbation (BI = 0-5). - Commonly; *Thalassinoides*, *Palaeophycus hiberti*, *Palaeophycus beverliensis*, *Helminthopsis*, *Planolites* and *Palaeophycus*. - Sparsely; *Ophiomorpha*, *Ophiomorpha irregulaire*, *Teichichnus* and *Skolithos*. Some intervals display burrow-mottled texture.	- Mud-dominated sedimentation with very fine sand occurrences suggests an overall low-energy depositional setting. - Deposition primarily occurs from suspension in an environment with little to no variability in hydrodynamic levels. - Absent to abundant bioturbation suggests that favorable paleoecological conditions for bioturbating infauna prevailed (e.g., substrate consistency, stable salinity levels and food resources) and/or low sedimentation rates. - Preponderance of horizontal and inclined traces suggests food resources mostly but not exclusively deposited on the substrate. - Possible sediment transport mechanisms include wave currents as well as water agitation after storm-generated currents. - Conclusion: distal lower shoreface deposits. Impoverished proximal *Cruziana* ichnofacies with subordinate elements of the *Skolithos* ichnofacies.

Table 1.1.– *Contined*.

containing rhizoliths can be up to 30 cm thick and exhibit "rhizolith-mottling" (Fig. 2.5A). No burrowing is discernible in, or associated with, the coal beds (BI 0-2).

The presence of poorly sorted sandstones with abundant root traces suggests subaerial exposure and proximity to the water table, which allowed plants to colonize the substrate. The upwards-conformable passage into autochthonous coal deposits points towards accumulation of vegetal material in low-energy peat swamps in a humid environment (Fig. 2.5A). The thickness of coal beds (meter-scale) indicates that these conditions were persistent rather than ephemeral, thus allowing the generation and accumulation of significant amounts of vegetative material (Retallack 1990, 1997). Coal seams identified in Facies 1 are interpreted to have been formed by alteration during burial of peats that accumulated in swamp and marshes associated with estuaries (Dashtgard and Gingras 2005a; Gingras et al., 2012). These characteristics are commonly associated with marginal-marine settings, where paleosols normally exhibit features of waterlogged and reducing conditions, such as preserved organic matter and rootlets (Collinson 1996; Dashtgard and Gingras 2005a; Phillips 2011). Facies 1 reflects sedimentation in sheltered peats and swamps, leading to the formation of paleosols and accumulation of vegetative organic matter that formed coal beds in estuarine settings (Retallack 1997; MacEachern and Gingras 2007; Gingras et al., 2012).

Facies 2 (F2): Interbedded very fine- to fine-grained sandstone and mudstone. – Facies 2 comprises very fine- and fine-grained sandstone interbedded with mudstone (Fig. 2.7). Sedimentary structures consist of synaeresis cracks, lenticular bedding, low-angle and wavy lamination, flaser bedding, reactivation surfaces, carbonaceous double mud drapes, and current ripples (Fig. 2.7). Where present, the ichnofossil suite exhibits poorly developed, locally abundant and mono-generic trace-fossil assemblages. Overall, ichnofossils are diminutive and bioturbation varies from absent to uncommon (BI 0–2). Trace fossils include a mixture of horizontal and inclined traces such as *Planolites*, *Thalassinoides*, *Skolithos*, and *Palaeophycus* (Fig. 2.7B, D, E-F).

The presence of current ripples associated with flaser bedding suggests subaqueous sediment transport and deposition, more likely with low to moderate energy levels. Such structures reflect lower- flow-regime conditions in non-cohesive substrates (Dalrymple 2010). Abundant single and double carbonaceous mud drapes and thinly interbedded siltstone and sandstone displaying flaser, wavy, and lenticular bedding suggest tidal influence at the time of sediment deposition

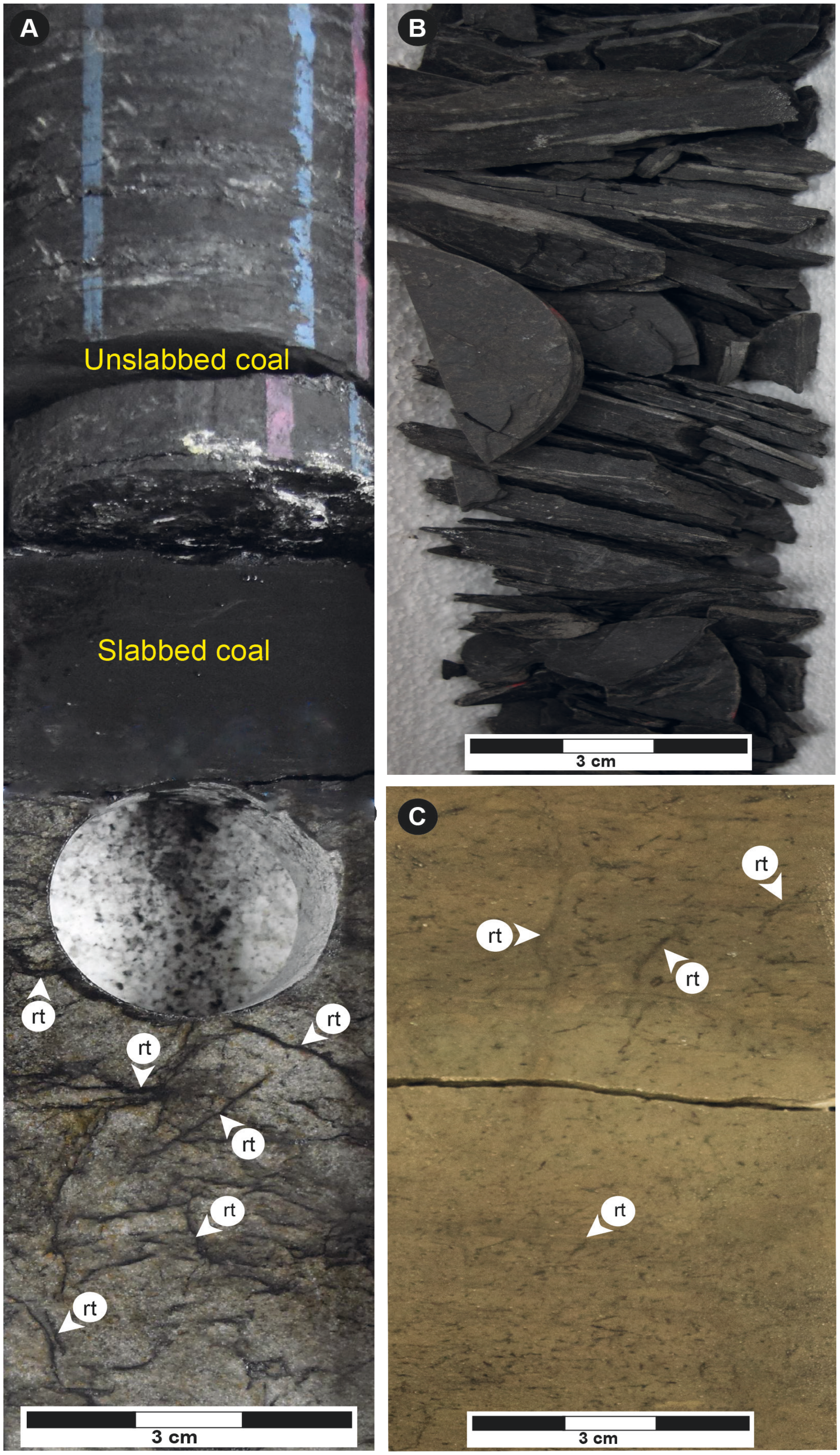


Figure 2.5. Occurrences and characteristics of Facies 1. A) Sandy paleosol with abundant plant root traces (rt) passing upward conformably into *in situ* (i.e., not reworked) coal deposits, Well 2. B) Dark, fissile carbonaceous mudstone, Well 2. C) Sandy paleosol with abundant plant root traces (rt) and "rhizolith mottling", Well 2.

(Reineck and Wunderlich 1968; Reineck, 1972) (Fig. 2.7A, B, D). Mud drapes are interpreted to be the result of settling of suspended sediment during slack-water periods (Hovikoski et al., 2008; Mackay and Dalrymple 2011). The presence of synaeresis cracks points towards clay shrinkage resulting from salinity changes, likely as a result of mixing marine and fresh water (Plummer and Gostin 1981). Facies 2 shows evidence of both tidal and fluvial influence, and the proportion of predominantly tidal-generated versus fluvial-generated structures leads to a classification of a tide-dominated, fluvial-influenced system (Tf) (cf. Ainsworth et al., 2011)

The trace-fossil suite of Facies 2 is dominated by infaunal dwelling and grazing structures of trace makers interpreted to reflect predominantly deposit feeding (e.g., *Planolites*, *Thalassinoides and Palaeophycus*) and suspension feeding (e.g., *Skolithos*) behaviours (Fig. 2.7B, D, E, F). This low-diversity assemblage exhibits an impoverished expression with facies crossing elements of the *Skolithos* and *Cruziana* ichnofacies. The diminutive size, low diversity, and limited abundance of this ichnofossil suite suggest stressful conditions for bioturbating infauna (cf. Pemberton et al., 1982; Beynon and Pemberton 1992; Ranger and Pemberton 1997; MacEachern and Pemberton 1994; Buatois et al., 1999; Buatois et al., 2002; Buatois et al., 2005; MacEachern and Gingras 2007; Lacroix and Dashtgard 2015; Lacroix et al., 2015). Salinity fluctuations and repeatedly changing conditions can be discerned by the presence of synaeresis cracks and reactivation surfaces, respectively (Fig. 2.7D, E) and are very likely responsible for a reduced trace-fossil diversity in the facies (e.g., Bann et al., 2004; Buatois et al., 2005). Similar physico-chemical stresses common in estuarine settings include variations in substrate consistency, sedimentation rates, salinity, oxygen content, water turbidity' and temperature, resulting in a reduced trace fossil-diversity, at least in comparison to quiescent marine conditions (e.g., Pemberton et al., 1982; Wightman et al., 1987; Pemberton and Wightman 1992; MacEachern and Pemberton 1994; Gingras et al., 1999; Gingras et al., 2012; Hodgson et al., 2015; Dashtgard and MacEachern 2016). Trophic resources, almost but not exclusively deposited on the substrate, can be interpreted in the occurrences of deposit-feeding ichnotaxa. This facies reflects deposition in estuarine settings and exhibits a diminutive, highly stressed, low-diversity, mixed expression of the *Skolithos* Ichnofacies and the *Cruziana* Ichnofacies (MacEachern et al., 2007a; Gingras and MacEachern 2012).

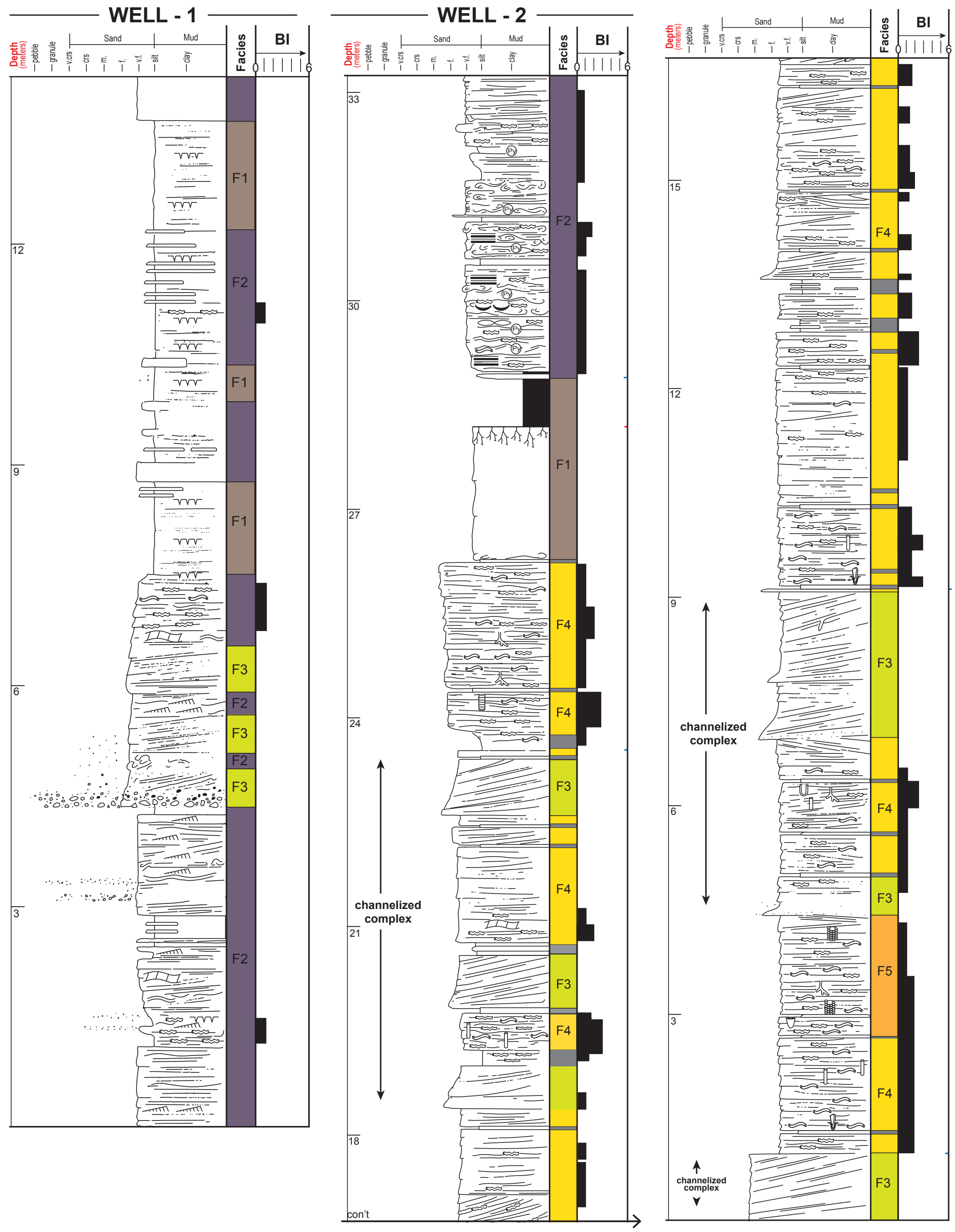


Figure 2.6. Vertical succession of facies and trace-fossil distribution in Wells 1 and 2. For legend in all core logs, please refer to Figure 2.14.

Facies 3 (F3): Very fine- to medium-grained, cross-bedded silty sandstone. – Facies 3 comprises very fine- to medium-grained, moderately to well-sorted sandstones in beds that range from centimeter to meter scale, commonly display sharp, erosional bases, and a fining-upwards trend (Fig. 2.8). Some intervals display thin siltstone beds (commonly of centimeter scale) and carbonaceous-rich drapes (Fig. 2.9). Sedimentary structures are dominated by cross-stratification and

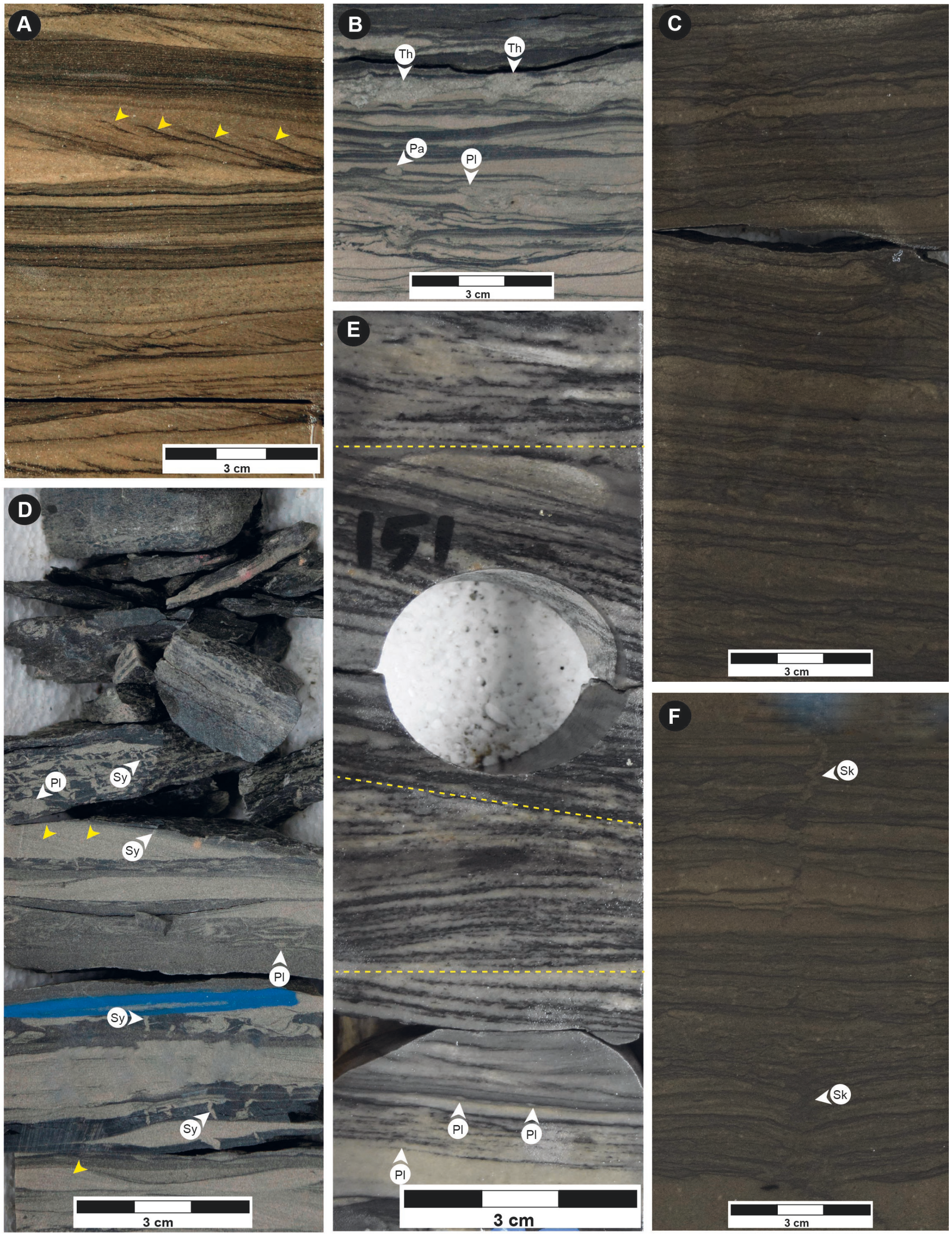


Figure 2.7. Occurrences and characteristics of Facies 2. A) Interbedded double mud drapes and current-rippled, cross-laminated (yellow arrows) bedsets separated by reactivation surfaces, Well 1. B) Segment with flaser and lenticular bedding along with sparse bioturbation, including *Thalassinoides* (Th), *Planolites* (Pl), and *Palaeophycus* (Pa), Well 1. C) Abundant double mud drapes with top part of image showing dips in the opposite direction compared to the area at the bottom of the image, Well 9. D) Sparsely bioturbated interval displaying lenticular bedding, current ripples (yellow arrows), and abundant synaeresis cracks (sy). Discernible trace fossils in this particular segment consist only of a mono-generic suite of diminutive *Planolites* (Pl), Well 1. E) Cosets of cross-bedded sandstone with discernible burrowing at the base with mono-generic diminutive *Planolites* (Pl), separated by reactivation surfaces. Mud laminae are rich in carbonaceous flakes, Well 2. F) Segment with abundant double mud drapes and *Skolithos* (Sk), Well 9.

rhythmic single and double silt and mud drapes forming inclined heterolithic stratification (IHS) (Thomas et al., 1987; Lettley et al., 2007; Gingras and MacEachern 2012; Dashtgard and La Croix 2015; La Croix et al., 2015) (Fig. 2.9). The latter may occur as thin and thick alternations of lamina sets at the bed-set scale interbedded with dark, structureless mudstone (Fig. 2.9B). Reactivation surfaces are common, and planar and wavy-parallel lamination occurs locally. They are well displayed in core samples from Wells 3 to 5 (Figs. 2.8, 2.10). Bioturbation is absent (BI 0) or burrowing is indiscernible due to the lack of lithological contrast within beds of this facies.

The presence of abundant rhythmic single and double mud drapes in crossbedded sets, erosional basal contacts, and a fining-upwards grain-size trend are commonly associated with tidally influenced settings (Dalrymple and Choi 2007; Dalrymple 2010) (Fig. 2.9). In tidally deposited heterolithic successions, siltstone and mudstone drapes mantling foresets can be a characteristic feature resulting from the passive settling of suspended sediment during slack-water periods (Mackay and Dalrymple 2011). The resulting crossbedding can be attributed to inclined heterolithic stratification (IHS) formed as fluvio-tidal and tidal channels accrete downstream and laterally (Thomas et al., 1987; Lettley et al., 2007; La Croix and Dashtgard 2015; La Croix et al., 2015) (Fig. 2.9D, C). Reactivation surfaces can be associated with current reversals characteristic of tidal settings (Ichaso and Dalrymple 2009; Dalrymple and Rhodes 1995) (Fig. 2.9D). Dark, structureless, unburrowed mudstone (Fig. 2.9D) suggest fluid-mud deposition (e.g., Bhattacharya and MacEachern 2009; Ichaso and Dalrymple 2009) as mud-size particles accumulated dynamically from near-bed, high-density suspensions (sediment concentration > 10 g L-1) such as the ones observed in modern tidal channels, particularly near the turbidity maximum (Mackay and Dalrymple 2011; Lacroix and Dashtgard 2015). The lack of bioturbation in cross-stratified sets, coupled with tidal indicators (e.g., double silt and mud drapes), indicates constantly changing conditions, which led to impoverishment of ichnological suites in a marginal-marine setting (e.g., Pemberton et al., 1982; Wightman et al., 1987; Pemberton and Wightman 1992; MacEachern and Pemberton 1994; Gingras et al., 2002; Desjardins et al., 2012; Gingras et al., 2012; Dasgupta et al., 2016). Daily and seasonal variations in hydraulic energy, sediment erosion, sediment deposition, substrate firmness, and overall paleoecological aspects in these environments impose stressful conditions on organisms (Pemberton et al., 1982; Pemberton and Wightman 1992; Hodgson et al., 2015). In estuarine environments, tide-induced

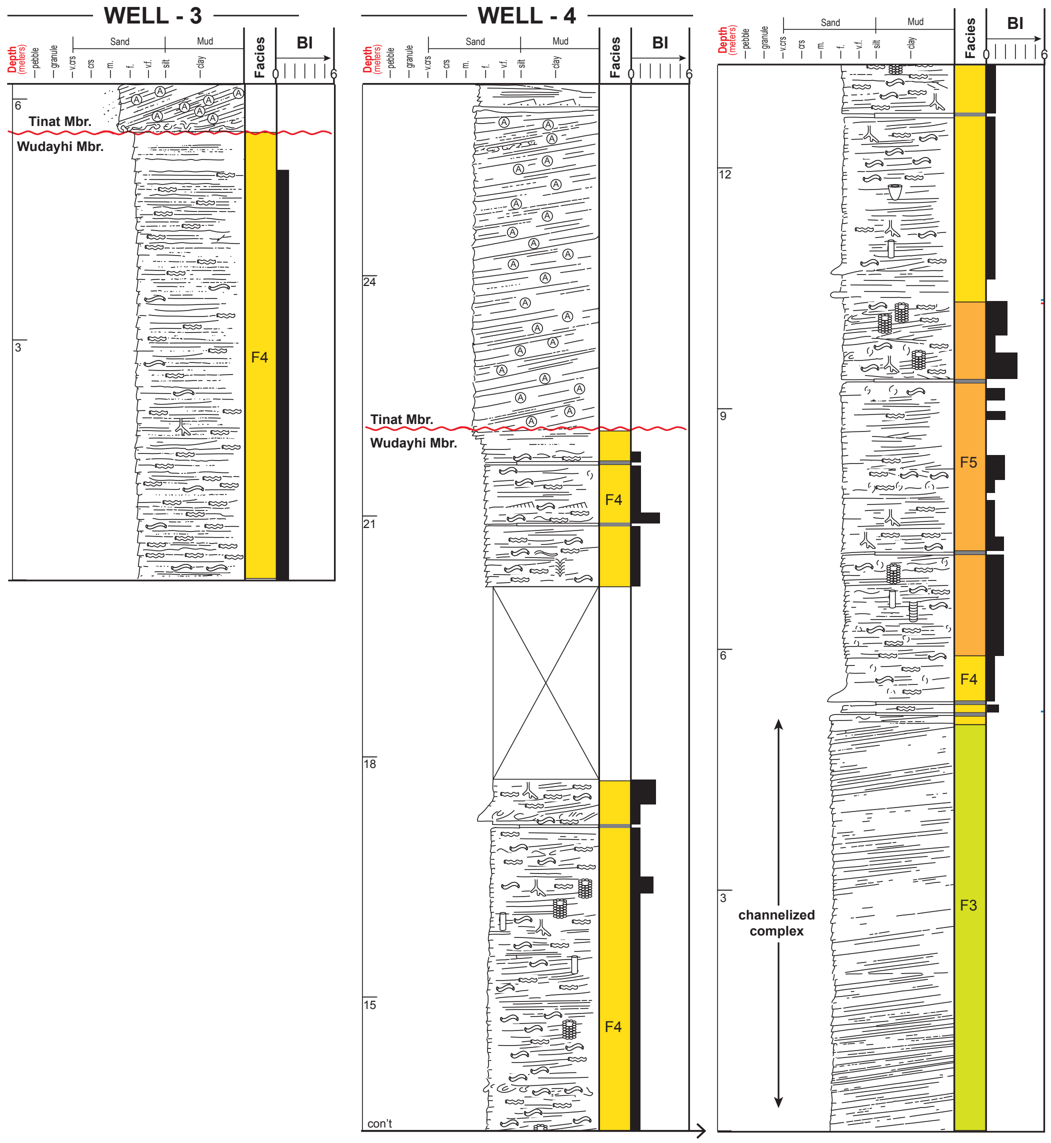


Figure 2.8. Vertical succession of facies and trace-fossil distribution in Wells 3 and 4. For legend in all core logs, please refer to Figure 2.14.

stresses also include clay flocculation and fluid-mud deposition (Gingras et al., 2002; Buatois et al., 2008; Lacroix and Dashtgard 2015). In brackish-water subtidal sand bodies such as the ones located in zones immediately seaward of intertidal areas, actively migrating bedforms preclude benthos colonization in spite of its proximity to open marine environments. The absence of bioturbation in the cross-stratified beds and bedsets in Facies 3 suggests continuous migration of tidally influenced fluvial and fluvio-tidal channels and an overall dominance of freshwater conditions (Fig. 2.10). Although this facies shows widespread evidence of both tide-generated and fluvial-generated structures, the absence of bioturbation leads to a classification of the channel fills as fluvial-dominated, tide-influenced deposits (Ft) (cf. Ainsworth et al., 2011). Facies 3 is interpreted to record sedimentation in

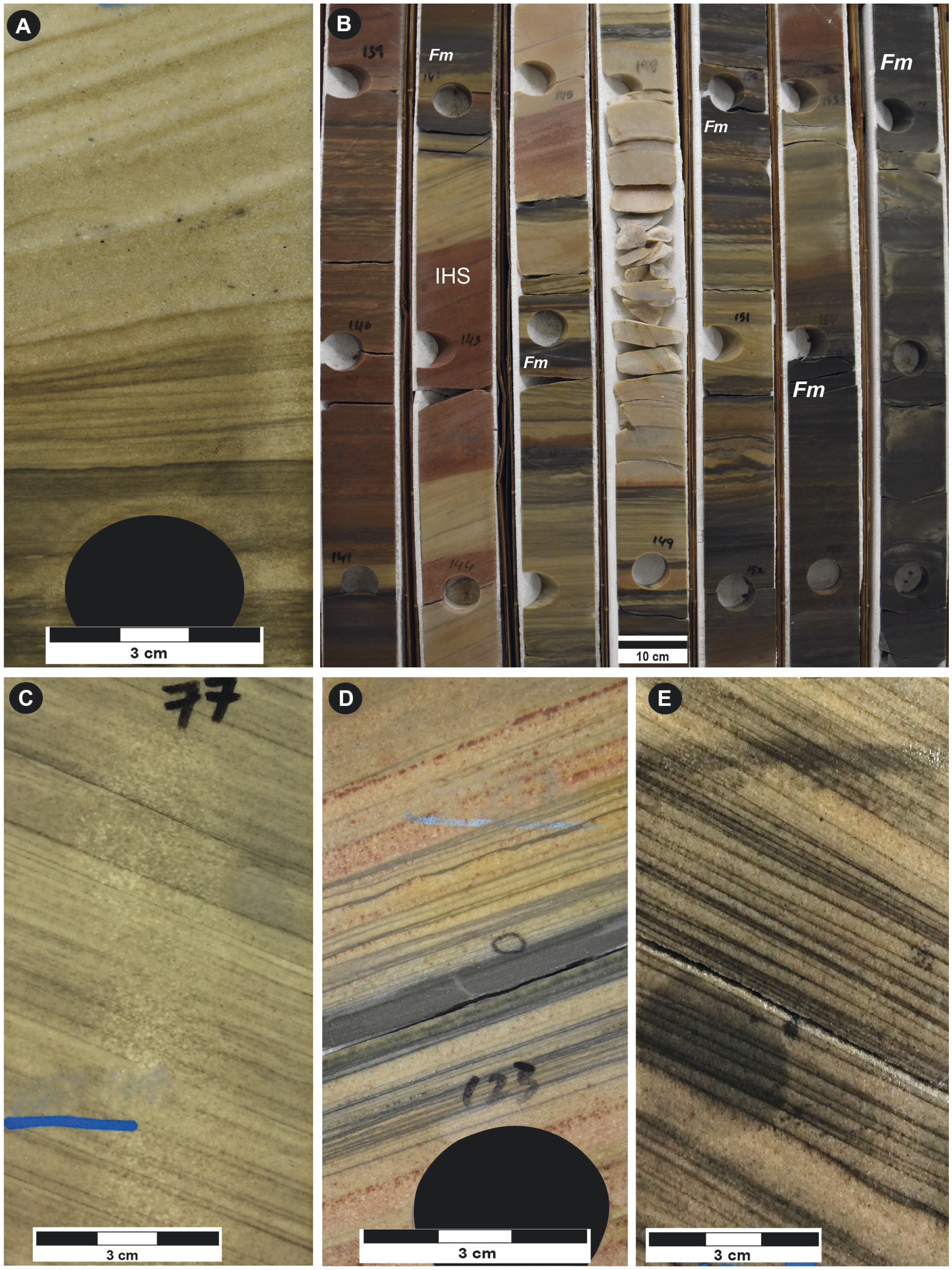


Figure 2.9. Occurrences and characteristics of Facies 3. A) Cross-bedded interval displaying sharp base with pebbles. The dip angle of the fine-grained laminae increases progressively toward the top, Well 3. B) Unburrowed dark, structureless fluid mud and beds displaying IHS devoid of discernible burrowing, Well 5. (C) Rhythmic, almost equally spaced double mud drapes, Well 7. D) Well-defined silt and clay laminae. Note the preservation of the laminae without any disruption or discernible burrowing. The thickness of the mud bed in the middle reflects high suspended-sediment concentrations and fluid-mud deposition as tidal channels accreted laterally. Thin and thick cycles of cross-lamination and cross-bedding, respectively suggesting neap-spring tidal cyclicity, Well 7. E) Interval displaying IHS with laminae rich in carbonaceous material, Well 5.

tidally influenced settings such as fluvial and fluvio-tidal channels in sheltered, marginal-marine and estuarine settings (Gingras and MacEachern 2012).

2.4.1.2 Shallow-Marine, Tide- and Storm-Influenced Facies Association (FA2)

Facies 4 (F4): Burrowed fine- to medium-grained sandstone. – Facies 4 consists of very fine- to medium-grained sandstone with scattered carbonaceous detritus (Fig. 2.11). Commonly, the facies occurs as bioturbated, argillaceous sandstone consisting of predominantly rounded to subrounded quartz, feldspar, deformed mud-clasts/pellets, and pyrite specks. Sedimentary structures are dominated by low-angle and horizontal, planar parallel, wavy, crinkly, and wavy parallel lamination. Planar tabular trough cross-bedding and current-ripple trough cross-lamination, along with wave-ripple laminae and low-angle cross lamination occur locally (Fig. 2.12). The ichnofossil suite exhibits moderately robust and diverse burrows, and the intensity of bioturbation varies from absent to moderate (BI 0–3). The ichnofossil assemblage consists of a mix of horizontal, inclined, and vertical traces such as *Planolites*, *Thalassinoides*, *Ophiomorpha* isp., *Ophiomorpha irregulaire*, *Palaeophycus*, *Bergaueria*, *Lockeia*, *Teichichnus*, *Skolithos*, *Arenicolites*, and fugichnia (Fig. 2.11). Locally, beds display mono-generic *Planolites* suites displaying high abundances (Fig. 2.11C).

The presence of subaqueous, traction-associated sedimentary structures (e.g., wavy lamination, low-angle cross-stratification) suggests exposure to increased nearshore wave activity, more likely with low to moderate energy levels (Fig. 2.11) (Dalrymple 2010). The presence of trough cross-bedding, low- and high-angle planar cross-stratification, and sporadic distribution of trace fossils suggests a middle- to upper-shoreface setting (MacEachern and Pemberton, 1992; Dashtgard et al., 2012; Pemberton et al., 2012). Therein, benthic organisms must overcome hardships imposed by the interplay of salinity, sediment mobility, hydrodynamic energy, and substrate type in a dynamic nearshore environment. These conditions result in rare, sporadically distributed trace fossils, such as the ones in upper-shoreface successions where continuously migrating substrates commonly inhibit infaunal colonization (e.g., Howard and Frey 1975; MacEachern and Pemberton 1992). Absent to moderate bioturbation (BI 0–3) and a trace-fossil suite with limited diversity suggest periods less favorable for bioturbating infauna. Based on the predominance of wave-generated sedimentary structures, with a subordinate

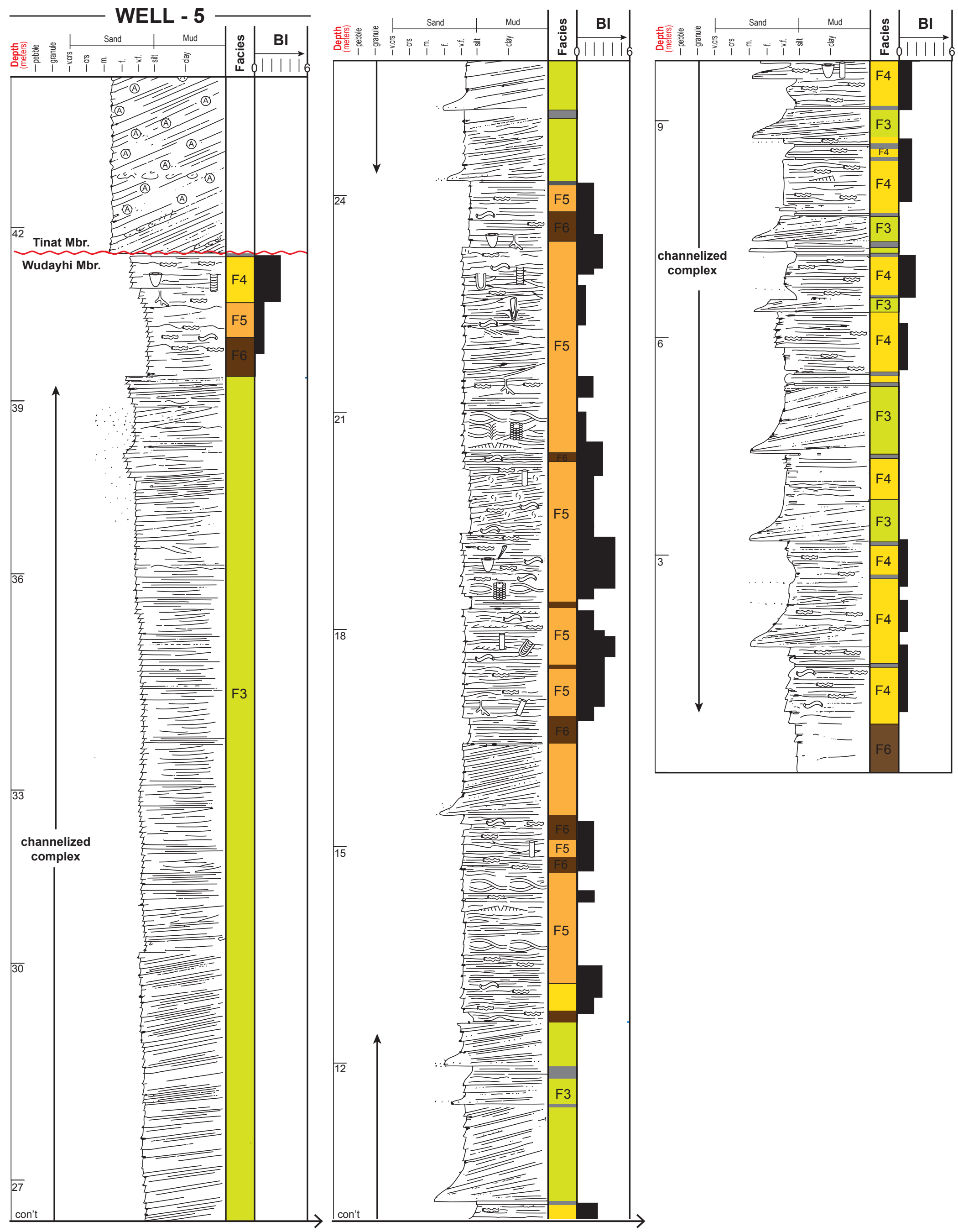


Figure 2.10. Vertical succession of facies and trace-fossil distribution in Well 5. For legend in all core logs, please refer to Figure 2.14.

proportion of possible tide-generated structures and the absence of fluvial-generated structures, Facies 4 is classified as a wave-dominated, tide-influenced, fluvial-affected system (Wtf) using the scheme of Ainsworth et al. (2011).

The trace-fossil suite of Facies 4 is dominated by infaunal dwelling structures of ichnotaxa interpreted to reflect predominantly suspension feeding (i.e., *Arenicolites*, *Skolithos*, *Bergaueria*, *Ophiomorpha*, *Ophiomorpha irregulaire*,

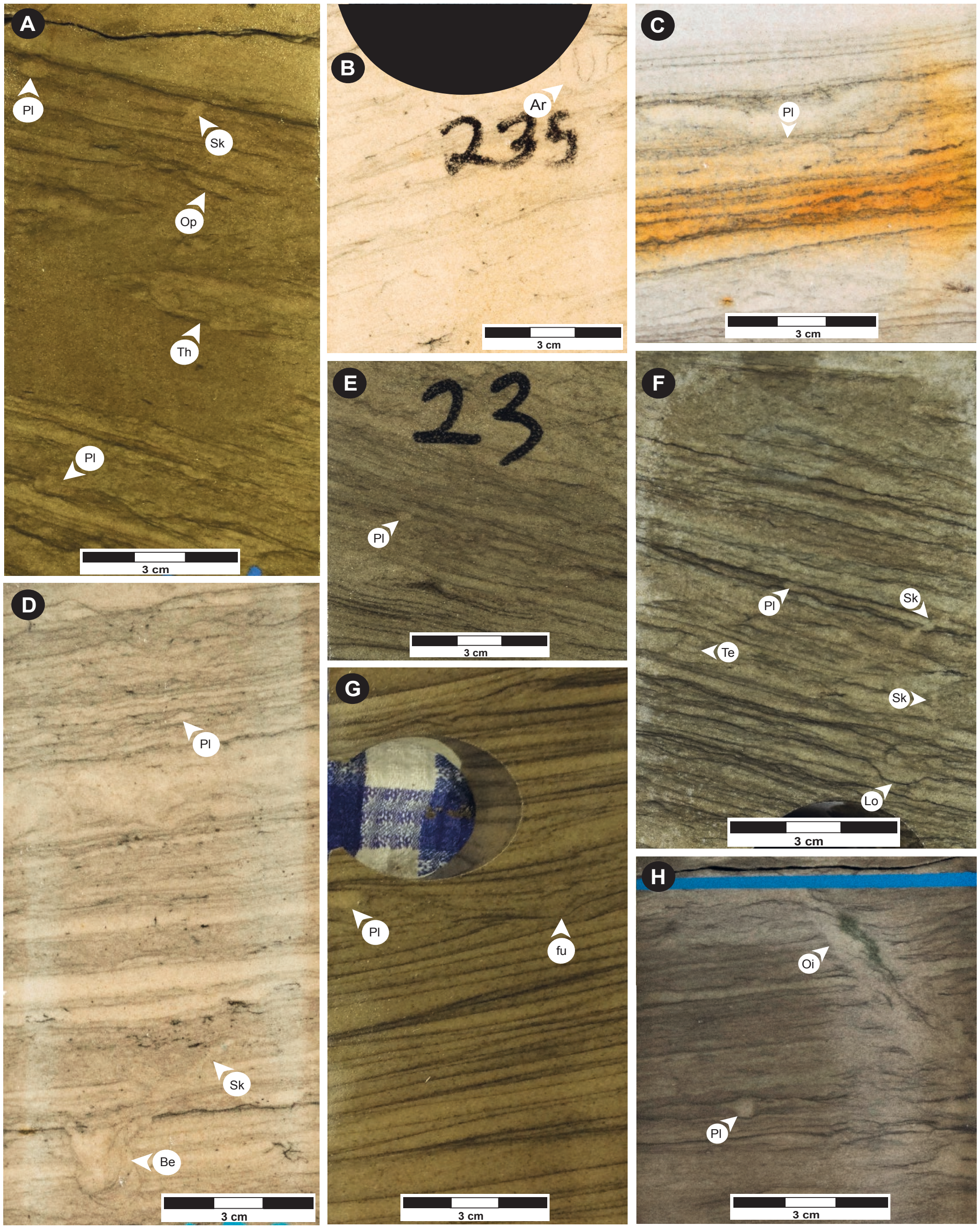


Figure 2.11. Occurrences and characteristics of Facies 4. A) Low-angle, wavy and crinkly parallel-laminated sandstone with a mixture of horizontal and vertical burrows that includes *Planolites* (Pl), *Skolithos* (Sk), *Thalassinoides* (Th), and *Ophiomorpha* (Op), Well 7. B) Burrow-"mottled" interval with *Arenicolites* (Ar) (top right). Poorly defined, low-angle lamination disrupted by bioturbation. The lack of lithological contrast makes other types of burrowing hard to discern, Well 2. C) Segment with wavy and low-angle lamination, mono-generic suite of diminutive *Planolites* (Pl), and intense burrow "mottling", Well 1. D) Burrow "mottled" interval with scattered carbonaceous flakes as well as low-angle and wavy lamination displaying *Skolithos* (Sk), *Planolites* (Pl), and *Bergaueria* (Be) Well 2. E) Cross-laminated interval with abundant, poorly developed *Planolites* (Pl), and some double mud drapes discernible towards the base of the picture, Well 6. F) Burrow-"mottled" segment displaying *Skolithos* (Sk) *Teichichnus* (Te), *Planolites* (Pl), and *Lockeia* (Lo), Well 2. G) Interval displaying planar tabular and trough cross-bedding with sparse bioturbation that includes fugichnia (fu), and *Planolites* (Pl). Note the abundant double mud drapes throughout the unit, Well 6. H) Interval with wavy and low-angle lamination containing *Planolites* (Pl), and moderately robust *Ophiomorpha irregulaire* (Oi), Well 7.

and fugichnia) with subordinate dwellings of interpreted deposit feeders (i.e., *Thalassinoides*, *Planolites*, *Teichichnus*, and *Palaeophycus*) and resting structures (i.e., *Lockeia*). This moderate- to low-diversity assemblage delineates an impoverished (stressed) proximal expression of the *Skolithos* Ichnofacies, and is consistent with upper-shoreface settings (MacEachern and Pemberton 1992; Pemberton et al., 2001; MacEachern et al., 2007a). Trophic resources mostly, but not exclusively, suspended in the water column can be interpreted through the dominance of ichnotaxa consistent with suspension-feeding tracemakers, such as *Arenicolites*, vertical and inclined *Skolithos*, and *Ophiomorpha* (Fig. 2.11F, H). Sediment deposition took place in a shallow-marine setting above fair-weather wave base in upper-shoreface environments, and exhibit elements of an impoverished, proximal expression of the *Skolithos* Ichnofacies (MacEachern et al., 2007a; MacEachern et al., 2010).

Facies 5 (F5): Burrowed very fine- to fine-grained muddy sandstone. – Facies 5 occurs mostly in wells located in the center and towards the east of the study area (Fig. 2.1). It is particularly well preserved in Wells 5 and 6 (Figs. 2.10, 2.12). The facies consists of burrowed, very fine- to fine-grained muddy sandstone interbedded sporadically with centimeter-scale mud beds (Fig. 2.13). Primary physical sedimentary structures are dominated by planar parallel, wavy, crinkly and wavy-parallel lamination (Fig. 2.13B–G). Hummocky cross-stratification (HCS), wave ripples, combined-flow ripples, and low-angle cross-lamination are common (Fig. 2.14). Swaly cross-stratification (SCS) is subordinate (Fig. 2.13A). The trace-fossil assemblage exhibits moderately robust and diverse burrows. The degree of bioturbation varies from absent to common (BI 0–4). Locally, beds display mono-generic suites of abundant *Planolites* (Fig. 2.13D). Two distinctive trace-fossil associations are observed. Assemblage (i) occurs in laminated beds and individual beds, locally display absent to common bioturbation (BI 0–4) representative of a resident, fair-weather ichnocoenose with *Planolites*, *Thalassinoides*, *Helminthopsis*, *Palaeophycus heberti*, *Palaeophycus* isp., *Skolithos*, *Diplocraterion*, *Arenicolites*, *Lockeia*, *Cylindrichnus*, *Teichichnus*, and *Bergaueria* (Fig. 2.13B–G). Assemblage (ii) occurs in intervals with HCS and SCS, and exhibits absent to uncommon bioturbation (BI 0–2), representative of a storm-bed ichnocoenose with *Ophiomorpha*, *Ophiomorpha irregulaire*, *Ophiomorpha nodosa*, and fugichnia (Fig. 2.13A, D).

Subaqueous, current-formed structures such as planar cross-bedding suggest

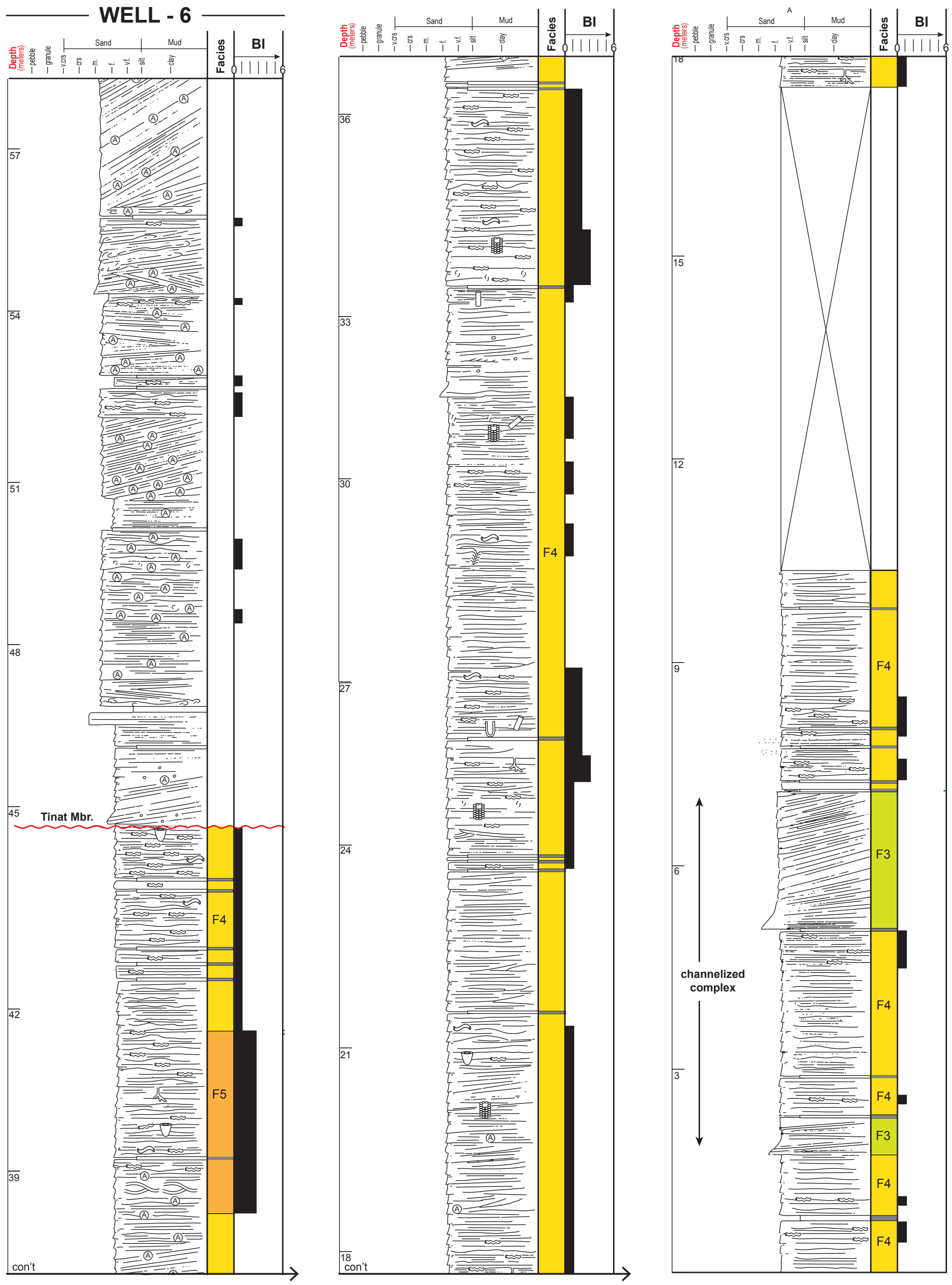


Figure 2.12. Vertical succession of facies and trace-fossil distribution in Well 6. For legend in all core logs, please refer to Figure 2.14.

sediment transport by traction, such as migration of subaqueous sand dunes. Overall high-intensity bioturbation in sandstone generally points towards well-oxygenated and non-cohesive substrates (e.g., MacEachern et al., 2007b; MacEachern et al., 2010). Hummocky cross-stratification (HCS) and swaley cross-stratification (SCS)

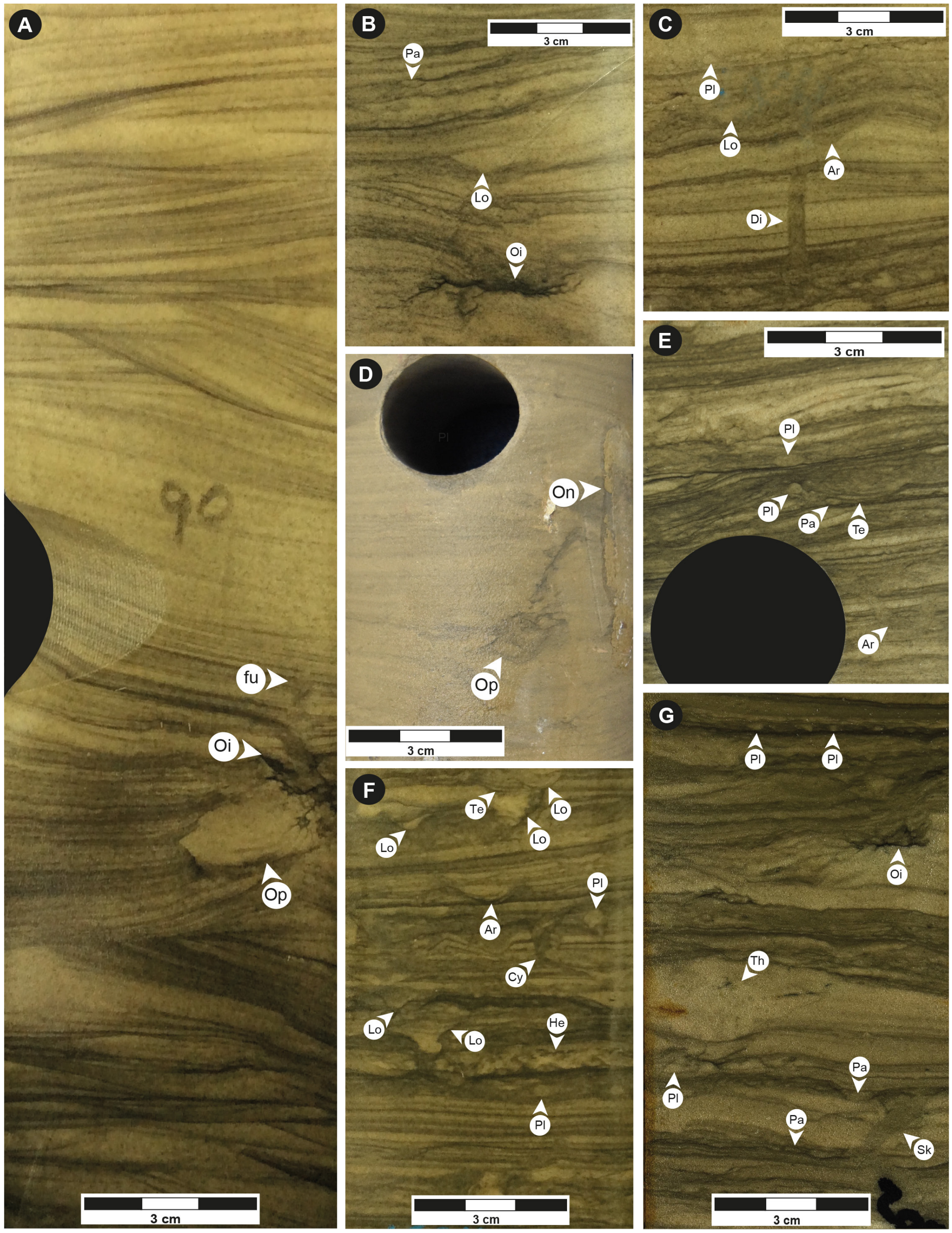


Figure 2.13. Occurrences and characteristics of Facies 5. A) Hummocky cross-stratification (HCS) in very fine-grained sandstone with oscillation- ripple cross-lamination and incipient ?swaly cross-stratification (SCS), exhibiting robust *Ophiomorpha* isp. (Op), fugichnia (fu), and *Ophiomorpha irregulaire* (Oi), Well 5. B) Segment with low-angle and wavy parallel lamination with *Palaeophycus* (Pa) *Lockeia* (Lo), and *Ophiomorpha irregulaire* (Oi), Well 5. C) Interval exhibiting *Diplocraterion* (Di), *Planolites* (Pl) *Arenicolites* (Ar), and *Lockeia* (Lo), Well 5. D) Segment displaying HCS along with *Ophiomorpha nodosa* (On), and *Ophiomorpha* isp. (Op), Well 7. E) Interval with wavy- and low-angle parallel lamination with abundant *Planolites* (Pl), *Teichichnus* (Te), and *Arenicolites* (Ar), Well 5. F) Mixed horizontal, inclined, and vertical traces that include *Lockeia* (Lo), *Helminthopsis* (He), *Arenicolites* (Ar), *Cylindrichnus* (Cy), *Teichichnus* (Te), and *Planolites* (Pl), Well 7. G) Segment includes *Thalassinoides* (Th), *Skolithos* (Sk), *Ophiomorpha irregulaire* (Oi), *Palaeophycus* (Pa),

and *Planolites* (Pl), Well 5.Figure 14. Vertical succession of facies and trace-fossil distribution in Well 7 with symbols legend. Figure 15. Occurrences and characteristics of Facies 6. A) Segment with abundant wavy, low-angle and crinkly parallel lamination. The ichnofossil suite consists of *Planolites beverlyensis* (Pb), *Planolites* isp. (Pl), *Palaeophycus heberti* (Ph), *Palaeophycus* isp. (Pa), *Helminthopsis* (He), *Teichichnus* (Te), and *Ophiomorpha* (Op), Well 8. B) Interval with poorly preserved, low-angle and wavy parallel lamination. Ichnofossils include *Palaeophycus heberti* (Ph), *Palaeophycus* isp. (Pa), *Thalassinoides* (Th), *Ophiomorpha irregulaire* (Oi), and *Ophiomorpha* isp. (Op). Note the preservation of double mud drapes at the base of the unit, Well 8. C) Interval with abundant wavy parallel lamination and hints of double mud drapes with *Skolithos* (Sk), *Thalassinoides* (Th) and *Planolites* (Pl), Well 8. D) Segment with low-angle lamination and a majority of horizontal biogenic structures that includes Thalassinoides (Th), *Planolites* (Pl), *Lockeia* (Lo) and *Palaeophycus* (Pa), Well 8. E) Segment displaying a mixed association of of moderately robust and abundant horizontal, inclined and vertical forms that include, *Ophiomorpha irregulaire* (Oi), *Ophiomorpha* isp. (Op), *Thalassinoides* (Th), *Teichichnus* (Te), *Planolites* (Pl), *Skolithos* (Sk), and *Palaeophycus* (Pa), Well 8. F) Interval with remnant low-angle and wavy parallel lamination showing a mixed association of horizontal and inclined trace fossils that includes *Palaeophycus heberti* (Ph), *Palaeophycus* isp. (Pa), moderately robust, *Ophiomorpha iregulaire* (Oi), *Ophiomorpha* isp. (Op), and *Planolites* (Pl), Well 8.

suggest elevated wave activity and storm-influenced sedimentation in the lower shoreface below fair-weather wave base (Harms et al., 1975; Leckie and Walker 1982; Dumas and Arnott 2006). These structures are also interpreted to record high-energy oscillatory and combined flows during storms (Cheel and Leckie 1993; Buatois et al., 2008). Based on the predominance of wave-generated sedimentary structures, with a subordinate percentage of tide-generated structures and the absence of fluvial-generated structures, Facies 5 is classified as a wave-dominated, tide-influenced system (Wt) using the scheme of Ainsworth et al. (2011).

A moderately diverse and robust trace-fossil suite suggests an environment with favorable ecological conditions, such as normal marine and stable salinities, available food resources, and optimal oxygenation for bioturbating infauna to develop (Fig. 2.13C, E, F). However, some units display rare trace-fossil occurrences (Fig. 2.13D). Intervals displaying HCS along with SCS and sporadically distributed bioturbation are evidence of post-storm colonization (Pemberton et al., 1992b; Pemberton and MacEachern 1997; Buatois et al., 2008). Storm beds exhibit moderately robust *Ophiomorpha* isp., *Ophiomorpha irregulaire*, *Ophiomorpha nodosa*, and fugichnia (Fig. 2.13A, D). Abundant bioturbation recorded in the fair-weather beds and thin beds with HCS suggests a reduced frequency of storms, allowing the reestablishment of fair-weather conditions and subsequent colonization by bioturbating organisms between events (Pemberton et al., 1992b; Pemberton and MacEachern 1997). Event beds also exhibit a marked decline in deposit-feeding structures compared with the resident ichnocenoses (Fig. 2.13F, G). This is interpreted to be the result of storm activity in a lower shoreface setting,

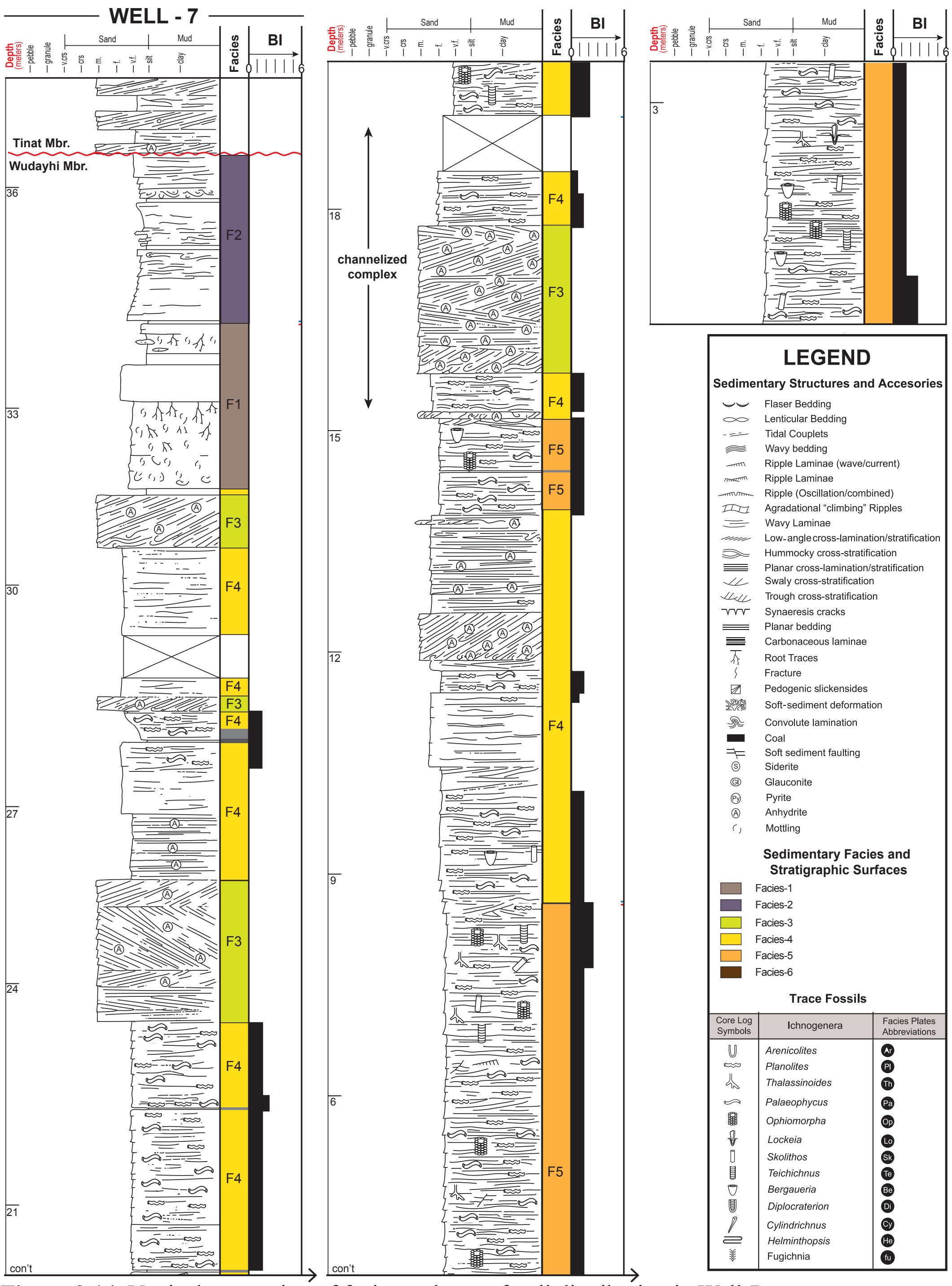


Figure 2.14. Vertical succession of facies and trace-fossil distribution in Well 7.

where horizontal traces of the resident fair-weather suite decline as overall ambient energy increases (MacEachern and Pemberton 1992; MacEachern et al., 2007b). The presence of fugichnia suggests episodic and elevated sedimentation rates, causing organisms to burrow upwards to reach the new sediment-water interface. In summary, Facies 5 is interpreted to have been deposited in proximal-lower-shoreface settings under the influence of storms, and exhibits an impoverished, (stressed) proximal expression of the *Cruziana* Ichnofacies interbedded with elements of an impoverished, (stressed) distal expression of the *Skolithos* Ichnofacies (e.g., MacEachern et al., 2007a).

Facies 6 (F6): Burrowed sandy mudstone. – Facies 6 occurs primarily in wells located in the southern and eastern part of the study area (Fig. 2.1). The facies is particularly well developed in Wells 5 and 8 (Figs. 2.10, 2.15, 2.16) and consists of burrowed sandy mudstone locally interbedded with very fine-grained sandstone (Fig. 2.15). Primary physical sedimentary structures are dominated by horizontal, wavy, crinkly, and wavy-parallel lamination (Fig. 2.15A, F). The ichnofossil assemblage exhibits moderately robust and diverse burrows (Fig. 2.15). The degree of bioturbation varies from absent to abundant (BI 0–5). Increased lithological contrast assists trace-fossil identification, including internal structures and ornamentation (Fig. 2.15). The trace-fossil suite is dominated by horizontal burrows, whereas inclined and vertical traces are less common. Ichnotaxa present include *Planolites* isp., *Planolites beverliensis*, *Thalassinoides*, *Ophiomorpha*, *Ophiomorpha irregulaire*, *Palaeophycus isp.*, *Palaeophycus heberti*, *Helminthopsis*, *Lockeia Teichichnus*, and *Skolithos* (Fig. 2.15).

The fine-grained lithology and the presence of sedimentary structures dominated by horizontal, wavy, crinkly, and wavy-parallel lamination suggest a low-energy depositional environment beyond the influence of normal nearshore current agitation or wave processes. Sedimentation occurred predominantly from suspension, under stable, fair-weather conditions. The moderate diversity and abundance of trace fossils observed in Facies 6 indicates relatively stable physico-chemical conditions with normal salinity, available food resources, optimal oxygenation, and low sedimentation rates (cf. MacEachern et al., 2007b; Pemberton et al., 2012). Based on the predominance of wave-generated sedimentary structures, the minor proportion of inferred tide-induced stresses on benthic fauna, and increased fair-weather conditions, Facies 6 is classified as a wave-dominated, tide-influenced system (Wt) using the classification scheme of Ainsworth et al. (2011).

The trace-fossil suite is dominated by infaunal dwelling and grazing structures of ichnotaxa, interpreted to reflect predominantly deposit feeding (e.g., *Thalassinoides*, *Planolites* isp., *Planolites beverliensis*, *Helminthopsis*, *Teichichnus*, *Palaeophycus* isp., and *Palaeophycus heberti*) with subordinate dwellings of interpreted suspension feeders (e.g., *Skolithos*, *Ophiomorpha* isp., and

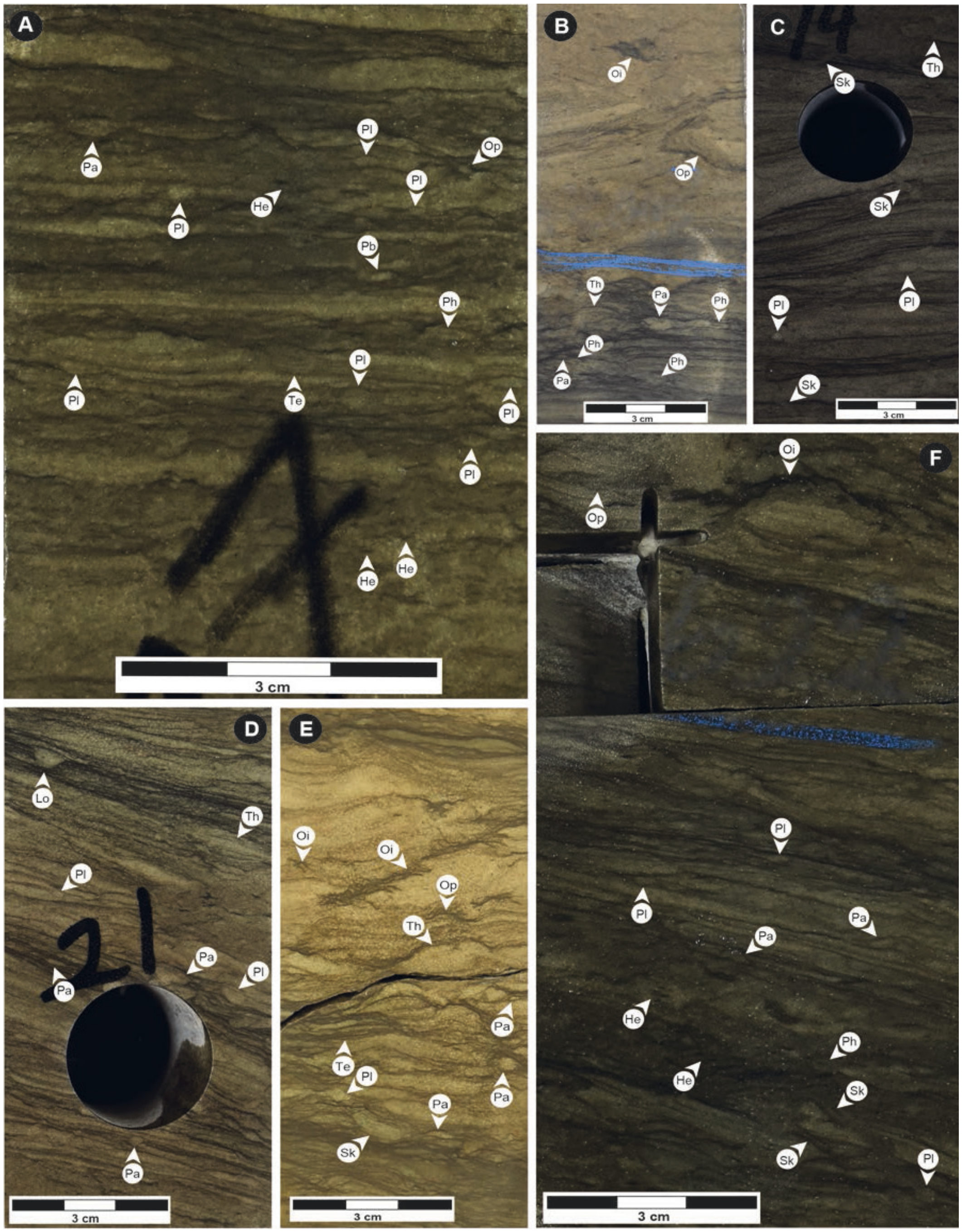


Figure 2.15. Occurrences and characteristics of Facies 6. A) Segment with abundant wavy, low-angle and crinkly parallel lamination. The ichnofossil suite consists of *Planolites beverlyensis* (Pb), *Planolites* isp. (Pl), *Palaeophycus heberti* (Ph), *Palaeophycus* isp. (Pa), Helminthopsis (He), *Teichichnus* (Te), and *Ophiomorpha* (Op), Well 8. B) Interval with poorly preserved, low-angle and wavy parallel lamination. Ichnofossils include *Palaeophycus heberti* (Ph), *Palaeophycus* isp. (Pa), *Thalassinoides* (Th), *Ophiomorpha irregulaire* (Oi), and *Ophiomorpha* isp. (Op). Note the preservation of double mud drapes at the base of the unit, Well 8. C) Interval with abundant wavy parallel lamination and hints of double mud drapes with *Skolithos* (Sk), *Thalassinoides* (Th) and *Planolites* (Pl), Well 8. D) Segment with low-angle lamination and a majority of horizontal biogenic structures that includes *Thalassinoides* (Th), *Planolites* (Pl), *Lockeia* (Lo) and *Palaeophycus* (Pa), Well 8. E) Segment displaying a mixed association of of moderately robust and abundant horizontal, inclined and vertical forms that include,

Ophiomorpha irregulaire (Oi), *Ophiomorpha* isp. (Op), *Thalassinoides* (Th), *Teichichnus* (Te), *Planolites* (Pl), *Skolithos* (Sk), and *Palaeophycus* (Pa), Well 8. F) Interval with remnant low-angle and wavy parallel lamination showing a mixed association of horizontal and inclined trace fossils that includes *Palaeophycus heberti* (Ph), *Palaeophycus* isp. (Pa), moderately robust, *Ophiomorpha iregulaire* (Oi), *Ophiomorpha* isp. (Op), and *Planolites* (Pl), Well 8.

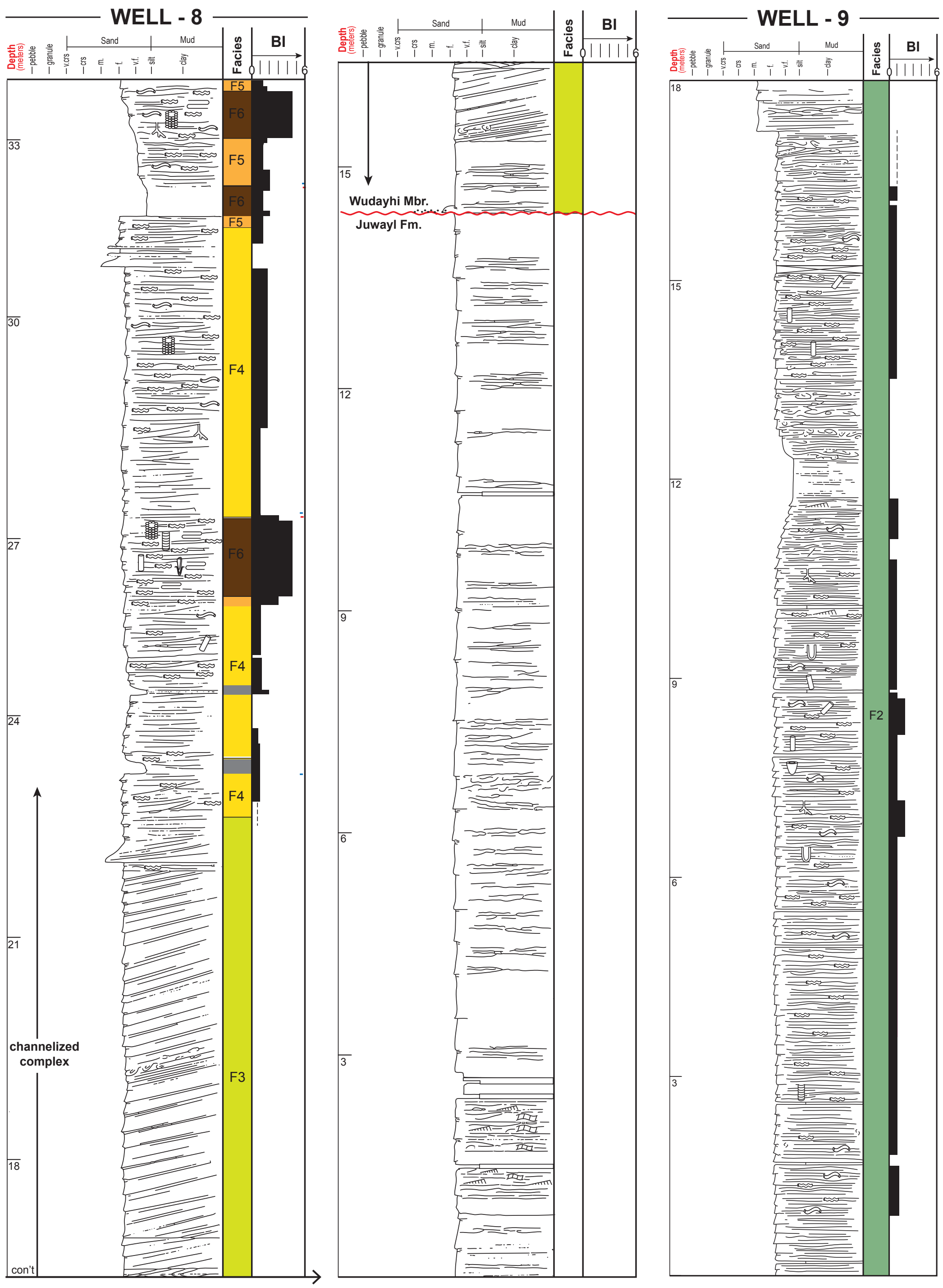


Figure 2.16. Vertical succession of facies and trace-fossil distribution in Wells 8 and 9. For legend in all core logs, please refer to Figure 2.14.

Ophiomorpha irregulaire) as well as resting structures (e.g. *Lockeia*). This moderately robust and diverse assemblage corresponds to an impoverished and moderately stressed proximal expression of the proximal *Cruziana* Ichnofacies, and is commonly associated with soft, cohesive muddy substrates in a relatively low-energy environment such as the distal lower shoreface and upper offshore (MacEachern and Pemberton 1992; Pemberton and MacEachern 1997; Pemberton et al., 2001; MacEachern and Bann 2008).

2.5 DISCUSSION

2.5.1 Marginal-Marine, Tidally Influenced Facies Association (FA1)

Facies Association 1 of the Wudayhi Member includes coal deposits (Facies 1), interbedded very fine- to fine-grained sandstone and mudstone (Facies 2), and very fine- to medium-grained, cross-bedded silty sandstone (Facies 3) (Fig. 2.17). They are reflective of sedimentation in marginal-marine, sheltered, tidally influenced estuarine environments in peat-rich swamps with abundant vegetative material, tidal channels, and tidal flats (Figs. 2.5, 2.7, 2.9). The term “estuarine” is used herein in the geological sense as summarized by Dalrymple, (2010): “estuaries are transgressive coastal embayments with at least some amount of river influence”. The use of the term in our paper encompasses also the geological definition in regards that estuaries trap the river sediment load landwards from the main coast and import sediment from the sea, thus receiving sediment derived from both the marine and fluvial realms (Dalrymple, 2010). Overall, beds in Facies 2 show very low trace-fossil diversity, with dominance of infaunal traces rather than the epifaunal trails, and comprising structures typically found in the marine realm (Fig. 18). In addition, simple infaunal dwelling structures produced by trophic generalists and the presence of mono-generic assemblages reflect a low-diversity assemblage of facies-crossing trace fossils that are characteristic of stressed sedimentary environments, especially brackish-water settings (cf. Pemberton et al., 1982; Pemberton and Wightman 1992; MacEachern and Pemberton 1994; Mangano et al., 2002; Buatois et al., 2005, MacEachern and Gingras 2007; Buatois et al., 2008; Gingras et al., 2011, 2012). This spatially and temporarily recurrent assemblage has been documented to be associated with brackish-water conditions in marginal-marine settings, and it is characterized by: 1) low ichnodiversity with locally high abundances; 2) facies-crossing forms typically found in the marine realm; 3) a mixture of diminutive vertical, inclined, and horizontal forms; 4) abundance of infaunal traces with subordinate epifaunal trails; 5) simple behavioral structures of

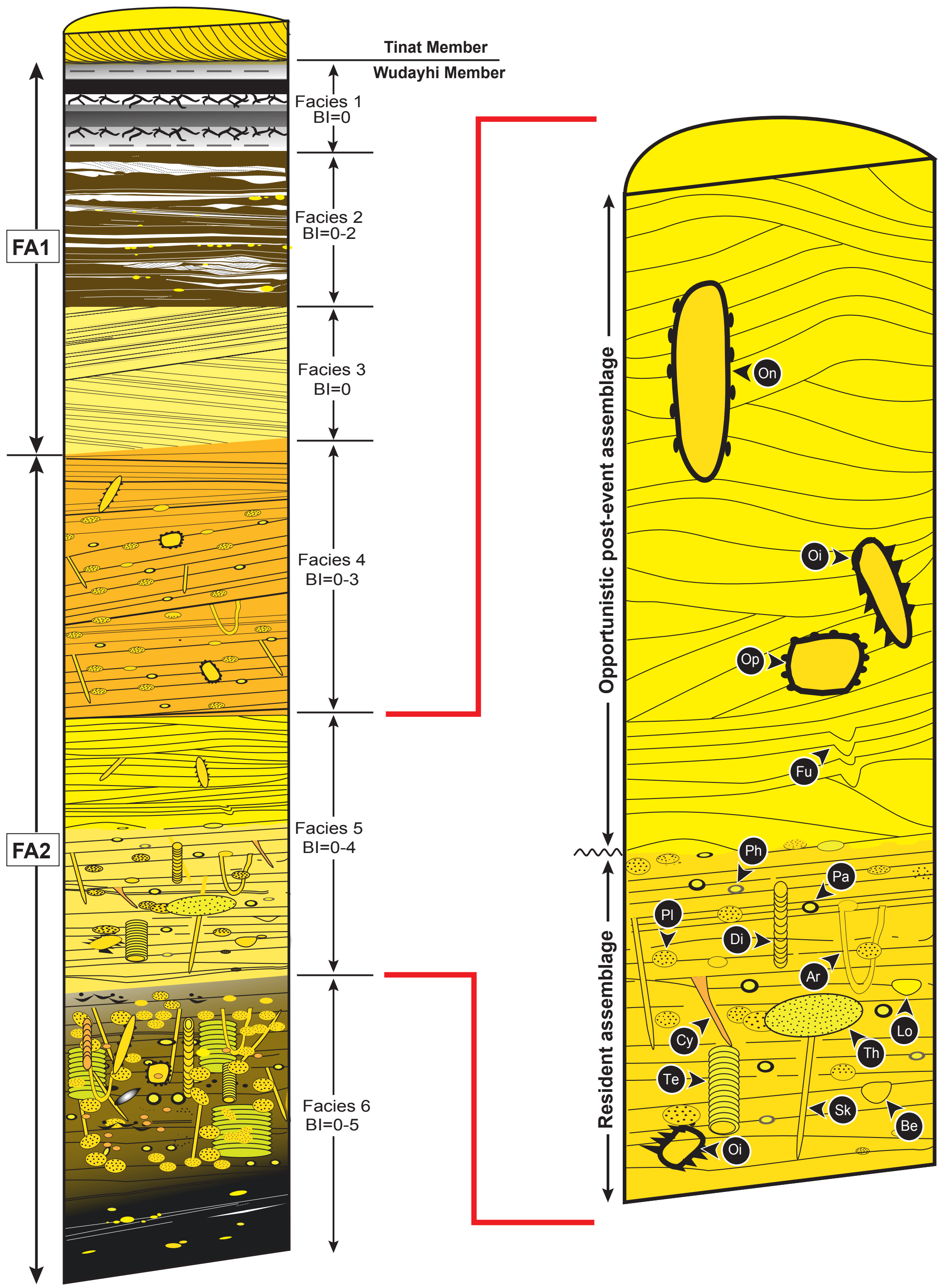


Figure 2.17. Schematic model summarizing the vertical evolution of ichnologic and sedimentologic characteristics for each facies association (FA1 and FA2) of the Wudayhi Member; as well as the co-occurrence of storm-wave-generated structures and tidally generated structures. Core model at the right displays, from base to top, each constituent facies (from proximal offshore upwards into estuarine environments) with its corresponding bounding surfaces, primary sedimentary structures, bioturbation index (BI), and representative ichnotaxa. Note the overall upwards decrease in BI, diversity of ichnotaxa, and density of burrowing. Core model at the right exhibits an expanded version of event-bed deposition in Facies 5 by illustrating its resident ichnofossil assemblage and the opportunistic, post-event suite, thereby showing the alternation between storm-related and fair-weather ichnocoenoses.

trophic generalists, and 6) an overall abundance of small forms largely attributed to morphological adaptations to physiological stress (i.e., enforced diminution); and body-size requirements (facultative diminution) to move solutes in low- and fluctuating-salinity environments (Pemberton et al., 1982; Pemberton and Wightman 1992; MacEachern and Pemberton 1994; Mangano et al., 2002; Gingras et al., 2011). Deposits of FA1 are particularly well preserved in the northeast (wells 8 and 2) and west (wells 1, 10 and 11) of the study area, where it can make up almost the entirety of the preserved Wudayhi strata (Figs. 2.19, 2.20). Estuarine settings, with abundant synaeresis cracks in Facies 2 are indicative of riverine input from western and northwestern areas and suggest marginal-marine conditions with brackish-water characteristics as the result of fresh water mixing with saline water (Fig. 2.21). The presence of estuarine deposits in both Wells 1 and 2 (Figs. 5-7) in the western and eastern of the study area, respectively (Fig. 2.1) and separated more than 200 km indicates regionally persistent marginal-marine estuarine conditions with multiple sources of fresh water draining into the southeast in the Arabian Peninsula (Fig. 2.21). Coal deposits and carbonaceous mudstones also found in these two wells suggest regionally widespread rather than localized occurrences of plants able to develop into coal beds of meter scale, such as the ones found in Facies 1 (Fig. 2.5). More importantly, the presence of a brackish-water ichnological assemblage along with abundant flora accumulated in peats and swamps and the overall evidence of estuarine sedimentation (FA1) suggest warmer climatic conditions after the Late Carboniferous to Early Permian glaciation at the time of Wudayhi deposition (Melvin et al., 2010b).

The record of a warmer climate can be depicted in palynological assemblages from several subsurface core samples, where *in situ* (i.e., not reworked) palynomorphs were recovered such as Wells 1 and 2 in this paper (see palynological charts as Appendix 1 and 2, respectively). Wells 1 and 2 in this study display palynomorph assemblages that are sparse to very rich and generally dominated by pollen, with locally abundant spores, rare acritarchs, and algae. Pollen include *Barakarites rotatus*, *Complexisporites polymorphus*, *Caheniasaccites ovatus*, *Circumstriatites talchirensis*, *Limitisporites rectus*, *Marsupipollenites scutatus*, *M. striatus*, *Plicatipollenites malabarensis*, *Vittatina costabilis*, *V. saccata*, and *V. subsaccata*. This assemblage corresponds to the P3B Palynosubzone of Saudi Aramco and is Early Permian (late Sakmarian-early Artinskian) in age (Fig. 2.4). This recurrent palynological assemblage characterizes the Wudayhi Member of the Nuayyim Formation in the subsurface of central Saudi Arabia. Assemblages recovered from

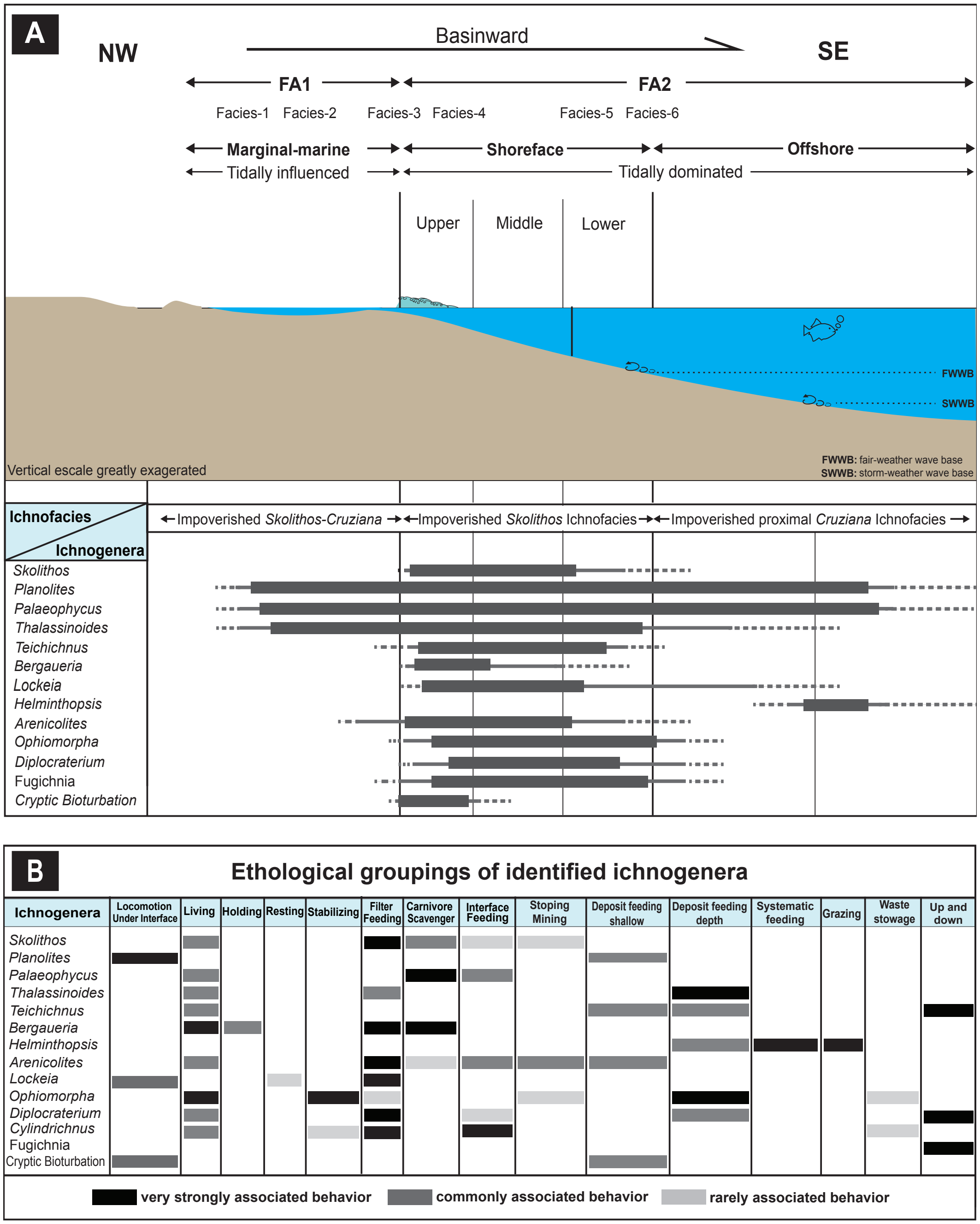


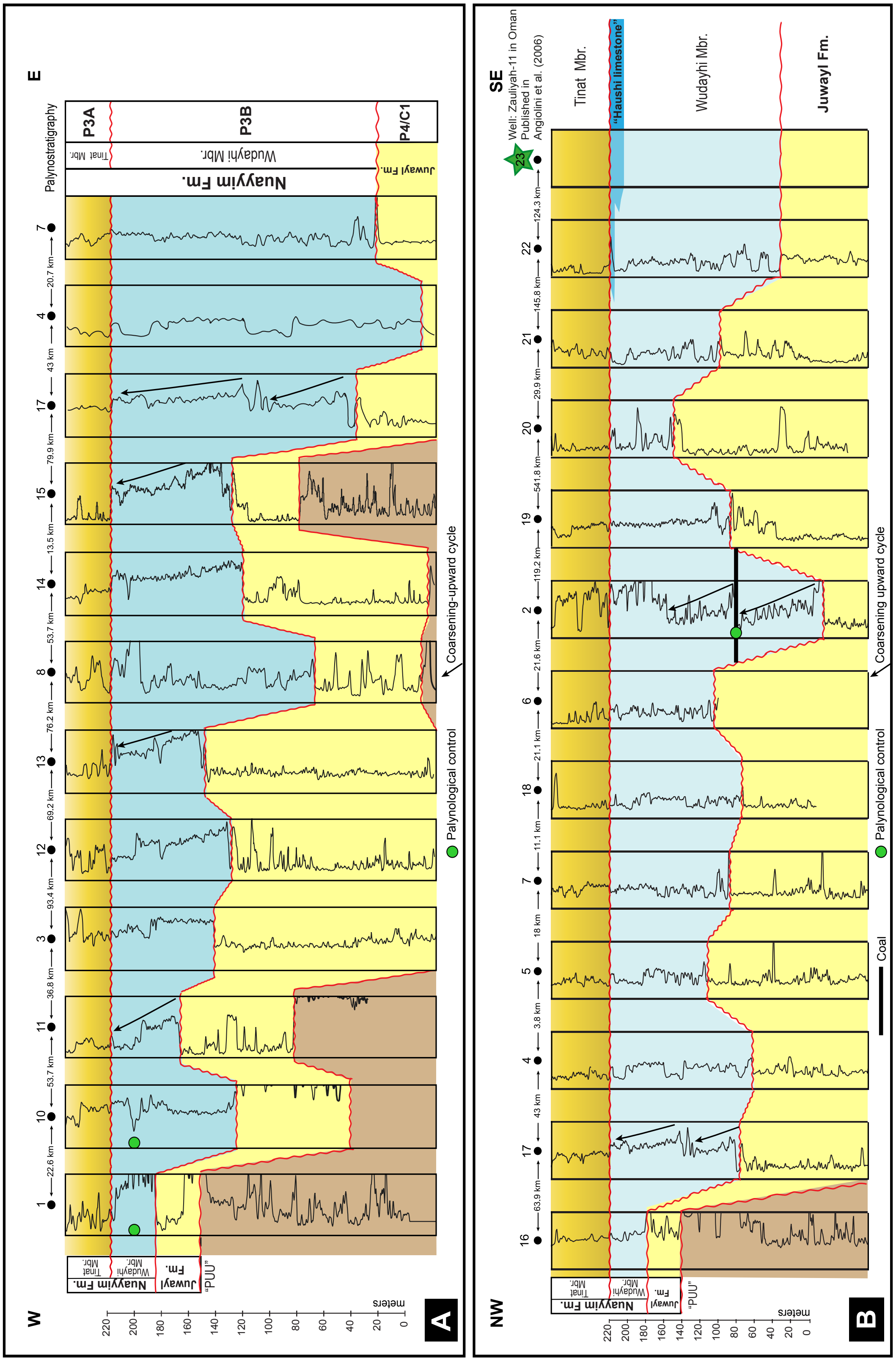
Figure 2.18. Schematic distribution of ichnotaxa identified in the Wudayhi Member of the Nuayyim Formation along the depositional profile. A) Approximate boundaries of each facies and dominant ichnotaxa are shown above and below the depositional profile, respectively. Trace-fossil diversity and abundance increases towards the southeast, suggestive of increased marine conditions in that direction; albeit still in a depositional setting showing a strong tidal influence. Correspondingly, ichnofossil suites resemble more those of an impoverished mixture of diminutive facies-crossing elements common to both the *Skolithos* Ichnofacies and the *Cruziana* Ichnofacies. B) Ethological groupings of ichnotaxa identified in the Wudayhi Member of the Nuayyim Formation (adapted from Gingras et al. 2007). Permanent and semi permanent dwellings of bioturbating infauna exhibiting filter-feeding behaviors dominate across the shoreface profile. Deposit-feeding ethologies (both, shallow and deep-tier feeding) play a subordinate role, along with interface feeders.

samples derived from coal beds and carbonaceous-rich deposits support estuarine settings in Facies 1 (Figs. 2.5, 2.7, 2.9) from Wells 1 and 2. Palynological suites reflect development of swampy conditions, probably produced by an elevated water table rather than increased precipitation, permitting development of a spatially restricted macroflora of mainly lycopsid spore-bearing shrubs and small trees. In Well 2, the spore assemblages are associated with a rooted coal and sedimentological evidence of marginal-marine deposition (Fig. 2.5), but they still occur in an overall pollen-dominated succession (Appendices 1 and 2), thus indicating persistence of generally arid climatic conditions.

2.5.2 Shallow-Marine, Tide- and Storm-Influenced Facies Association (FA2)

The shallow-marine, tide-, and storm-influenced facies association (FA2) in the Wudayhi Member includes upper-shoreface and proximal- through distal-lower-shoreface deposits. They are reflective of an overall shoaling-upwards, storm-dominated, fluvial- and tide-influenced, progradational sequence that displays tidal modulation locally (cf. Dashtgard et al., 2009; Dashtgard et al., 2012; Vakarelov et al., 2012). The succession displays an overall upward decrease in bioturbation (Fig. 2.17) with impoverished elements attributable to a proximal expression of the *Cruziana* Ichnofacies at the base, corresponding to proximal- and distal-lower-shoreface deposits (Facies 5–6) (Figs. 2.13, 2.15, 2.18). These pass into an impoverished expression of the *Skolithos* Ichnofacies in the upper shoreface (Facies 4) (Fig.2.11). Tidally influenced and heterolithic deposits of estuarine environments from FA1 overlie the succession and display an impoverished mixture of traces common to the *Skolithos* Ichnofacies and *Cruziana* Ichnofacies (Facies 1–3) (Figs. 2.5, 2.7, 2.9, 2.18).

The cross section shown in Figure 2.20 was generated based on the vertical succession of facies identified in the core samples studied in each well. It summarizes the spatial distribution of facies and resulting architecture, based on the process classification proposed by Ainsworth et al., (2011). The logs are colored per relative process dominance assigned to each facies. Where facies change markedly either vertically or laterally, a process boundary was assigned based on the relative influence of tidal, wave, and fluvial processes that acted on the sediments at the time of deposition (Table 2.1; Ainsworth et al., 2011; Vakarelov and Ainsworth 2013). In the Wudayhi example, the vertical succession of facies displays several transgressive-regressive (T-R) cycles, which suggest that sediment deposition took



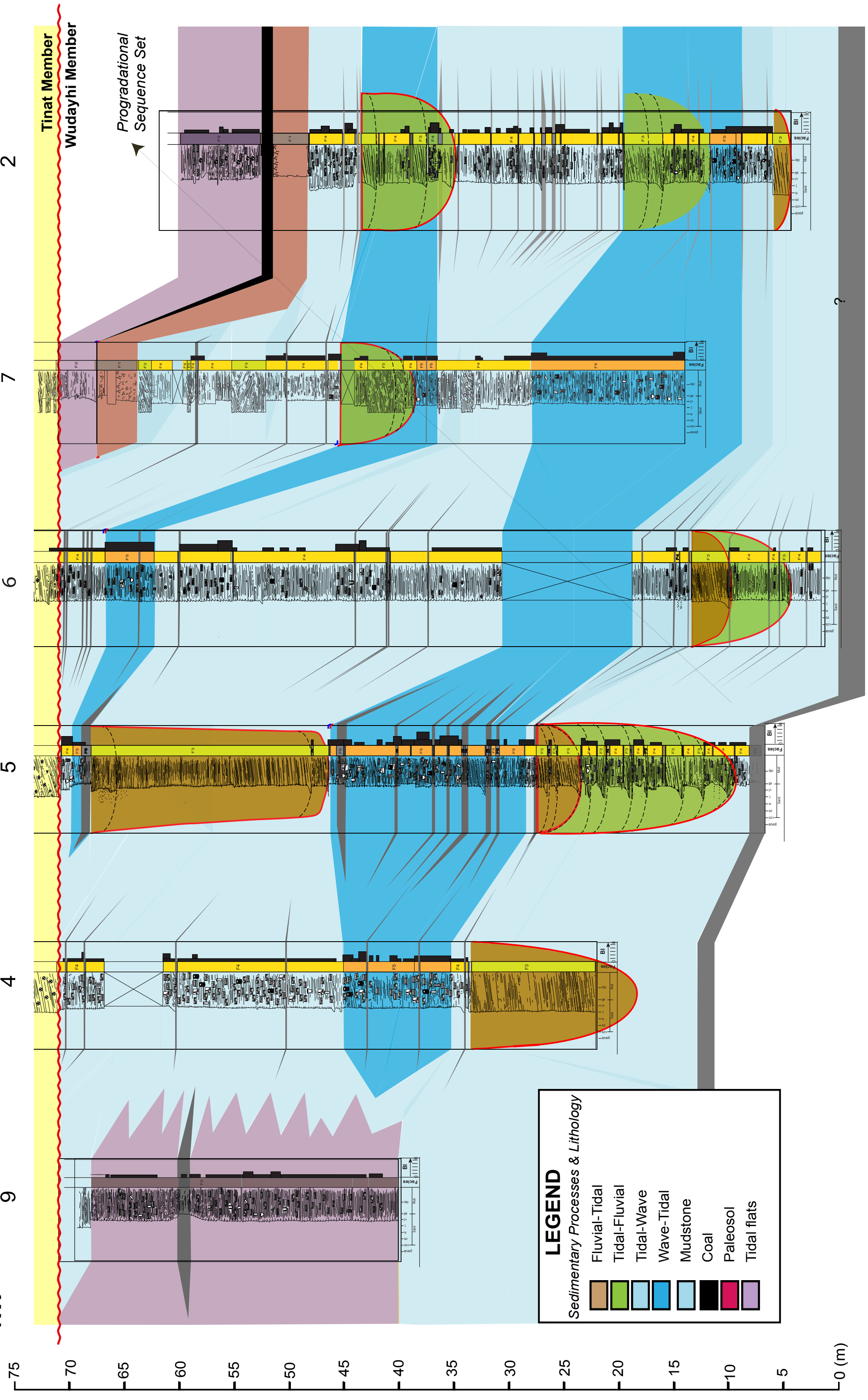
A
W
E
Palynostratigraphy
P3A
P3B
P4/C1
Nuayyim Fm.
Tinat Mbr.
Wudayhi Mbr.
Juwayl Fm.
"PUU"
meters
Palynological control
Coarsening-upward cycle
B
NW
SE
Well: Zauliyah-11 in Oman
Published in
Angiolini et al. (2006)
Tinat Mbr.
"Haushi limestone"
Wudayhi Mbr.
Juwayl Fm.
Coal
Palynological control
Coarsening upward cycle

Figure 2.19. Regional stratigraphic cross-sections of the Wudayhi Member in the study area and correlation to Oman across the Rub'Al-Khali Basin. The orientation of each cross-section and the wells involved are specified in Figure 1. Well numbers are annotated at the top, and the datum used as a reference level is the top of the Wudayhi Member, encountered in a total of 23 wells that compose the dataset for this study. Regional cross-sections were built using gamma-ray (GR) log motifs, observations in core samples, and palynological determinations. GR increases from left to right in all wells. Gamma ray log-profile were used to mark grain-size trends annotated with black arrows (A) Regional W–E cross-section showing the thickening of the Wudayhi Member towards the east. (B) Regional NW–SE cross-section showing the thickening of the Wudayhi Member towards the southeast and its correlation with the "Haushi Limestone" in Oman, by using biostratigraphic data for the Lower Gharif Member of the Gharif Formation published in Angiolini et al. (2006). Note the coal occurrence in Well 2 and the progradational cycles in several wells, marked by a coarsening-

place in mixed-process (wave-, tide-, and fluvial-influenced) environments (Fig. 2.20). Based on the dominance of facies in each well, Figure 2.20 also illustrates the spatial location where a particular process (i.e., fluvial, tides, waves) dominates. Due to the regional scale of the model presented in this study, three main areas with markedly dominant influences on sedimentation are identified and discussed below.

2.5.2.1 Fluvial Influence and T-R Fluvio-Estuarine Channel Fills

Fluvial influence towards the north and northwest of the study area is manifested in an overall paucity of bioturbation and sediment architecture displaying amalgamated, sharp-based sandstone beds with IHS that commonly lack bioturbation (Fig. 2.20). These beds are commonly interstratified with fluid mud such as the ones at the base of Well 5 (see also wells 4 and 5; Figs. 2.8, 2.10). Fluvial and tidal influences on sediment deposition result in amalgamated, alternating bedsets with variable bioturbation in an overall impoverished assemblage (i.e. Facies 3, BI=1-2). Increased tidal influence is manifested in a slight increase of burrowing in adjacent basinward positions along with IHS beds interbedded with tidal flats and fluid muds (Well 5; Fig. 2.10B). This is more evident in the sediments of kilometer-scale wide and meter- to decimeter-scale thick incisions displaying single and multistory fills, such as those observed in wells 4, 5, and 7. These are herein termed "channelized complexes" (Figs. 2.8, 2.10 and 2.12), based on their dimensions and filling architecture (e.g., Ainsworth et al., 2015). These channelized complexes are filled by fluvio-tidal highstand deposits following progradation, downstepping, and large-scale incision (Fig. 2.20). The channel fill is made of meter-scale, multiple stacked bars that show paleocurrents oriented predominantly towards the southeast (Fig. 2.21). These observations suggest that the channelized complexes, such as the one at the base of Well 5 (Fig. 2.20), represent fluvio-estuarine incised valleys that were



NW
SE
9
4
5
6
7
2
~ 59 km
~ 3.8 km
~ 4.9 km
~ 20.5 km
~ 40 km
Tinat Member
Wudayhi Member
Progradational Sequence Set
LEGEND
Sedimentary Processes & Lithology
Fluvial-Tidal
Tidal-Fluvial
Tidal-Wave
Wave-Tidal
Mudstone
Coal
Paleosol
Tidal flats
0 (m)
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

Figure 2.20. NW–SE stratigraphic cross section, using the top of the Wudayhi Member as a datum. The stratigraphic surfaces were delineated correlating the facies identified in each well and defined on the basis of their sedimentological and ichnological characteristics. Well numbers are annotated at the top, and the orientation of each cross section and the wells involved are specified in Figure 1. Several transgressive-regressive (T-R) cycles have been identified in an overall regressive succession, based on the vertical shift of depositional settings and the relative dominance and/or mixing of river-, tide-, and wave influences in the depositional environment (see Ainsworth et al. 2011 for the classification scheme). Progradation and downstepping occurs towards the southeast, and the overall succession reflects deposition in mixed-process (river-, tide-, and wave-influenced) environments. For legend of core symbols, please refer to Figure 2.14.

filled during transgression after downstepping and incision. Several case studies document this process in tidally influenced, falling-stage, progradational shoreline environments (Willis and Gabel 2001, 2003; Olivero et al., 2008; Carmona et al., 2009; Willis and Fitris, 2012; Ainsworth et al., 2011, 2015). In the Wudayhi deposits, this process occurred in more than one cycle, as illustrated in Figure 2.19, as shorelines and tidally influenced settings regressed into the low-gradient shelf (accompanied of erosion and incision) and gradually backstepped. The resulting underlying erosion surface, termed here "lowstand, channelized erosion surfaces" (LCES), commonly incised down to genetically associated distal- lower-shoreface deposits (see Fig. 2.19). This observation, coupled with continuous cross-cutting of tidal and fluvial deposits, also suggests a low-accommodation setting. A seaward shifting of facies from the north is marked by wave action becoming more abundant towards the center and south of the study area (Fig. 2.21). This is manifested in an overall increase in the diversity, size, and specialization of ichnotaxa, accompanied by higher BI values.

2.5.2.2 Wave Action and Storm Influence in the Wudayhi Member

Evidence of wave action is recorded in deposits of Facies 4 through Facies 6, and these deposits display a marked increase towards the southeast (Fig. 2.20). Overall, the facies consist of bioturbated sandy mudstone and horizontally, crinkly, low-angle laminated and parallel-laminated sandstones, with subordinate cross-bedding and intercalations of thin (centimeter-scale) siltstone beds. Evidence of storm-influenced deposition is interpreted from Facies 5 (Fig. 2.13). It includes hummocky cross-stratification, combined-flow ripples, cross-lamination, and a significant change in bioturbation patterns (Figs. 2.13, 2.17). The latter alternate between storm- and fair-weather assemblages (cf. Pemberton and MacEachern 1997; MacEachern et al., 2007b; Buatois et al., 2008) (Fig. 2.17). The distributions of storm beds and post-storm-associated bioturbation are important because they record high-energy oscillatory and combined flows during repeated storms (Harms et al., 1975; Leckie and Walker 1982; Cheel and Leckie 1993; Dumas and Arnott 2006). Thin, storm beds occur sporadically distributed within layers dominated by the aforementioned resident fair-weather assemblage, suggesting long-term stable periods with episodic emplacement of tempestites and connection to the open sea. The fair-weather ichnofossil suite is attributable to the proximal expression of the *Cruziana* Ichnofacies, with intercalated storm-related suites attributable to opportunistic expressions of the *Skolithos* Ichnofacies (Fig. 2.17). These event beds occur mainly in wells towards the center and southeast of the study area and are particularly well developed in Well 5 (Fig. 2.10).

Preservation of abundant storm deposits in Facies 5 (Fig. 2.13) suggests repeated storm-wave action that obliterated the background fair-weather suite, resulting in sparsely bioturbated, *Ophiomorpha*-dominated, opportunistic, post-event assemblages in the proximal-lower-shoreface, as documented by MacEachern and Pemberton (1992), Pemberton et al., (1992), Pemberton and MacEachern (1997), Buatois et al., (2008), and Baniak et al., (2014). MacEachern and Pemberton (1992) erected a classification scheme for storm-influenced shoreface settings, taking into account their ichnological and sedimentological character such as intensity and frequency of storms from temporally and spatially recurrent ichnofossil suites associated with tempestites. This resulting scheme described intense, moderate, and weak storm influences of lower- and middle-shoreface settings. Intense-energy shorefaces tend to exhibit erosionally amalgamated storm beds with minimal bioturbation, intermediate-energy shorefaces consist of a series of laminated and burrowed horizons, and low-energy (sheltered) shorefaces are intensely bioturbated with a diverse series of ichnofauna and minimal preservation of storm beds (MacEachern and Pemberton 1992; Pemberton et al., 2001; MacEachern and Bann 2008; Dashtgard et al., 2012). Thin occurrences (Fig. 2.10) and overall sparse bioturbation (BI 1) in Facies 4 storm beds with laminated and burrowed horizons (Fig. 2.13) are interpreted in the Wudayhi Member to reflect shoreface profiles that are moderately influenced by storms (Fig. 2.20).

2.5.2.3 Tidal Modulation in Wudayhi Member Strata

Sediments that exhibit tidal modulation in the examined core material are concentrated in the center of the study area (Fig. 2.21) and are best exhibited in Wells 5 and 8 (Figs. 2.10, 2.16). Wudayhi strata display: 1) an overall reduction in both the diversity of ichnotaxa and density of burrowing across the shoreface profile

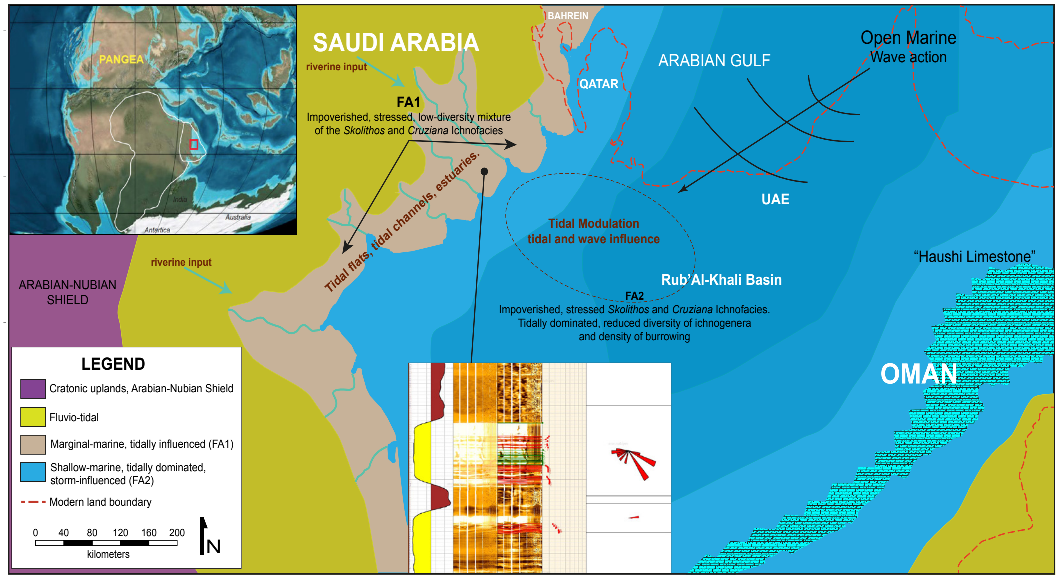


Figure 2.21. Proposed schematic regional depositional model during the Early Permian (late Sakmarian to early Artinskian) in the southern portion of the Arabian Peninsula, showing the most prominent characteristics of the ichnological assemblages of FA1 and FA2. Episodic emplacement of tempestites in Facies 5 as well as the subordinate presence of more normal marine trace fossils in Facies 6 suggest connection to high-energy, open marine processes (e.g., storm and waves) and short periods of ambient marine conditions subject to tidal modulation at the center and southeast of the study area. Top left inset shows the approximate projection of the study area (red square) on the paleogeographic reconstruction of the Middle to Late Permian (inset is adapted from Blakey 2011). Lower center shows rose diagram from interpreted image log at the base of Well 5, showing preferential paleocurrent flow towards the southeast, with dispersion suggesting meandering conditions, interpreted as fluvio-tidal channels.

from the distal-lower-shoreface deposits (Facies 6; BI 0–5) to upper shoreface deposits (Facies 4; BI 0–3) and; 2) an apparent lack of middle-shoreface deposits with intermixing of upper-shoreface (Facies 4) and proximal lower-shoreface (Facies 5) sediments (Fig. 17). Dashtgard et al., (2009) and Dashtgard et al., (2012) have documented similar effects on the shoreface and have associated them with settings that experience macrotidal (4–8 meters) and megatidal (8–12 meters) regimes resulting from tidal modulation. Therein, tidally influenced deposits and shoreface successions coexist and constitute a continuum along the depositional profile (cf. Vakarelov et al., 2012). In the Wudayhi case, shoreface deposits appear to be devoid of the middle-shoreface member in an idealized depositional profile (see Plint, 2010). This fact can be largely attributed to a macrotidal regime able to mobilize sediment and then spread out that middle-shoreface signature across the shoreface profile onto upper-shoreface (Facies 4) and lower-shoreface (Facies 5–6) sub-environments. Consequently, the sedimentological and ichnological criteria commonly employed to identify middle-shoreface deposits, mainly 1) swaly cross-stratification, and 2) the predominance of suites attributable to the *Skolithos*

Ichnofacies (in the landward direction) (e.g., MacEachern and Pemberton 1992; Saunders et al., 1994; MacEachern et al., 1999b; Dashtgard et al., 2009), at the time of sediment deposition may be obscured by the tidal regime, making recognition of middle-shoreface deposits challenging in Wudayhi strata (cf. Dashtgard et al., 2009; Dashtgard et al., 2012). A recurrent tidal imprint responsible for a lower ichnodiversity in the shoreface deposits of Facies 4 through Facies 6 (Fig. 2.18) suggests that wave influence may have been displaced along the depositional profile from middle- to lower-shoreface deposits (displaying wavy lamination, combined-flow ripples, HCS, and SCS) to laminated upper-shoreface deposits (exhibiting planar-tabular and trough cross-stratification). Additionally, the existence of unburrowed, meter-scale subtidal dunes with well-developed inclined heterolithic stratification (IHS) interbedded with bioturbated, wave-generated structures across the shoreface (Figs. 2.11, 2.13, 2.15) suggest tidally influenced sediment mobilization and deposition in water depths equivalent to the upper, middle, and lower shoreface that were subjected to variable wave processes. A good illustration of this phenomenon is seen in Wells 5 and 8 (Figs. 2.10, 2.16) towards the central and eastern portion of the study area. Therein, evidence of tidal processes is given in the forms of unbioturbated subtidal sand bars with well-developed (IHS) that can reach up to 7 meters thick and that are interbedded with burrowed sediments of Facies 4 and Facies 5 (Figs. 2.10, 2.16). This indicates that wave and tidal processes responsible for sediment mobilization were operative during the tidal cycle in positions equivalent to the upper and lower shoreface, providing evidence for tidal modulation at the time of deposition (Figs. 2.17, 2.21) (sensu Dashtgard et al., 2009; Dashtgard et al., 2012; Vakarelov et al., 2012).

2.5.3 Paleogeographic Implications

Due to the scale of this study, a basic assumption for applying these aforementioned influences on sedimentation are that the subsurface core samples studied are representative of the study area. Thus, the relatively small amounts of core data inevitably lead to a level of uncertainty in the interpretations derived from our dataset. Mixed-influence settings are very complex and spatially variable (Ainsworth et al., 2011), and so larger numbers of closely spaced wells are required to confirm the relative importance of the depositional processes. Variability in depositional environments is expected along depositional dip and strike due to the well spacing (tens to hundreds of kilometers; Figs. 2.1, 2.20). Based on the examined core samples, the Wudayhi Member in the subsurface of central and eastern Saudi Arabia was deposited on a broad and sandy, partially restricted shelf under the dominant influence of tidal currents with subordinate fluvial and wave influence (Fig. 2.21). Sediment accumulation was the product of several T-R cycles, as shorelines and tidally influenced settings first prograded into the basin, and then gradually backstepped, creating mixed-process depositional settings and regional erosional surfaces. As a whole, from base to top, vertical stacking of facies and trace-fossil distributions in (FA1) and (FA2) show affinities with an idealized wave-dominated, storm-influenced strandplain succession (cf. MacEachern et al., 2007a; MacEachern et al., 2010; Plint 2010) (Fig. 2.17). An idealized wave-dominated, storm-influenced strandplain shoreface succession displays (from base to top), an overall decrease in bioturbation intensity and abundance, and upward succession of trace-fossil suites attributable to: 1) the distal expression of the Cruziana Ichnofacies (lower offshore); 2) the archetypal *Cruziana* Ichnofacies associated with storm-related suites characteristic of the *Skolithos* Ichnofacies (upper offshore), and 3) proximal expression of the *Cruziana* Ichnofacies to archetypal *Skolithos* Ichnofacies (lower-middle to upper shoreface) (Buatois et al., 2008; MacEachern and Bann 2008; MacEachern et al., 2010). However, the Wudayhi strata depart from this idealized scenario due to: 1) persistent brackish-water conditions expressed in a stressed, low-diversity diminutive ichnofossil assemblage; and 2) a strong tidal overprint that resulted in tidal modulation across the shoreface (cf. Dashtgard et al., 2009; Dashtgard et al., 2012; Vakarelov et al., 2012). The latter imposes further stressful conditions on endobenthic communities, which results in impoverished assemblages when compared to their archetypal counterparts (cf. MacEachern et al., 2007b; Dashtgard et al., 2012; Dashtgard et al., 2015). Persistent brackish-water conditions are largely attributable to the paleogeography of the basin (Fig. 2.21). Estuarine deposits and ichnofossils recorded in FA1 suggest riverine, fresh-water input from the northern and northwestern parts of the Arabian Peninsula (Fig. 2.21). Tidal modulation (cf. Dashtgard et al., 2009) and a trace-fossil assemblage with affinities to brackish-water settings and with abundant *Teichichnus* characteristic of FA2 are consistent with deposition in a semi-restricted embayment (MacEachern and Gingras 2007) (Fig. 2.21). Punctuated occurrence of storm deposits is concentrated towards the center and southeast of the study area (Fig. 2.21). Although storm deposits in Facies 5 (Fig. 2.13) are thin and sporadically distributed, as seen in Well 5 (Fig. 2.10), they provide evidence that suggests communication with high-energy, open-marine waves (Figs. 2.21) and the presence of burrowing organisms reflecting periods of more normal marine conditions and behavioral specialization, This is manifest in Facies 5 and 6 (Figs 2.13, 2.15, 2.18), which displays moderately abundant *Helminthopsis*. The recognition of these recurrent sedimentological and ichnological characteristics is important, as they constitute predictable stratigraphic and spatial distributions that may assist in correlating fully marine and brackish-marine strata across central and eastern Saudi Arabia in sediments associated with late Paleozoic postglacial transgressions that affected southern Gondwana.

Several authors have studied the influence of glacial meltwater on endobenthic fauna in deposits associated with late Paleozoic postglacial transgressions in Gondwana (e.g., Buatois et al., 2010, Desjardins et al., 2010, López-Gamundí 2010; López-Gamundí and Buatois 2010). However, we attribute brackish-water characteristics to fluvial processes that may or may not be glacially influenced, and in fact are likely to be post-glacial, Importantly, the Wudayhi Member overlies the Jawb Member and represents a younger age (Fig. 2.2) (late Sakmarian-early Artinskian). It lacks sedimentological features indicative of glacial deposition and displays a trace-fossil assemblage dominated by elements of a stressed, impoverished expression of the *Skolithos* Ichnofacies and the *Cruziana* Ichnofacies. These suites locally display subordinate ichnological forms that are more commonly found in the marine realm presented herein in FA1 and FA2. These observations confirm that sedimentation in the Wudayhi Member took place in a postglacial climatic phase in the Arabian Peninsula, as has also been documented in several basins in southern Gondwana by Iannuzzi et al. (2010), Buatois et al. (2010), and López-Gamundí and Buatois (2010). Furthermore, Iannuzzi et al. (2010) reports the persistence of the *V. Costabiliz* Palynozone of late Sakmarian-early Artinskian in age from the postglacial Rio Bonito Formation of the southern Brazilian Parana Basin. Therein, the *V. Costabiliz* Palynozone is dominated by pollen-rich assemblages characterized by "bilaterally and radially symmetrical monosaccate pollen grains" (Iannuzzi et al., 2010, p. 117) such as *Cannanoropollis*, *Plicatipollinites*, *Caheniasaccites*, and *Potonieisporites*. Polyplicate species of the genus *Vittatina* (*V. saccata*, *V. subsaccata*, *V. costabiliz*, *V. vittifera*) as well as species of *Protohaploxypinus* (*P. goraiensis*, *P. limpidus*), with spores are also common in the *V. Costabiliz* Palynozone and are even locally dominant in the coal beds (Iannuzzi et al., 2010, Figure 2.10). This *V. Costabiliz* Palynozone of Iannuzzi et al. (2010) reported from the Rio Bonito Formation bears a marked resemblance to the P3B Palynosubzone that characterizes the Wudayhi Member on the Nuayyim Formation in the subsurface of central and eastern Saudi Arabia, in that 1) both are late Sakmarian-early Artinskian in age, although, Cagliari et al., (2014, 2016) repositioned this unit in the Asselian to Sakmarian ages 2) they share roughly the same taxa (Fig. 2.4) and 3) they occur in shallow-marine shoreface, tidal-flat sandstones and shales that locally exhibit interbedded coal seams (see Iannuzzi et al., 2010, their Figure 2) and central bay deposits based on ichnological content and facies associations. This strongly suggests postglacial amelioration of climate, towards more temperate conditions in the Parana Basin of southern Gondwana as well as the Arabian Plate (Fig. 2.22). Following melting of glacial ice, marine incursions occurred with subsequent colonization by bioturbating fauna, as encountered in FA1 and FA2 of the Wudayhi Member of the Nuayyim Formation. Regionally, coeval fully marine strata are present south into Oman at the base of the Saiwan Formation (Dubreuilh et al., 1992), informally known as the "Haushi Limestone" (Figs. 2.19B, 2.21). In its original designation, the Saiwan Formation corresponds to the Lower Gharif Formation of Hughes-Clarke (1988) and was introduced by Dubreuilh et al. (1992), for the fossiliferous marine beds

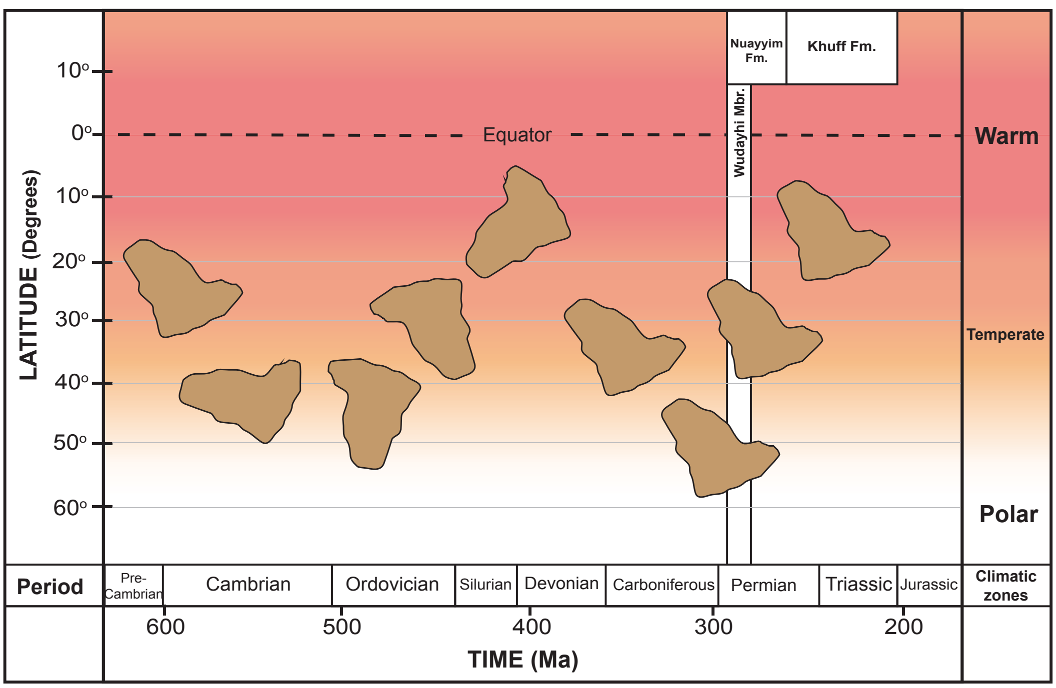


Figure 2.22. Evolution of the orientation and paleolatitudinal positions of the Arabian Plate during the Paleozoic, indicating the climatic setting and timing of the onset of the Nuayyim Formation deposition including the Wudayhi Member (adapted after Konert et al. 2001). The Arabian Plate reached its southernmost position during the Paleozoic (reaching approx. 55o S latitude) in Late Ordovician to Carboniferous-Permian times. As suggested by Konert et al. (2001), this is coincident with two periods of glaciation affecting the western and southern margins of the Arabian Plate. More importantly, during the same time interval (Ordovician to Carboniferous), the Arabian Plate rotated dramatically up to 90° accompanied by latitudinal drift. Deposition of the Wudayhi Member took place after the southernmost position was reached, followed by northwards migration to a more temperate zone, causing regional transgression during the late Sakmarian-early Artinskian.

(*Metalegoceras* and *Bellerophon* Limestones of Hudson and Sudbury 1959) as well as for the occurrence of a regional unconformity at its top, which separates it from the overlying continental middle Gharif Formation (Angiolini et al., 2003) (Fig. 2.2). According to Roger et al. (1992) the Saiwan Formation conformably overlies the Rahab shale and starts with a marine bioclastic sandstone. The latter evidence of marine sedimentation in coeval deposits in Oman reconciles with marginal-marine and shallow-marine sedimentation of age-equivalent deposits in the subsurface of central Saudi Arabia, as described in this paper and previously suggested by Melvin and Sprague (2006). Recent paleogeographic reconstructions (e.g., Blakey, 2011) show marginal-marine to shallow-marine conditions that extended into areas of present-day southern Saudi Arabia and the southern parts of the Arabian Peninsula into Oman (Figs. 2.19B, 2.21).

2.6 CONCLUSIONS

1) This study provides evidence for marine sedimentation in the Unayzah Group in central and eastern Saudi Arabia. Integration of ichnological and sedimentological observations in the Nuayyim Formation allowed the identification of a marginal-marine, tidally influenced facies association and a shallow-marine, wave- and storm-dominated sedimentation with subordinate tidal and fluvial influence in the Wudayhi Member. Sediment deposition took place on a broad and sandy, partially restricted shelf under the dominance of wave and storm energy and influenced by tidal and fluvial processes characterized by several depositional environments reflecting mixed processes (Figs. 2.18, 2.21).

2) Tidally influenced marginal-marine, and shallow-marine tidally dominated, storm-influenced deposits that characterize the Wudayhi Member of the Nuayyim Formation in the study area (FA1 and FA2, respectively) reflect a regressive, mixed-process (wave-, tide-, and fluvial-influenced) progradational succession that exhibits tidal modulation locally (cf. Dashtgard et al., 2009; Dashtgard et al., 2012) (Fig. 2.21). Marine evidence is given by ichnological assessments in the form of an impoverished suite attributable to a proximal expression of the *Skolithos* Ichnofacies through to a proximal expression of the *Cruziana* Ichnofacies (FA2). This is augmented by primary sedimentary structures that are suggestive of marginal-marine, tidally influenced sedimentation (e.g., flaser bedding, double mud drapes, and synaeresis cracks) (FA1). FA2 also exhibits storm-influenced laminated-to-burrowed deposits displaying hummocky cross-stratification and bioturbation patterns alternating between fair-weather resident assemblages and

post-storm opportunistic assemblages (Facies 5).

3) Wudayhi strata reflect an upwards decrease in bioturbation intensity and trace-fossil abundance from distal to proximal settings, and are represented in the deposits of FA1 and FA2 (Fig. 2.17). The succession displays an overall upward decrease in bioturbation with elements of the *Cruziana* Ichnofacies at the base in proximal- and distal-lower-shoreface deposits (Facies 5-6), passing into suites of the Skolithos Ichnofacies in upper-shoreface deposits (Facies 2.4). Tidally influenced and heterolithic facies of estuarine environments overlie this succession, and display an impoverished mixture of traces, with elements common to both the *Skolithos* Ichnofacies and the *Cruziana* Ichnofacies. This reflects an ichnological suite characteristic of brackish-water, estuarine settings (Facies 1–3).

4) The upward passage from FA2 to FA1 reflects a progressive increase in nearshore fluvial and tidal activity that influenced oxygenation levels, sand content, suspended sediment, and substrate consistency (Fig. 2.17). These paleoecological factors controlled the distribution of trace fossils and is reflected in the vertical stacking of ichnofacies (Figs. 2.17, 2.20). Wave action is better exemplified by storm-influenced deposits in Facies 5, with two distinctive trace-fossil assemblages that reflect the behavioral response of the benthic fauna under contrasting environmental conditions (Figs. 2.13, 2.17). The resident fair-weather trace-fossil suite records a benthic community developed under stable and rather predictable conditions, and reflects an impoverished, stressed expression of the *Cruziana* Ichnofacies. By contrast, storm-related trace-fossil assemblage records opportunistic colonization following storm deposition, and consist of elements typical of an impoverished expression of the *Skolithos* Ichnofacies (MacEachern and Pemberton 1992) (Fig. 2.17). In the Wudayhi example, the occurrence and overall sparse bioturbation (BI 1) in Facies 4 storm beds with laminated and burrowed horizons (Figs. 2.13, 2.17) reflect moderately storm-influenced shoreface profiles (cf. MacEachern and Pemberton 1992; Dashtgard et al., 2012).

5) Tidal modulation of the shoreface suggests that wave influence may have been displaced along the depositional profile, resulting in: 1) an overall reduction in both the diversity of ichnotaxa and the density of burrowing across the shoreface (Fig. 2.17); 2) the apparent lack of middle-shoreface deposits, suggesting that macrotidal (4-8 m) conditions were operative at the time of sedimentation; and 3) the occurrence of stormwave-generated structures interspersed with tidally generated structures across some areas of the shoreface profile, similar to predictive models put forth by Dashtgard et al. (2009) and Dashtgard et al. (2012).

6) Marginal-marine and shallow-marine, tidally influenced sedimentation in the Wudayhi Member coincides with a change in palynofloras from the Juwayl to the Nuayyim Formation as the Arabian Plate migrated northwards, likely accompanied by isostatic rebound following the initial stages of deglaciation in the Early Permian (Fig. 2.22). The postglacial palynofloras, assigned to the P3B Palynosubzone (Wudayhi Member), occur in Wells 1 and 2 and point towards significant climatic change causing marine incursions in the Arabian Peninsula before and during mid-to-late Sakmarian times. Climatic amelioration occurred as a consequence of melting of glacier ice following the Late Carboniferous to Early Permian glaciation that affected southern Gondwana. Trace-fossil assemblages reflecting a low-diversity, facies-crossing, impoverished expression of the *Skolithos* Ichnofacies and the *Cruziana* Ichnofacies that only locally display subordinate fully marine ichnotaxa (Fig. 2.21) suggest that sedimentation in the Wudayhi Member took place in a postglacial climatic phase. This likely corresponded to the termination of the Gondwanan Ice Age, which resulted in regional transgression in central and eastern Saudi Arabia. Palynofloras in Wells 1 and 2 are also indicative of a progression from cool, moist climatic conditions during deglaciation and the deposition of the Jawb Member of the Juwayl Formation (P4 Palynozone of Saudi Aramco) towards increasingly dry conditions in the postglacial period starting with deposition of the Wudayhi Member (P3 Palynozone of Saudi Aramco).

7) Trace fossils and ichnofacies documented in this paper are significant because they refine existing interpretations of the paleoenvironmental history in the study area and provide evidence for marginal-marine, tide- and wave-influenced processes in Saudi Arabia during the Early Permian (late Sakmarian-early Artinskian) (Fig. 2.22). Furthermore, the model presented in this paper shows affinities with previously proposed regional models showing fluvial sedimentation in western areas of Saudi Arabia passing into brackish-water, marginal-marine settings in central and eastern Saudi Arabia into fully marine coeval deposits south of the Arabian Peninsula into Oman (Figs. 2.19B, 2.21).

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CHAPTER 3– ICHNOLOGY AND SEDIMENTOLOGY OF AEOLIAN AND SHALLOW-MARINE INTERACTIONS IN THE PERMIAN UNAYZAH GROUP OF CENTRAL SAUDI ARABIA: TOWARDS A MECHANISM FOR INFAUNAL COLONIZATION OF COASTAL DUNE FIELDS AND ERG MARGINS*

3.1 INTRODUCTION

The sedimentary record of most modern aeolian systems remains largely unknown and relatively few studies document the interactions between aeolian, marginal-marine and shallow-marine environments in the rock record (e.g. Brookfield, 1977; Blakey and Middleton, 1983; Dott et al., 1986; Fryberger, 1990a,b,c; Fryberger et al., 1990; Lancaster, 1993; Simpson and Eriksson, 1993; Blakey et al., 1996; Jordan and Mountney, 2010; Jordan and Mountney, 2012; Rodríguez-López et al., 2006; Rodríguez-López et al., 2008, 2012; Wakefield and Mountney, 2013). Even more elusive are any references to trace fossil assemblages in deposits resulting from the interaction among these depositional systems. The vast majority of studies dealing with ichnofossils in aeolian environments are related to the dune and interdune settings in the context of the *Mermia* Ichnofacies (Buatois and Mángano, 1995) or the *Scoyenia* Ichnofacies (Seilacher, 1967a,b) in terrestrial depositional subenvironments that include lake and fluvial channel margins and overbanks, progressively desiccated crevasse splays, and wet interdune areas (e.g. Seilacher 1967a,b; Chamberlain, 1975; Ahlbrandt et al., 1978; Ekdale et al., 1984; Frey et al., 1984; D'Alessandro et al., 1987; Frey and Pemberton, 1987; Gray, 1988; Pollard, 1988; Maples and Archer, 1989; Bromley and Asgaard, 1991; Smith, 1993a,b; Buatois and Mángano, 1995, 2004; Buatois et al., 2002; Hasiotis, 2004). The main tracemakers are inferred to be wasps, beetles, flies, ants, crickets, termites, arachnids, molluscs, dinosaurs, toads and rodents (Ahlbrandt et al., 1978; Loope, 2006, 2008). Preservation of these structures is favoured by increased moisture, sediment cohesiveness, rapid burial or organic reinforcement such as secretion of binding organic mucus (Hasiotis, 2002, 2007; Kraus and Hasiotis, 2006; Mancuso et al., 2016). Therein, the record of animal-sediment interactions is dominated by

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tracks and trails recording surface locomotion structures with subordinate presence of invertebrate trace fossils and subsurface invertebrate activity (Hasiotis, 2002; Ekdale et al., 2007; Ekdale and Bromley, 2012). Organisms inhabiting the dune and interdune environment, such as insects and hemipterans, have been well documented and constitute in most cases diagnostic criteria to identify these subenvironments (e.g. McKee, 1934, 1944, 1947; Hanley et al., 1971; Piccard, 1977; Stokes, 1978; Ekdale and Picard, 1985; Hasiotis, 2002; Hasiotis and Bown, 1992; Hasiotis and Dubiel, 1994; Mancuso et al., 2016). More recently, Krapovickas et al. (2016) provided a succinct review of the ichnology, colonization trends and ichnofacies models of aeolian settings including aeolian dunes, interdunes, sand sheets, wet interdunes, playa lakes, lake margins and overbanks. Through systematic analysis of the ichnological record of desert environments, these authors proposed a model that involves five main phases of colonization of deserts through time, starting from the early Palaeozoic and continuing to the establishment of modern desert communities (Krapovickas et al. 2016). In spite of these efforts, the characterization of ichnofossil suites in deposits reflecting marginal-marine and aeolian interactions has received less attention and remains relatively poorly documented compared to its continental counterpart (Krapovickas et al. 2016).

Historically, sedimentation in the Tinat Member of the Nuayyim Formation in the subsurface of central and eastern Saudi Arabia (Fig. 3.1) has been ascribed chiefly to continental settings dominated by aeolian processes (Senalp and Al-Duaiji, 1995; Melvin and Heine, 2004; Melvin et al., 2005; Melvin et al., 2010a,b; Al-Masrahy, 2011). Despite several attempts to understand temporal and spatial relationships in this unit, including sedimentologic and biostratigraphic studies (e.g. Al-Laboun, 1982, 1986, 1987; Ferguson and Chambers, 1991; McGillivray and Husseini, 1992; Senalp and Al-Duaiji, 1995; Evans et al., 1997; Al-Hajri and Owens, 2000; Melvin and Heine, 2004; Melvin et al.,, 2005; Price et al., 2008; Melvin et al., 2010a,b; Al-Masrahy, 2011; Polo et al., 2018), vertical facies successions and depositional environments of its constituent members remain a matter of active interest. This study documents aeolian and shallow-marine, tidally influenced interactions based on subsurface core observations from the Tinat Member in subsurface Saudi Arabia (Figs. 3.1 and 3.2), thereby confirming the influence of marine processes operating at the time of sediment deposition in an overall continental succession (Fig. 3.3). The study: (i) describes the sedimentological and architectural relationships of the resulting deposits of these marine incursions; (ii) describes the resulting trace fossil suites; (iii) presents the Tinat Member of the Nuayyim Formation as an erg margin dune field by providing a modern analogue to contribute to the understanding of coeval aeolian, marginal-marine and shallow-marine, tidally influenced interactions; and (iv) proposes a mechanism for the colonization of bioturbating infauna in marginal-marine settings where aeolian and shallow-marine processes interact that can be used for similar successions elsewhere in the rock record.

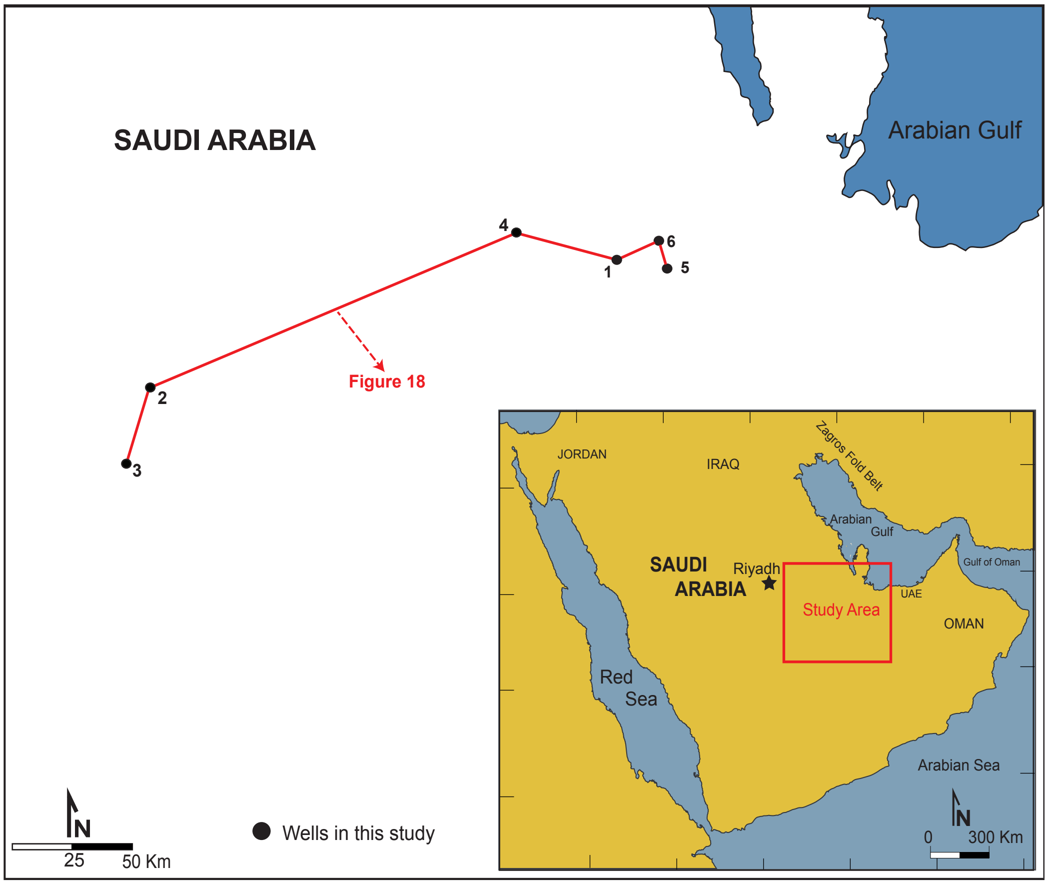


Figure 3.1. Location map showing within the Arabian Peninsula the location of the wells involved in this study.

3.1.1 Background

The understanding of the sedimentological record of inland aeolian depositional environments is comparatively more advanced than those environments where shallow-marine and aeolian processes interact (Rodríguez-López et al., 2012). A relatively small research body documents the coexistence of mixed-process (wave-, tide- and river-influenced) sedimentary environments with ancient desert systems in the rock record. Dott et al. (1986) described the aeolian to marine transition in Cambro-Ordovician cratonic sheet sandstones of the northern Mississippi Valley, USA. By studying facies patterns in the Cambrian

Wonewoc and Ordovician St. Peter sandstones, their study documented aeolian, fluvial and shallow-marine interactions. They found an overall absence of trace and body fossils from inferred nonmarine deposits, whereas burrowed and trough cross-stratified facies characterized by medium-scale cross-bedding alternating with bioturbated intervals and rare brachiopod or trilobite-mould coquinas were interpreted as shallow-marine. Similarly, Fryberger et al. (1990) documented a tidally flooded back-barrier dunefield from a modern setting in the Guerrero Negro area, Baja California, Mexico. The authors demonstrated that overall landward progradation of the dune system from the barrier has occurred during relative rise in sea-level. Consequently, aeolian sediments exist at or below the water table over a wide area. The progradation of dunes across marshes, tidal flats, and tidal channels, as well as the repeated submergence of interdune areas by tidal waters, created a complex suite of mixed aeolian and subaqueous sediments in the back barrier. Another mixed-process system was documented by Jordan and Mountney (2010) by showcasing the coexistence of aeolian, fluvial and shallow-marine environments in the Pennsylvanian to Permian lower Cutler beds, of southeast Utah, USA. Their study described shallow-marine facies that comprise carbonate ramp limestones, tidal sand ridges and bioturbated marine mudstones. In the Cutler beds, aeolian, fluvial and marine interactions occurred on two distinct scales and represent the preserved expression of both small-scale autocyclic behaviour of competing, coeval depositional systems and broader allocyclic changes (Jordan and Mountney 2010). These authors identified trace fossils in shallow marine carbonate ramp facies subject to significant siliciclastic input (e.g. *Phycodes*, *Scolicia*) and in channel mouth bar and migrating subaqueous dunes within a shallow or marginal-marine environment (e.g. *Protichnites*, *Phycodes*, *Glockia* and *Thalassinoides*). A mixed-process depositional system was also presented by Rodríguez-López et al., (2012) who described the controls on the variability of marine–erg margin cycles in the mid-Cretaceous Iberian desert system in Spain. The study documented interactions between aeolian dunes of the Iberian erg and Tethys waters during the mid-Cretaceous that led to diverse sedimentary facies associations including subtidal environments, aeolian dunes, playa lakes, coastal lakes with tidal creeks, and marshes and lagoonal embayments with tide-influenced delta deposits. An increased groundwater flux accompanied by basin subsidence favoured permanent coastal lakes in the fore-erg margin and local development of vegetation. Their study demonstrated that tidal channels were active in places where such lagoons were connected to the sea, as seen nowadays along the desert coast of Qatar (Rodríguez-López et al., 2012).

More recently, Wakefield and Mountney (2013) recognized migrating subaqueous bar forms in a shallow-marine or marginal-marine setting with a recurrent trace fossil assemblage that included *Protichnites*, *Scolicia* and *Thalassinoides* in the Pennsylvanian to Permian lower Cutler beds of the Paradox Basin in southeastern Utah. These beds constitute a mixed aeolian, fluvial, and shallow marine carbonate succession (Jordan and Mountney, 2010) where the aeolian, fluvial and shallow-marine processes operate coevally.

3.2 GEOLOGICAL SETTING

The study area is located in the subsurface of central eastern Saudi Arabia, southeast of Riyadh (Fig. 3.1). A sandy Palaeozoic succession is widespread with strata ranging in age from Cambrian through Permian; it includes the Late Carboniferous–Middle Permian Unayzah Group (Fig. 3.2). The Unayzah Group consists of a series of sand-rich sediments deposited on, and infilling the paleotopography of the Hercynian Unconformity ("Pre-Unayzah Unconformity", PUU), and is bounded at the top by the "Pre-Khuff Unconformity" (PKU) in subsurface Saudi Arabia (Husseini, 1992; Al-Husseini, 2004; Price et al., 2008; Faqira et al., 2009; Melvin et al., 2010a,b; Melvin and Norton, 2013; Fig. 3.2). Age-equivalent deposits can be found throughout the subsurface of the Arabian Peninsula, from Kuwait, Saudi Arabia, Bahrain, United Arabs Emirates (UAE) and south into Oman where they host significant hydrocarbon reserves (Al-Laboun 1982; Levell et al. 1988; Konert et al., 2001; Tanoli et al. 2008; Melvin and Norton 2013; Polo et al. 2018).

3.2.1 Stratigraphy of the Unayzah Group in subsurface central and eastern Saudi Arabia

Based on subsurface core observations, Ferguson and Chambers (1991) identified a lithostratigraphic succession constituting an upper sandy Unayzah A Member that overlies sandstones of the Unayzah B Member, commonly separated by a prominent red siltstone interval. They also recognized a basal interval they referred to as the Unayzah C Member (Fig. 3.2). Subsequent studies incorporated this informal lithostratigraphic framework for the Unayzah Group in the subsurface of central and eastern Saudi Arabia (e.g. McGillivray and Husseini, 1992; Senalp and Al-Duaiji, 1995; Aktas et al., 2000; Al-Qassab et al., 2001; Wender et al., 1998;

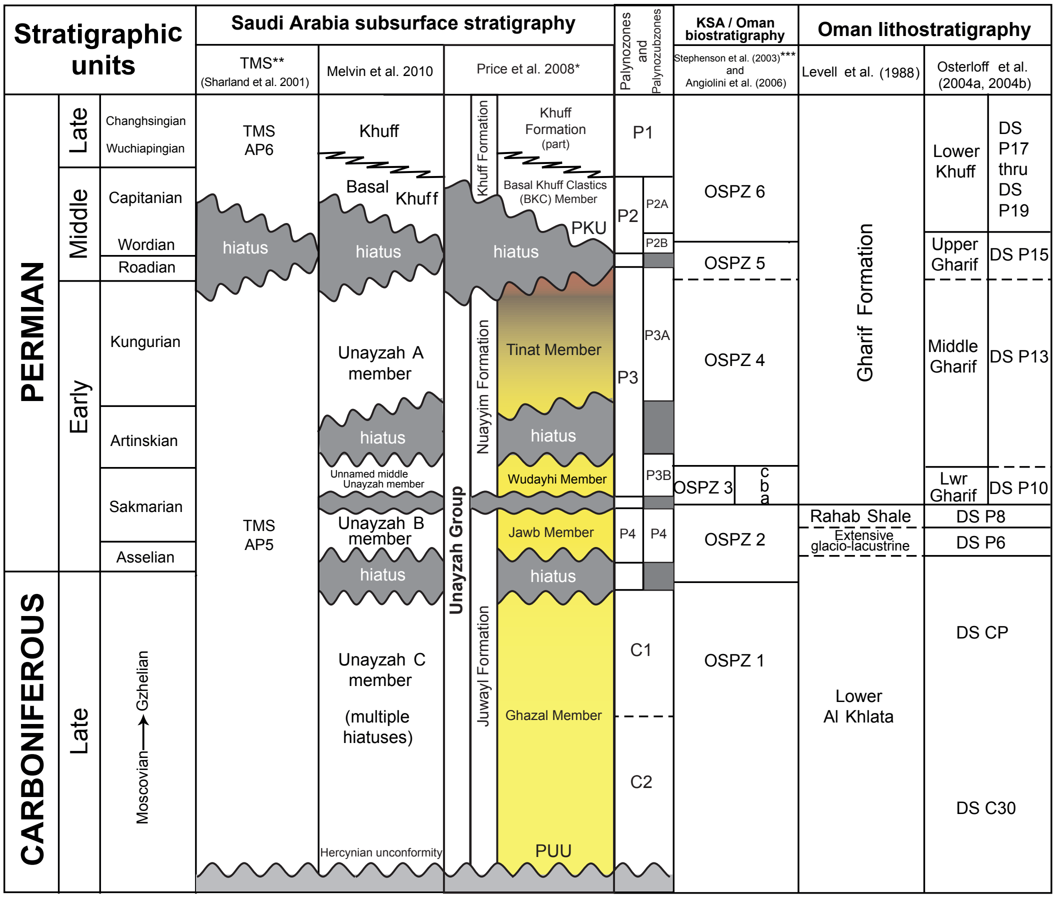


Figure 3.2. Late Carboniferous–Permian stratigraphic framework of the Kingdom of Saudi Arabia (KSA) and Oman. (*) This study follows the stratigraphic nomenclature proposed by Price et al. (2008) for subsurface Saudi Arabia. (**) Tectonostratigraphic Megasequences (TMS) of Sharland et al. (2001) and (***) biostratigraphic zonation (OSPZ1-OSPZ6) of Stephenson et al. (2003) provide the regional context to compare age-equivalent successions across the Arabian Peninsula extending south into Oman (Modified ~ Melvin et al. 2010b).

Al-Husseini, 2004; Melvin et al., 2010a,b; Melvin and Norton, 2013). Sharland et al. (2001) identified a number of “Tectonostratigraphic Megasequences” (TMS) based on the integration of outcrop and subsurface datasets that underpin that sequence stratigraphic framework for the entire Arabian Plate (Fig. 3.2). The entire Unayzah Group falls within their TMS AP5 megasequence (Fig. 3.2). It is bounded at its base by the Hercynian Unconformity (Pre-Unayzah Unconformity of Al-Husseini (2004), which represents the mid-Carboniferous “Hercynian tectonic event” in Arabia. The upper boundary of TMS AP5 is the “Pre-Khuff Unconformity” of Senalp and Al-Duaiji (1995). Melvin and Sprague (2006) confirmed and characterized the Unayzah C and B members. From the study of core samples, those members were interpreted to comprise facies that were demonstrably representative of the late Palaeozoic Ice Age (LPIA). The Unayzah C Member consists of synglacial outwash deposits that have been deformed by multiple glacier front advances; the Unayzah B consists of glaciofluvial and glaciolacustrine outwash deposits indicative of the terminal meltout of the ice sheets at the end of the LPIA (Melvin and Sprague, 2006) (Fig. 3.3). Melvin and Sprague (2006) identified a new lithostratigraphic unit within the lowest part of the Unayzah A Member of Ferguson and Chambers (1991). This was informally referred to by these authors as the "Un-named middle Unayzah member" (Fig. 3.2) and characterized by red siltstones that commonly pass upward into red, very fine-grained silty sandstones.

This study follows the stratigraphic framework by Price et al. (2008) and summarized in Figure 3.2. The rocks that occurred between the Hercynian Unconformity (Pre-Unayzah Unconformity) and the Pre-Khuff unconformity were formally arranged by those authors into two formations, each of which was subdivided into two members (Fig. 3.2). At its base, the Juwayl Formation represents sediments deposited during the late Palaeozoic Ice Age and is subdivided into two members overlain by the Nuayyim Formation (formerly the Unayzah A Member), which is entirely postglacial in character. Price et al. (2008) subdivided the latter into two members: 1) the Wudayhi Member (formerly the "Un-named middle Unayzah member"), which is overlain by 2) the Tinat Member (the subject of this

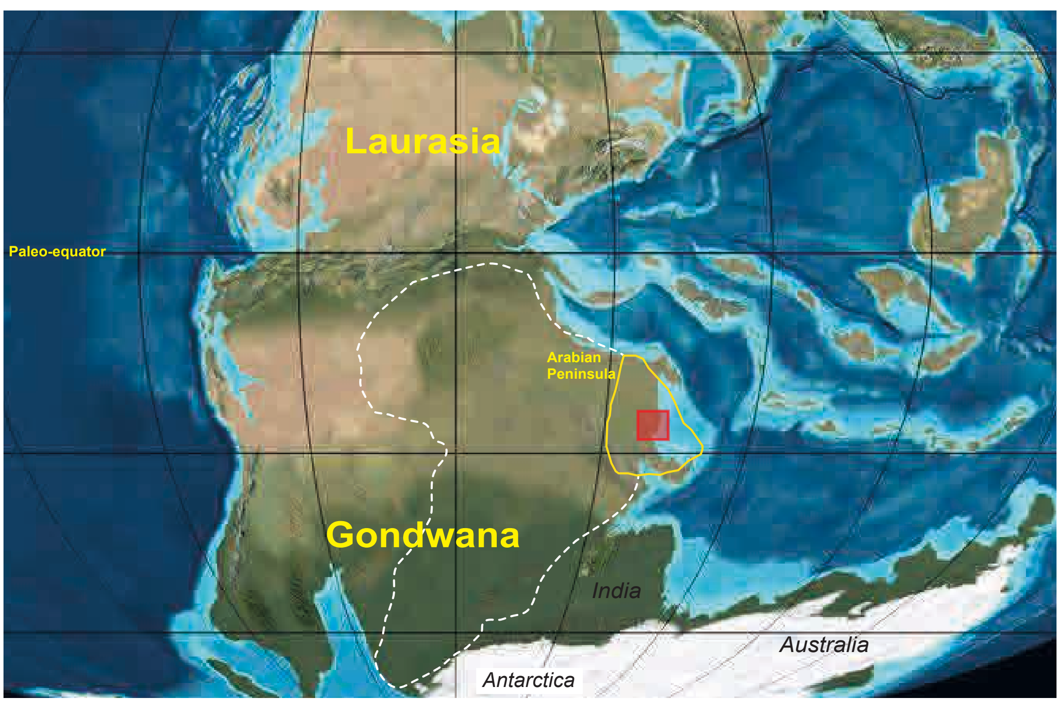
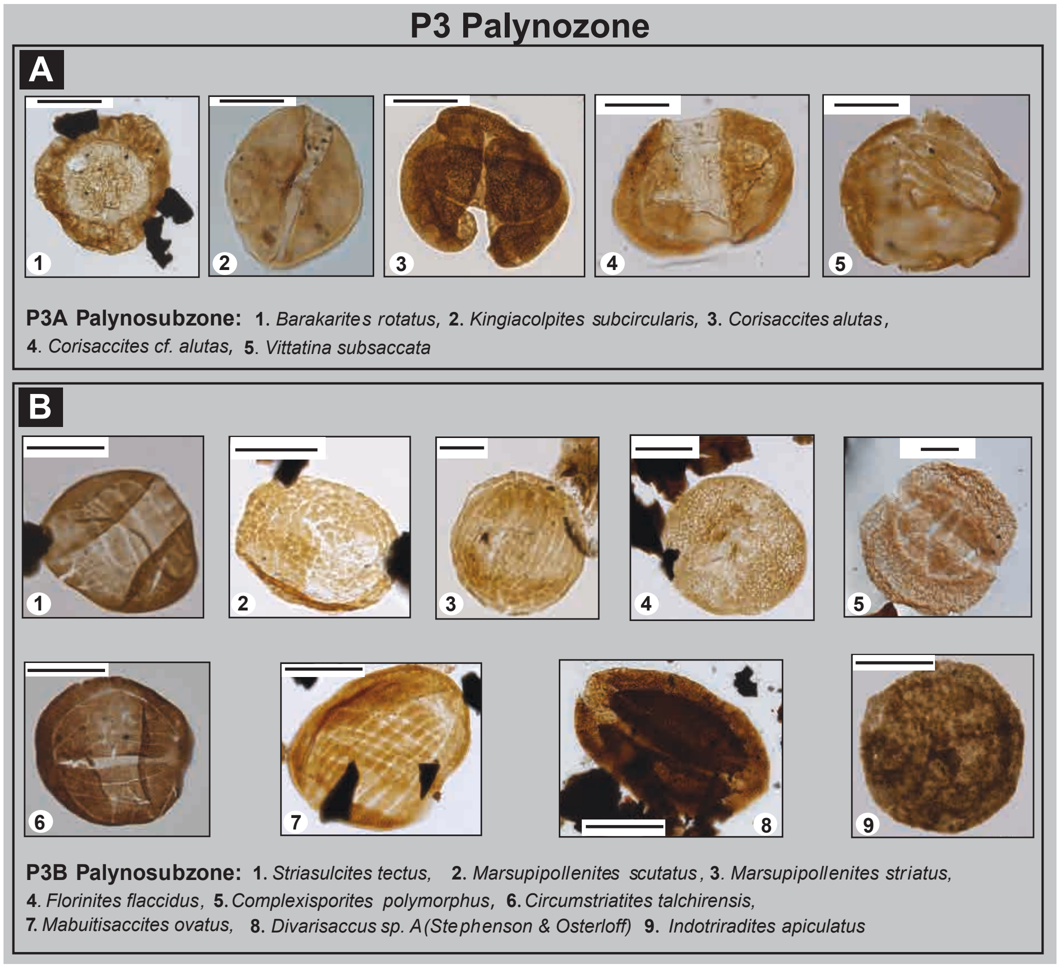


Figure 3.3. Molleweide projection of palaeogeography during the Middle to Late Permian (Approx. 260 Ma) showing the land and oceans distribution. During this period, the area corresponding to the modern day Arabian Peninsula was located between 15° and 35° of latitude, south of the equator in the temperate zone. Red square marks the approximate palaeogeographic location of the study area for this paper (adapted from Blakey, 2011).

study), which is truncated at its top by the "Pre-Khuff Unconformity".

Age dating is provided by biostratigraphic control with palynology as the only tool currently used to establish temporal and spatial relationships within the Nuayyim Formation. Melvin and Norton (2013) found the Unayzah C and B members in the subsurface to be equivalent to the Juwayl Formation where it crops out in the Wajid region of southwest Saudi Arabia (Fig. 3.2). These deposits are also equivalent to the glaciogenic Al Khlata Formation which crops out in Oman (see Osterloff et al., 2004a,b). This equivalence is confirmed in that both these lower Unayzah members and the Al Khlata Formation are characterized by the same palynological assemblages.

Sediment deposition for the Nuayyim Formation took place during the postglacial phase after the LPIA (Price et al. 2008; Melvin and Norton 2013; Polo et al. 2018). In terms of its biostratigraphic markers, palynomorphs in the Nuayyim Formation are assigned to the P3 Palynozone of Saudi Aramco (Fig. 3.4), in part equivalent to the *K. subcircularis* Assemblage of Love (1994). The P3 Palynozone is subdivided into an older P3B Palynosubzone (Wudayhi Member), and the overlying P3A Palynosubzone (Tinat Member) (Fig. 3.4A). The P3B assemblage is late Sakmarian-early Artinskian and the P3A assemblage is late Artinskian to Kungurian. The P3B Palynosubzone of Saudi Aramco contains persistent *Marsupipollenites* spp. (notably *M. scutatus* and *M. striatus*) and assemblages are generally pollen-dominated and characterized by forms that can be described as taeniate sulcate (*Striasulcites*), taeniate bisaccate (*Protohaploxypinus*), pseudo-bisaccate (*Caheniasaccites)*, taeniate monosaccate (*Striomonosaccites*, *Mabuitisaccites*) and large costate (*Vittatina*) (Fig. 3.4B). The earliest records of rare *C. alutas* and similar forms (*C. cf. alutas* and *Lueckisporites cf. virkkiae*) occur in the upper part of P3B Palynosubzone (Fig. 3.4). The P3A Palynosubzone assemblages (characteristic of the Tinat Member) are entirely pollen-dominated with forms similar to those in the P3B Palynosubzone (Fig. 3.4). However, the absence of verrucate *Marsupipollenites* (*M. scutatus*) and a greater frequency and persistence of *C. alutas* and similar forms allow differentiation of the P3A from the P3B Palynosubzone (Fig. 3.4). In terms of recovery of palynomorphs, P3A Palynosubzone assemblages are less commonly encountered compared with the older P3B Palynosubzone, although they are still geographically widespread. This clear distinction between P3B and P3A assemblages provides a tool to correlate deposits of the Tinat Member regionally and allows temporal differentiation with the underlying Wudayhi Member (Fig. 3.4).



P3A Palynosubzone: 1. *Barakarites rotatus*, 2. *Kingiacolpites subcircularis*, 3. *Corisaccites alutas*, 4. *Corisaccites cf. alutas*, 5. *Vittatina subsaccata*

P3B Palynosubzone: 1. *Striasulcites tectus*, 2. *Marsupipollenites scutatus*, 3. *Marsupipollenites striatus*, 4. *Florinites flaccidus*, 5. *Complexisporites polymorphus*, 6. *Circumstriatites talchirensis*, 7. *Mabuitisaccites ovatus*, 8. *Divarisaccus sp. A (Stephenson & Osterloff)* 9. *Indotriradites apiculatus*

Figure 3.4. P3 Palynozones of Saudi Aramco and corresponding subdivisions of the Nuayyim Formation with representative palynological taxa. A) P3A Palynosubzone characterizes the Tinat Member and is Early Permian (late Artinskian-Kungurian) in age; whereas B) P3B Palynosubzone characterizes the Wudayhi Member and is Early Permian (late Sakmarian-early Artinskian). Scale bar is 20 microns in all figures.

3.3 METHODS AND DATASET

A total of 23 slabbed cores, extending 316 meters covering the Nuayyim Formation were examined. Core were logged in detail to assess the sedimentological and ichnological characteristics that allowed a facies scheme to be proposed. Sedimentological analysis concentrated on characteristics such as: 1) lithology; 2) grain composition; 3) sorting; 4) bed thickness; 5) bedding contacts; 6) identification of primary physical sedimentary structures, and 7) deformation structures. Ichnological analysis included: 1) identification of ichnotaxa; 2) assessment of their relative abundance; 3) ichnofossil size; 4) ethologic and trophic types; 5) assemblage diversity, and 6) intensity of bioturbation recorded as Bioturbation Index (BI) (sensu Taylor and Goldring, 1993). Bioturbation intensity and descriptive criteria are based on the key presented by MacEachern et al. (2010).

In addition to the logging of core samples for sedimentological and ichnological analysis, 22 core samples were collected for palynological determinations from Well 6 in the study area (Fig. 3.1). Incorporating palynological assessments allowed the authors to constrain the age of the studied dataset, gain insight into the palaeoclimatic setting, and integrate the results of palynological assemblages with the depositional environments derived from ichnological and sedimentological assessments. Processing of the samples was done using standard palynological extraction techniques. Strew mount slides were systematically logged to produce palynomorph range and abundance data. Results are presented in Appendix 3 of the supplementary material.

3.4 RESULTS AND INTERPRETATION

3.4.1 Tinat Member Facies, Facies Associations and Depositional Environments

Eight facies, grouped into two facies associations (FA), were identified from Tinat Member in the study area (Table 1). These are: 1) aeolian and continental, groundwater related environments (FA1) and 2) shallow-marine and tidally influenced environments (FA2). FA1 consists of six facies that differentiate arid from moist environments and reflect the level of interaction of the depositional setting relative to the water table. Arid sediment deposition comprises: 1) fine- to medium-grained, high-angle, cross-bedded sandstone (facies 1) and 2) fine- to medium-grained, low-angle, cross-bedded sandstone (facies 2). Moist depositional environments are reflected in 3) fine- to medium-grained, irregularly and crudely defined laminated sandstone (facies 3); 4) very fine- to fine-grained silty sandstone (facies 4); 5) interbedded, very fine- to coarse-grained pebbly sandstone (facies 5), and 6) poorly sorted, pedogenically altered very fine- to coarse-grained sandstone and siltstone (facies 6).

FA2 is significantly less recurrent than FA1 and consists of two facies: 1) interbedded very fine- to fine-grained silty sandstone and mudstone (facies 7), and 2) finely laminated, burrowed, very fine- to fine-grained silty sandstone (facies 8). Table 1 summarizes the most relevant lithological, sedimentological and ichnological characteristics of each facies.

LITHOFACIES	LITHOLOGY & ACCESSORY MINERALS	PRIMARY SEDIMENTARY STRUCTURES	ICHNOLOGY	CONTACTS	ENVIRONMENTAL INTERPRETATION
Facies 1: **Fine- to medium-grained, high angle, cross-bedded sandstone.**	• Fine- to medium-grained, well to very well sorted sandstones. • Nodular anhydrite cement is common. • Patchy anhydrite cement is abundant. • Sand grains display frosted surfaces, are well-rounded and display good sphericity.	• High angle (>30°), grain size-segregated cross laminae and cross bedding. • Laminae thickness varies from widely spaced (cm-scale) to densely packed "pin-striped" (mm-scale). • Grain size may display polymodal and bimodal distribution. • Wind-ripple lamination is dominant. Laminae display gradual thinning downward on the lee slope. • Alternating thick and also thin, inversely graded sand beds are occasionally present. • Deformed laminae at the base of beds and bedsets are occasionally present.	• Bioturbation is absent. • Bioturbation Index (BI = 0)	• Mostly sharp. • Occasionally upper boundaries are marked by abruptly truncated horizontal surfaces. • Abrupt horizontal truncations of aeolian cross-strata are identified as "Stokes surfaces".	• Well to very well sorted sand suggests continuous transport mechanisms promoting grain sorting and rounding. • The presences of Stokes surfaces suggest fluctuating levels in the paleo–water table. • Main sediment transport mechanism includes wind transport through saltation. • Closely spaced (densely packed) lamination with inverse grading suggests migration of wind ripples. • Alternating thick and thin sand beds can be interpreted as grain flow cross-strata formed by gravity sliding of sand down aeolian dune slip faces and grain fall respectively. • Interpretation: Aeolian dune foresets.
Facies 2: **Fine- to medium-grained, low angle, cross-bedded sandstone.**	• Fine- to medium-grained well sorted sandstones. • Nodular anhydrite cement is common. • Patchy anhydrite cement is abundant. • Sand grains display frosted surfaces, are well-rounded and display good sphericity.	• Low angle (<30°) to flat, grain size-segregated cross laminae and cross bedding. • Laminae are commonly closely spaced, densely packed "pin-striped" (mm-scale). • In places, laminae is inversely graded. Grain size may display polymodal and bimodal distribution. • Wind-ripple laminae are abundant. • Very low-angle truncations separating different sets of the low-angle laminated sand are occasionally present.	• Bioturbation is absent. • Bioturbation Index (BI=0).	• Mostly, abrupt. • Occasionally, transitional. • Locally, erosive at the base overlaying deflation surfaces and "Stokes surfaces".	• Well to very well sorted sand suggests continuous transport mechanisms promoting grain sorting and rounding. • "Pin-stripe" lamination suggests deposition of silt and very fine sand in the troughs of the advancing wind ripples. • Main sediment transport mechanism includes wind transport through saltation. • Continuous wind action and a fluctuating water table may be the most important factors contributing to the preservation of these deposits. • Interpretation: Dry interdunes and aeolian sandsheets.

Table 3.1. Lithological, sedimentological and ichnological characteristics of each facies identified for the Tinat Member of the Nuayyim Formation in the study area. Particular interpretations are expanded on the main body of the text for each facies.

Facies 3: **Fine- to medium-grained, irregularly and crudely laminated sandstone.**	• Fine- to medium-grained sandstones. • Nodular anhydrite cement is common. • Patchy anhydrite cement is abundant. • Sand grains display frosted surfaces, are well-rounded and display good sphericity.	• Adhesion ripples and adhesion laminae are abundant. • Irregular to crinkly, variably continuous laminae are common. • Horizontal and low- angle, poorly defined (i.e. faint) greyish lamination is occasionally present.	• Bioturbation is absent. • Bioturbation Index (BI = 0).	• Mostly, abrupt. • Occasionally, transitional. • Locally, erosive.	• The degree of dampness or dryness may have been a function of rainfall during wetter periods and/or fluctuations in the level of the ground water table. • Continuous deflation by wind action and a fluctuating water table may be the most important factors contributing to the “wetting” and preservation of these deposits. • Abundant irregular laminae and adhesion structures suggest sedimentation upon a damp substrate in close proximity to the palaeo–water table. • Interpretation: Ephemeral damp interdune or sandy sabkha.
Facies 4: **Very fine- to fine grained silty sandstone.**	• Very fine- to fine grained silty sandstones. • Patchy and nodular anhydrite cement is common. • Coarser-grained sand laminae are present occasionally. • Thin silt beds can be found occasionally.	• Lenticular to indistinct crinkly lamination, and locally, ripples and small-scale ripple cross-lamination are dominant. • Planar and quasi planar adhesion laminae are common. • Thin, flat-lying (horizontal) laminae with grains of well rounded, medium to coarse sand are common. • Sub-vertical sand-filled cracks (desiccation cracks).	• Bioturbation is absent • Bioturbation Index (BI = 0).	• Mostly, transitional. • Occasionally, abrupt. • Locally, lower contacts display “Stokes surfaces”.	• Sedimentation may have occurred at times when the water table rose above the depositional surface within an otherwise arid (desert-like) environment. • Fluctuation of the lake levels may be a function of seasonal rainfall or water table variations. • Sediment transport mechanisms include wind and water. Deposition occurred within very shallow interdune ponds. • Sedimentary structures are interpreted here to have been formed in a predominantly wet environment and/or associated to subaqueous sedimentation. • Interpretation: Perennial interdune lake.

Table 3.1.– *Contined.*

Facies 5: **Very fine- through coarse-grained pebbly sandstone.**	• Very fine- through coarse-grained sandstone dominates. • Very fine-grained silty sandstone with mud in form of mud drapes. • Towards the base of some individual beds, granules, pebbles and small mud clasts. • Patchy and nodular anhydrite cement is common.	• Generally, either massive or flat laminated. • Ripple cross-lamination is common with abundant mud drapes. • Thin-bedded units dominate. Some segments display amalgamated beds. • Some beds comprise very fine-grained silty sandstone that displays well-developed ripple cross-lamination. • Desiccation cracks associated to mud drapes.	• Bioturbation is absent. • Bioturbation Index (BI = 0).	• Commonly, sharp erosional lower contacts.	• Basal harp-based beds and coarser sandstones with granules, pebbles and small mud clasts of these upward-fining cycles suggest rapid deposition. • Finer-grained, and ripple laminated sediment may be indicative of the waning flow deposits of episodic flood events. • Desiccation in the finer, mud-draped portions suggests settling down of finer material after episodes of sedimentation and subsequent cracking after periods of widespread exposure in a semiarid environment. • Main sediment transport mechanisms include seasonal or episodic water flows. • Low laying topographic relief and wadis may have been affected by ephemeral floods that resulted in fluvial gravels with intraclast derived from Facies 1 through Facies 4 in this table. • Interpretation: Semiarid Ephemeral Stream Deposits.
Facies 6: **Poorly sorted, pedogenically altered very fine- through coarse-grained sandstone and siltstone.**	• Very fine- through coarse-grained sandstone and siltstones. • Overall, sorting is poor due to chemical and physical weathering. • Silcrete nodules and development of silcrete cement. • Patchy and nodular anhydrite cement can be found locally.	• Mostly, mottled texture resulting in a "spotty" appearance. • Locally, discernable original primary sedimentary structures are preserved (e.g. horizontal and low-angle lamination). • Commonly, aggregates, lumps or clods of soil (i.e. peds) structures and cutans. • Sand-filled cracks between peds.	• Bioturbation is absent to moderate • (BI = 0-3). • Rhizoliths occurring at different levels vertically (i.e. punctuated).	• Mostly, transitional. • Locally, sharp (truncated) upper boundaries.	• Continental deposits and their association to plant roots suggest low to no sedimentation, allowing the establishment of flora. • Peds and cutans point towards pedogenesis (soil forming) processes that altered the parental rock into soil. • Rhizoliths associated to palaeosols horizons suggest that the paleo–water table was relatively high at the time of their formation and that water table dynamics influenced soil formation. • Widespread rhizoliths suggest long-term, favorable paleoecological conditions (e.g. substrate consistency, climate and food resources) and/or low sedimentation rates. • Interpretation: Palaeosol horizons colonized by land plants and Mangrove-type flora in the coastal intertidal zone.

Table 3.1.– *Contined*.

Facies 7: **Heterolithic Deposits**	• Very fine- and fine-grained sandstone interbedded with mudstone. • Carbonaceous drapes and laminae occur locally.	• Abundant synaeresis cracks. • Some intervals display flaser bedding. • Double mud drapes occur rhythmically. • Current ripples. • Parallel and wavy lamination, locally current ripple cross-lamination and single mud drapes. • Reactivation surfaces are common. • Lenticular bedding throughout.	• Bioturbation is absent to uncommon. • (BI = 0-2). • *Planolites, Palaeophycus* and *Thalassinoides* are sparsely distributed. • Burrow-mottled texture occurs locally.	• Commonly gradational or sharp but conformable surfaces.	• Interbedded very fine-, to fine-grained sand and mud suggest variable hydrodynamics at the time of sedimentation, likely tidal influence. • Abundant synaeresis cracks suggest that sediment transport mechanisms may have included marine waters (i.e. tidal currents) interacting with riverine fresh water input. • Carbonaceous drapes suggest proximity to the shore/sediment source, likely a fluvial input and/or a marginal marine setting. • Absent to uncommon bioturbation suggest that burrowing organisms developed under stressed paleoecological conditions (e.g. short termed salinity fluctuations). • Interpretation: Tidal flat deposits. Highly stressed, low-diversity mixed expressions of the *Cruziana* Ichnofacies with subordinate elements of the *Skolithos* Ichnofacies.
Facies 8: **Laminated, burrowed, very fine- to fine-grained, sandstone.**	• Very fine- to fine-grained, sandstone. • Single and double silt laminae are recurrent.	• Low-angle, wavy and horizontal laminae are abundant. • Decimetric-scale thick, finely laminated segments occur locally.	• Bioturbation is absent to moderate. • (BI = 0-3). • *Planolites* and *Palaeophycus* are common. • *Thalassinoides* occurs sparsely. • Some intervals display mono-ichnogeneric *Planolites* suites. • Burrow-mottled texture occurs locally.	• Commonly, gradational or sharp but conformable surfaces.	• Recurrent very fine- to fine-grained sandstone with mud (e.g. low-angle, wavy and horizontal lamination) suggests subaqueous sedimentation with variable hydrodynamic levels, likely tidal influence. • Absent to moderate bioturbation suggest that burrowing organisms developed under stressed paleoecological conditions (e.g. periodical salinity fluctuations). • Possible sediment transport mechanisms include tidal currents. • Interpretation: Marginal-marine, partly restricted coastal-lagoon tidally influenced deposits, likely located between aeolian dunes. Impoverished, stressed, low-diversity mixed expressions of the proximal *Cruziana* Ichnofacies with subordinate elements of the proximal *Skolithos* Ichnofacies.

Table 3.1.– *Contined.*

3.4.1.1 Aeolian and continental, water-table related environments (FA1)

3.4.1.1.1 Dry-related depositional environments

3.4.1.1.1.1 Facies 1 (F1): Fine- to medium-grained, high-angle, crossbedded sandstone.

This facies consists of fine- to medium-grained, high-angle, crossbedded sandstone that ranges in color from brick-red and red brown to buff yellow and pale to dark grey (Fig. 3.5). Sandstones are well to very well sorted, with very well-rounded and frosted grains of quartz. Beds and bedsets exhibit high angle, well sorted cross-laminae (Figs 3.5D and 6). Lamination is mostly thin, and closely spaced, "pin-striped" (cf. Fryberger and Schenk, 1988; Fig. 3.5F). These laminae are commonly abruptly truncated and overlain by adhesion laminae and adhesion ripples (cf. Hunter, 1980; Fig. 3.5B, C and E). In some cases, cross-lamination displays thick and thin alternations (Fig. 3.5D and F). Locally, deformation and microfaulting can be observed towards the base of facies 1 beds (Fig. 3.5A and C).

The dominance of very well-sorted sand suggests a continuous transport favoring grain sorting and rounding associated with the percussive action of wind transport. Very closely spaced, "pin-striped" and inversely graded laminae and lamina sets are interpreted as wind-ripple laminations that formed on the slip faces of aeolian dunes (cf. Fryberger et al., 1979; Fryberger et al., 1983; Fryberger and Schenk, 1988; Jerram et al., 2002; Mountney, 2006a,b; Mountney and Thompson, 2002). Sharp truncations toward the top of these lamina sets, abruptly overlain by adhesion laminae and adhesion ripples, are interpreted as relating to rises in the palaeo-water table in moist interdune surfaces that inhibited further deflation (Fryberger et al., 1988). The former promoted, the preservation of sediments in an aeolian setting by inhibiting wind deflation and are interpreted as "Stokes surfaces" (Stokes, 1968; Fryberger et al., 1988; Fig. 3.5B, C and E). Variability in the thickness of laminae reflect alternating grainflow and grainfall sedimentation on the slip faces of migrating aeolian dunes (Kocurek and Dott, 1981; Mountney, 2006a; Melvin et al., 2010b; Al-Masrahy, 2011; Fig. 3.5B, C and E). This facies represents sediment accumulation in migrating aeolian dunes.

3.4.1.1.1.2 Facies 2 (F2): Fine- to medium-grained, low angle, crossbedded sandstone.

This facies consists of fine- to medium-grained sandstones, with well-

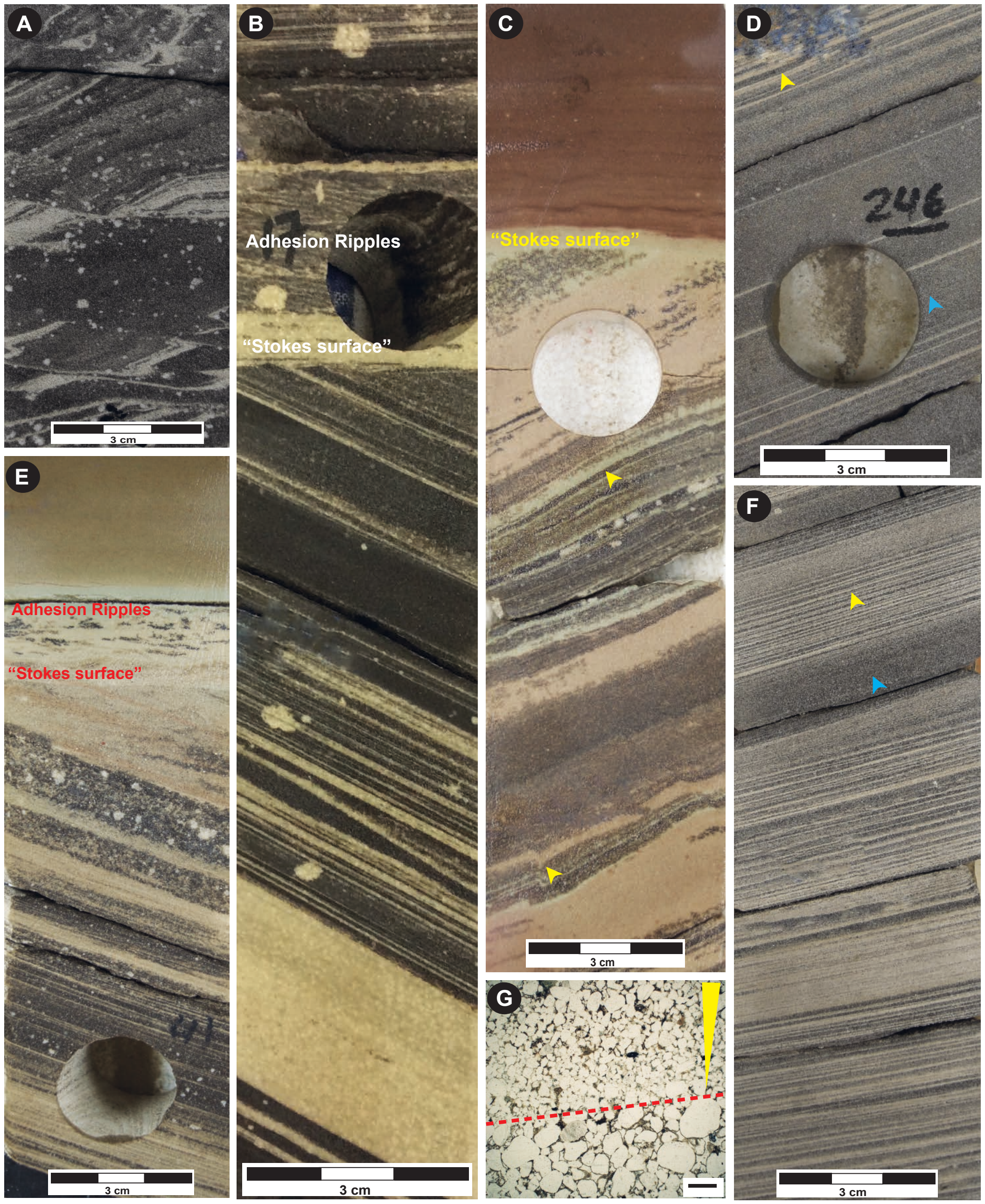


Figure 3.5. Occurrences and characteristics of facies 1: Fine- to medium-grained, high-angle, cross-bedded sandstone. (A) Deformed lamination at the base of aeolian dune, Well 5. (B) Alternating wind-ripple lamination and grain flow beds on migrating lee side of aeolian dune truncated up by a "Stokes surface" that passes abruptly into adhesion ripples, Well 1. (C) Deformed and microfaulted (yellow pointers), crossbedding in the lee slope of a migrating aeolian dune. Note the sharp upward truncation demarcated by a "Stokes surface" overlain by wavy-laminated red beds, Well 3. (D) Interval displaying grainflow (blue pointers) and grainfall (yellow pointers) cross-lamination, Well 5. (E) High-angle cross-lamination dominated by wind ripple laminae and thicker grain flow cross-laminae truncated upward by adhesion ripples in a wet interdune setting, Well 3. (F) Example of significant variation in thickness produced by grainflow (blue pointer) and grain fall (yellow pointer) lamination on the lee slope of a migrating dune. Also note the gradually downward thinning lee slope of grainfall (yellow pointers) and grainflow, millimetric laminae (blue pointer). The closely spaced lamination reflects subcritically climbing translatent strata and wind-ripple lamination at the dune apron, Well 5. (G) Thin section photomicrograph showing well sorted cross-lamination and inverse grading, Well 1.

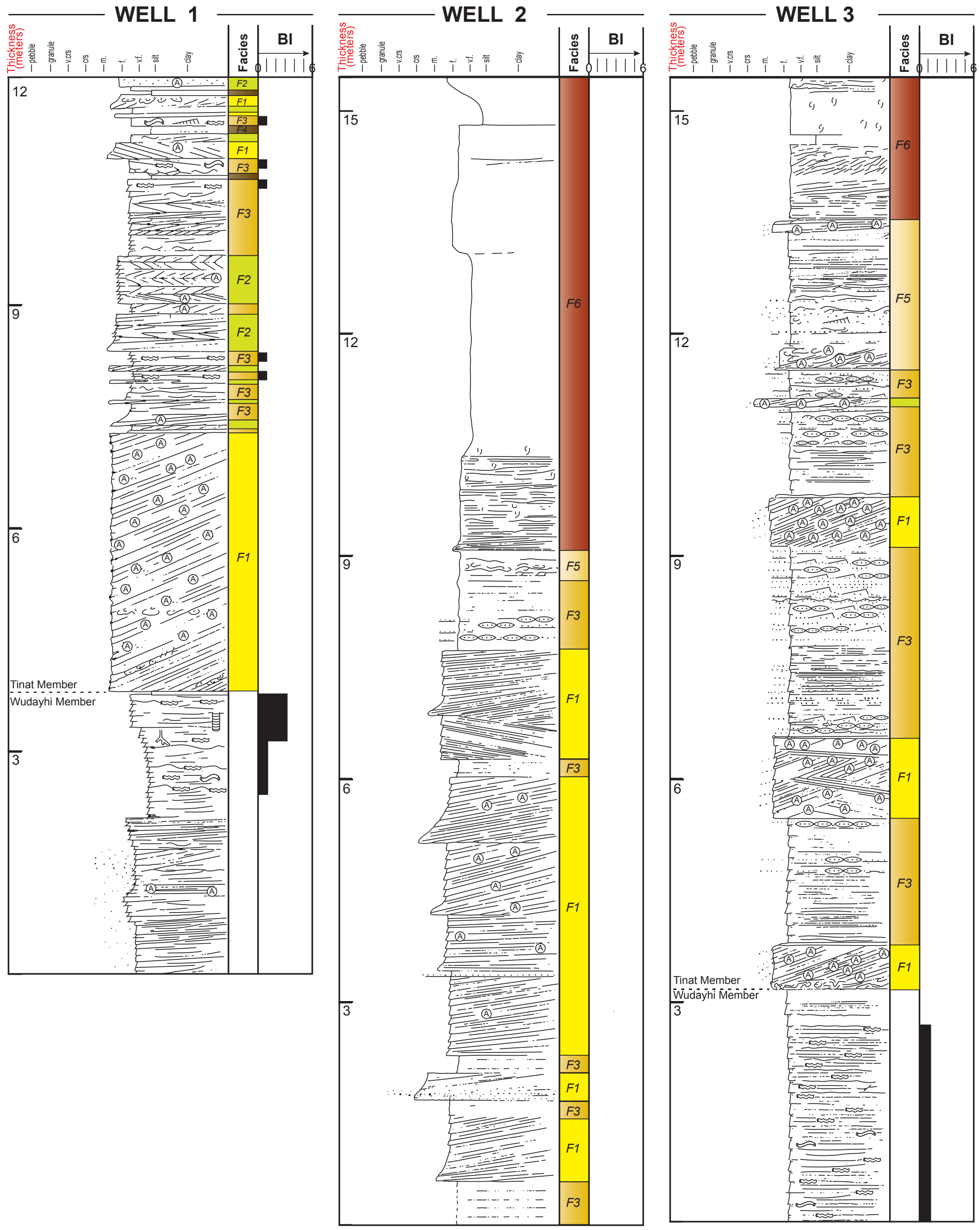


Figure 3.6. Core log displaying the vertical succession of facies and trace-fossil distribution in Wells 1 to 3 (see Fig. 3.8 for symbol legend in all core logs).

rounded and frosted grains of sand that occur in horizontal to low-angle, well sorted laminae (Figs 3.7 and 3.8). Beds and bedsets exhibit recurrent lamination that is closely spaced and "pin-striped" (Fryberger et al., 1979; Fryberger and Schenk, 1988; Fig. 3.7C and D). Some occurrences display very low-angle truncations that separate different sets of the low-angle laminated sandstone (Fig. 3.7B, D and E).

The presence of well- to very well-sorted sand suggests a continuous

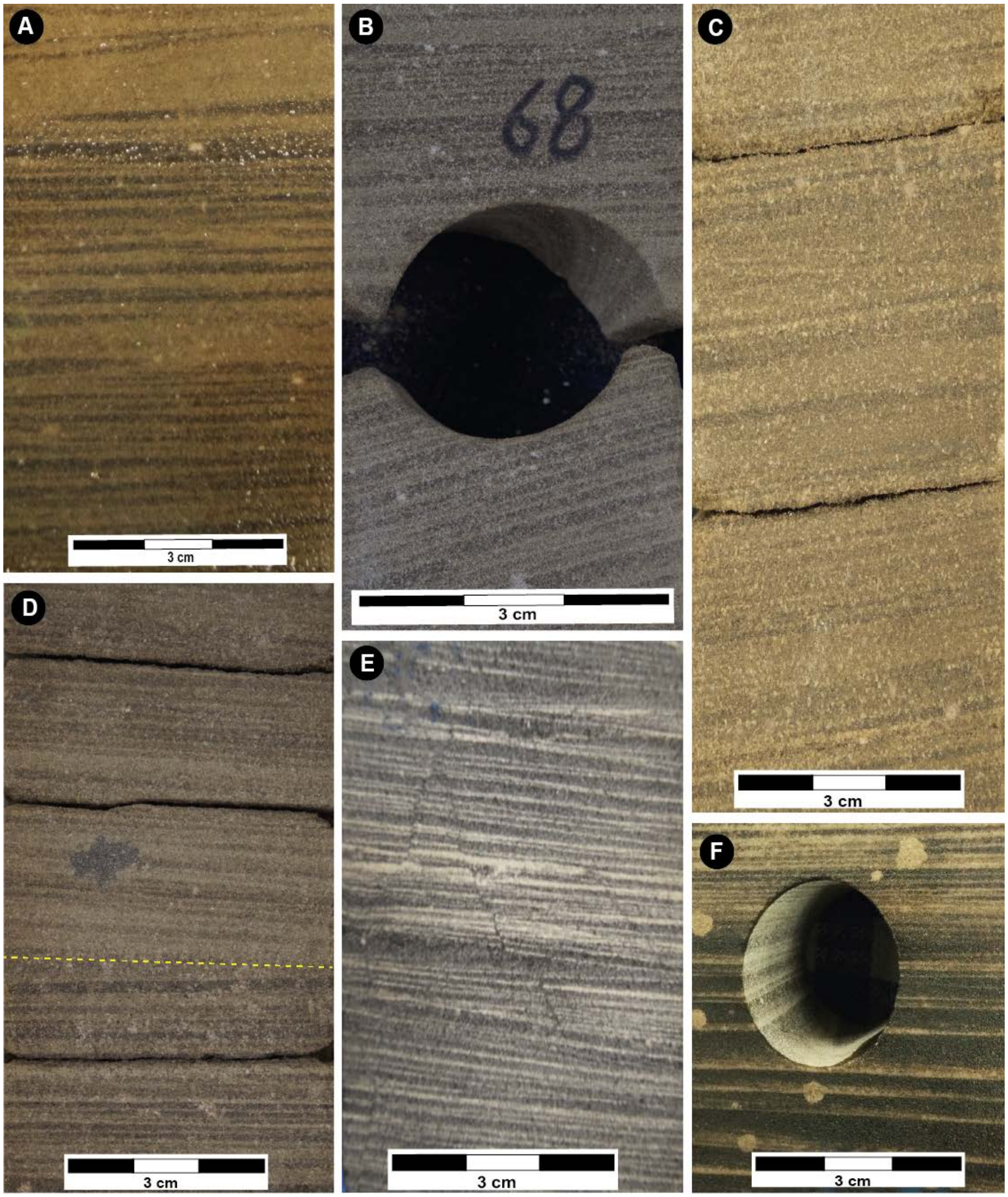


Figure 3.7. Occurrence and characteristics of facies 2: Fine- to medium-grained, low-angle, cross-bedded sandstone. (A) Wind-ripple, cross-laminated sandstone. Darker and lighter colors are due to differential oil stain caused by well sorted cross-lamination that created different pore sizes, Well 1. (B) Densely packed, "pin-striped" wind ripple lamination, Well 6. (C) Interval displaying low-angle, wind-ripple cross-lamination, Well 1. (D) Co-set of low-angle, wind-ripple laminated, medium-grained sandstone. Dashed yellow line represents low-angle truncations separating different sets of low-angle, "pin-striped" laminated sandstones, Well 5. (E) Segment that exhibits very low-angle wind ripple lamination, Well 1. (F) Grain size-segregated cross-laminations resulting from migrating aeolian ripples on a dry interdune setting, Well 1.

transport mechanism promoting grain sorting and rounding such as the percussive action associated with aeolian transport (Howell and Mountney, 2001; Mountney et al., 2009). Many sets of these laminae have a pin-striped appearance pointing toward an origin from wind-ripple migration (Fig. 3.7A to C). Low-angle lamination exhibiting a pin-stripe arrangement suggests deposition of silt and very fine sand in the troughs of the advancing wind ripples as sand grains transported by wind mainly through saltation (Mountney and Jagger, 2004; Melvin et al., 2010b; Al-Masrahy, 2011; Fig. 3.7). Grain segregation by wind ripple migration is inferred by changes in color of the laminae and lamina sets (Fig. 3.7F). This facies represents sediment deposition in dry interdune zones as sand sheets in an aeolian setting (Mountney, 2006).

3.4.1.1.2 Wet-related depositional environments

3.4.1.1.2.1 Facies 3 (F3): Fine- to medium-grained, irregularly and crudely laminated sandstone.

This facies consists of moderately- to well-sorted, fine- to medium-grained sandstones. Sedimentary structures include irregular to crinkly (Fig. 3.9A and B), variably continuous lamination (Fig. 3.9D) and very thin (centimeter scale) beds with well-developed adhesion ripples and adhesion laminae (cf. Hunter, 1980). Horizontal and low-angle, poorly defined (i.e. faint) greyish lamination occurs locally (Fig. 3.9C). Bed thickness ranges from centimeter to decimeter scale (Figs 3.9 and 3.10). Locally, adhesion ripple cross-lamination can be identified along adhesion laminae (Fig. 3.9D and E).

The abundance of moderately- to well-sorted sand points toward continuous sediment mobilization promoting the sorting and rounding related to the percussive action associated with aeolian transport. The presence of adhesion features such as adhesion laminae and adhesion ripple lamination (Hunter, 1980) suggests sedimentation upon a damp substrate where the surface is in proximity to the water table capillary fringe (Fryberger et al., 1983; Kocurek and Fielder, 1982; Fig. 3.9C to E). Close proximity to the palaeo-water table is suggested by the preservation of these deposits (Jerram et al., 2002; Mountney and Thompson, 2002; Mountney, 2006a; Kiersnowski, 2013). Fluctuating water table levels allowed the wetting of the surface and inhibited downwind deflation further (Mountney and Howell, 2000; Mountney and Jagger, 2004). Similar structures have been observed in damp interdune and coastal sabkha environments (e.g. Fryberger et al., 1983; Mountney, 2006a). The close proximity of this facies to aeolian deposits described previously such as aeolian dunes and dry interdune or sand sheets (facies 1 and facies 2 respectively) suggests deposition in a damp interdune environment, ephemeral

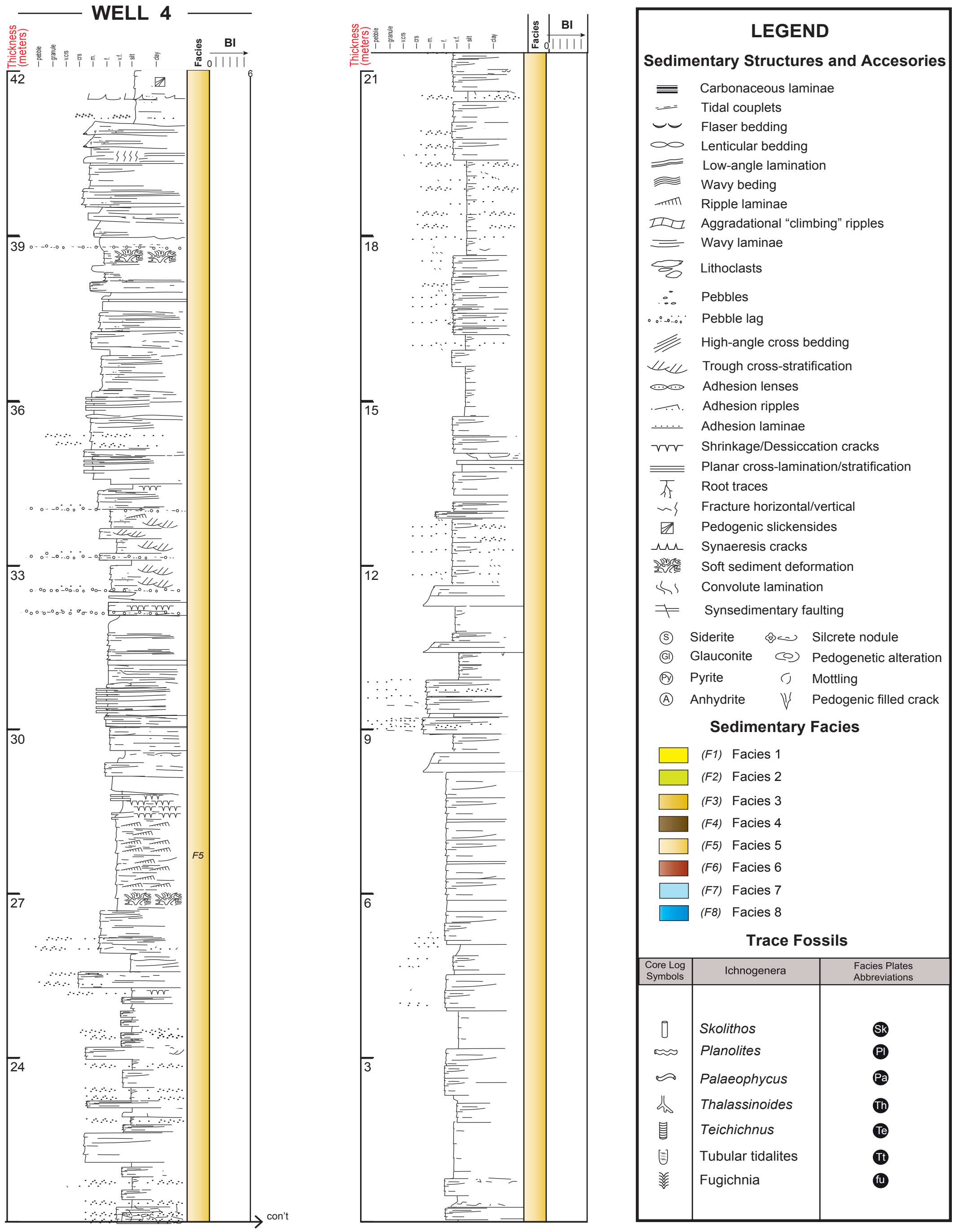


Figure 3.8. Core log displaying the vertical succession of facies and trace fossil distribution in Well 4 and symbol legend used in all core logs.

playa lake margin or coastal sabkha (Glennie and Singhvib, 2002; Melvin et al., 2010b; Al-Masrahy, 2011).

3.4.1.1.2.2 Facies 4 (F4): Very fine- to fine-grained silty sandstone.

This facies consists of grey and dark grey siltstones and silty and very fine-grained sandstones. (Fig. 3.11A and B). Commonly these sediments occur in weakly laminated to structureless intervals, usually of decimeter to meter scale (Fig. 3.12).

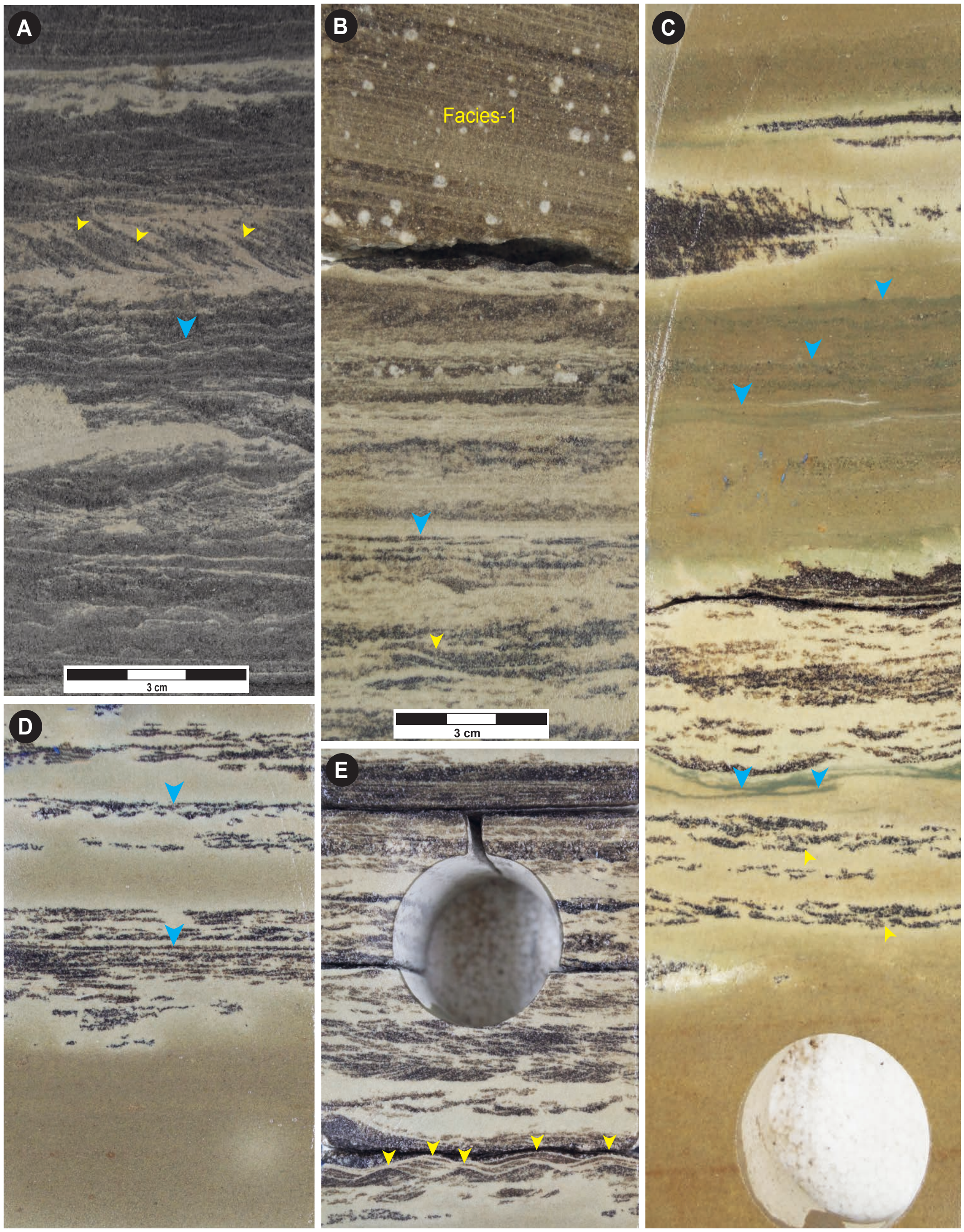


Figure 3.9. Occurrence and characteristics of facies 3: Fine- to medium-grained, irregularly and poorly defined laminated sandstone. (A) Interval displaying adhesion ripples (yellow pointers) and irregular lamination (blue pointer), Well 5. (B) Segment displaying adhesion laminae (blue pointer) and adhesion ripples (yellow pointer) passing upward into the toeset of a migration aeolian dune marking a reactivation of sand movement by wind and the resulting wind-ripple cross-lamination of facies 1 deposits, Well 3. (C) Greenish, low-angle to wavy, continuous silty laminae (blue pointers) that pass into irregular, coarser-grained crinkly lamination (yellow pointers). Also note the coarse-grained lenses and irregular laminae, probably from windblown sand, Well 3. (D) Well developed, continuous adhesion laminae (blue pointers) between structureless segments, Well 3. (E) Segment

exhibiting well-developed, symmetric adhesion ripples (yellow pointers) and adhesion laminae associated with damp interdune conditions. Note the aggradational (i.e. climbing) ripples reflecting waning of water flow in the wet interdune area at the base of the segment, Well 3.

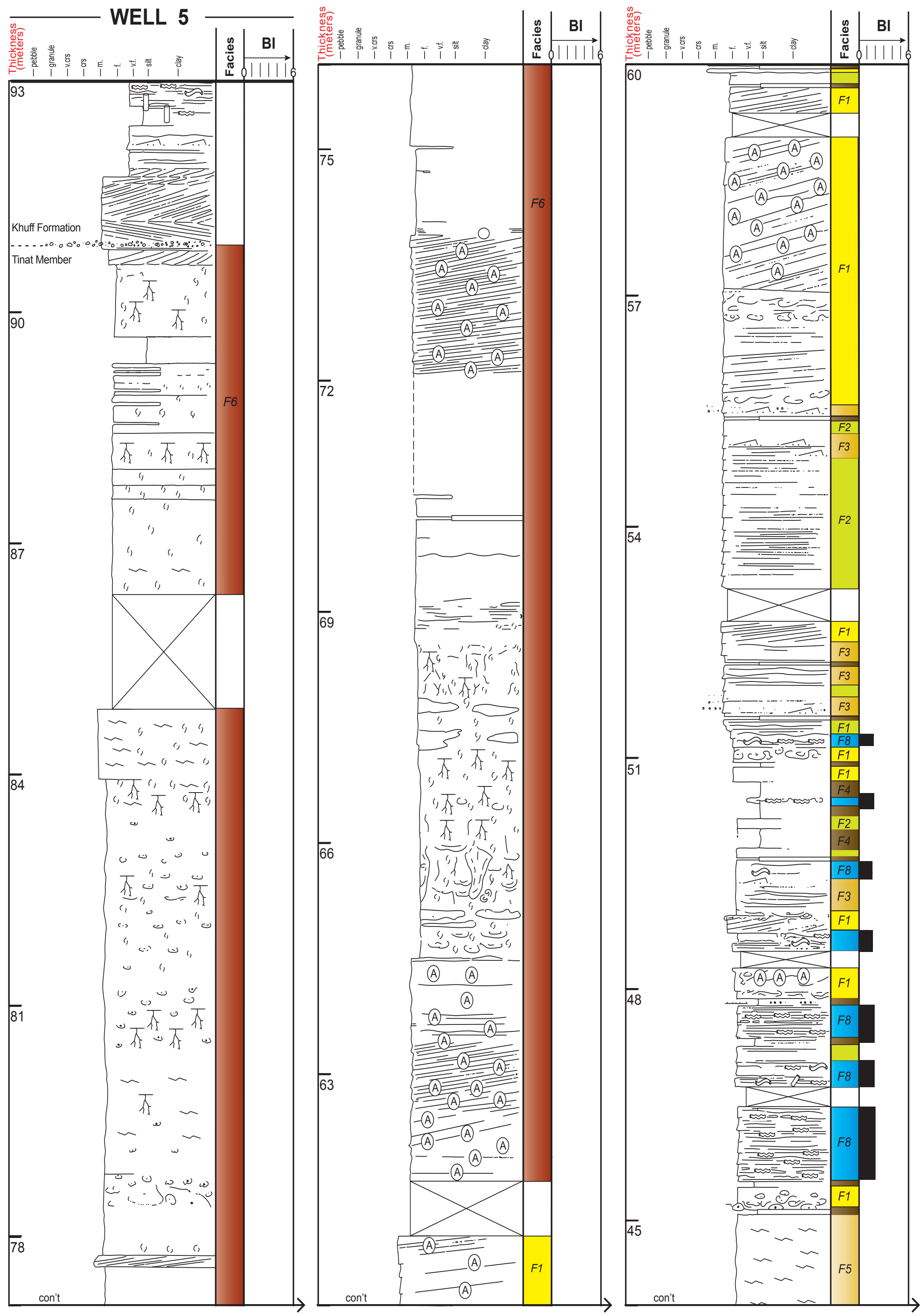
Where they occur, primary sedimentary structures are dominated by horizontal lamination and variably continuous to wavy lamination (Fig. 3.11A). In very localized occurrences, facies 4 deposits exhibit faint adhesion features (Fig. 3.11B)

The overall very fine-grained lithology and sporadic occurrence of lamination indicates subaqueous deposition under quiet hydrodynamic conditions (Fig. 3.11A and B). The close proximity of this facies with the deposits described previously suggests deposition in the wet interdune areas that formed relatively long-lived water bodies that were near the water table or the sea (Melvin et al., 2010b). They are therefore interpreted not as ephemeral (playa) lake sediments but rather as the deposits of temporary, shallow interdune ponds (Glennie, 1987; Melvin et al., 2010b; Al-Masrahy, 2011) that formed at times when the water table rose above the depositional surface (Mountney, 2006a; Kiersnowski, 2013; Minervini et al., 2013). Adjacent deposits with adhesion structures of facies 3 (Fig. 3.9) suggest that these conditions were not permanent and led to cycles of desiccation and the reestablishment of arid conditions (Fig. 3.11A).

3.4.1.1.2.3 Facies 5 (F5): Interbedded very fine- to coarse-grained pebbly sandstone.

This facies consists of interbedded sandstones, silty sandstones and siltstones (Fig. 3.13). The sandstones are thin-bedded units, rarely more than 30 cm thick that make up the lower parts of fining-upward couplets (Fig. 3.13A and C). They are fine- to medium-grained moderately to poorly sorted, and are generally either massive or horizontally laminated with sharp, erosional lower contacts. Locally, granules, pebbles and small mud clasts are present at the base of fining-upward beds (Fig. 3.13E and F). These sandstones can be single units or comprise thin amalgamated beds (Fig. 3.13A, E, and C). They are commonly overlain by finer-grained beds of similar thickness that form the upper parts of the depositional couplets referred to above. These beds consist of very fine-grained silty sandstone that displays well-developed ripple cross-lamination (Fig. 3.13B and F). In places these silty, rippled sandstones contain an abundance of mud drapes that display well-developed desiccation features (Fig. 3.13A and D).

The presence of sharp-based, coarser sandstones with pebbles and granules of upward-fining couplets suggests rapid deposition such as by flash floods, (e.g. Glennie, 2005) (Fig. 3.13E, and F) although, small granules can also be transported by the wind. Such events have been documented from modern and ancient settings, and they record the sudden change in conditions largely attributed to seasonal rains (Glennie, 1998). The overlying, finer-grained, and ripple-laminated sediment with desiccation cracks represents the waning flow deposits of those episodic flooding events and subsequent desiccation resulting in polygonal cracks (Fig. 3.13A and D). As suggested by Melvin et al. (2010b), the recurrence of sharp-based sandstones



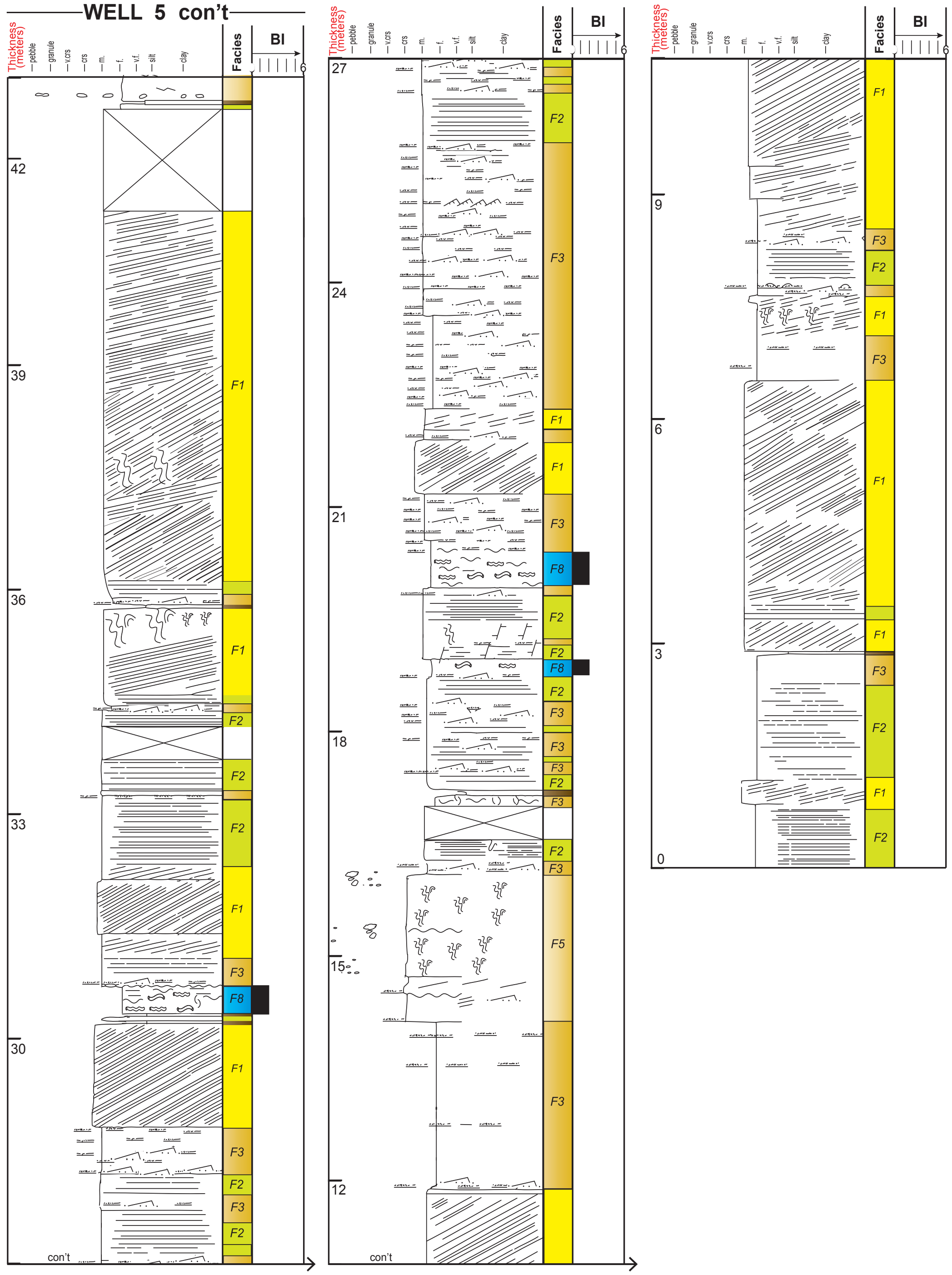


Figure 3.10. Core log displaying the vertical succession of facies and trace fossil distribution in Well 5 (see Fig. 8 for symbol legend in all core logs).

with pebbles, ripple cross-lamination and desiccation cracks in the finer, mud-draped sediment points toward an episodic nature of bed deposition in a semiarid environment consistent with features of wet or damp interdunes (Fig. 3.13B, E and F). This facies represents sediment deposition by ephemeral stream deposits in an arid or semiarid setting as documented by Melvin et al. (2010b).

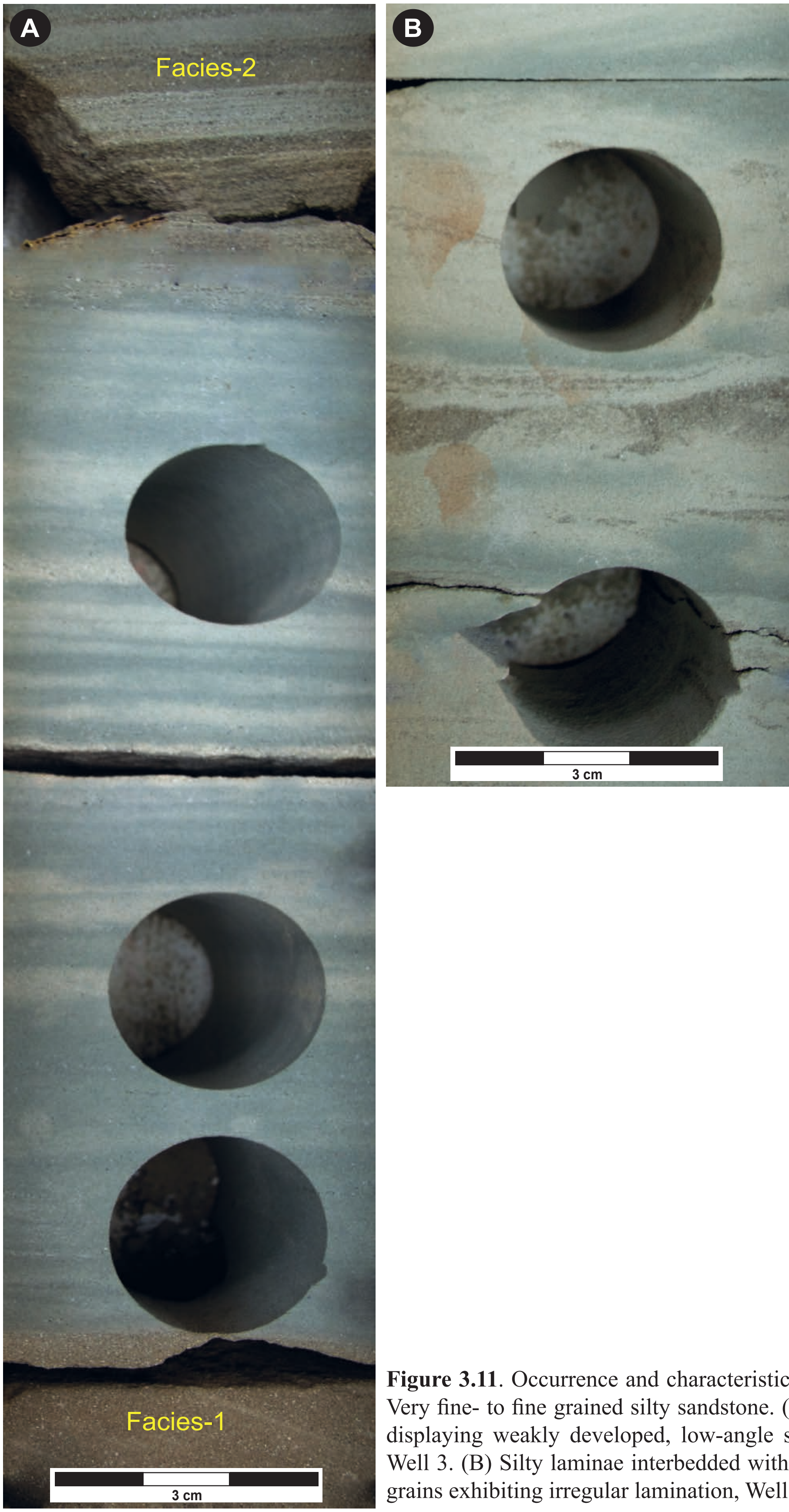


Figure 3.11. Occurrence and characteristics of facies 4: Very fine- to fine grained silty sandstone. (A) Silty bed displaying weakly developed, low-angle silty laminae, Well 3. (B) Silty laminae interbedded with coarser sand grains exhibiting irregular lamination, Well 3.

3.4.1.1.2.4 Facies 6 (F6): Poorly sorted, pedogenically altered very fine- through coarse-grained sandstone and siltstone.

This facies consists of red to brick-red, grey, greyish and light green to dark, poorly sorted, very fine- to medium-grained sandstones showing varying degrees of disrupted texture (Fig. 3.14). Commonly, beds in this facies exhibit aggregates, lumps or clods of soil (i.e. peds), silcrete nodules and cutans (Retallack, 1997a, 1998; Fig. 3.14A, D and E). Locally, filled cracks between peds and faint original primary sedimentary structures are preserved (e.g. low-angle lamination) (Fig. 3.14A). Gradational changes in color, texture and traces of biogenic activity can be observed at different levels, commonly as fossilized root traces (i.e. rhizoliths).

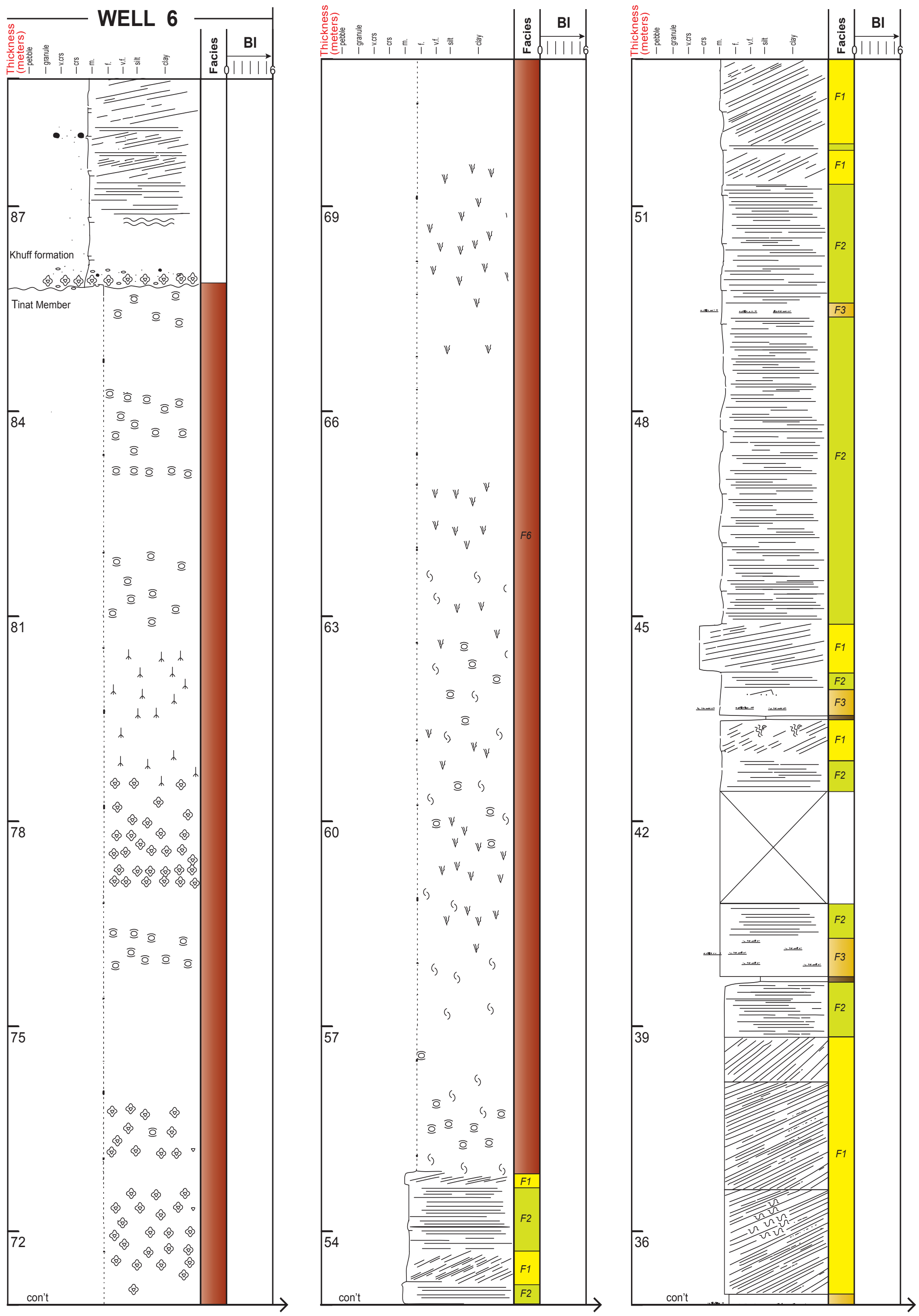
The presence of abundant root traces suggest that the palaeo-water table was relatively high at the time of plant colonization (Kocurek et al., 2001; Kraus and Hasiotis, 2006; Fig. 3.14B and C). Pedogenically altered sandstones and siltstones suggest an overall depositional environment dominated by subaerial exposure and nondeposition (diastems) that promoted the formation of silcrete nodules and abundant bioturbation by plants (Melvin et al., 2010a; Fig. 3.14B and E). This facies represent pedogenically altered deposits interpreted as palaeosols.

3.4.1.2 Shallow-marine and tidally influenced environments (FA2)

3.4.1.2.1 Facies 7 (F7): Interbedded very fine- to fine-grained silty sandstone and mudstone.

This facies consists of very fine- and fine-grained silty sandstone thinly interbedded with mudstone (Fig. 3. 15). Sedimentary structures consist of synaeresis cracks (Fig. 3.15A, C, D and G), lenticular bedding (Fig. 3.15A), low-angle and wavy lamination, flaser bedding, reactivation surfaces, carbonaceous double mud drapes (Fig. 3.15B and G) and current ripples (Fig. 3.15B). The ichnofossil suite within this facies exhibits poorly developed forms that can be locally mono-generic and display high abundances. Trace fossils are diminutive and bioturbation varies from absent to uncommon (BI 0–2) and includes a mixture of horizontal and inclined traces such as *Planolites*, *Thalassinoides*, *Palaeophycus* and fugichnia (Fig. 3.15). The fill of *Planolites* differs texturally from the surrounding matrix; whereas *Palaeophycus* fills display the same characteristics. In cross-sections, *Planolites* exhibit an elliptical shape, smooth, unornamented walls and differs from *Palaeophycus* by the presence of lining in the latter. *Thalassinoides* displays and elliptic shape and walls are essentially thinly-lined or unlined and unornamented.

In addition, tubular tidalites (cf. Gingras and Zonneveld 2015) occur commonly in facies 7 (Fig. 3.15E-G). The presence of current ripples and flaser bedding is indicative of subaqueous sediment transport and deposition likely with variable, low to moderate energy levels reflecting lower flow-regime conditions (Dalrymple,



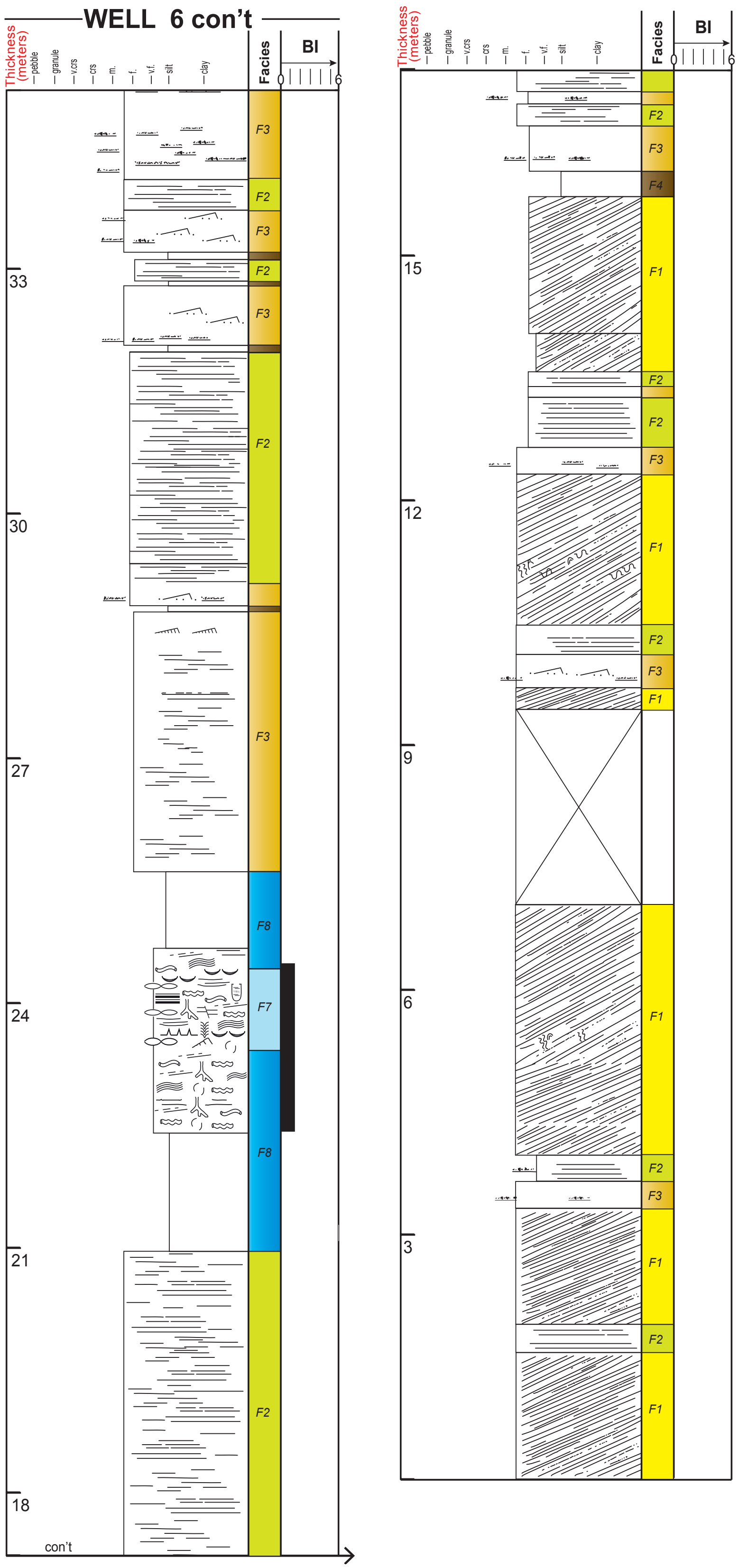


Figure 3.12. Core log displaying the vertical succession of facies and trace fossil distribution in Well 6 (see Fig. 8 for symbol legend in all core logs).

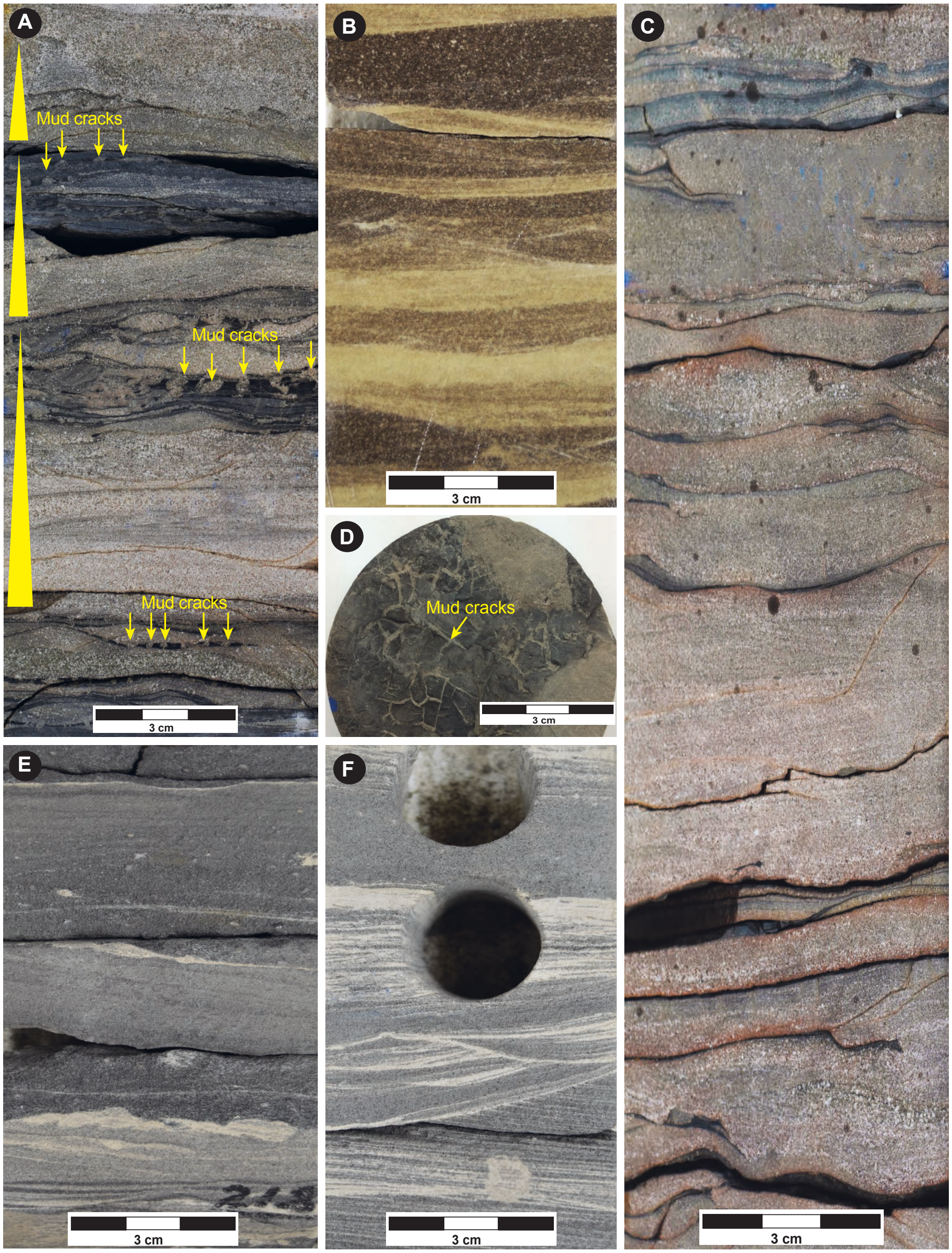


Figure 3.13. Occurrence and characteristics of facies 5: Interbedded very fine- through coarse-grained pebbly sandstone. (A) Interbedded mudstone and sandstone with ripple cross-lamination and fining-upward trends with mudstone towards the top of individual beds. Mudstone intervals display desiccation cracks shown from top view (bedding plane in (D) in mud laminae after segments displaying cracks, Well 4. (B) Ripple cross-lamination produced by ephemeral streams deposits, Well 3. (C) Amalgamated medium- to coarse-grained sandstones with ripple cross-lamination and mudstone with wavy lamination towards the top. Note at the base soft-sediment deformation triggered by interdune flooding, Well 3. (D) Bedding plane showing polygonal, sand-filled cracks developed in mud deposited in the waning stage of a flood in an ephemeral stream. Top view of segments displayed in (A). At a first glance, the interval gives the impression of exhibiting

flaser bedding; however, upon close examination of bedding planes, the mud cracks can be better appreciated, Well 4. (E) Poorly sorted sandstone with granules, wavy-, and low-angle lamination, showing amalgamated, centimetric beds with scoured bases. Poor grain sorting and scoured contacts suggest rapid, high-energy sedimentation likely by flash floods, Well 5. (F), well developed through cross-bedding produced by ephemeral stream deposits, Well 3.

2010a,b). Abundant single and double carbonaceous mud drapes and thinly interbedded siltstone and sandstone displaying flaser, wavy, and lenticular bedding suggest tidal influence at the time of sediment deposition (MacEachern and Gingras 2007; Dalrymple, 2010a,c Gingras and MacEachern 2012; Fig. 3.15A and C). Mud drapes are interpreted to be the result of settling of suspended sediment during slack-water periods (Hovikoski et al., 2008; Mackay and Dalrymple 2011). The presence of abundant synaeresis cracks points towards clay shrinkage resulting from salinity changes – likely as a result of marine and fresh water mixing (MacEachern and Pemberton 1994; MacEachern and Gingras 2007; Fig. 3.15A, C, D and G). Similar tidally influenced facies have been described by Rodríguez-López et al. (2012) in the mid-Cretaceous Iberian desert system. Therein, tidal channels, tidal flats and lagoonal embayments coexisted as a product of the interaction between aeolian dunes of the Iberian erg and Tethys waters (Rodríguez-López, et al. 2012).

The ichnofossil suite of F7 is dominated by infaunal dwelling structures of ichnotaxa which are interpreted to reflect predominantly deposit-feeding (i.e. *Planolites* and *Thalassinoides*) and suspension feeding or predatory behaviours (i.e. *Palaeophycus*) (MacEachern et al., 2012; Fig. 3.15B and C). Due to the textural difference in the fills of *Planolites* and *Palaeophycus* compared to the host rock, the former is interpreted to represent active filling of the burrow trough sediment processing by the tracemaker; whereas the latter is inferred to represent passive filling within open, lined burrows (Pemberton and Frey 1982). This assemblage resembles an impoverished expression with diminutive forms likely reflecting ichnofacies crossing elements of the *Skolithos* and *Cruziana* ichnofacies. The small size, localized high abundance and low-diversity of this suite suggest stressful conditions for bioturbating organisms (cf. Pemberton et al., 1982; Ranger and Pemberton 1997; Buatois et al., 2005; Lacroix et al., 2015). Salinity fluctuations and constantly changing conditions can be discerned by the presence of synaeresis cracks and reactivation surfaces (Fig. 3.15C) and are very likely responsible for a lowered trace fossil diversity within facies 7 deposits (MacEachern and Gingras 2007; Bann et al., 2004; Buatois et al., 2005). Tubular tidalites are interpreted as the result of rhythmically bedded alternating layers of fine- and coarse-grained

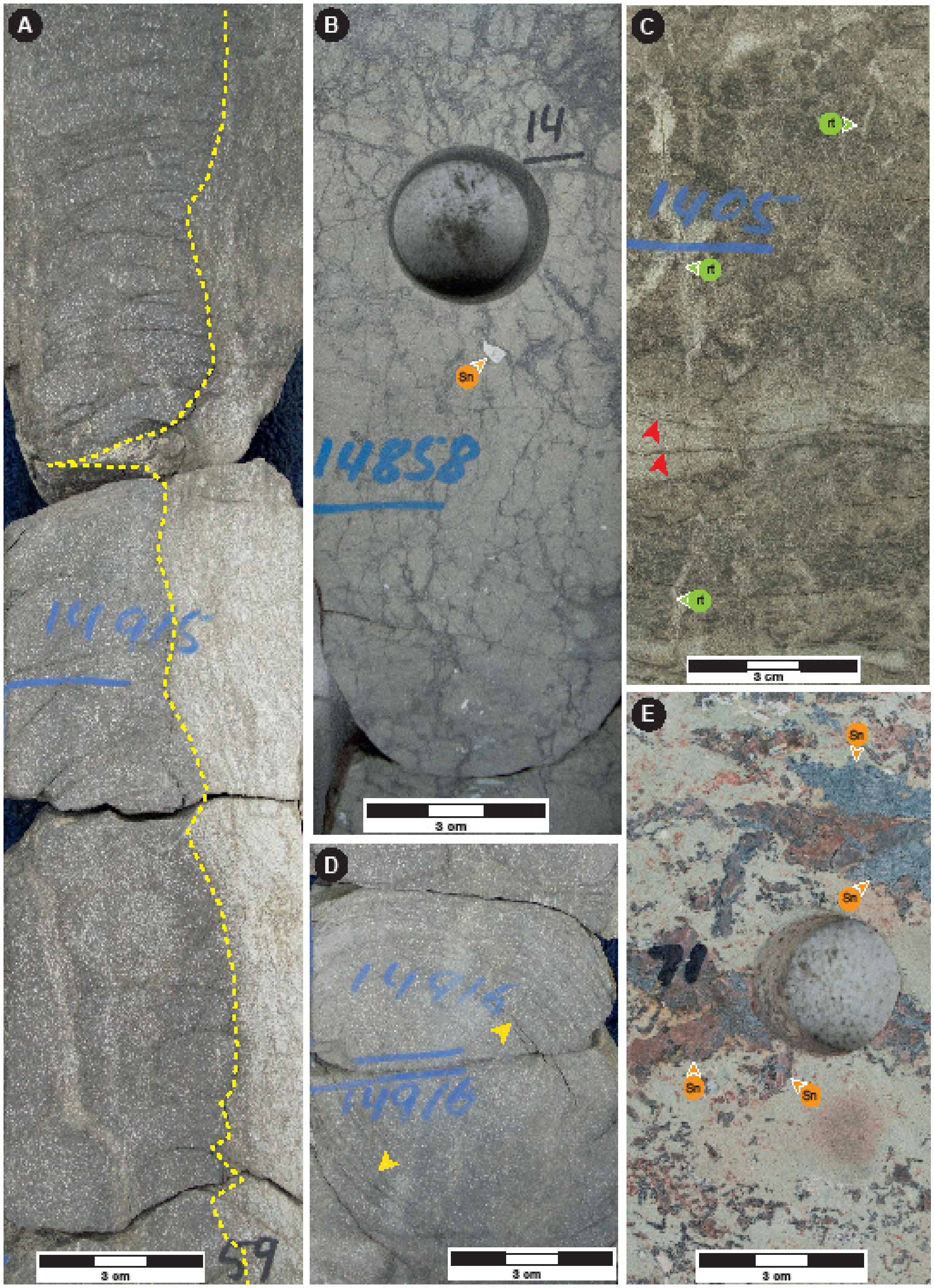


Figure 3.14. Occurrence and characteristics of facies 6: Poorly sorted, pedogenically altered very fine-through coarse-grained sandstone and siltstone. (A) Large ped with filled crack (yellow dashed line). Note concave-downward cracks as product of alteration of the parental substrate after subaerial exposure, resulting in development of shrink–swell (vertic) structures (yellow pointers) and “onion-rings like” features, Well 5. (B) Palaeosol with silcrete nodule (Sn), Well 5. (C) Pedogenic mottling in palaeosols with abundant rhizoliths (Rt). Note remaining primary physical sedimentary structures in the form of wavy lamination in the bottom half of the image (red pointers), Well 5. (D) Pedogenesis alteration with development of shrink–swell (vertic) structures (yellow pointers) observed as an “onion-ring-like” physical alteration of the parental substrate, Well 5. (E) Palaeosol with silcrete nodules (Sn) in sandy matrix, Well 5.

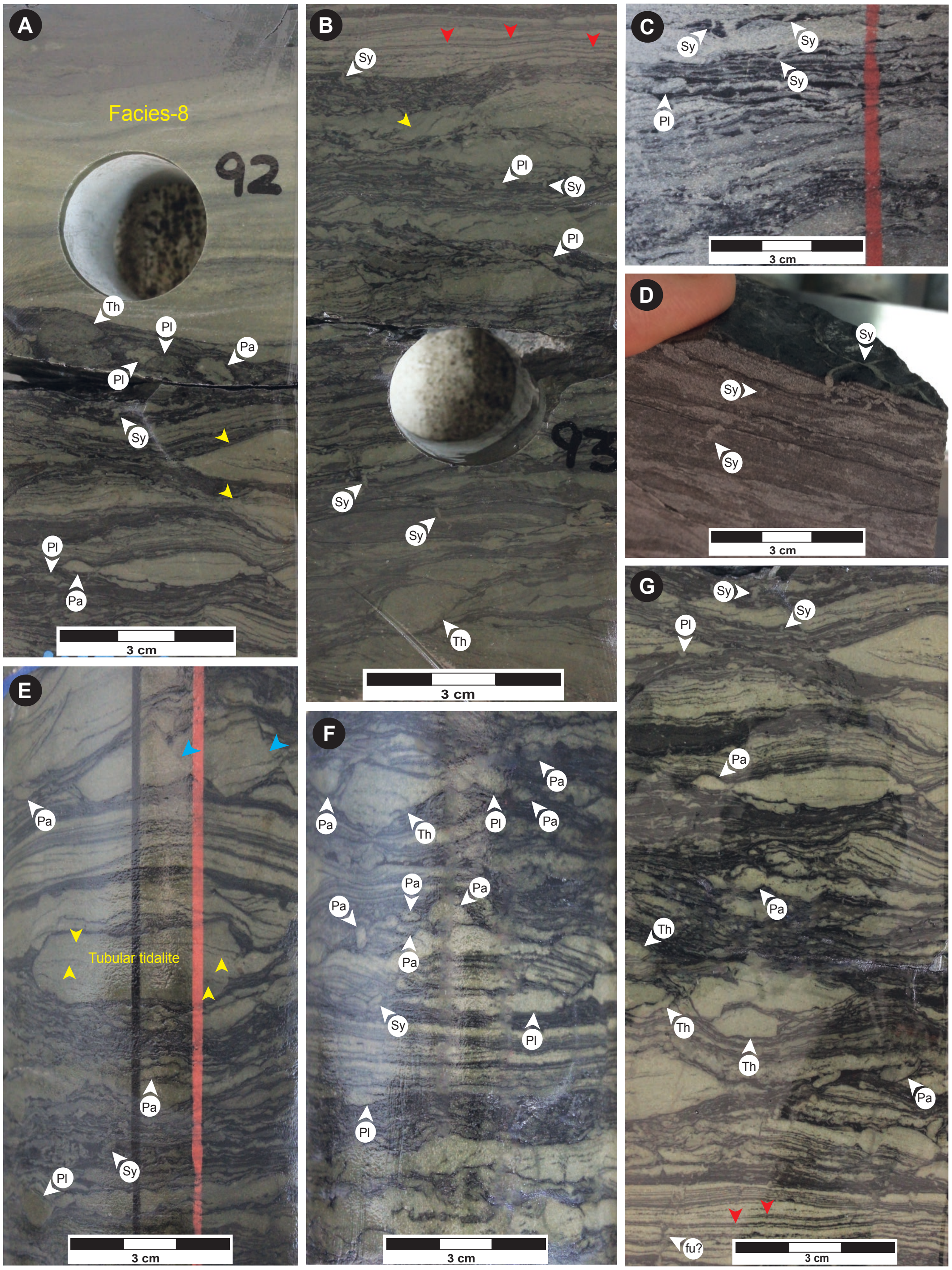


Figure 3.15. Occurrences and characteristics of facies 7: Interbedded very fine- to fine-grained silty sandstone and mudstone. (A) Segment displaying lenticular bedding (yellow pointers) carbonaceous mud drapes along with *Planolites* (Pl), *Palaeophycus* (Pa), *Thalassinoides* (Th) and synaeresis cracks (Sy). Note contact with facies 8 in the upper central part of the picture, Well 6. (B) Interval with current ripples (yellow pointer), double clay drapes (red pointers) along with *Planolites* (Pl), *Thalassinoides* (Th) and synaeresis cracks (Sy), Well 6. (C) Segment exhibiting abundant synaeresis cracks (Sy) and isolated occurrences of *Planolites* (Pl), Well 6. (D) Oblique (partially top) view of an interval exhibiting abundant synaeresis cracks (Sy). Note the discontinuity of the cracks and the absence of polygonal patterns that allow differentiating them from surficial desiccation cracks, Well 6. (E) Interval displaying micro faulting (blue pointers), abundant rhythmic carbonaceous double clay drapes, tubular tidalites with preserved tidal couplets (yellow pointers), along with *Planolites* (Pl), *Palaeophycus* (Pa) and Synaeresis cracks (Sy), Well 6. (F) Segment showing synaeresis cracks

(Sy), abundant rhythmic carbonaceous double clay drapes and tubular tidalites with preserved tidal couplets (yellow pointers). Burrow overprinting characterizes this segment. Discrete forms include *Planolites* (Pl), *Palaeophycus* (Pa) and *Thalassinoides* (Th), Well 6. (G) Interval with lenticular, flaser bedding, synaeresis cracks (Sy), abundant rhythmic carbonaceous double clay drapes (red arrows at the base) and tubular tidalites with preserved tidal couplets (yellow pointer). Ichnofossils include robust *Thalassinoides* (Th) along with *Planolites* (Pl), *Palaeophycus* (Pa), and fugichnia (fu), Well 6.

laminae deposited within open framework burrows in settings such as intertidal flats and lagoons (Gingras and Zonneveld 2015; Fig. 3.15E to G). This facies reflects deposition in tidal flats and exhibits a diminutive, highly stressed, low-diversity, mixed expression of the *Skolithos* and *Cruziana* ichnofacies (Gingras and MacEachern 2012).

3.4.1.2.2 Facies 8 (F8): Finely laminated, burrowed, very fine- to fine-grained silty sandstone.

This facies consists of very fine- to fine-grained sandstone with closely spaced single and double silt laminae (Fig. 3.16). Sedimentary structures are dominated by a recurrent, horizontal, low-angle and wavy lamination that exhibit rhythmicity (Fig. 3.16B and D). As identified in facies 7, ichnofossils are diminutive and scattered throughout facies 8 occurrences (Fig. 3.16). Bioturbation ranges from absent to uncommon (BI 0–2) and includes a mixture of horizontal and inclined traces such as *Planolites*, *Palaeophycus*, and *Thalassinoides* with subordinate occurrences of *Teichichnus* and fugichnia (Fig. 3.16A to C).

The presence of subaqueous, current-formed structures (i.e. low-angle, wavy, and horizontal lamination) suggests sedimentation likely with low to moderate energy levels (e.g. settling from suspension). Recurrent, closely spaced, horizontal, low-angle and wavy lamination and the presence of single and double silt laminae suggest fluctuating energy levels such as the ones in tidally influenced settings (Mackay and Dalrymple, 2011). Therein, benthic organisms must overcome the hardship imposed by the interplay of salinity, sediment mobility and hydrodynamic energy that results in an impoverished and sporadically distributed assemblage (BI 0–2). The trace fossil suite is dominated by infaunal dwelling structures of ichnotaxa interpreted predominantly to reflect deposit-feeders (i.e. *Planolites*, *Palaeophycus*, *Thalassinoides* and *Teichichnus*) (Fig. 3.16). This poorly diverse assemblage delineates impoverished, stressed, low-diversity and mixed expressions of the *Skolithos* Ichnofacies with elements of the *Cruziana* Ichnofacies (Pemberton et al., 2001; MacEachern et al., 2007a). Salinity fluctuations and constantly shifting substrates could be responsible for a lowered ichnodiversity as is typically found

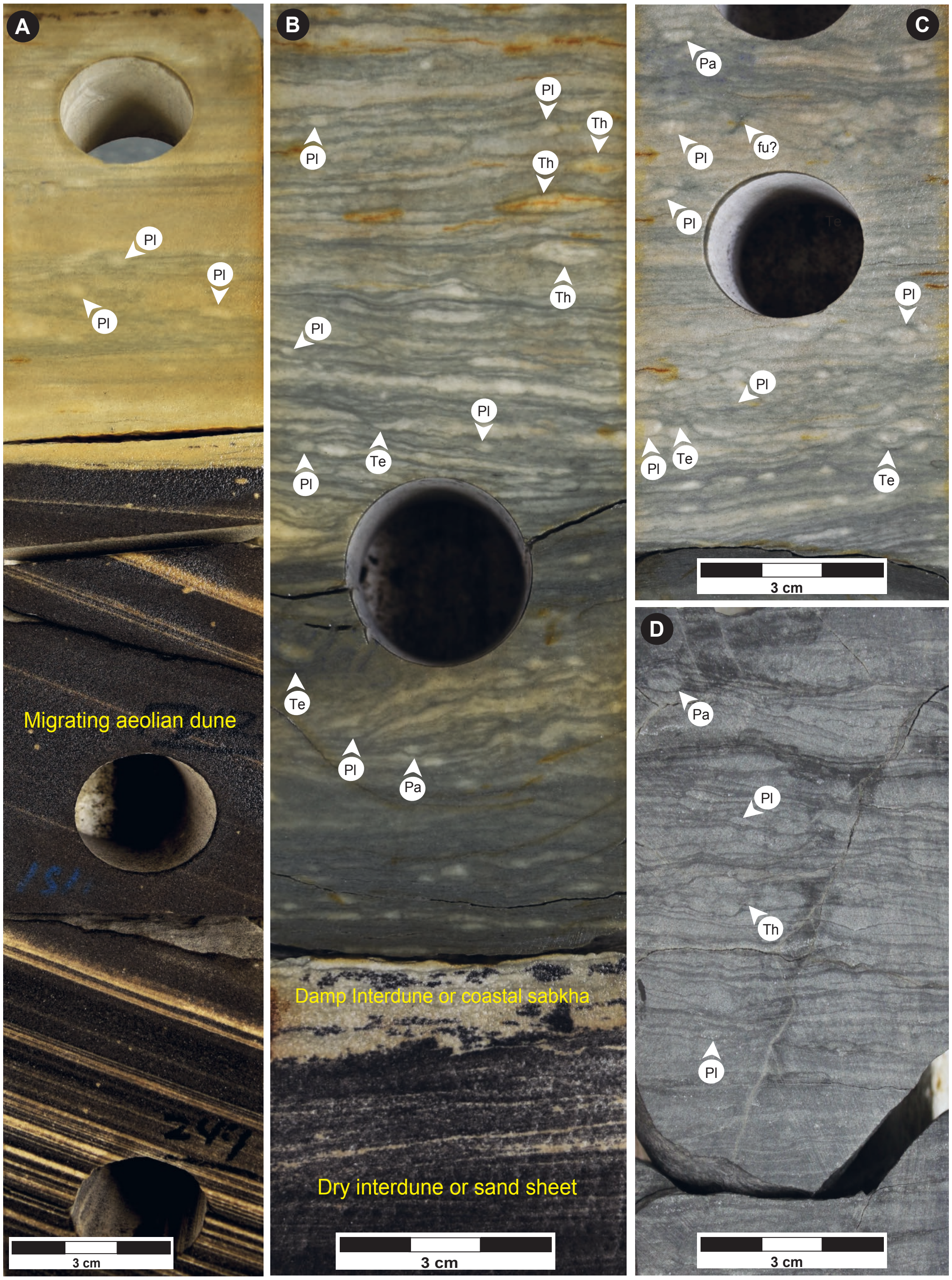


Figure 3.16. Occurrence and characteristics of facies 8: Finely laminated, burrowed, very fine- to fine-grained silty sandstone. (A) Sharp truncation at the top of moderate- to high-angle crossbedded sandstone that exhibits low-angle planar lamination passing upward into bed with wavy lamination and *Planolites* (Pl), Well 5. (B) Interval with sharp contacts between dry interdune or sand sheets and damp interdune or costal sabkha, passing abruptly into a burrowed segment that display abundant horizontal, low-angle and wavy lamination that exhibit rhythmicity towards the top. Ichnofossils include moderately robust *Thalassinoides* (Th) along with *Planolites* (Pl), *Teichichnus* (Te), and *Palaeophycus* (Pa), Well 5. (C) Segment displaying abundant horizontal, low-angle and wavy lamination and tidal rhythmicity obliterated as a product of biogenic reworking. Ichnofossils include *Planolites* (Pl), *Teichichnus* (Te), *Palaeophycus* (Pa), and fugichnia (fu), Well 5. (D) Interval with disrupted tidal couplets and wavy lamination. Trace fossils include *Planolites* (Pl), *Palaeophycus* (Pa) and *Thalassinoides* (Th), Well 6.

in sheltered, shallow-marine, tidally influenced deposits (Gingras and MacEachern, 2012). These structures are also suggestive of a setting with moderately to well circulated waters, likely with connection to the sea, allowing adequate oxygen levels at the sediment-water interface which were able to sustain bioturbating infauna (MacEachern et al., 2007a). Sediment deposition took place in a shallow-marine, restricted, tidally influenced setting and exhibits elements of a mixed, impoverished expression of the proximal *Skolithos* and *Cruziana* ichnofacies (Pemberton and MacEachern, 1995; MacEachern et al., 2010).

3.5 DISCUSSION

3.5.1 Aeolian and continental, water-table related environments (FA1)

The Tinat Member of the Nuayyim Formation in the study area comprises dune, interdune, playa lake, ephemeral stream deposits as well as palaeosol horizons summarized in FA1 (facies 1 to 6; table 1). Facies 1 and facies 2 reflect wind-dominated sedimentation (dry facies); whereas, facies 3 to facies 6 are the product of sediment accumulation controlled by the relative level of the water table (moist facies) (*sensu* Carr-Crabaugh and Kocurek, 1998). The vertical succession of facies in FA1 reflects sedimentation in a continental depositional system with a variety of environments controlled by the level of the water table and points toward sedimentation within an arid to semiarid setting as suggested by Melvin et al., (2010a,b) and Al-Masrahy (2011). The termination of these conditions is represented in the examined wells across the study area by a distinctive level with palaeosols developed in interdune zones or associated with exhumation of previously buried substrates (Figs 3.17 and 3.18).

Moist-related continental facies (F3, F4, F5 and F6) of the FA1 in the Tinat Member are attributable to variations on relative change in the level of the water table identifiable on a regional scale (Fig. 3.18); and related to relative sea-level fluctuations (Carr-Crabaugh and Kocurek 1998) that allowed bioturbating biota of shallow-marine affinity to rework erg margins and interdune zones (Figs 3.17 and 3.19). In the Tinat Member case, these changes were controlled by relative sea-level fluctuations caused by eustasy accompanied by regional and local subsidence as a product of climatic amelioration after the late Palaeozoic Ice Age (LPIA) accompanied by Neotethys expansion. A fluctuating water table in the Permian aeolian setting that characterizes the Tinat Member in the study area as identified by Melvin et al. (2010a) is interpreted, by the presence of recurrent abrupt horizontal truncations of aeolian cross-strata (Fig. 3.5). These sharp truncations in facies 1 are interpreted as "Stokes surfaces" (Stokes, 1968) or may reflect wet-interdune settings favoring the preservation of aeolian dune cross-bedded sandstones (Fryberger et al., 1988; Mountney and Thompson, 2002; Mountney and Jagger, 2004; Mountney, 2006a). In the Unayzah Formation, Melvin et al. (2005) emphasized the stratigraphic significance of identifying in subsurface core samples such rises in the ground water level. These authors also outlined the role that a rising water table plays in preserving architectural elements of an aeolian setting, such as beds with high-angle cross-stratification interpreted by them as aeolian dunes (e.g. Kocurek, 1998, 1999). Melvin et al. (2005) studied subsurface core samples of the Tinat Member at the southern end of the giant Ghawar structure in eastern Saudi Arabia (Fig. 3.1). Therein, stacked aeolian dune cross-bedded sandstones are abruptly cut by "Stokes surfaces" and reflect the interplay between the groundwater table and the depositional system. Interactions between the surface and water table interactions that mediate deposition and preservation of similar deposits in aeolian settings have been documented from the rock record (e.g. Glennie, 1994; Mountney and Howell, 2000; Kocurek and Robinson, 2001; Mountney and Thompson, 2002; Mountney and Jagger, 2004; Kiersnowski, 2013; Minervini et al., 2013) and modern settings in the Arabian Peninsula (e.g. Fryberger et al., 1983; Glennie, 1994, 1998, 2005; Al-Masrahy and Mountney, 2016). Palaeosol development and plant colonization have been inferred to represent the end product of episodes of widespread deflation and paucity of sedimentation. The pervasive occurrence of palaeosols as illustrated in Figure 18 likely lowered the accumulation surface nearly to the water table (Mountney and Thompson, 2002; Mountney and Jagger, 2004) and controlled the vertical succession of facies. Thereby, different architectural elements within aeolian environments – like the ones documented herein to occur in the Tinat Member in FA1 – were progressively obliterated by winds. When wind is undersaturated with respect to its potential carrying capacity it can lead to continuous deflation (Mountney, 2006b), before or during pedogenesis and subsequent colonization by land plants and mangrove-like vegetation in coastal intertidal zone as illustrated in facies 6 (Retallack, 1990, 1997c; Fig. 3.14).

3.5.2 Shallow-marine and tidally influenced environments (FA2)

The marginal-marine, tidally influenced facies association in the Tinat Member identified in this study is of significance because it is documented herein for the first time. It appears that, to date, there has been no reference in

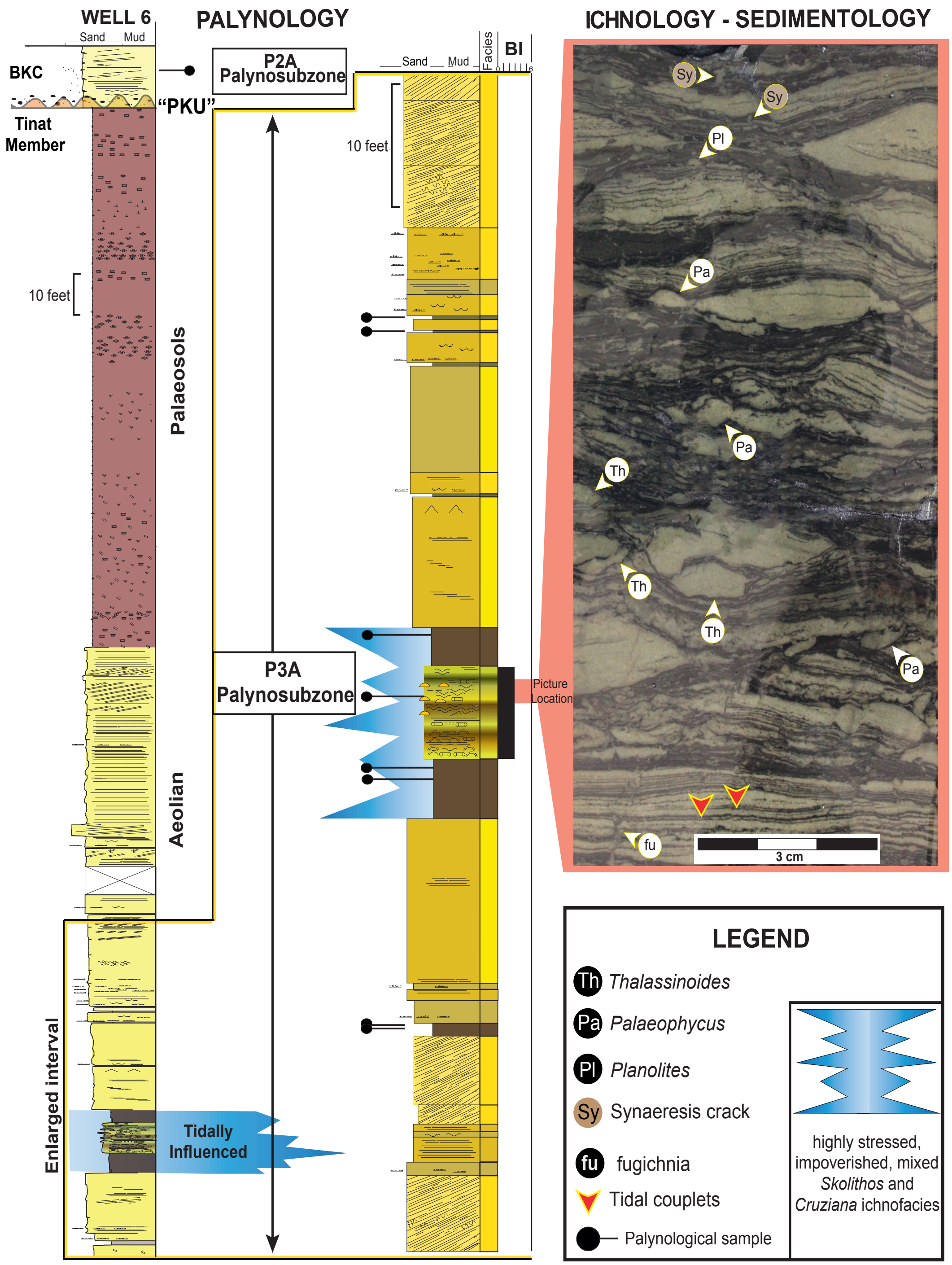


Figure 3.17. Vertical succession of facies in Well 6 showing aeolian deposits from FA1 interbedded with marginal-marine and shallow-marine tidally influenced deposits of FA2. The regionally widespread palaeosol horizon atop of the Tinat Member is abruptly cut by the Pre-Khuff Unconformity "PKU" as shown on the top left of the figure. The location of palynological samples and their resulting Palynosubzone is shown in the center of the figure. The photo on the right exemplifies tidal flat deposits and their trace fossil suite, demonstrating that marine and aeolian processes interacted at the time of deposition of the Tinat Member in central-eastern Saudia Arabia, as constrained by palynological assemblages.

the geoscience literature to shallow-marine and aeolian interactions in the Tinat Member. This facies association includes interbedded heterolithic deposits with abundant synaeresis cracks, lenticular bedding, low-angle and wavy lamination, flaser bedding, reactivation surfaces, carbonaceous double mud drapes and current ripples (facies 7; Figs 3.15 and 3.16). They reflect deposition in tidally influenced settings such as tidal flats and sheltered shallow bays that exhibit finely laminated, burrowed, very fine- to fine-grained sandstone displaying tidal rhythmicity (facies 8; Figs 3.15 to 3.17). The existence of heterolithic deposits composed of interbedded sand and mud indicates tidal influence at the time of deposition (FA2). Significantly, abundant synaeresis cracks suggest fresh-water input in marginal-marine conditions. A low-diversity and implicitly stressed ichnofossil suite in FA2 (Figs 3.15 and 3.16) records tidally influenced conditions that are characteristic of many marginal-marine settings and reflects an impoverished, low-diversity, mixed expression of the *Skolithos* and *Cruziana* ichnofacies (cf. Gingras and MacEachern, 2012; Lacroix et al., 2015). The association of diminutive, poorly diverse and abundant and locally monospecific ichnofossils with synaeresis cracks, lenticular bedding, low-angle and wavy lamination, flaser bedding, reactivation surfaces, carbonaceous mud drapes and current ripples (Fig. 3.15) has been documented as spatially and temporally recurrent in marginal-marine settings with tidal influence (e.g. Buatois et al., 2005; MacEachern and Gingras, 2007; Lacroix et al., 2015; Figs 3.15 and 3.16). This association is characterized by: 1) low ichnodiversity with locally high abundance, 2) forms typically found in the marine realm, 3) a diminutive mixture of inclined and horizontal forms with elements of the *Skolithos* and *Cruziana* ichnofacies, 4) abundance of infaunal traces with subordinate epifaunal trails, 5) simple behavioural structures of trophic generalists and 6) an overall abundance of forms made by a predominantly juvenile taxa resulting in small sizes (Pemberton et al., 1982).

In addition, tubular tidalites (sensu Gingras and Zonneveld, 2015) common in facies 7 (Fig. 3.15) are interpreted as the result of rhythmically bedded alternating layers of fine- and coarse-grained laminae deposited within open framework burrows. Gingras and Zonneveld (2015) have attributed such burrows as natural sediment traps that can preserve depositional cycles that otherwise might be missing due to high levels of bioturbation in settings such as intertidal flats and lagoons. As documented by Gingras and Zonneveld (2015), tubular tidalites have been identified from tidally influenced successions in Mesozoic, Cenozoic, and modern deposits. These structures provide evidence of tidal influence at the time of deposition in sedimentary successions. In modern settings, open framework burrows such as *Arenicolites*, *Ophiomorpha*, *Palaeophycus*, *Psilonichnus*, and *Thalassinoides* have also been documented to record tidal cyclicity (Gingras and Zonneveld, 2015; Hogson et al., 2015). The presence of tubular tidalites in facies 7 (in Figs. 3.17E to G) implies that biogenic structures record these types of rhythmicity in marginal-marine settings further back into the late Palaeozoic or, at least in Early Permian during deposition of the Tinat Member.

Shallow-marine, tidally influenced sediments (FA2) are interbedded conformably in a succession displaying a variety of deposits of aeolian origin (FA1). Their conformable nature suggests coeval, laterally adjacent deposits reflective of shallow-marine and aeolian interactions, so that the Tinat Member of the Nuayyim Formation can be described as a coastal dune field of a marine erg margin system (Figs. 3.18 and 3.19). This observation is significant because it allocates a seaward limit to the model of continental deposition dominated by aeolian sedimentation that has hitherto been largely accepted for the Tinat member of the Nuayyim Formation in subsurface central Saudi Arabia (Figs. 3.17 and 3.18).

3.5.3 The climate of the Tinat coastal dune field

Al-Masrahy (2011) analyzed the distribution of azimuthal variability in palaeowind direction using statistical methods derived from image log data and core observations in the Unayzah-A reservoir (i.e. Tinat Member in this paper). The study was located in central eastern Saudi Arabia and demonstrated sediment deposition in an arid to semiarid setting with a dominant palaeowind direction east-northeast in aeolian dune facies. The findings of Al-Masrahy (2011) are significant to our study because they allocate an upwind direction to the west that supplied wind-driven sand to the east. His study demonstrates a preferential eastward migration of aeolian dunes like the ones presented in this study in FA1 (Fig 3.5), where they were eventually reworked by tidal currents and bioturbating infauna (FA2). This allocates an eastern limit to the Tinat dune field in positions equivalent to the location of Wells 5 and 6, where sediments of FA2 with shallow-marine affinity are more abundant (Figs 3.17 and 3.18).

In addition to sedimentology and ichnology, palynological analyses were performed on samples from Well 6 (Figs 3.1 and 3.17). Samples collected from tidal flat facies in FA2 (Fig. 3.17) are barren of age-diagnostic palynomorphs. Limited assemblages recovered include rare long-ranging spores, bisaccate pollen and sparse to common granulate and thin-walled leiospheres. Although they are not age-

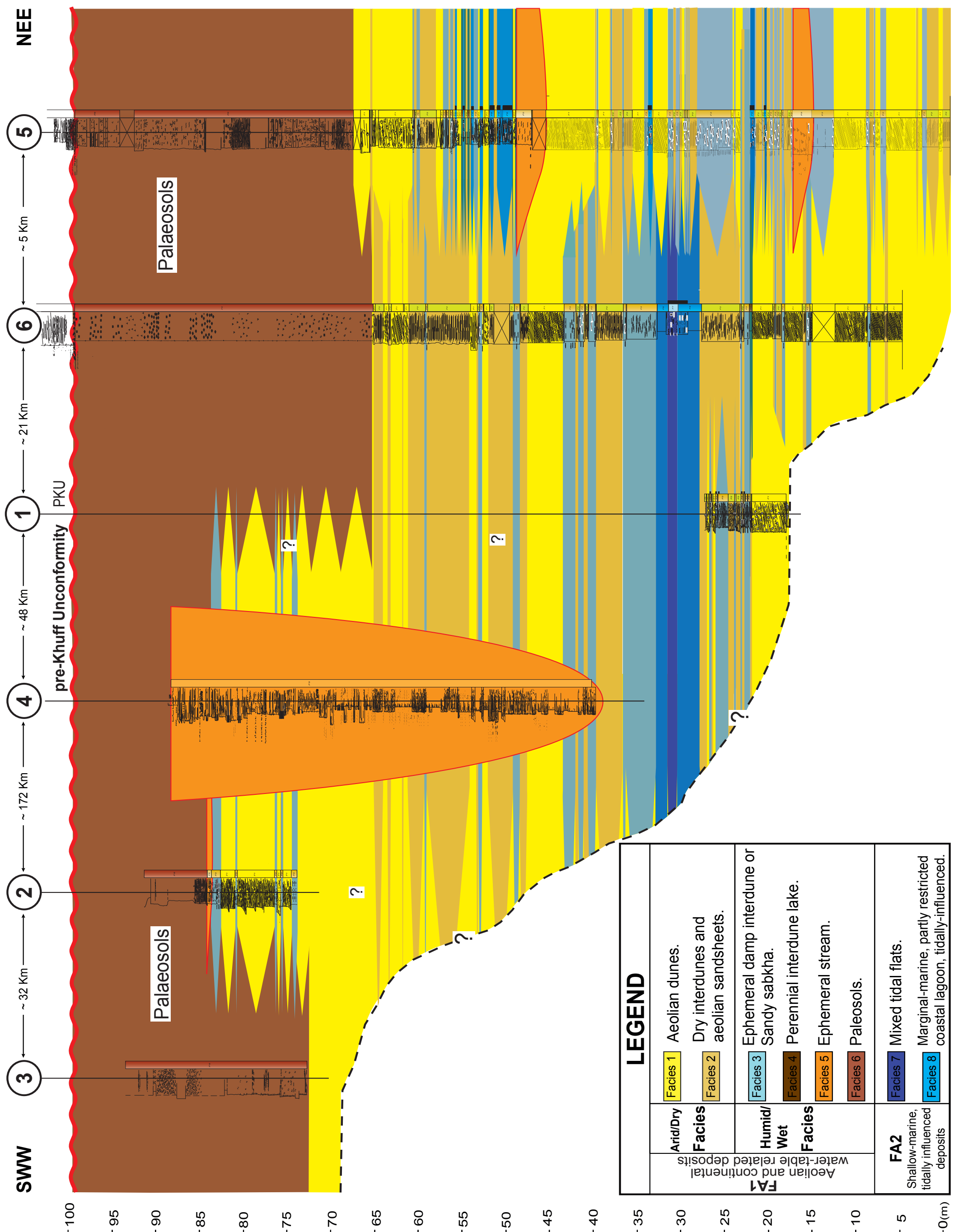


Figure 3.18. Regional stratigraphic cross-section for the Tinat Member of the Nuayyim Formation in subsurface central Saudi Arabia. The wells and cross-section are specified in Figure 3.1. The datum used as a reference level is the top of the Tinat Member. The regional cross-section was built using observations in core samples and palynological determinations. Note the increase in sediment deposition with shallow-marine affinity (FA2) concentrated towards the east (Wells 5 and 6); whereas western areas (Wells 1 and 4) are dominated by aeolian sedimentation in a continental system (FA1).

diagnostic, these leiospheres are more typical of the Tinat Member of the Nuayyim Formation as opposed to the Basal Khuff Clastics of the Khuff Formation. In the case of the samples recovered from Well 6 (Fig. 3.1), they occur below palaeosols at the top of the Tinat Member and below the Pre-Khuff Unconformity "PKU" (Fig. 3.17). The palynomorph assemblages recovered from core samples above the "PKU" in this well are relatively diverse and display good preservation. *Laevigatosporites* spp., *Lueckisporites virkkiae*, *Protohaploxypinus uttingii*, *Tiwariasporis angulistriatus*, *Vittatina costabilis*, *Vittatina* spp. and *Maculatasporites* spp. indicate assignment to the Middle Permian age (Capitanian—late Wordian), P2A Palynosubzone of Saudi Aramco and define the Basal Khuff Clastics Member of the Khuff Formation above the "PKU" (Figs 3.2 and 3.17). The relative stratigraphic position of the samples examined below the "PKU", and below the palaeosols of the upper portion of the Tinat Member in this well, suggest that the sparse to common granulate, thin-walled leiosphere assemblage could be broadly coeval with the P3A Palynosubzone of Saudi Aramco (Fig. 3.4) defined on spore-pollen characteristics and of late Artinskian to Kungurian age (Figs 3.2 and 3.17). This confirms that sediments with shallow-marine affinity and conformably interbedded aeolian strata belong to the Tinat Member of the Nuayyim Formation (Fig. 3.17).

Palynological assemblages, along with aeolian sedimentation, also suggest that sedimentation took place in an arid to semiarid setting as the Arabian Peninsula migrated northwards from a temperate zone to a more equatorial position during the late Early to Middle Permian (Hughes-Clarke, 1988; Konert et al., 2001; Appendix 4-supplementary material). Increasingly arid conditions are inferred from palynological assessments reflective of warmer conditions compared to the underlying Wudayhi Member and the Juwayl Formation. Increased aridity and warmer climate took place likely accompanied by tectonically driven variations in relative sea level as the Neotethys propagated into the Arabian Peninsula (Melvin et al. 2010a,b). The palynological assemblage recovered from samples of the Tinat Member can be placed within the P3A Palynosubzone of Saudi Aramco. The P3A Palynosubzone assemblages are completely pollen-dominated, are very similar to those in the P3B Palynosubzone, but lack the verrucate *Marsupipollenites* (*M. scutatus*) and show a greater frequency and persistence of *Corisaccites alutas* and related forms. Although they were still geographically widespread, P3A Palynosubzone assemblages overall are less frequently encountered compared with the older P3B Palynosubzone. The P3A Palynosubzone is recognized across the Arabian Peninsula, suggesting regionally warmer and drier conditions as the Arabian

Plate migrated northwards in late Early Permian times. In southern Saudi Arabia and Oman, P3A Palynosubzone assemblages have been recovered *in situ* from core samples within the lower part of the Middle Gharif Formation. The similarity in the palynological assemblages in the Middle Gharif Formation in Oman to those found in the Tinat Member of the Nuayyim Formation in subsurface central Saudi Arabia, provide evidence for strong latitudinal palaeoclimate control at the time of sediment deposition. This latitudinal control for southern Gondwana, including the Arabian Plate, is further emphasized by a similar palynological assemblage documented by Iannuzzi et al. (2010) in the Rio Bonito Formation in the southern Paraná Basin of Brazil.

3.5.4 Towards an ichnological and sedimentological model for aeolian and shallow marine interactions

In coastal aeolian systems and erg margins, a rise in relative sea level is typically associated with a rising water table (Jordan and Mountney, 2012; Rodríguez-López et al., 2006; Fig. 3.20). Typically, this rise occurs with a lag time that becomes progressively larger with increasing distance from the coastline (sensu Kocurek et al., 2001; Jordan and Mountney, 2012; Fig. 3.20). The associated rise of the inland water table also controls dune-field construction, migration and accumulation by exerting controls on the depth and areal extension of deflation, thereby shaping the architecture of the preserved succession (Blakey and Middleton, 1983; Jordan and Mountney, 2012).

Aeolian strata interbedded with thin occurrences of burrowed, marginal-marine, tidally influenced sediments in the Tinat Member underwent deflation prior to the onset of marine transgression, resulting in the generation of a nearly horizontal upper aeolian surface with associated intense mottling and rhizolith development (Figs 3.14 and 3.20). Marine incursions in the Tinat Member would likely play a role in the inland water table dynamics associated with the onset of a rise in relative sea level (Kocurek et al., 2001; Jordan and Mountney, 2012). The associated water table rise results in a decrease of sediment supply to dune fields, especially if the upwind sediment source is affected by relative sea level changes that pushed upward the deflation surface prior to marine incursions (Radies et al., 2004; Jordan and Mountney, 2012; Fig. 3.20). In the Tinat Member case presented herein, this has been emphasized by a fluctuating water table inferred from the presence of recurrent, abruptly horizontal truncations of aeolian cross-strata interpreted a

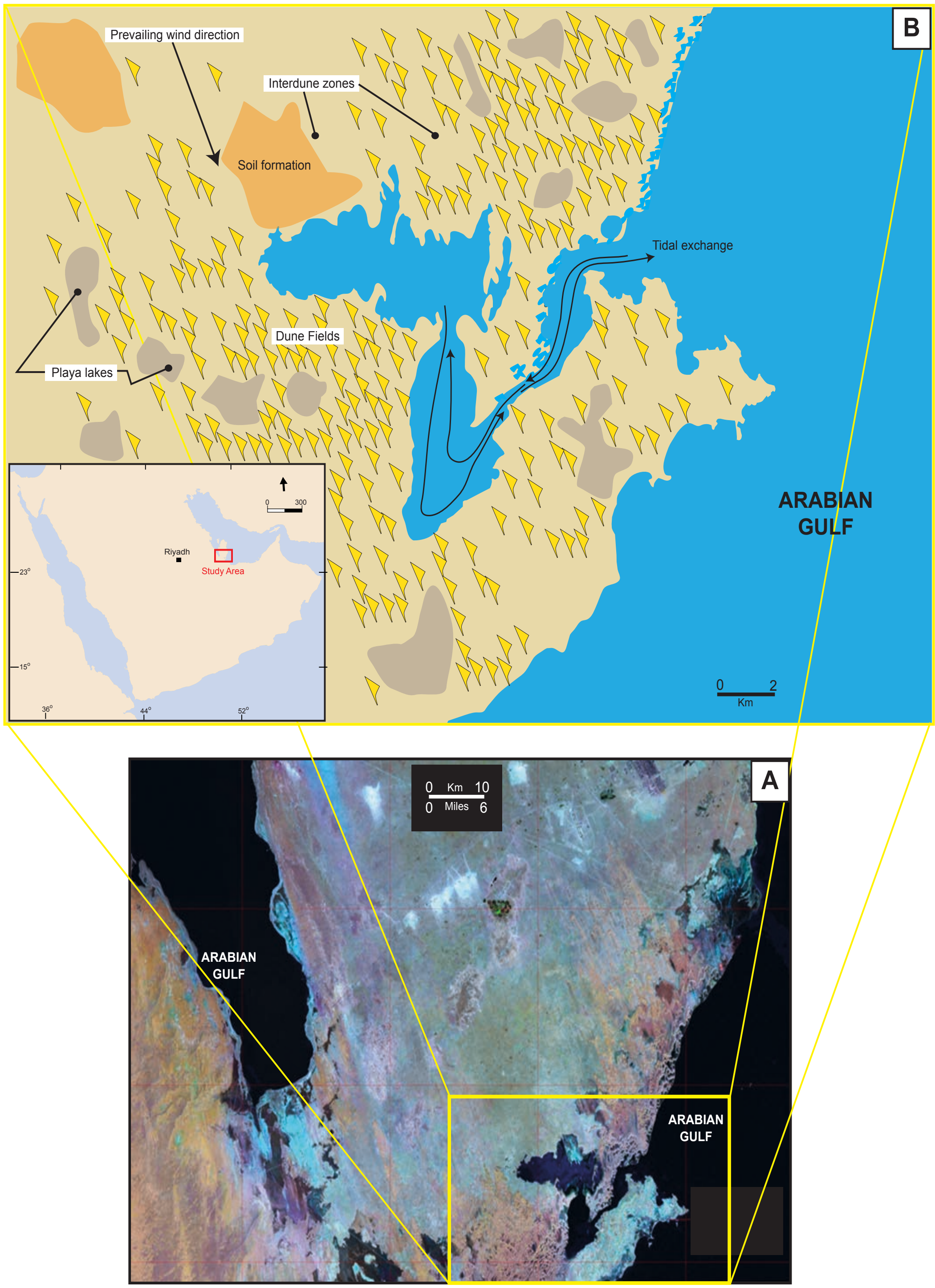


Figure 3.19. Modern analogue for shallow-marine and aeolian interactions seen in the Tinat Member of the Nuayyim Formation. Shallow-marine and aeolian interactions can be seen today across the Arabian Gulf and the western coast Mauritania among others. Therein, tide, waves and aeolian processes interact shaping the coastal morphology and lateral distribution of sediments. The Tinat Member case study constitutes an example of sediment deposition reflecting mixed-process (aeolian- and tide-influenced) depositional environments presented in FA1 and FA2 respectively.

“Stokes surfaces” in facies 1 (Fig. 3.5), thus influencing the vertical succession of facies and favoring the preservation of aeolian dune strata (Fryberger et al., 1988; Mountney and Howell, 2000; Mountney and Thompson, 2002; Mountney and Jagger, 2004; Mountney, 2006a). Alternatively, they may reflect interdune surfaces of a climbing aeolian dunefield during transgression leading also to preservation of aeolian strata (Rodríguez-López et al. 2013). The stratigraphic significance of the identification in core samples of such surfaces marking rises in the ground water level and their role in preserving aeolian deposits in the Tinat Member was illustrated by Melvin et al. (2005) and Melvin et al. (2010a,b). Their studies included core samples located at the southern end of the giant Ghawar structure in eastern Saudi Arabia (Fig. 3.1). Therein, stacked aeolian dune cross-bedded sandstones are abruptly cut by “Stokes surfaces” and reflect the interplay between the ground water table and the depositional system (Fig. 3.20).

Marine incursions identified in the Tinat Member by trace fossil associations described in FA2 can be used to delineate the extent and distribution of marine incursions in the study area (Fig. 3.20). Bioturbation of this interval is interpreted to be the result of sea-level rise that flooded low-lying topographic relief, coastal embayments, aeolian dune toesets and interdune playa lakes farther inland (Fig. 3.20). Colonization took place as a consequence of a water table influenced by sea-level changes and seasonal fluctuations that exerted influence on erg margins and coastal dune fields as interpreted in many examples from the rock record (e.g. Blakey and Middleton, 1983; Dott et al., 1986; Chan, 1989; Lancaster, 1993; Rodríguez-López et al., 2012) and modern settings across the Arabian Peninsula (e.g. Fryberger et al., 1983; Glennie, 1994, 1998, 2005; Al-Masrahy and Mountney, 2016; Fig. 3.20). Several authors have noted regional surfaces formed by contraction of erg boundaries resulting from changes in relative sea-level or tectonic setting (Brookfield, 1977; Brookfield, 2008; Brookfield and Silvestro, 2010; Rodríguez-López et al. 2013). As demonstrated by Lancaster (1993) and Blakey and Middleton (1983), such surfaces can be of local or regional (i.e. desert-wide) extent. Although the ones identified in the Tinat Member case appear to be of a rather local extent, the effect on shallow-marine burrowers was of great importance. This is largely attributable to the fact that such surfaces are especially common in coastal deserts as outlined by Rodríguez-López et al. (2013). Therein, sea-level changes directly affect desert and erg margins and groundwater levels farther inland (Brookfield and Silvestro, 2010) as postulated for the Tinat Member case presented in this study. Furthermore, in coastal dune settings, sequence-stratigraphic concepts have been

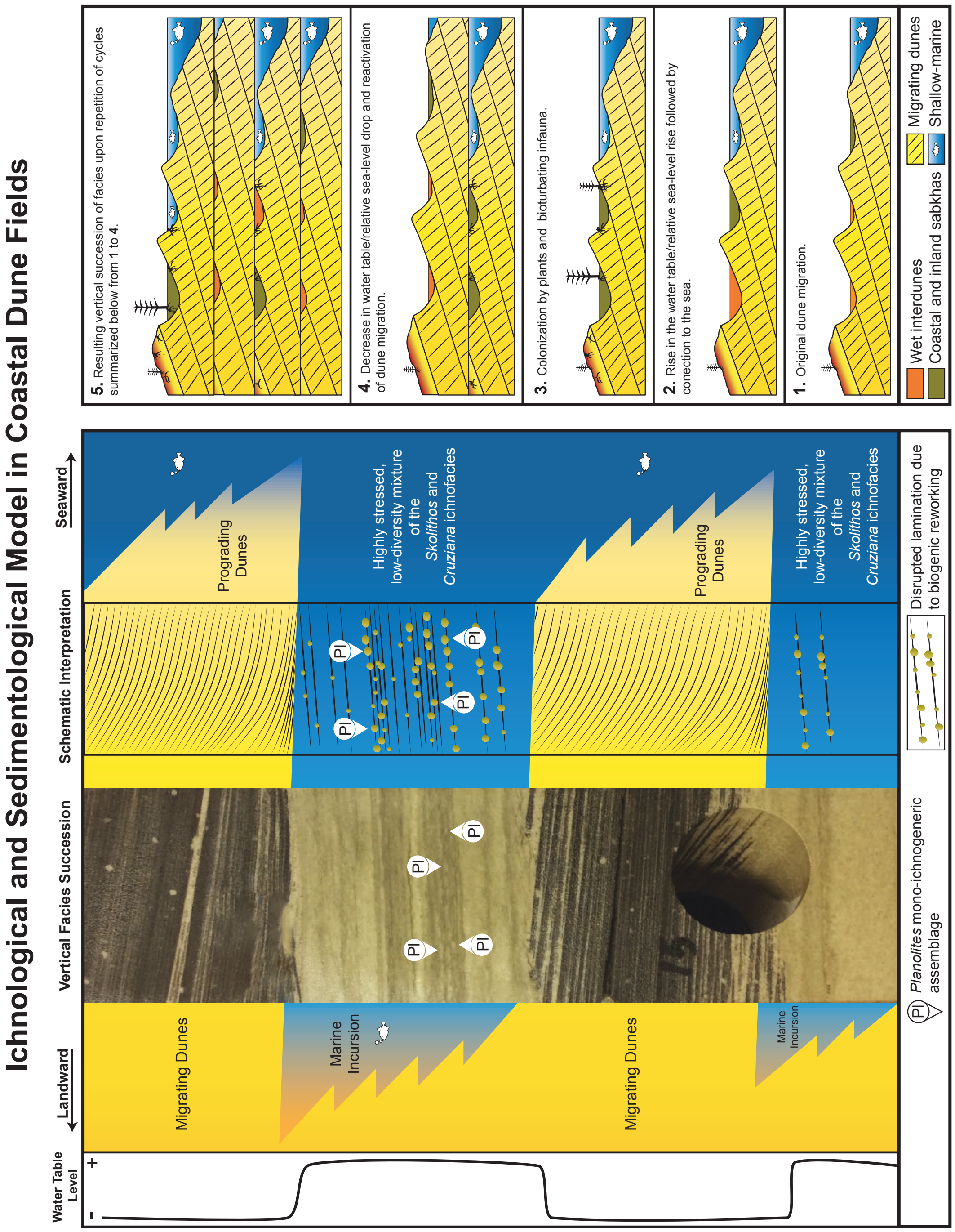


Figure 3.20. Schematic depiction of the mechanism for colonization of inland arid to semiarid environments in the Tinat Member of the Nuayyim Formation. (Left) Vertical facies succession and interplay of the groundwater table and relative sea level with its resulting ichnological suite. The core interval displays at least one transgressive surface with reworked aeolian dune toesets (cf. Rodríguez-López et al., 2013) prior to colonization by bioturbating infauna, Well 6. (Right) Vertical evolution of processes that shaped the ichnological and sedimentological signature of shallow-marine and aeolian interactions in the study area. Adapted from Langford and Chan (1988).

introduced (e.g. Rodríguez-López et al. 2013) to document coastal aeolian accumulations and their relationships with relative fluctuations in sea-level. Rodríguez-López et al. (2013), provided a succinct nomenclatural scheme for supersurfaces, allowing the distinction of different geological controls (e.g. climate change, sea-level change, and tectonics and erg migration) that determine the main aeolian bounding surfaces. Sea-level variations that shaped facies architecture in the Tinat Member are likely the product of increased tectonic activity associated with the propagation of the Neotethys onto the Arabian Peninsula. Increased tectonism in the study area could have mediated seasonal and/or longer-term flooding-induced changes in water table level such as those identified by Mountney and Russell (2009) in the largest aeolian dune complex on the sandur Skeiđarársandur of southern Iceland. Therein, seasonal and longer-term flooding-induced changes in water table levels were associated to the episodic expansion and contraction of the wet interdune ponds. In the Tinat case, rising sea level conditions allowed previously ephemeral and isolated coastal and inland playa lakes – as well as wet interdune settings described in FA1 – to be subjected to the marine influences documented in FA2 (Figs. 3.18, 3.19 and 3.20). As transgression progressed, standing water bodies could have found a connection to already established marine embayments, thus allowing trace-makers (i.e. burrowing organisms) to colonize (Fig. 3.20). Mountney and Jagger (2004) documented water table-controlled, aeolian-dominated erg margin deposits in the Permian Cedar Mesa Sandstone in Utah. Their study demonstrated that the erg margin portion of this succession represents a wet aeolian system in which spatial and temporal variations in regional water-table level determined the preserved sedimentary architecture. Sediment accumulation was controlled by progressive water table rise coupled with ongoing dune migration and the associated changes in supply and availability of sediment for aeolian transport (Mountney and Jagger, 2004; Fig. 3.20). Variation in the level of the water table relative to the depositional surface determined the nature of interdune sedimentary processes and a range of dry, damp and wet (flooded) interdune elements (such as facies 3 and facies 4 in this study; Figs 3.5 and 3.7) were recognized by these authors. Rodríguez-López et al. (2013) demonstrated that increased desert-ground water flux favored permanent coastal lakes in the fore-erg margin and the local development of vegetation in aeolian dunes of the mid-Cretaceous Iberian erg in Spain. In the Tinat Member case, groundwater-mediated interactions led to a variety of sedimentary facies associations with aeolian and tidal affinity (FA1 and FA2 respectively) as presented by Rodríguez-López et al. (2013).

They demonstrated the coexistence of aeolian dunes, playa lakes, coastal lakes with tidal creeks, marshes and lagoonal embayments with tide-influenced deposits. The same authors postulated that in places where such lakes (lagoons) were connected to the sea, tidal channels were active, and illustrated this fact with modern examples found along the desert coast of Qatar in the Persian Gulf (Rodríguez-López et al. 2012; their Figure 3.18).

Modern analogues for seasonal variability of the groundwater levels in the Tinat Member can be seen in coastal desert areas such as Qatar and Saudi Arabia in the Arabian Peninsula. As documented by Glennie (1998, 2005) and Glennie and Singhvib (2002), this variability can promote colonization by bioturbating organisms in these settings (Figs. 3.19 and 3.20), thus demonstrating the adaptability of fauna to new ecological conditions. Such studies document the role that water table plays in erg margins or coastal dune fields and they show that when transgression persists it likely allows opportunistic colonization by bioturbating organisms that enter from the marine realm (Fig. 3.20). Opportunistic colonization and ecospace utilization by bioturbating fauna following the opening of a new ecological niche has been documented to be a recurrent adaptation of organisms since the early Palaeozoic and is evidenced in the trace-fossil record (e.g. Chamberlain, 1975; Pemberton et al., 1982; MacEachern and Pemberton, 1992; Buatois et al., 1998; Hasiotis, 2002, 2007; Buatois et al., 2005; MacEachern et al., 2007a,b; Ekdale and Bromley, 2012; Lacroix et al., 2015). This demonstrates that arid and semiarid settings – as constrained by palynological data and a variety of facies of aeolian affinity (FA1) – can be colonized by organisms that inhabit the more stable ecological conditions of the fully marine realm (sensu MacEachern et al., 2007a,b). This can be illustrated by an ichnofossil suite displaying a mixture of diminutive, inclined and horizontal forms with elements of the *Skolithos* and *Cruziana* ichnofacies with brackish affinities (*sensu* Pemberton et al., 1982; Gingras and MacEachern, 2012). For the Tinat Member this case is presented in FA2 within beds conformably interbedded with aeolian deposits of FA1 (Figs 3.17 and 3.18).

3.6 CONCLUSIONS

The aeolian and shallow-marine tidally influenced sediments and their ichnological signature discussed in this paper constitute an example for future studies of aeolian and marine interactions in ancient and modern settings. It also serves as a basis for the establishment of a framework that can act as a reference model for future comparison, prediction and refining of similar successions (Walker, 1979a,b; 1984, 1992; Mountney, 2006a; Brookfield and Silvestro, 2010; Dalrymple 2010b,c). This study provides evidence for predominantly continental sedimentation with shallow-marine tidally influenced interactions within the Tinat Member of the Nuayyim Formation in subsurface of central and eastern Saudi Arabia. Integration of ichnological and sedimentological observations demonstrate that within the Tinat Member several depositional environments existed which were dominated by aeolian dune and interdune deposits, fluvial sediments and widespread palaeosols (FA1) that interacted with marine settings (FA2). Although occurrences of sediments exhibiting marine incursions are subordinate, they shaped the architecture and vertical succession of facies within this interval (Figs 3.17 and 3.20).

Continental deposits, as outlined in FA1, point toward: 1) aeolian dune and dry interdune systems, 2) wet interdune zones dominated by ephemeral and perennial lakes and 3) pedogenetic alteration from increased subaerial exposure, resulting in palaeosols. Accumulation and preservation of different aeolian environments are attributed to the interplay between the depositional environment and the groundwater table, which was likely influenced by sea level fluctuation (Melvin et al., 2010a; Fig. 3.20). Rises in the relative water table favored preservation of these deposits and prevented deflation prior to subsequent marine incursion. As transgression proceeded, likely the previously ephemeral and isolated coastal and inland playa lakes – as well as interdune settings described in FA1 – were subjected to rises in the water table which enabled the establishment of permanent water bodies that connected to the sea. As documented in FA2, this promoted subsequent colonization by the burrowing organisms which exploited the new ecological niche. Furthermore, FA2 evidence provides proof for the mechanism of colonization in coastal and inland arid to semiarid settings (Fig. 3.20).

Shallow-marine, tidally influenced deposits described in FA2 are reflective of: 1) tidal flats and 2) shallow-marine, restricted, tidally influenced sedimentation. Therein, the ichnofossil suite of biogenic structures reflects elements of a stressed, mixed, impoverished expression of the proximal *Skolithos* and *Cruziana* ichnofacies. Similar assemblages have been demonstrated to be spatially and temporally recurrent in marginal-marine settings associated to brackish settings with tidal influence.

Palynological assessments of core in this area suggest arid conditions in a predominantly continental setting (Appendix 1-supplememtary material).

Palynomorphs recovered from the core samples associated with shallow-marine deposits of FA2 and interbedded conformably with FA1 (Fig. 3.17) are completely pollen-dominated with spores and bisaccates and sparse to common granulate, thin-walled leiospheres. Although they are not age-indicative, leiospheres are considered recurrent in the Tinat Member of the Nuayyim Formation. The observed palynological assemblage can be assigned to the P3A Palynosubzone of Saudi Aramco (Fig. 3.4), thus allocating a late Artinskian to Kungurian age characteristic of the Tinat Member. In a regional context, P3A Palynosubzone is recognized across the Arabian Peninsula, suggesting regionally warmer conditions compared to the underlying Wudayhi Member and the Juwayl Formation, as the Arabian Peninsula migrated northwards from a temperate zone to a more equatorial position during the late Early Permian.

Ichnofossils documented in this paper are significant because they refine existing interpretations of the paleoenvironmental history in the study area. Aeolian and marginal-marine, tidally influenced sedimentation occurred during deposition of the Tinat Member of the Nuayyim Formation, thus confirming marine influence on sedimentation in an interval historically interpreted as being dominated by aeolian continental settings. More importantly, documenting the ichnological signature of aeolian and shallow-marine tidally influenced interactions in the Tinat Member constitutes a case study that can be used: 1) to build sedimentological and ichnological facies models in coastal dune fields and erg margins and 2) to characterize the resulting trace fossil association in these particular settings which can be used elsewhere in the rock record. This work fills a gap in the geoscience literature by documenting the colonization of these particular settings in late Palaeozoic time.

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CHAPTER 4 – ICHNOLOGY, PALEOSOLS AND PALIMPSEST SURFACES IN THE TINAT MEMBER OF THE NUAYYIM FORMATION (UNAYZAH GROUP), SUBSURFACE SAUDI ARABIA: TRACE FOSSILS AND GENETIC STRATIGRAPHY IN CONTINENTAL SETTINGS*

4.1. INTRODUCTION

Recent advances in ichnology document the applications of ichnology to genetic stratigraphy, and trace fossils analysis has become an important tool in recognizing and delineating the presence of stratigraphic discontinuities in sedimentary successions (MacEachern et al., 2007c). In most cases, intervals displaying superposition of ichnofossil assemblages resulting from two different colonization episodes in two different depositional settings are known as palimpsest surfaces (Pemberton and Frey, 1985; Mangano et al., 1998, 2002; Buatois and Mangano, 2004, 2011a; Dafoe et al., 2006; MacEachern et al., 2007a; Díez-Canseco et al., 2015). This is done by integrating the analysis of ichnofossil suites, physical sedimentary structures and sequence stratigraphic principles (e.g., Pemberton et al., 1992a; Pemberton and MacEachern, 1995; Pemberton et al., 2004; Savrda et al., 2001a,b; Bann et al., 2004). In turn, this yields refined interpretations through the record in situ of animal and sediment interactions and in some cases particular ecological aspects operating in the depositional setting can be also discerned by stablishing relationships (i.e., tiering analysis) between suites that may or may not be genetically related. Continuous research has led to refinements in the understanding and application of substrate-controlled *Glossifungites*, *Trypanites* and *Teredolites* Ichnofacies and they have been accepted as a tool to recognize stratigraphic surfaces (e.g., Pemberton and Frey; 1985; Gingras et al. 1999, 2000; MacEachern et al., 2007c). A vast body of research documents cases where omission suites are demarcated by trace fossils, thus allowing recognition of discontinuities of significant sequence stratigraphic hierarchy. Historically, the recognition of breaks in sedimentation has been chiefly associated with elements of the *Glossifungites* Ichnofacies and regarded as *Glossifungites*-demarcated discontinuity surfaces

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Less attention has been drawn to the application of these paradigms into the continental realm compared to the marginal-marine, shallow-marine and deeper marine counterparts (e.g., Bromley, 1975; Hayward, 1976; Savrda, 1991b; Bhattacharya, 1993; Mangano et al., 1998; Savrda et al., 2001a,b; Pemberton et al., 2001; Bann et al., 2004; Pemberton et al., 2004; Buatois and Mangano, 2009; Díez-Canseco et al., 2015; Genise, 2017). In these settings the recognition of autocyclic generation of omission has been well documented including the spatial and temporal variations in the recurring character of their assemblage (MacEachern et al., 2007c). This stems largely from the decrease of preservation potential of trace fossil assemblages in continental settings compared to the marginal-marine and shallow-marine suites (Hasiotis, 2002; Ekdale and Bromley, 2012). Buatois and Mangano (2009) evaluated the potential and limitations of lacustrine trace-fossils in sequence stratigraphy and proposed a model of trace-fossil distribution in overfilled, balanced-fill, and underfilled basins. These authors highlighted that when compared with their marine couterparts (particularly the firmground *Glossifungites* Ichnofacies), substrate-controlled ichnofossil suites in lacustrine successions are only rarely indicative of erosional exhumation. This was largely attributed to the fact that substrate-controlled assemblages in lacustrine settings are commonly related to desiccation of water bodies (Buatois and Mangano, 2004; 2009). However, and similarly to shallow-marine settings, the main applications of ichnology to genetic stratigraphy paradigms in the continental realm are underpinned in the recognition of stratigraphically important discontinuities (MacEachern et al., 2007c). Recognizing breaks in the record of autocyclic or allocyclic origin is largely done on the on the basis of the recognition of omission suites and juxtaposition of recurrent suites that do not reflect the archetypical assemblage associated with a particular depositional environment (MacEachern et al., 2007a,b). In many instances, sedimentology alone may assist on this (*sensu* Swift et al., 1971) but in some particular cases, multiple stages of colonization and modification of the primary sedimentary fabric can be significantly enhanced by the recognition of more than one phase of colonization of a substrate and the study of their ichnofossil suites relationships (Mangano et al., 1998; MacEachern et al., 2010; Genise, 2017). Díez-Canseco et al. (2015) summarized the ichnological suites of fluvio-tidal transitions based in a number of case studies drawn from neoichnological studies and trace-fossil analysis from the rock record. Their study found that ichnofossil assemblages of the fluvial-tidal deposits in Mezosoic-Cenozoic strata commonly reflect a composite suite wherein previously emplaced brackish-water assemblages are overprinted by a younger suite reflecting elements of the *Scoyenia* Ichnofacies (Díez-Canseco et al., 2015). As outlined by MacEachern et al. (2007c) specific characteristics of a vertical successions such as the character of the discontinuity, and hence the omission suite associated with it, is determined by the complex interplay of: (i) the lithologic character of the underlying exhumed strata; (ii) the nature of the substrate coherence; (iii) the energy conditions at the time of the colonization; and (iv) the duration of the colonization window. In continental settings, the recognition of substrates hosting biogenic suites demarcating autocyclic as well as allocyclic boundaries are commonly associated with elements reflecting the *Scoyenia* and *Coprinisphaera* Ichnofacies (Genise et al., 2000, 2004; Genise, 2017). Therefore, a systematic approach that involves a diligent, independent analysis of both, pedofabric and ichnofabric it is necessary to understand complex temporal and spatial tiering relationships (cf. Genise et al., 2004a; Genise, 2017). However, this is still a growing field and the documentation of case studies will contribute to refine and to stablish a framework in settings wherein sedimentology alone may yield inconclusive results (Genise et al., 2000, 2004; MacEachern et al., 2007a,b; Genise, 2017).

This study describes the ichnology and sedimentology of the Tinat Member of the Nuayyim Formation in the subsurface of central Saudi Arabia (Fig. 1). Documented herein are: (i) animal-sediment interactions at the time of sedimentation with particular emphasis in the paleosols that occur on top of the Tinat Member; (ii) trace fossil suites paired with sedimentological observations as bases of further refinement of the environment of this interval; (ii) widespread paleosols on top of the Tinat Member presented as palimpsest surfaces wherein biogenic modifications demarcate the end of a whole sedimentation cycle. Furthermore, this study documents the utility of trace fossils in genetic stratigraphy in continental settings where spatial and temporal complexities can be resolved by incorporating trace fossil analysis.

4.2. STUDY AREA AND GEOLOGICAL SETTING

The Upper Carboniferous–Middle Permian Unayzah Group is part of a sand-rich Paleozoic succession in the subsurface of Saudi Arabia (Fig. 4.1) that encompasses strata ranging from Cambrian through Permian in age (Fig. 4.2). The Unayzah Group (sensu Price et al., 2008) consists of a series of predominantly sand-rich strata deposited on, and filling-in the paleotopography of the Hercynian Unconformity, so-called "pre-Unayzah Unconformity" of Al-Husseini (2004), and is bounded at the top by the "Pre-Khuff Unconformity" of Senalp and Al-Duaiji (1995) in the subsurface of Saudi Arabia (Husseini, 1992; Al-Husseini, 2004; Faqira et al., 2009; Price et al., 2008; Melvin and Heine, 2004; Melvin et al., 2005; Melvin et al., 2010a,b; Melvin and Norton, 2013; Polo et al., 2018).

Ferguson and Chambers (1991) identified a lithostratigraphic succession that in ascending stratigraphic order comprises a basal interval they referred to as the Unayzah C Member, although this was variable laterally. The Unayzah C Member was overlaid by a sand-prone Unayzah B Member that was in turn capped by sandstones of the Unayzah A Member. The former being separated from the latter by a red siltstone.

Sharland et al. (2001) proposed a sequence stratigraphic framework encompassing the Phanerozoic rocks of the entire Arabian Plate. They identified a

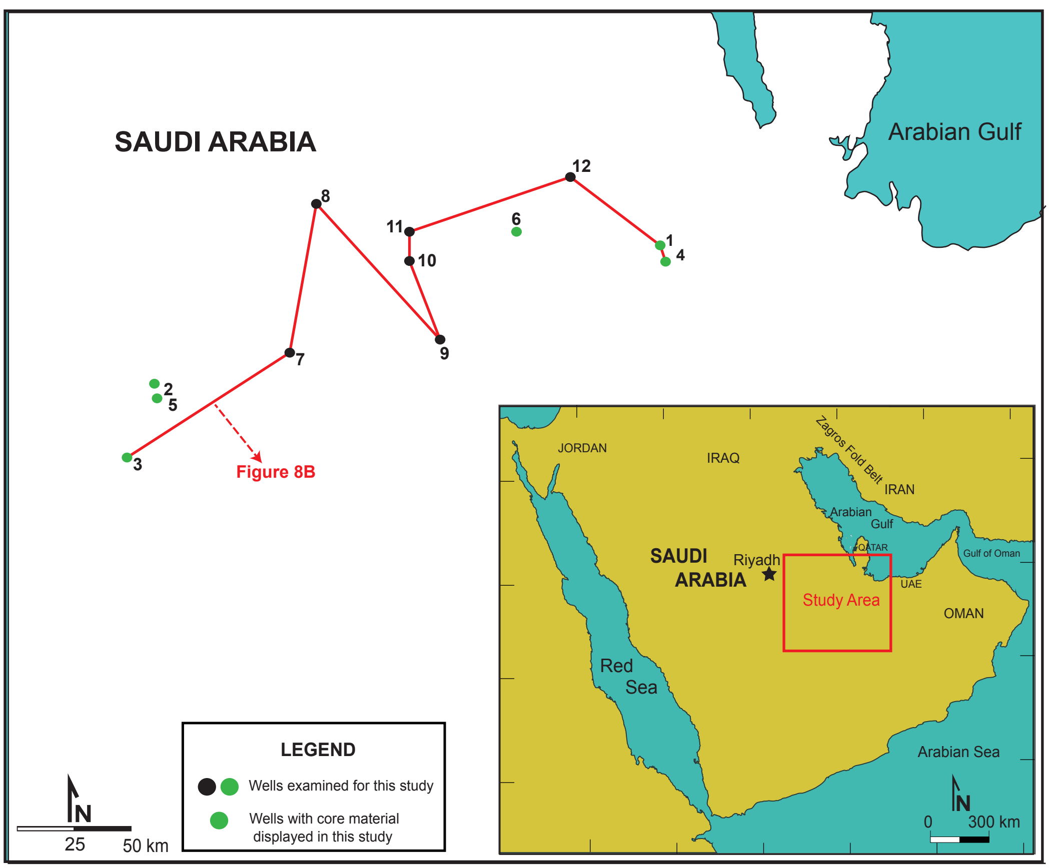

Figure 4.1. Location map showing the Arabian Peninsula and the location of the wells involved in this study.

number of "Tectonostratigraphic Megasequences" (TMS) based on the integration of outcrop and subsurface datasets that underpin that sequence stratigraphic framework. The entire Unayzah Group falls within their TMS AP5 megasequence (Fig. 2). It is bounded at its base by the Hercynian Unconformity (Pre-Unayzah Unconformity), representing the mid Carboniferous "Hercynian tectonic event" in Arabia and by the "Pre-Khuff Unconformity" at the top.

Melvin and Sprague (2006) interpreted the Unayzah C and B members to comprise facies representative of the Late Paleozoic Ice Age (LPIA). They identified a new lithostratigraphic unit within the lowest part of the Unayzah A Member of Ferguson and Chambers (1991). This was informally referred to as the "Un-named middle Unayzah member" (Fig. 4.2). Those authors proposed that the "Un-named middle Unayzah member" was equivalent to the Lower Gharif Member that rests directly above the Al Khlata Formation in Oman (Polo et al., 2018).

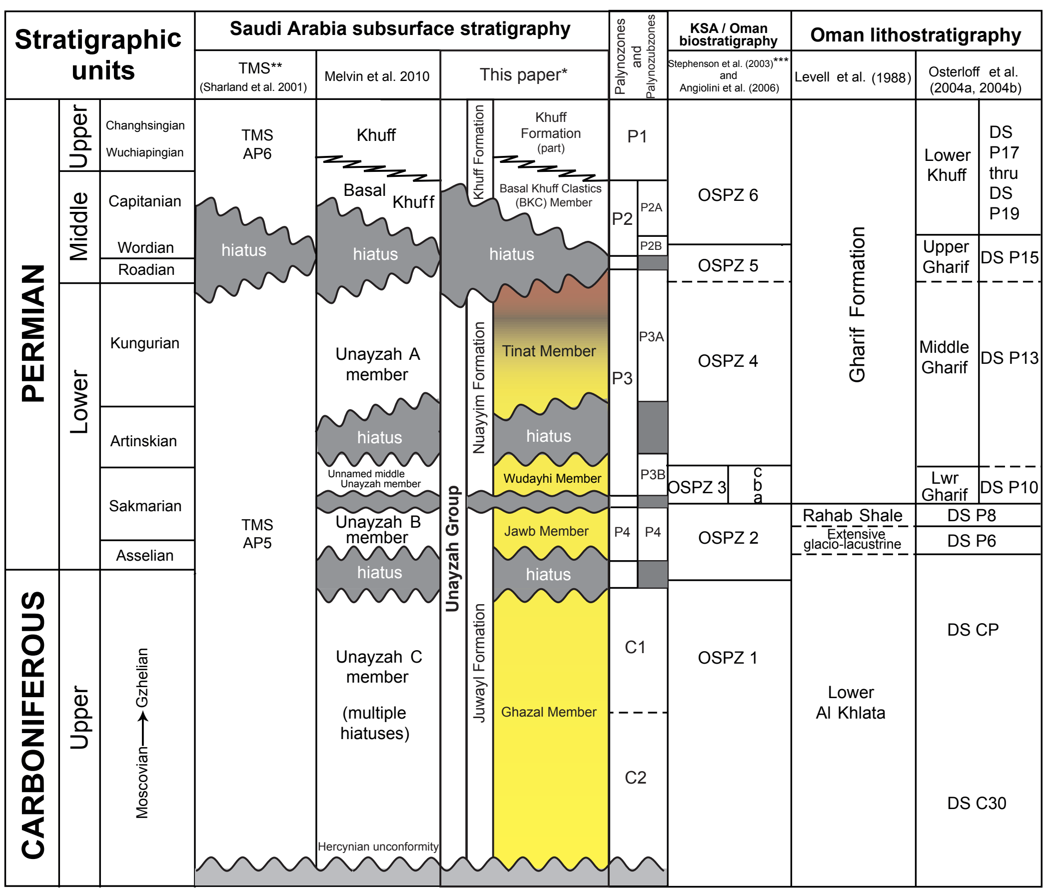

Figure 4.2. Late Carboniferous-Permian stratigraphic framework of Saudi Arabia (KSA) and Oman. (*) This study follows the stratigraphic nomenclature proposed by Price et al., (2008) for subsurface Saudi Arabia. (**) Tectonostratigraphic Megasequences (TMS) of Sharland et al., (2001) and (***) biostratigraphic zonation (OSPZ1-OSPZ6) of Stephenson et al., (2003) provide the regional context to compare age-equivalent successions across the Arabian Peninsula extending south into Oman.

Price et al. (2008) proposed a new stratigraphic framework for the strata between the Hercynian Unconformity and the "Pre-Khuff Unconformity". At the base, the Juwayl Formation represents sediments deposited during the Late Paleozoic Ice Age. It was further subdivided into two members, namely the Ghazal Member (formerly the Unayzah C Member), that rests upon the Hercynian Unconformity and represents syn-glacial deposition and deformation. It is overlain by the Jawb Member (formerly the Unayzah B Member) which comprises the deposits associated with the terminal melting of the ice sheets. The Juwayl Formation is overlain by the Nuayyim Formation which is entirely postglacial in character and is also further subdivided it into two members named: 1) the Wudayhi Member (formerly the "Un-named middle Unayzah member") overlain by 2) the Tinat Member which is truncated at the top by the "Pre-Khuff Unconformity" following a significant phase of paleosol development.

Melvin and Norton (2013) found the Unayzah C and B members in the subsurface to be equivalent to the Juwayl Formation and equivalent to the glaciogenic Al Khlata Formation in Oman on the basis of their same palynological signature (see Osterloff et al., 2004a, 2004b). Thus, the Unayzah C Member of subsurface Saudi Arabia and the lower Al Khlata Formation of Oman can be assigned palynologically to the *Potonieisporites* Assemblage of Love (1994), OSPZ1 Zone of Stephenson et al. (2003) and C1 Palynozone of Saudi Aramco and are dated as late Carboniferous (Moscovian to Gzhelian) (Fig. 4.2). The overlaying Unayzah B Member and the upper Al Khlata Formation (of subsurface Saudi Arabia and Oman respectively), are assigned to the *Microbaculispora* and *C. cymbatus* Assemblages of Love (1994), OSPZ2 of Stephenson et al. (2003) and P4 Palynozone of Saudi Aramco. The assignation for most part of an Early Permian (Cisuralian), Asselian-early Sakmarian age for this member, is based on comparison with faunally callibrated *Converrucosisporites confluens* Oppel Zone palynofloras in Western Australia (Foster and Waterhouse, 1988). However, Stephenson (2009), referencing radiometrically age controlled palynological assemblages from sediments in Namibia has suggested that assemblages similar to those in the middle part of OSPZ2 and containing *Converrucosisporites confluens*, could be of latest Carboniferous (Gzhelian) age (~302 Ma). This suggests that the lower part of OSPZ2 could also be of Late Carboniferous (Gzhelian-Kasimovian) age (Stephenson, 2009).

Palynomorphs found in the Nuayyim Formation are assigned to the P3 Palynozone of Saudi Aramco, which is in part equivalent to the *K. subcircularis*

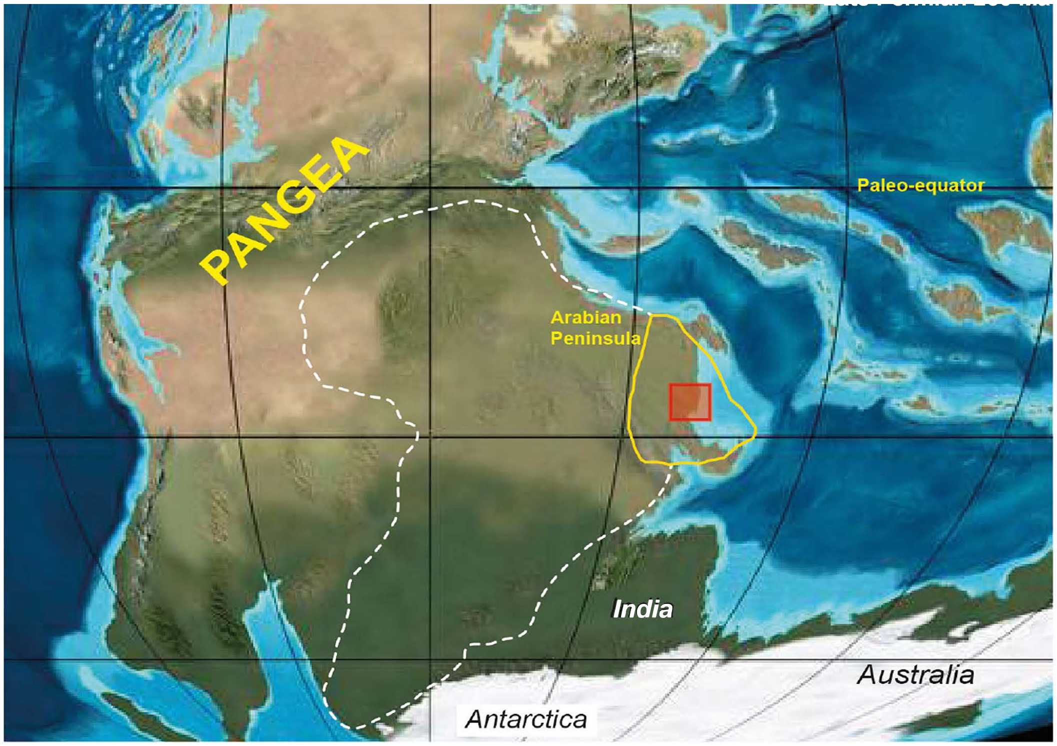

Figure 4.3. Molleweide projection of paleogeography during the Middle to Late Permian (Approx. 260 Ma) showing the land distribution and the Tethys and Panthalassa oceans. During this period, the area corresponding to the modern day Arabian Peninsula was located between 15° - 35° South of the equator in the temperate zone. Red square marks the study area for this paper in present day central Saudi Arabia, (modified from Blakey, 2011).

Assemblage of Love (1994). The P3 Palynozone is subdivided into the older P3B Palynosubzone which is limited to the Wudayhi Member. This is overlain by P3A Palynosubzone (Tinat Member). The P3B assemblage is Sakmarian-early Artinskian and the P3A assemblage is late Artinskian to Kungurian in age. The P3B Palynosubzone contains persistent *Marsupipollenites spp*. (notably *M. scutatus* and *M. striatus*) and assemblages are generally pollen-dominated and characterized by taeniate sulcate (*Striasulcites*), taeniate bisaccate (*Protohaploxypinus*), pseudo-bisaccate (*Caheniasaccites*), taeniate monosaccate (*Striomonosaccites*, *Mabuitisaccites*) and large costate (*Vittatina*) forms. Earliest records of rare *C. alutas* and similar forms, *C.* cf. *alutas* and *Lueckisporites* cf. *virkkiae*, occur in the upper part of P3B Palynosubzone. With reference to data presented by Angiolini et al. (2006) and Stephenson and Osterloff (2002), this equates to a level within OSPZ3 described by Stephenson et al. (2003), that is probably equivalent to the base of the OSPZ3b-c interval, above the P10 mfs within the tectonostratigraphic framework of the Arabian Peninsula of Sharland et al. (2001) (Fig. 4.2). The implication of these age assignment is significant in that the P3B Palynosubzone equates to the OSPZ3 of Stephenson et al. (2003) which characterizes the Lower Gharif Member of the Gharif Formation in Oman. P3A Palynosubzone assemblages are entirely pollen dominated with forms that are very similar to those in the P3B Palynosubzone. The absence of verrucate *Marsupipollenites* (*M. scutatus*) and a greater frequency and persistence of *C. alutas* and similar forms allow differentiation of the P3A from the P3B Palynosubzone.

4.3. DATASET AND METHODS

A total of 19 subsurface core samples from 6 wells covering the Tinat Member of the Nuayyim Formation in eastern and central Saudi Arabia were examined in order to describe their sedimentological and ichnological characteristics. Sedimentological analysis focused on characteristics such as lithology, grain size and composition, sorting, bed thicknesses, bedding contacts and the identification of primary physical sedimentary structures. Trace fossil assessments were focus on the identification of ichnotaxa, their distribution and abundance. These characteristics are reflected in the intensity of bioturbation (Bioturbation Index (BI), sensu Reineck, 1963; Taylor and Goldring, 1993).

4.4. RESULTS AND INTERPRETATION

The Tinat Member of the Nuayyim Formation in the study area is characterized by six facies that reflect continental deposition (Table 4.1). These are aeolian dune (Facies-1), dry interdune (Facies-2), damp interdune and ephemeral sabkha (Facies-3), wet interdune and perennial sabkha (Facies-4), ephemeral stream deposits (Facies-5), and paleosols (Facies-6) (Figs. 4.4, 4.5, 4.6, 4.7, 4.9 and 4.11). The vertical distribution of these facies and their ichnological suites is summarized for each well examined starting in Figure 5. Similarly, Table 1 outlines the most relevant lithological, sedimentological and ichnological characteristics of each facies.

4.4.1. Facies-1: Aeolian dune

This facies consists of fine- to medium-grained, moderately high to high angle, crossbedded sandstone that ranges in color from brick red and red brown to buff yellow and pale to dark gray (Fig. 4.4). Sand grains are well to very well

CONTINENTAL FACIES ASSOCIATION				
FACIES NUMBER AND NAME	**LITHOLOGICAL OBSERVATIONS & CONTACTS**	**SEDIMENTARY STRUCTURES AND PRIMARY FABRIC**	**ICHNOLOGICAL CHARACTERISTICS**	**PALEOENVIRONMENTAL REMARKS**
Facies-1: ***Aeolian dune***	• Well to very well sorted, fine- to medium-grained, sandstones. • Nodular and patchy anhydrite is widespread as cement. • Sand grains display well roundedness, sphericity and frosted surfaces, • Occasionally upper boundaries are marked by abruptly truncated horizontal surfaces. • Abrupt horizontal truncations of eolian cross-strata are identified as *Stokes surfaces* (cf., Stokes, 1968). • Bed contacts are mostly sharp.	• High angle (>30°), grain size-segregated cross laminations and cross bedding. • Laminations thickness varies. It could be widely spaced (cm-scale) or densely packed "pin-striped" (mm-scale). • Grain size may display polymodal and bimodal distribution. • Common wind-ripple laminations. Lamina displays gradual thinning downwards on the lee slope. • Occasionally, alternating thick and also thin, inversely graded sand beds. • Occasionally, deformed laminae at the base of beds and bedsets.	• Bioturbation is absent. • Bioturbation Index (BI = 0)	• Well to very well sorted sand suggests continuous transport mechanisms promoting grain sorting and rounding. • The presences of Stokes surfaces suggest fluctuating levels in the groundwater table. • Main sediment transport mechanism includes wind transport through saltation and sand particles collision. • Closely spaced (densely packed) lamination with inverse grading suggests migration of wind ripples. • Alternating thick and thin sand beds can be interpreted as grain flow cross-strata formed by gravity sliding of sand down aeolian dune slip faces and grain fall respectively. • Conclusion: Aeolian dune.
Facies-2: ***Dry interdune***	• Fine- to medium-grained well sorted sandstones. • Common, nodular and patchy anhydrite cement. • Sand grains display frosted surfaces, well roundedness and sphericity. • Locally, erosive at the base overlaying deflation surfaces and *Stokes surfaces.* • Contacts are mostly abrupt. Occasionally, transitional.	• Low angle (<30°) to flat, grain size-segregated cross laminations and cross bedding. • Laminations are commonly closely spaced, densely packed "pin-striped" (mm-scale). • Inversely graded. Grain size may display polymodal and bimodal distribution. • Abundant wind-ripple laminations. • Locally, very low angle truncations separating different sets of the low-angle laminated sand.	• Bioturbation is absent. • Bioturbation Index (BI=0).	• Well to very well sorted sand suggests continuous transport mechanisms promoting grain sorting and rounding. • "Pin-stripe' lamination suggests deposition of silt and very fine sand in the troughs of the advancing wind ripples. • Main sediment transport mechanism includes wind transport through saltation. • Continuous wind action and a fluctuating water table may be the most important factors contributing to the preservation of these deposits. • Conclusion: Aeolian sand sheet.

Table 4.1. Lithological, sedimentological and ichnological characteristics of each facies identified for the Tinat Member of the Nuayyim Formation in the study area. Particular interpretations are expanded on the main body of the text for each facies.

Facies-3: ***damp interdune and ephemeral sabkha***	• Fine- to medium-grained sandstones. • Common, nodular anhydrite cement. • Abundant, patchy anhydrite cement. • Sand grains display moderate to well sorted, and well roundedness. • Contacts are mostly abrupt. • Occasionally, transitional. • Locally, erosive.	• Abundant adhesion ripples and adhesion laminae, irregular to crinkly, variably continuous laminations. • Commonly, horizontal and low-angle, poorly defined (i.e., faint) greyish lamination	• Bioturbation is absent. • Bioturbation Index (BI = 0).	• The degree of dampness or dryness may have been a function of rainfall during wetter periods and/or fluctuations in the level of the ground water table. • Continuous deflation by wind action and a fluctuating water table may be the most important factors contributing to the "wetting" and preservation of these deposits. • Abundant irregular laminations and adhesion structures suggest sedimentation upon a damp substrate in close proximity to the groundwater table. • Conclusion: Ephemeral damp interdune or sandy sabkha.
Facies-4: ***Wet interdune and perennial sabkha***	• Very fine- to fine grained silty sandstones. • Locally, small silt beds, centimeter scale. • Occasionally, coarser-grained sand laminae. • Common, nodular anhydrite cement. • Abundant, patchy anhydrite cement. • Contacts are mostly transitional. • Occasionally, abrupt. • Locally, lower contacts display *Stokes surfaces.*	• Chiefly, lenticular to indistinct crinkly lamination, and locally, ripples and small-scale ripple cross-lamination. • Subordinate, planar and quasi planar adhesion laminae. • Commonly, thin, flat-lying (horizontal) laminae with grains of well rounded, medium to coarse sand. • Locally, sub-vertical sand-filled cracks (desiccation cracks).	• Bioturbation is absent. • Bioturbation Index (BI = 0).	• Sedimentation may have occurred at times when the water table rose above the depositional surface within an otherwise arid (desert-like) environment. • Fluctuation of the lake levels may be a function of seasonal rainfall or water table variations. • Sediment transport mechanisms include wind and water. Deposition occurred within very shallow interdune ponds. • Sedimentary structures are interpreted here to have been formed in a predominantly wet environment and/or associated to subaqueous sedimentation. • Conclusion: Perennial interdune lake.

Table 4.1.– *Contined.*

Facies-5: ***Ephemeral stream deposits***	• Dominated by very fine- through coarse-grained sandstone. • Commonly, very fine-grained silty sandstone with mud in form of mud drapes. • Locally, towards the base of individual beds, granules, pebbles and small mud clasts. • Commonly, nodular and patchy anhydrite cement. • Contacts are commonly, sharp erosional lower contacts.	• Generally, either massive or flat laminated. • Ripple cross-lamination is common with abundant mud drapes. • Mostly thin-bedded units. But, commonly, beds can be found amalgamated. • Locally, beds comprise very fine-grained silty sandstone that displays well-developed ripple cross-lamination. • Occasionally, desiccation cracks associated to mud drapes.	• Bioturbation is absent. • Bioturbation Index (BI = 0).	• Finer-grained, and ripple laminated sediment may be indicative of the waning flow deposits of episodic flood events. • Desiccation in the finer, mud-draped portions suggests settling down of finer material after episodes of sedimentation and subsequent cracking after periods of widespread exposure in a semiarid environment. • Main sediment transport mechanisms include seasonal or episodic water flows. • Low laying topographic relief and wadis may have been affected by ephemeral floods that resulted in fluvial gravels with intraclast derived from Facies-1 through Facies-4 in this table. • Conclusion: Semiarid Ephemeral Stream Deposits.
Facies-6: ***Paleosols***	• Very fine- through coarse-grained sandstone and siltstones. • Poorly sorted as a result of pedogenic alteration. • Silcrete nodules and development of silcrete cement. • Locally, nodular and patchy anhydrite cement. • Locally, sharp (truncated) upper boundaries. • Contacts are mostly transitional.	• Mostly, burrow mottled texture resulting in a "spotty" appearance. • Locally, discernable original primary sedimentary structures are preserved (e.g., horizontal and low-angle lamination). • Commonly, aggregates, lumps or clods of soil (i.e., peds) structures and cutans. • Locally, filled cracks between peds.	• Bioturbation varies from uncommon to complete bioturbation. • (BI = 0-6). • Palimpsest-demarcated discontinuity colonization. • Subsequent colonization displays continental ichnogenera that includes; *Taenidium, Planolites and Palaeophycus tubularis* • Commonly, the assemblage is associated to plant root traces (i.e., rhizoliths).	• Continental infaunal ichnofossils and their association to plant roots suggest low to no sedimentation, allowing the establishment of bioturbating infauna and flora. • Peds and cutans point towards pedogenesis (soil forming) processes that altered the parental rock into soil. • Rhizoliths associated to paleosol horizons suggest that the groundwater table was relatively high at the time of their formation and that water table dynamics influenced soil formation. • Robust and abundant bioturbation and intense burrow overprinting obliterating the original primary sedimentary structures suggest long-term, favorable paleoecological conditions (e.g., substrate consistency, climate and food resources) and/or low sedimentation rates. • Absent to complete bioturbation, tiering analysis and crosscutting relationships between discrete traces suggest that at least two episodes of colonization by bioturbating infauna may have taken place in two different depositional settings (i.e., palimpsests) • Conclusion: Burrowed sandy paleosol horizons. *Scoyenia* ichnofacies.

Table 4.1.– *Contined.*

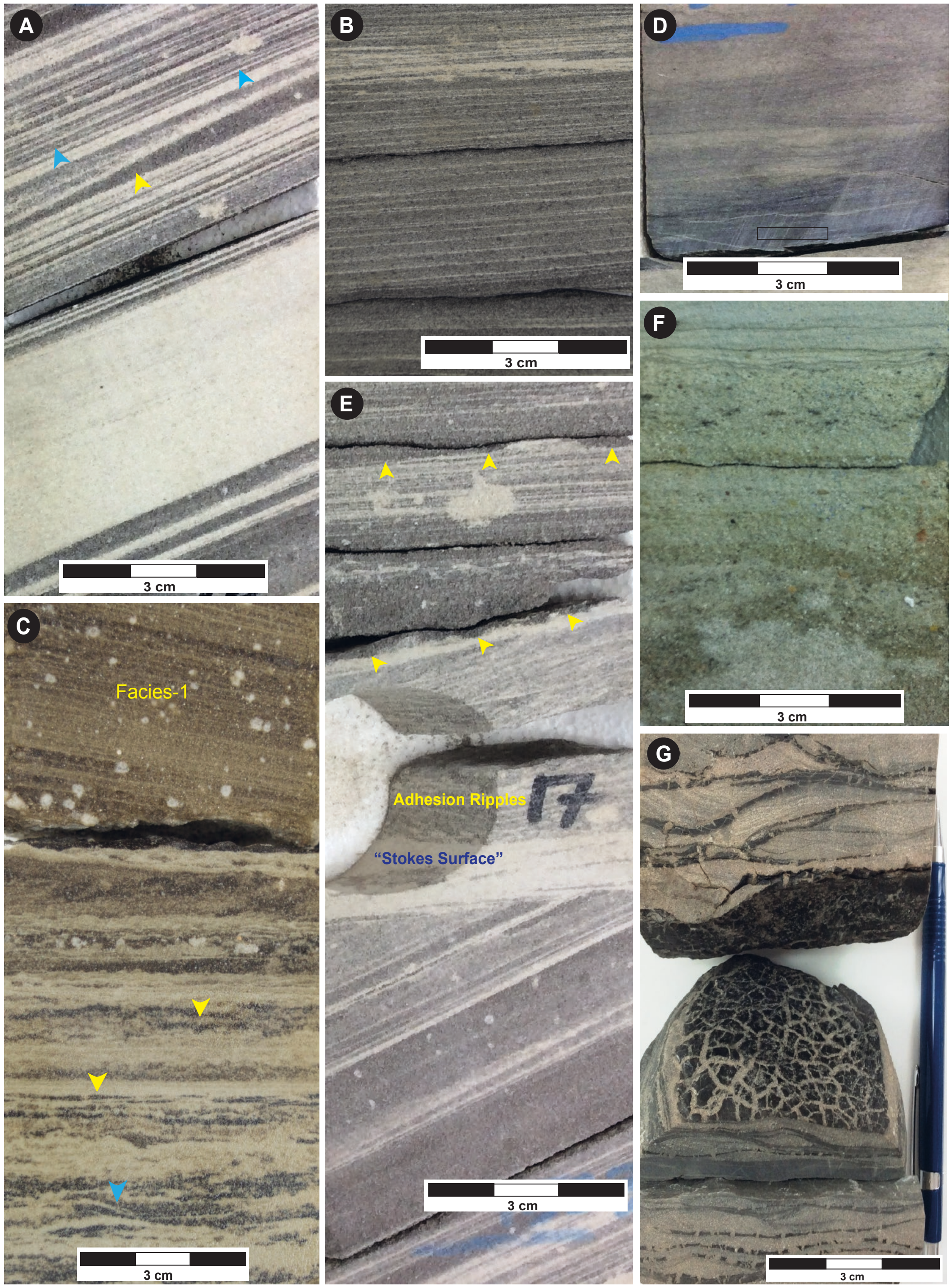

Figure 4.4. Occurrences and characteristics of Facies 1 to 5: (A) Facies-1: example of significant variability in thickness produced by grainflow and grainfall lamination on the lee slope of a migrating dune. Note also gradual thinning downwards lee slope of grainflow (yellow arrowhead) and grainfall, mm-scale laminae (blue arrowhead), well-1. (B) Facies-2: interval displaying "pin striped", wind ripple- cross lamination, well-1. (C) Facies-3: adhesion ripples (blue arrowhead) and adhesion laminae (yellow arrowheads), well-3. (D) Facies-4: silty bed displaying wavy and low angle silty laminae, well-1. (E) Facies-1: high-angle cross-lamination dominated by wind ripple laminations and thicker grain flow laminations (bottom of the picture). The latter are truncated upwards by horizontal "Stokes surface" that passes into adhesion ripples overlain by deflation surfaces (yellow

arrowhead) between sets of wind ripple dominated strata of Facies-2, well-1. (F) Facies-5: Poorly sorted sandstone with granules, wavy-, and low-angle lamination, well-5. (G) Facies-5: ripple cross laminated sandstone with cracked mud drapes in a "polygonal fashion". At a first glance the interval gives the impression of exhibiting flaser bedding, however upon close examination on bedding planes, the mud cracks can be better appreciated, well-6.

sorted, exhibit very well- to well-rounded and frosted grains of quartz. Beds and bedsets exhibit high angle, grain size–segregated cross-laminations that are mostly thin, and closely spaced, "pin-striped" (cf., Fryberger and Schenk, 1988) (Fig. 4.4A, E). Inversely graded laminae can also be identified (Fig. 4.4A, E). Locally, cross-laminations display thin and thick alternations of sand laminae that thin downwards (Fig. 4.4A). Commonly, sharp truncations can be seen on top of these laminasets and pass upwards into adhesion laminae and adhesion ripples (Hunter, 1980) (Fig. 4.4E). Deformation is also present at the base of set and laminasets in the form of contorted bedding (Fig. 4.5).

The presence of moderate- to high-angle, closely spaced, "pin-striped" and inversely graded laminae are interpreted as wind-ripple laminations that formed on the slip faces of migrating aeolian dunes (cf., Fryberger and Schenk, 1988; Jerram et al., 2002; Mountney, 2006a; Mountney and Thompson, 2002) (Fig. 4.4A, E). Sharp truncations at the top of these moderately high to high angle laminasets, abruptly overlain by adhesion laminae and adhesion ripples are interpreted to reflect rises in the groundwater (Fig. 4.4E). This promotes the preservation of sediments in an aeolian setting by inhibiting wind deflation further down and are interpreted as "Stokes surfaces" (Stokes, 1968). Thinning downwards and variability in the thickness of closely spaced laminae reflect alternating grainfall and grainflow deposition of sand on the slip faces of migrating aeolian dunes (Kocurek and Dott, 1981; Mountney, 2006a) (Fig. 4.4A, E). Sediment deposition for this facies took place in migrating aeolian dunes (Mountney, 2006a).

4.4.2. Facies-2: Dry interdune

This facies consists of fine- to medium-grained sandstones that display well-rounded and frosted grains of sand that occur in horizontal to low angle, grain size-segregated laminations (Fig. 4.4B). Beds and bedsets are tabular and are characterized by closely spaced, "pin-striped" lamination (cf., Fryberger et al., 1979) (Fig. 4.4B). Some occurrences display subtle changes in color of laminae alternating between light beige and brown and dark lamina (Fig. 4.4B). In places, very low angle truncations that separate different sets of the low-angle laminated

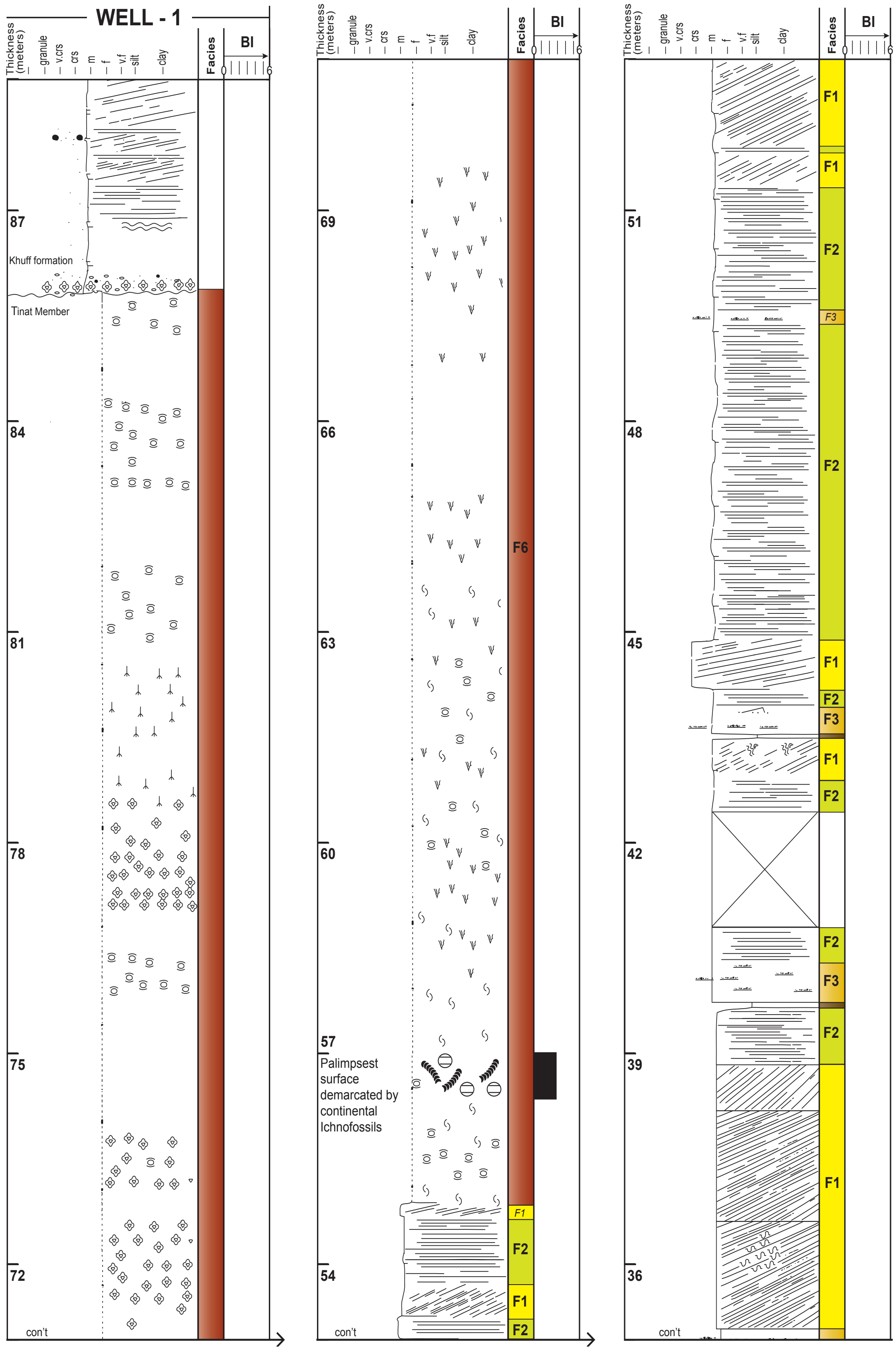

Figure 4.5. Vertical succession of facies and trace fossil distribution in well-1 and location of palimsest intervals demarcated by continental ichnofossils (see Figure-7 for symbol legend).

sandstone can be discerned (Figs. 4.4B).

The abundance of well to very well sorted sand grains points towards continuous transport mechanism promoting grain rounding and sorting such as wind transport (Howell and Mountney, 2001; Mountney, 2006a,b). Many sets of these laminations have a pin-striped appearance suggesting an origin from wind-ripple migration (Melvin et al., 2010a,b; Al-Masrahy, 2011) (Fig. 4.4B). Low-angle lamination exhibiting a "pin-striped" arrangement suggests deposition of silt and very fine sand in the troughs of the advancing wind ripples as sand grains transported by wind mainly through saltation (cf., Fryberger et al., 1979). Sediment deposition for this facies took place in dry interdune zones as sand sheets in an aeolian setting.

4.4.3. Facies-3: damp interdune and ephemeral sabkha

This facies consists of moderately to well-sorted, fine- to medium-grained sandstones. It is characterized by the widespread presence of irregular to crinkly, variably continuous laminations and very thin (centimeter scale) beds with well-developed adhesion ripples and adhesion laminae (Fig. 4.4C). In addition, weakly developed, horizontal and low-angle, poorly defined (i.e., faint) greyish lamination occurs locally (Fig. 4.4C). Bed thickness ranges from centimeter to decimeter scale and is commonly interbedded with Facies-4 (Figs. 4.4C and 7).

The occurrence of adhesion features such as adhesion laminae and adhesion ripple laminations throughout this facies, suggests sedimentation upon a damp substrate where the surface is in proximity to the groundwater table (Hunter, 1980; Kocurek and Fielder, 1982) (Fig. 4.4C, E). Fluctuating water table levels allowed the wetting of the surface and inhibited further down-wind deflation (Mountney and Howell, 2000; Mountney and Thompson, 2002; Mountney and Jagger, 2004) (Fig. 4.4C). This type of sedimentary structures has been documented in damp interdune and coastal sabkha environments where the surface sediment interacts with the capillary fringe of the water table (e.g., Fryberger et al., 1983; Mountney, 2006a). Sediment deposition for this facies took place in a damp interdune environment, ephemeral playa lake margin, or coastal sabkha (cf., Glennie and Singhvib, 2002).

4.4.4. Facies-4: Wet interdune and perennial sabkha

This facies consists of grey and dark grey, siltstones and silty, very fine-grained sandstones (Fig. 4.4D). Commonly, Facies-4 occurs in structureless intervals usually of decimeter to meter scale (Figs. 4.4D). Where they occur, primary sedimentary structures are dominated by weakly horizontal lamination (Fig. 4.4D).

In general, this facies passes into, or is interbedded with adhesion structures of Facies-3.

The overall very fine-grained lithology and sporadic occurrence of horizontal lamination indicates subaqueous deposition under quiet hydrodynamic conditions (Fig. 4.4D). They are therefore interpreted not as ephemeral (playa) lake sediments but rather as the deposits of temporary, shallow interdune ponds (Glennie, 1987, 1998; Melvin et al., 2010b; Al-Masrahy, 2011) that formed at times when the water table rose above the depositional surface (Minervini et al., 2013). Adjacent deposits with adhesion structures of Facies-3 suggest that these conditions were not permanent leading to multiple wetting-upwards followed by drying-upwards cycles and the reestablishment of arid conditions. The close proximity of this facies with deposits described previously that were deposited in an aeolian setting suggests deposition in wet interdune areas that formed relatively long-lived water bodies due to the proximity to surface of the water table or the sea (Kocurek et al., 2001; Melvin et al. 2010b).

4.4.5. Facies-5: Ephemeral stream deposits

This facies consists of interbedded sandstones, silty sandstones and siltstones and are well exhibited in well-6 (Fig. 4.4F, G). The sandstones are thin-bedded units, rarely more than ~1 ft (30 cm) thick that make up the lower parts of fining-upward couplets. They are fine- to medium-grained, moderately to poorly sorted, and are generally either massive or flat laminated with sharp, erosional lower contacts. Locally, granules, pebbles and small mud clasts are present at the base of fining upward beds (Fig. 4.4F). These sandstones can be single units or, in places, they comprise thin amalgamated beds. They are commonly overlain by finer-grained beds of similar thickness that form the upper parts of the depositional couplets referred to above. These beds comprise very fine-grained silty sandstone that displays well-developed ripple cross-lamination (Fig. 4.4G). In places these silty, rippled sandstones contain an abundance of mud drapes that display well-developed desiccation features (Fig. 4.4G).

Recurrent sharp-based, coarser sandstones with pebbles and granules of these upward-fining couplets suggests high-energy, rapid deposition such as flash floods or seasonal floods (e.g., Glennie, 2005; Melvin et al. 2010b). In modern arid and semi-arid settings, such events have been documented and attributed to the sudden change in conditions largely related to seasonal rains (Glennie, 2005). The overlying, finer-grained, and ripple-laminated sediment with desiccation cracks are interpreted as the waning flow deposits of those episodic flooding events and subsequent desiccation resulting in filled-in cracks with a polygonal geometry (see Fig. 4.4G). As suggested by Melvin et al. (2010b), the recurrent presence of sharp based sandstones with pebbles and desiccation cracks in the upper finer, mud-draped portions suggest episodic sedimentation followed by a waning down stage, thus allowing deposition of the finer-grained portion of the flow in a semi-arid environment (Fig. 4.4G). Sediment deposition for this facies took place in ephemeral stream deposits in an arid or semi-arid setting.

4.4.6. Facies-6: paleosols

This facies comprises reddish to pale gray, grayish and light green to dark grey, poorly sorted, very fine- to medium-grained sandstones showing varying degrees of disrupted texture (Figs. 4.5, 4.6, 4.7, 4.9 and 4.11). Commonly, beds in this facies exhibit aggregates, lumps or clods of soil (i.e., peds) structures and cutans (cf., Retallack, 1997a, 1998). Locally, filled cracks between peds and faint original primary sedimentary structures are preserved (e.g., low-angle lamination) (Fig. 4.6B, F). Gradational changes in color, texture and traces of biogenic activity can be observed at different levels (Fig. 4.6B, F), commonly as fossilized root traces (i.e., rhizoliths) as well as with trace fossils (Figs. 4.5, 4.6, 4.8, 4.9 and 4.11). The ichnofossil suite within this facies exhibits moderately- to well-developed burrows dominated by meniscate forms. The degree of bioturbation varies from absent to abundant (BI = 0-5). Trace fossils within this assemblage includes *Taenidium*, *Beaconites*, *Skolithos*, *Planolites* and *Palaeophycus* (Fig. 4.6A, C, D, E, G-I). This paper distinguishes *Taenidium* (Fig. 4.6) from other meniscate burrows, such as *Beaconites*, and *Scoyenia* commonly found in continental settings (e.g., Krapovickas et al., 2009; Díez-Canseco et al., 2016) based on morphological characteristics (see Buatois et al. 2007 for further discussion). Diez-Canseco et al. (2016) described meniscate burrows in transitional or marginal marine settings (the fluvial-tidal transition). Figure 4.6 displays *Taenidium* as unlined meniscate burrows devoided of wall, wall striations, and peripheral mantle, respectively (Keighley and Pickerill, 1994); whereas *Beaconites* exhibits a well-developed wall (Buatois et al., 2007; Genise, 2017).

Abundant fossilized root traces suggest proximity of the groundwater table at the time of plant colonization (Kocurek et al., 2001; Kraus and Hasiotis, 2006). Pedogenetical features such as peds and cutans provide evidence for soil forming processes from the alteration of the parental rock into soil (Retallack, 1991,1994,

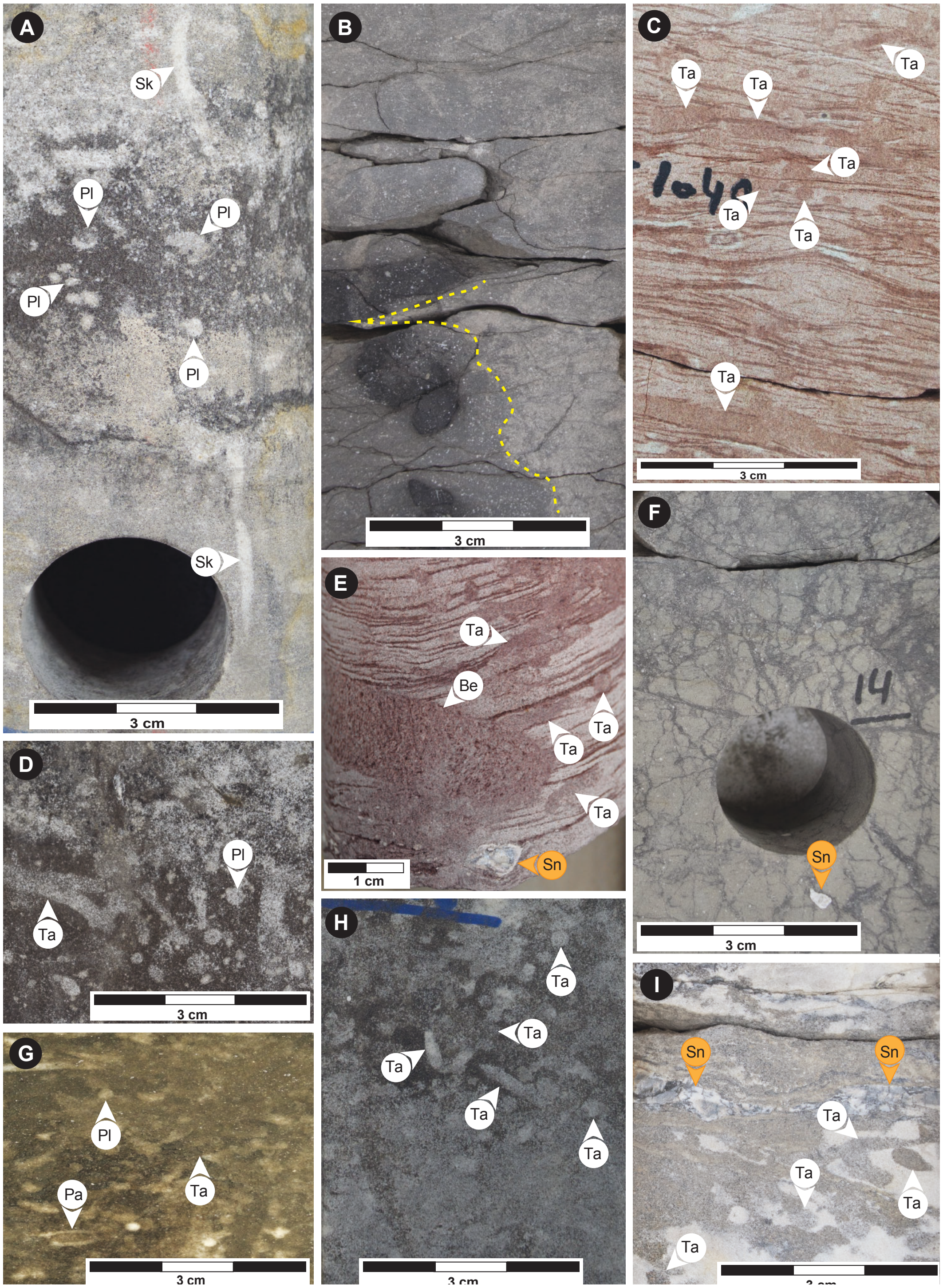

Figure 4.6. Occurrences and characteristics of Facies-6: (A) moderately robust and abundant assemblage with vertical and inclined burrows including (Sk):*Skolithos*; and (Pl):*Planolites*, well-4. (B) weathering profiles and pedogenesis processes include medium to large ped with crack filled (yellow dashed line), well-4. (C) interval dominated by horizontal burrows that exhibit (Ta):*Taenidium*. abundant bioturbation in this segment results in intense burrow overprinting, well-4. (D) segment exhibiting abundant burrows dominated by (Ta):*Taenidium*, and (Pl):*Planolites*, well-4. (E) Segment displaying remaining wavy- and low-angle lamination and (Sn):Silcrete nodule disrupted by bioturbation that includes (Be):*Beaconites* and (Ta):*Taenidium* overprinting tidal bundles, well-2. (F) paleosol with an example of (Sn):silcrete nodules, well-4. (G) suite dominated by horizontal traces that include (Pl):*Planolites*; (Pa):*Palaeophycus*; and (Ta):*Taenidium*, well-2. (H) interval displaying abundant (Ta):*Taenidium*, well-2. (I) segment exhibiting (Sn):Silcrete nodules and high abundances of (Ta):*Taenidium*, well-2.

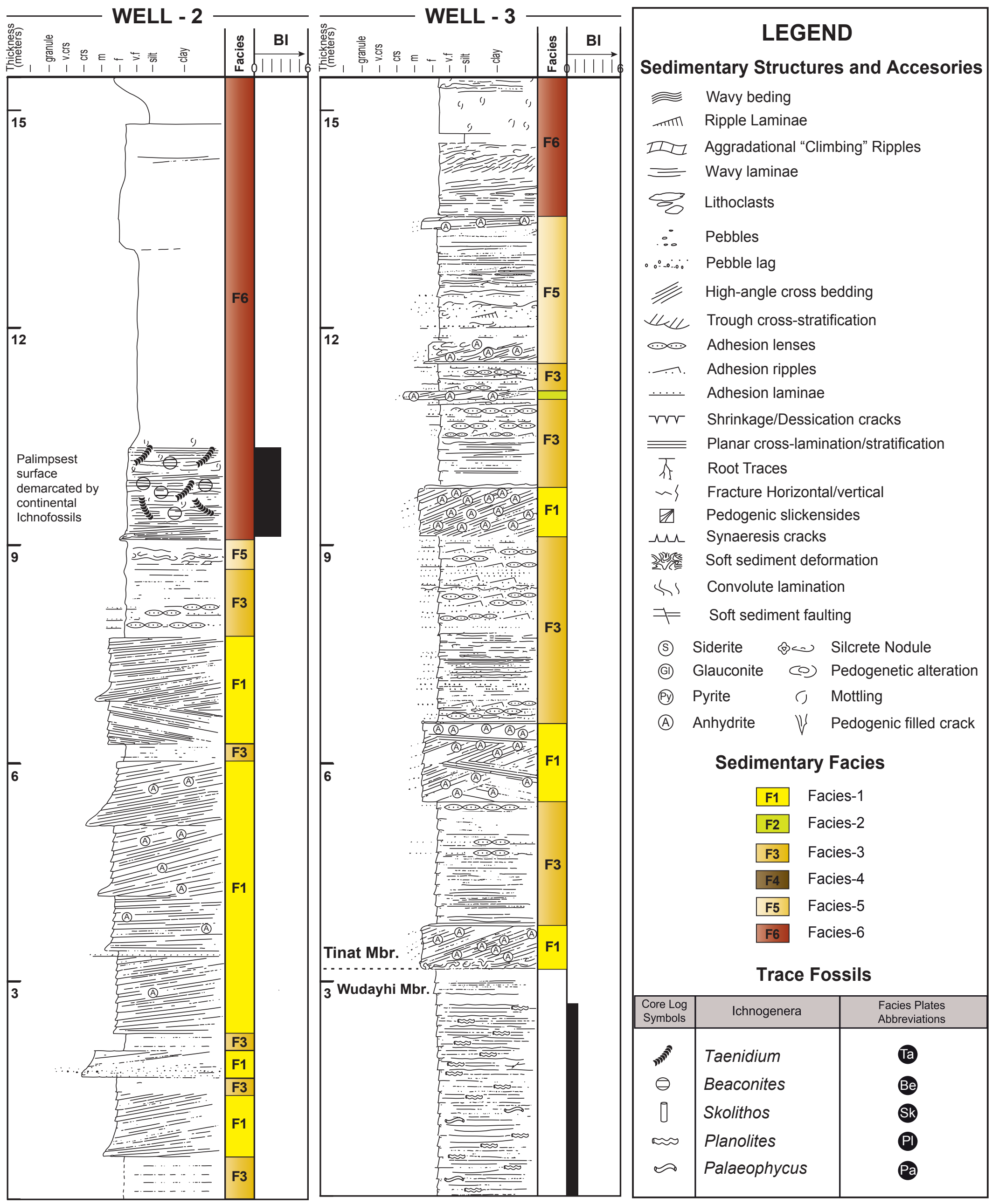

Figure 4.7. Vertical succession of facies and trace fossil distribution in wells 2 and 3 and location of palimsest intervals demarcated by continental ichnofossils. Note symbol legend used in all core logs on the right.

1998) (Fig. 4.6B, F). The trace-fossil assemblage exhibits low to moderate diversities, with localized high abundances (Fig. 4.6A, C). It includes deposit feeding structures with dwellings that exhibit horizontal, meniscate (backfilled) forms made by mobile deposit feeding organisms (e.g., *Taenidium*, *Beaconites*), horizontal mobile deposit feeding structures (e.g., *Planolites*), vertical dwelling structures (e.g., *Skolithos*), horizontal dwelling structures (e.g., *Palaeophycus*), and plant root traces. Ichnofossil forms such *Taenidium* with well-developed menisci, have been previously interpreted as a beetle larvae-generated dwelling and feeding structure (Smith et al., 2008); whereas *Beaconites* (Vialov, 1962; Bradshaw, 1981) represent the dwelling and feeding structure constructed by arthropods in continental settings (Keighley and Pickerill, 1994), probably formed by locomotory back-packing of arthropods or vertebrates (Graham and Pollard, 1982). In addition, *Taenidium* and *Beaconites* can be interpreted as a feeding and/or locomotion structure that can be produced by worm-like organisms (e.g. Squires and Advocate, 1984). The presence of meniscate, backfilled structures without ornamentation along with plant roots in Facies-6 deposits suggests biogenic activity in a soft substrate (MacEachern et al., 2010; Genise, 2017). Neoichnologic studies (e.g., Smith et al., 2008) demonstrate that soil-dwelling hemipterans produce meniscate, backfilled burrows (e.g., Hasiotis and Bown, 1992; Hasiotis and Dubiel, 1994; Hasiotis, 2004) such as the ones identified in this facies (Figs. 4.6, 4.8, 4.9 and 4.11). This facies represents pedogenically altered deposits interpreted as paleosols (Retallack, 1990, 1997a; Melvin et al., 2010b; Hasiotis, 2002, 2007; Genise, 2017).

4.5. DISCUSSION

4.5.1 Continental Deposits in the Tinat Member

The Tinat Member of the Nuayyim Formation in the study area comprises dune, interdune, playa lake, ephemeral stream deposits as well paleosol horizons that exhibit bioturbation (Facies 1 to 6) (Fig. 4.4). The vertical succession of facies points toward deposition within a semi-arid to arid setting as demonstrated by Melvin et al. (2010) and Al-Masrahy (2011). The termination of these conditions is represented in the examined wells across the study area by a distinctive level with paleosols developed in interdune zones or associated to exhumation of previously buried substrates resulting in palimpsest sediments (sensu Swift et al., 1971; Pemberton and Frey, 1985; Mangano and Buatois, 1991; Pemberton and MacEachern, 1995; Pemberton et al., 2000; Mangano et al., 2002; MacEachern et al., 2007a) (Figs. 4.10 and 4.12). Paleosols display bioturbation in the forms of plant root traces (i.e., rhizoliths) and various burrows constructed by continental fauna (Figs. 4.6, 4.10 and 4.12). Therein, a robust and abundant terrestrial assemblage records a substrate community developed under stable and rather predictable conditions in fully continental settings displaying structures with affinities to the *Scoyenia* Ichnofacies (Seilacher, 1967a; MacEachern et al., 2010; Genise; 2017).

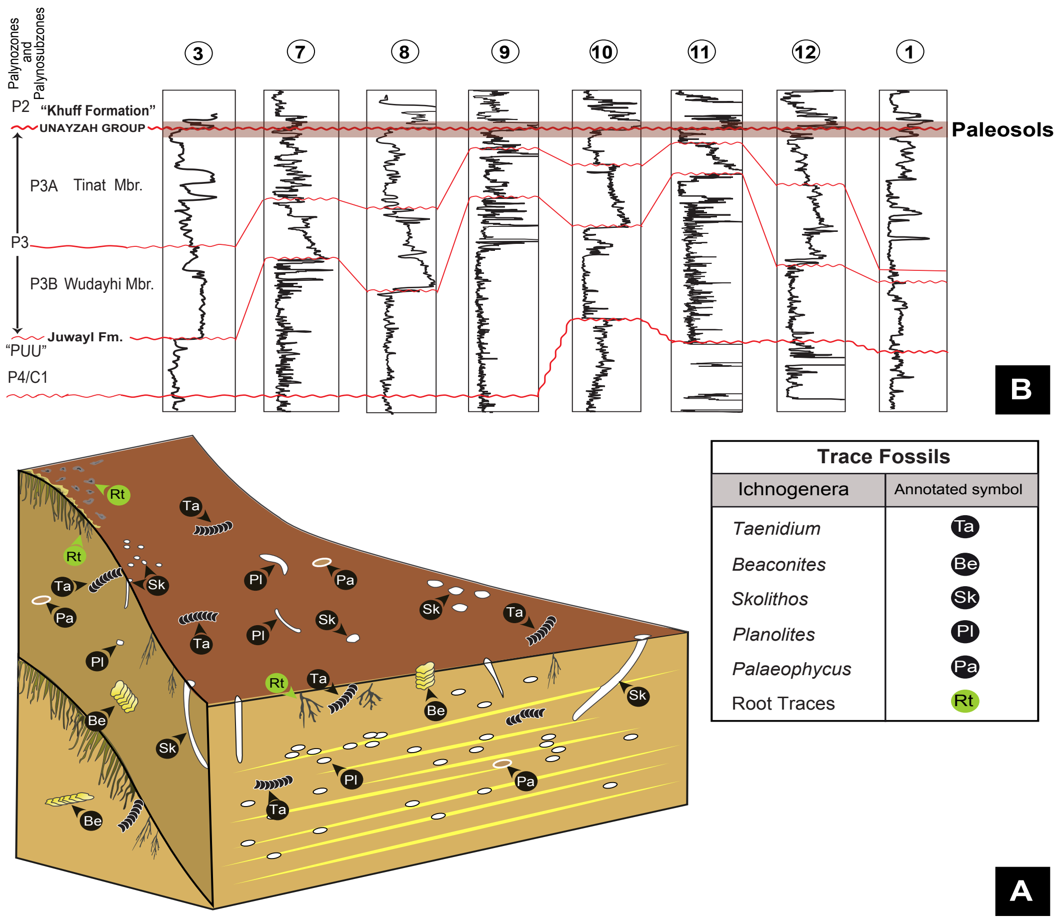

Figure 4.8. A) Schematic model of paleosols developed in the Tinat Member displaying the occurrences of different ichnogera of continental affinity. B) Regional stratigraphic cross-section for the Nuayyim Formation in subsurface central Saudi Arabia. The orientation of the cross-section and the wells involved is specified in Figure 4.1. The datum used as a reference level is the top of the Tinat Member. Gamma-Ray log for each well increase in value towards the right direction. Widespread development of paleosols occurs at the end of the Unayzah Group depositional cycle on top of the Tinat Member.

Due to increasing tectonic activity in the Arabian Peninsula throughout deposition of the Tinat Member of the Nuayyim Formation, colonization took place after exhumation of previously deposited strata (Figs. 4.10 and 4.12). The *Scoyenia* Ichnofacies is associated with low-energy continental environments characterized by short periods, or more permanent subaerial exposure (MacEachern et al., 2007a). Genise, (2017) describes the *Scoyenia* Ichnofacies to reflect the transitional settings between lacustrine, fluvial, and interdune or wetland ephemeral ponds and the adjacent permanently subaerial exposed substrates, vegetated or not. Several depositional environments that occur in continental settings reflect this recurrent trace fossil association. They include lake margins, fluvial channel margins, fluvio-tidal channels and overbanks, progressively desiccated crevasse splays, and wet

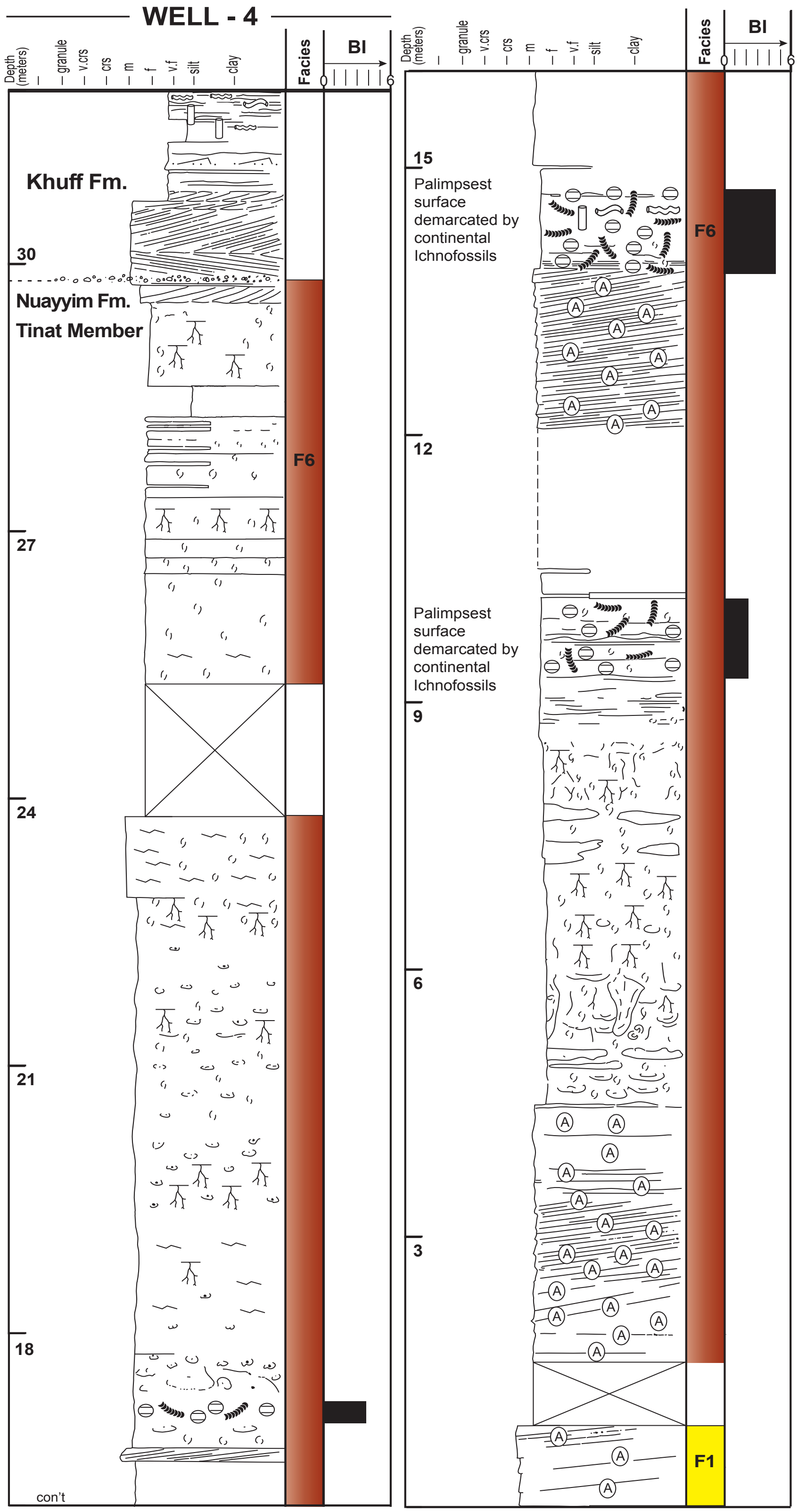

Figure 4.9. Vertical succession of facies and trace fossil distribution in well-4 and location of palimsest intervals demarcated by continental ichnofossils (see Figure-7 for symbol legend).

interdune areas (e.g., Seilacher, 1967a; 1967b; Chamberlain, 1975; Albrandt et al., 1978; Ekdale et al., 1984; Frey et al., 1984; D'Alessandro et al., 1987; Frey and Pemberton, 1987; Gray, 1988; Pollard, 1988; Maples and Archer, 1989; Bromley and Asgaard, 1991; Smith, 1993a,b; Buatois et al., 1998; Buatois and Mangano, 2004; Díez-Canseco et al. 2015; Krapovickas et al., 2016; Genise, 2017). Smith (1993a) described well-developed suites that correspond to the *Scoyenia* Ichnofacies from crevasse splay sandstone bedding planes in the Permian of South Africa (MacEachern et al., 2007b). Similarly, Krapovickas et al. (2009) described ichnofossil suites with abundant meniscate trace fossils and dwelling tubes (e.g. *Taenidium*, *Scoyenia* and *Palaeophycus*) from crevasse splay deposits and ascribed to the *Scoyenia* Ichnofacies. High abundances with low diversities of meniscate traces in Facies 6 (Fig. 4.6) points toward colonization in a continental setting wherein certain specific type organisms (e.g., arthropods) have developed adaptations to colonize the terrestrial realm in Permian times. Krapovickas et al. (2016) provided a succinct review of the ichnology, colonization trends and ichnofacies models of aeolian settings including ichnofossil assemblages in Permian aeolian strata. Based on the outstanding similarities among all Permian occurrences across North America, Europe and Gondwana, Krapovickas et al. (2016) suggested that desert communities were fully adapted and established in the Permian as seen in the Tinat Member paleosols presented in this paper (Figs. 4.6 and 4.8). Through the systematic analysis of the ichnological record of desert environments, these authors also found that sub-superficial activity largely attributable to arthropods was widespread resulting in simple vertical *Skolithos*, *Palaeophycus*, *Planolites* and meniscate forms such as *Taenidium* (Krapovickas et al. 2016) as documented for the Tinat Member case (Fig. 4.8). Genise, (2017) also outlined a similar assemblage that characterizes the *Scoyenia* Ichnofacies in paleosols, being dominated by meniscate forms as *Scoyenia*, *Taenidium*, *Beaconites*, *Spongeliomorpha* in addition to *Skolithos*, *Fuersichnus*, invertebrate and vertebrate trackways. The former assemblage bears remarkable similarities to the one interpreted for the Tinat Member in this paper (Fig. 4.8A) and supports the overall dominance of meniscate traces in paleosols typified by the *Scoyenia* Ichnofacies and summarized by Genise, (2017) based in many occurrences worldwide. Tracemakers in the Paleozoic for this type of continental environments are inferred to be mostly millipedes; without case studies of paleosols in which ichnofossils can be unequivocally attributed to insects (Genise, 2017). Buatois and Mangano (2004) indicated that meniscate structures such as the ones identified in Facies 6 (Fig. 4.6) are less common and less diverse

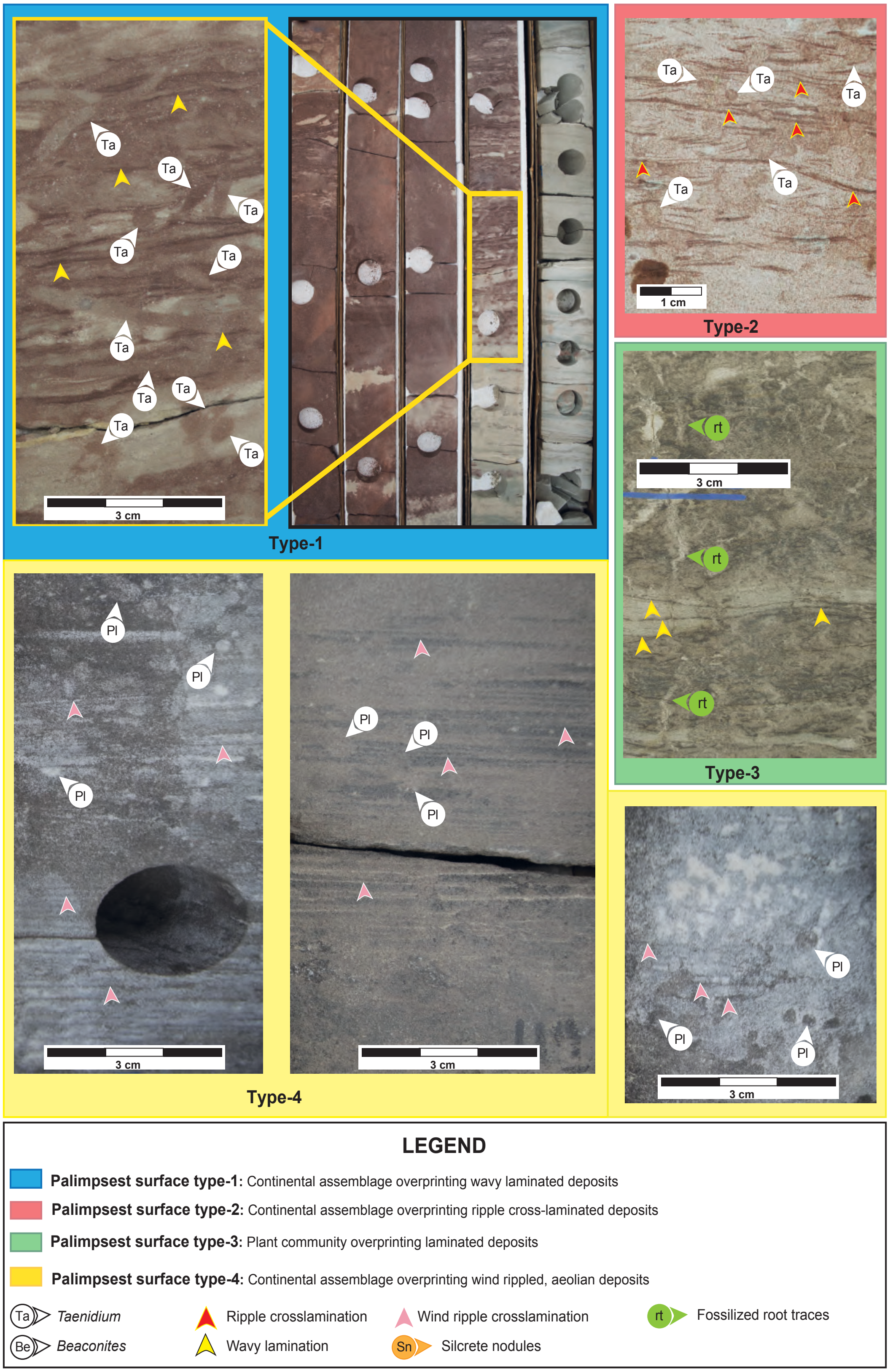

Figure 4.10. Occurrences and types of palimpsest surfaces marked by continental traces in the Tinat Member of the Nuayyim Formation.

in the Paleozoic. These suites are interpreted to be developed in damp conditions or water bodies that experienced progressive drying in the terrestrial realm such as wet interdunes and paleosols in proximity to the groundwater table (Hasiotis, 2002; MacEachern et al., 2007b; Krapovickas et al., 2009, Díez-Canseco et al. 2015; Krapovickas et al., 2016; Genise, 2017).

4.5.2 Paleogeographic implications

Depositional facies within the Tinat Member reflect terrestrial sedimentation dominated by aeolian processes. They are reflective of arid to semi-arid conditions that are characteristic of: 1) terminal alluvial fans and bajadas, 2) aeolian systems, 3) interdune zones dominated ephemeral lakes (playas) whose dimensions fluctuated throughout time (Melvin et al., 2010a) and, 4) sand sheets (Fig. 4.4). Fluctuations in the groundwater level (i.e., Melvin et al., 2010a) is suggested by the recurrence of high angle cross-bedded sandstones passing upward into "Stokes surfaces" accompanied by adhesion ripples and adhesion laminae (Fig. 4.4E) as identified by Melvin et al. (2010a). A robust and abundant trace fossil assemblage that displays elements of the *Scoyenia* Ichnofacies associated with rooted paleosols attests to near-surface moist conditions that allowed: 1) the preservation of beds with high angle cross-stratification interpreted as migrating aeolian dunes and 2) the colonization and flourishing of continental bioturbating infauna (Figs. 4.6, 4.10 and 4.12). Burrowed intervals within Facies-6 (Fig. 4.6) can be correlated regionally and analysis of one of these aeolian systems by Melvin et al. (2010a) has revealed a high degree of cyclicity among its facies. The authors suggested this internal stratigraphy within the aeolian-dominated Tinat Member to be a direct reflection of fluctuations in the level of the groundwater table at the time of deposition. The interplay between the groundwater table and the surface of the depositional system can have allostratigraphic significance and could be linked to the Earth's orbital fluctuations during the Permo-Carboniferous of Gondwana (Melvin et al., 2010b). Similar cases have been documented in the rock record (see Mountney and Howell, 2000; Mountney and Jagger, 2004; Mountney, 2006a; Kiersnowski, 2013; Minervini et al., 2013). Subsidence analysis by Mountney (2006b) within the Paradox Basin in Utah, together with comparisons to other similar age successions, suggest that the climatic cycles responsible for generating the Cedar Mesa erg sequences in Utah could be the product of 413,000-year so-called long eccentricity cycles. Therein, restricted episodes of non-aeolian accumulation would have occurred during humid (interglacial) phases (Mountney, 2006b). This resulted in

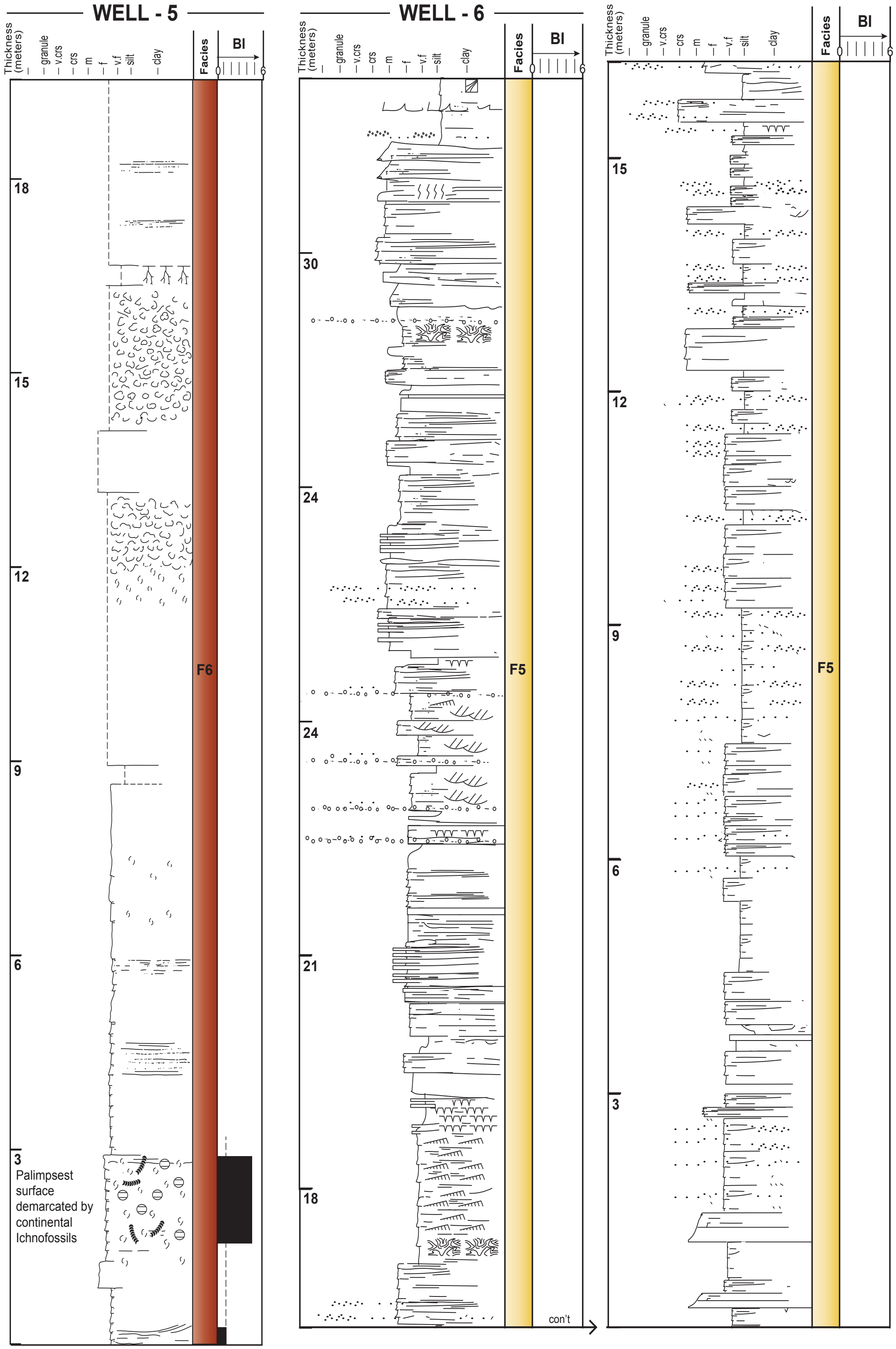

Figure 4.11. Vertical succession of facies and trace fossil distribution in wells 5 and 6 and location of palimsest intervals demarcated by continental ichnofossils (see Figure-7 for symbol legend).

accumulation and preservation of different aeolian environments attributed to slow rises in the relative water table like the ones described by Melvin et al. (2010b) in the Tinat Member (Fig. 4.4E).

4.5.3 Climatic evolution and paleosols development

The Tinat Member is a complex stratigraphic mosaic within which a large number of depositional facies are readily identified. A facies mosaic with continental affinity point towards deposition in an arid to semi-arid setting. This took place as the Arabian Peninsula migrated Northwards from a temperate zone to a more equatorial position during the late Early to Middle Permian (Hughes-Clarke, 1998; Konert et al., 2001) (see supplementary information-4 in the supplementary material at the end of this document).

Widespread paleosols at the end of Unayzah sedimentation within the study area are interpreted to reflect (probably prolonged) periods of minimal deposition to nondeposition (i.e., diastems) as proposed by Melvin et al. (2010b). Slow rises in the relative water table are interpreted to be responsible for the preservation of aeolian deposits during wetter phases (Stokes, 1968; Mountney and Russell, 2009; Mountney and Jagger, 2004; Mountney, 2006a) (Fig. 4.4E). Accordingly, these conditions allowed the establishment of suitable ecological factors for bioturbating infauna such as near-surface water tables (Seilacher, 1967a; Krapovickas et al., 2016; Genise, 2017). Root traces support this observation and increased moisture near the substrate-atmosphere interface permitted burrowing infauna to colonize paleosols and to produce meniscate forms such as *Taenidium* and *Beaconites* (Genise, 2107) (Figs. 4.6, 4.10 and 4.12). This took place after subaerial exposure and exhumation of previously buried deposits (Fig. 4.10). They reflect colonization of previously deposited strata after their exhumation and mark palimpsest surfaces wherein pedogenesis occurred along the establishment of plant and animal communities (cf. Genise, 2107) (Figs. 4.10 and 4.12). This is recognized in intervals displaying uncommon to abundant bioturbation (BI= 0-5), indicating low rates of sedimentation, and was manifested ultimately by the development of the very thick and pervasive paleosols seen in many places at the top of this unit (Melvin et al., 2010b; Al-Masrahy, 2011). Genise, (2017) presented outstanding examples of complex palimpsests soil fabrics that display equally complex tiering relationships regarding their trace fossil fauna (see Genise, 2017; Chap. 20 for detailed characterization) produced by environmental changes. These examples range from well developed to immature paleosols and are drawn from the Paleogene

Asencio Formation of western Uruguay and eastern Argentina (Genise and Bown, 1996), the Middle Eocene-Early Miocene Sarmiento Formation of Patagonia, Argentina (Genise et al., 2004a; Bellosi et al., 2010) and the quaternary of the Canary Islands of Spain (Genise et al., 2013a). Other examples that show complex tiering and cross-cutting relationships in paleosols that reflect changes in the water table summarized by Genise, (2017) include the Eocene Willwood (Hasiotis et al., 1993a) and Triassic Chinle (Hasiotis and Dubiel, 1994) formations of USA, as well as the Upper Jurassic-Early Cretaceous formations of Patagonia Argentina (Bedatou et al., 2009). In the Asencio Formation case, up to 5 different stages of paleosol developments and continental colonization can be inferred from the tiering relationships and the interpreted ecological changes trough time (Bellosi et al., 2016; Genise, 2017). Therein, an uneven distribution of trace fossils at different levels associated with variable moisture, pedogenetical alteration and laterite formation shows that palimpsests ichnofabrics can be unveiled trough a systematic approach that involves the careful analysis of both pedofabric and ichnofabric independently (Genise et al., 2004a). More importantly, and similar to the Tinat Member case presented herein, in the Quaternary soils of the Canary Islands high densities of trace fossils occur in relatively thin paleosol horizons developed on dunes and interdunes areas (Genise et al., 2013a). High densities in these paleosols have been interpreted to be the result of scarce water resources in an overall arid and semi-arid climate (Genise et al., 2013a). The Tinat Member paleosols probably reflect similar stressful conditions under comparable climatic conditions with a variable water table that results in high densities of traces with localized high abundances (Genise, 2017; Figs. 4.6 and 4.8A) characteristic of some stressed expressions of the *Scoyenia* Ichnofacies (Genise, 2017).

The development of a robust and locally abundant community of continental bioturbating infauna in the Tinat Member suggests a prolonged period of minimal deposition to nondeposition in the study area. Multiple paleosol developments along bioturbation can be linked to the overall tectono-stratigraphic evolution of Saudi Arabia. Therein, increased tectonic activity related to the onset of the Neo-Tethys marks a break in sedimentation resulting from tectonic uplifting of the Arabian Plate prior to the onset of the Khuff Formation (Sharland et al., 2001) (Fig. 4.12). Based on the regional correlatability of the ichnofossils associated to paleosols and their palimpsest nature in the Tinat Member case, they are interpreted to reflect allocyclic discontinuities rather than being isolated autocyclic surfaces with limited spatial distribution. This mean that biogenically-demarcated palimpsest surfaces presented herein constitute genetically related facies successions and are regionally mappable in extent as suggested by Melvin et al. (2010b), thus reflecting the end of a whole tectonostratigraphic sequence (i.e., Megasequence AP5 of Sharland et al. 2001).

4.5.4 Paleosols as palimpsest surfaces and genetic stratigraphic implications

Paleosols at the top of the Unayzah sedimentation cycle are interpreted above to mark the boundary of a TMS AP5 of Sharland et al. (2001) (Fig. 4.2). Across the Arabian Peninsula, this widespread development of paleosols is commonly interpreted to be the record of a major break up unconformity associated with the continental rifting and spreading of the Sanandaj-Sirjan and central Iran terranes from the Arabian Peninsula (Sharland et al., 2001). Stephenson and Filatoff (2000) have dated this event as mid-Tatarian in Saudi Arabia. In the Middle East region, this event has been assigned an early late Permian age (near base Kazanian) and has been termed the "Zagros rifting". The widespread paleosol documented in Saudi Arabia by Melvin et al. (2010a,b) also mark the end of an important sedimentation cycle in that after TMS AP5 ceased to be dominated by silisiclastic sediments (Fig. 4.2). Subsequent sedimentation in the Arabian plate is dominated by carbonate

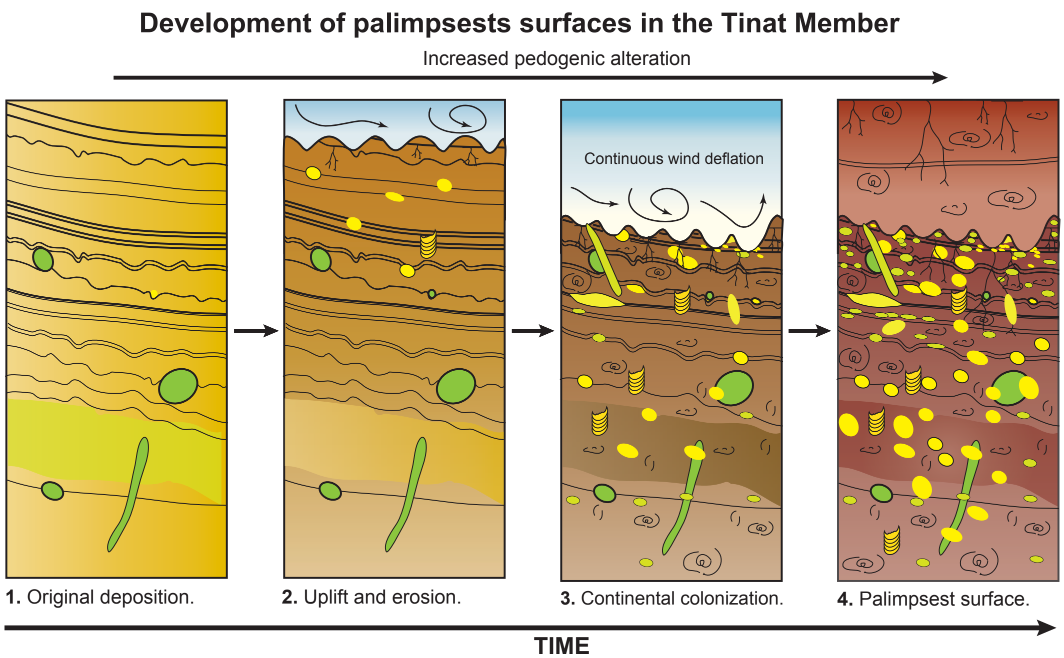

Figure 4.12. Schematic depiction of the development of paleosols and the formation of palimpsest surfaces demarcated by trace fossils in the Tinat Member of the Nuayyim Formation. The location of palimsest intervals demarcated by continental ichnofossils has been labeled in figures 4.5, 4.7, 4.9 and 4.11.

and evaporitic deposition accompanied with the movement of the plate into sub-tropical latitudes (see supplementary information-4). As suggested by Sharland et al. (2001), erosion of the Unayzah in Saudi Arabia and Gharif in Oman may have significantly modified the preserved thickness and original nature of the primary sedimentary fabric overprinted by subaerial exposure, pedogenetical processes and bioturbating organisms (Figs. 4.6, 4.10 and 4.12). Progressive thermal uplifting is interpreted to have occurred during the latest part of TMS AP5 along the present day Zagros fold belt, culminating in the regional 'Pre-Khuff unconformity' at the top of this megacycle (Sharland et al., 2001). Paleosols presented herein are likely the result of continental updoming caused by progressive thermal uplift and is interpreted as the pre-cursor of continental rifting and Neotethys spreading. In the late Early Permian, (Artinskian-Kungurian) the Arabian Plate is interpreted to have undergone to a second major phase of crustal extension that culminated with continental separation (Sharland et al., 2001).

Palimpsest intervals displaying intense bioturbation in the Tinat Member are associated with paleosol development (Figs. 4.10, 4.12). At this level, development of paleosols are widespread prior to the creation of the Pre-Khuff Unconformity (Fig. 4.8) across the Arabian Plate in Oman (Stephenson et al., 2003), Kuwait (Tanoli et al., 2008), Saudi Arabia (Melvin et al., 2010a,b), and Jordan (Sharland et al., 2001). An illustrative case of this widespread soil development is given south of the Arabian Peninsula in Oman. Therein, the uppermost part of the Middle Gharif Member of the Gharif Formation is characterized by stacked palaeosols developed in a semi-arid climate (Stephenson et al., 2003) as interpreted in this paper for the coeval Tinat Member of the Nuayyim Formation of Saudi Arabia. As documented by Melvin et al. (2010a), in the study area pedogenic alteration appears to comprise at least five types of paleosol deposits, each of which displaying a number of probable soil "zones" (see log for well-4 in Figure-4.9 as an example). These different levels of fossilized soils vary from burrowed, very argillaceous, poorly sorted sandstones with an abundance of cutans and rooting features to well developed, massive to nodular silcretes (Fig. 4.6). Pervasive pedogenetical alteration in the Tinat Member can be correlated regionally across the study area as demonstrated by Melvin et al. (2010b). For example, well-2, located some 300 km distant from well-4 (Fig. 4.1) displays aeolian facies passing upwards into burrowed paleosols (Figs. 4.6 and 4.10). Therein, the uppermost sandstones pass upward into an interval of low-angle laminated sandstone displaying laminations that are severely disrupted as a result of intensive biogenic activity (Figs. 4.10 and 4.12). Different stages of pedogenesis can be interpreted by the presence of thickly developed paleosols that appear to comprise a number (five or six) of stacked, individual paleosol in some cases (Melvin et al., 2010a) (Figs. 4.5, 4.6, 4.7, 4.9 and 4.11). Each soil exhibits textural characteristics, suggesting that soil zonation may have taken place due to prolonged times of exposure leading to pedogenic chemical and physical modifications (sensu Retallack, 1997c, 1998). Overall, in both wells 2 and 4, these zones display similar characteristics varying from very argillaceous, poorly sorted sandstones with an abundance of cutans and apparent root-related structures to well-developed massive to nodular silcrete (Melvin et al., 2010a). Similarities between the two wells in terms of occurrence, burrowing patterns and soil zonation suggest regional conditions that favored the formation of paleosols including plant and animal colonization accompanied locally by the development of silcrete horizons and silcrete nodules (Fig. 4.6). These conditions are interpreted to last long enough for the establishment of a trace fossil suite indicative of the Scoyenia Ichnofacies (Seilacher, 1967a; MacEachern et al., 2010; Krapovickas et al., 2016). This event appears to have significant spatial and temporal implications and can be used as a tool to correlate the prolific aeolian reservoir facies within the Tinat Member of the Nuayyim Formation (Unayzah Group) in central and eastern Saudi Arabia.

4.6. CONCLUSIONS

Integration of ichnological and sedimentological observations in the Tinat Member allowed the identification of several depositional environments that reflect continental sedimentation within the Nuayyim Formation of the Unayzah Group in central and eastern Saudi Arabia. The end of this sedimentation cycle is marked by widespread development of paleosols. Continental sedimentation is characterized by aeolian dune and interdune deposits, sediments deposited by ephemeral streams and widespread paleosols.

Sedimentological observations dominated showing a preponderance of aeolian sedimentation suggest arid to semi-arid conditions. Sedimentation of the Tinat Member of the Nuayyim Formation took place as the Arabian Peninsula migrated from a temperate zone to a more equatorial position during the Middle to Late Permian, resulting in increased aridity as constrained by the vertical succession of facies. Several segments displaying palimpsest sediments can be interpreted from the occurrences of fossilized soils formed after exhumation of previously buried deposits across the study area.

A robust and abundant trace fossil assemblage that exhibits elements of the *Scoyenia* Ichnofacies attests to prolonged periods of subaerial exposure and paucity in sedimentation. Therein, multiple stages of paleosol development, along with colonization by plants and animal infauna, mark the development of palimpsest intervals or relict surfaces. Paleosols at the top of the Unayzah sedimentation cycle are interpreted to mark the boundary correlatable across central and eastern Saudi Arabia and likely across the Arabian Peninsula.

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CHAPTER 5 – SUMMARY AND CONCLUSIONS

This thesis has introduced inchnological analysis to the characterization of the Late Carboniferous–Middle Permian Unayzah Group from subsurface Saudi Arabia using an integrated approach combining ichnology, sedimentology, and palynology. Historically, studies carried out in this interval include sedimentologic and biostratigraphic analyses at both local and regional scales (see Al-Laboun 1982, 1986, 1987; Ferguson and Chambers 1991; McGillivray and Husseini 1992; Senalp and Al-Duaiji 1995; Evans et al., 1997; Al-Hajri and Owens 2000; Melvin and Heine 2004; Melvin et al., 2005; Melvin and Sprague 2006; Price et al., 2008; Melvin et al., 2010a, 2010b). To date, the overwhelming majority of the studies in the geological literature for this sedimentary succession allocate sediment deposition to continental settings wherein aeolian sedimentation processes dominated (e.g. Senalp & Al-Duaiji, 1995; Melvin & Heine, 2004; Melvin et al., 2005; Melvin et al., 2010a,b; Al-Masrahy, 2011). However, this study presents an entirely new approach by documenting trace-fossil faunas and sedimentological characteristics from bioturbated intervals in both the Wudayhi Member and Tinat Member that confirms the presence of shallow-marine sedimentary environments. This new approach to the understanding of this interval significantly departs from traditionally held views by introducing new depositional models and sedimentary processes operating at the time of sediment deposition.

Underpinning this new approach, three major lines of evidence were presented in this thesis that support a fresher look to the post-glacial deposits in the Unayzah Group. Firstly, this study provides evidence for marine sedimentation in central and eastern Saudi Arabia (Fig. 1.1). Integration of ichnological and sedimentological observations in the Nuayyim Formation allowed the identification of marginal-marine, tidally influenced sedimentation (FA1); and shallow-marine, wave- and storm-dominated sedimentation with subordinate tidal and fluvial influence (FA2) in its basal Wudayhi Member (Fig. 1.2). Secondly, sedimentological and ichnological assessments in the overlaying Tinat Member allowed the identification of aeolian and marginal-marine, tidally influenced interactions in two facies associations (FA1 and FA2) that are conformably interbedded. Thirdly, facies, ichnofacies and palynological analysis in paleosol horizons from the upper part of the Tinat Member suggest an arid to semi-arid setting with biogenic activity in the form of continental fauna and plants in deposits associated with pedogenetical alteration in paleosol horizons marking palimpsest surfaces.

5.1 Chapter 2: Trace-fossil faunas and sedimentary environments in the Wudayhi Member of the Nuayyim Formation

• Chapter 2 documents a new understanding in the sedimentation of the Nuayyim Formation across subsurface central and eastern Saudi Arabia that has been previously ascribed to continental sedimentary environments. A number of levels in this formation show evidence for marginal-marine and shallow-marine sedimentation. This chapter brings attention to trace-fossil faunas and sedimentological characteristics from these facies, and presents a regional depositional model for the Wudayhi Member that confirms the presence of shallow-marine sedimentary environments.

• Marginal-marine and shallow-marine sedimentation in the Wudayhi Member includes estuarine deposits and upper-shoreface through lower-shoreface deposits. They are reflective of several transgressive-regressive (T-R) cycles in an overall shoaling-upwards, tidally influenced progradational succession that exhibit mixed-process (wave-, tide-, and fluvially-influenced) depositional environments. The succession displays an overall upward decrease in bioturbation intensity with elements of an impoverished proximal expression of the *Cruziana* Ichnofacies at the base in proximal- and distal- lower-shoreface deposits (Facies 5–6), passing into an impoverished expression of the *Skolithos* Ichnofacies in upper-shoreface deposits (Facies 4). Therein, Facies 5 records storm-influenced sedimentation and includes hummocky cross-stratification (HCS), combined-flow ripples, cross-lamination, and ichnofossils that alternate between storm-related and fair-weather assemblages. An overall reduction in both the diversity of ichnotaxa and the intensity of burrowing across the shoreface profile, an apparent lack of middle-shoreface deposits, and the occurrence of storm-wave-generated structures interspersed with tidally generated structures in the center and southeast of the study area are interpreted as tidal modulation, suggesting macrotidal conditions at the time of sediment deposition. Estuarine sedimentation includes coal deposits (Facies 1), tidal flats (Facies 2), and fluvio-tidal deposits (Facies 3) that overlie the succession, and display a stressed, impoverished mixture of traces with facies-crossing elements of the *Skolithos* and *Cruziana* Ichnofacies in the north and northwest of the study area. Sedimentation took place on a broad and sandy, partially restricted shelf, chiefly influenced by tidal currents that was variably fluvially influenced. The interplay of the aforementioned processes results in a complex architecture that is tractable, based on the sedimentological and ichnological content.

5.1.1 Chapter 2: A new approach to the post-glacial deposits in the Unayzah Group, following the Late Paleozoic Ice Age (LPIA)

• Colonization by bioturbating infauna exhibiting elements of an overall impoverished *Skolithos* and *Cruziana* Ichnofacies in the Wudayhi Member is interpreted to be related to sea-level rise, with regional transgression induced by the melting of glacier ice following the Late Carboniferous to Early Permian glaciation that affected southern Gondwana. Subsequently, as the Arabian Plate migrated northwards, isostatic rebound concomitant with increased tectonism associated with the Neotethys propagating into the Arabian Peninsula caused regional regression responsible for the progradational sequence presented herein in the Early to Middle Permian. Trace-fossil associations and ichnofacies presented in this chapter are significant, because they provide evidence for marginal-marine and shallow-marine tide- and storm-influenced processes in the Unayzah Group during deposition of the Wudayhi Member of the Nuayyim Formation. Furthermore, it establishes a framework than can be linked to fully marine coeval deposits southeastern of the Arabian Peninsula into Oman.

5.2 Chapter 3: Trace-fossil faunas and sedimentary environments in the Tinat Member

• Chapter 3 documents aeolian and shallow-marine interactions and describes their ichnofossil suites from the early Permian Tinat Member of the Nuayyim Formation of subsurface Saudi Arabia, thereby confirming marine sedimentation in an interval historically interpreted as being dominated by continental settings wherein aeolian processes prevailed. This study presents a characterization of in situ animal-sediment interactions in coastal dune fields and erg margins in an arid to semiarid setting; where the description of organism-sediment relationships, until now, has been focused on the landward portion including fresh-water suites.

• Sedimentological and ichnological assessments summarized in Chapter 3 allowed the identification of aeolian and marginal-marine, tidally influenced interactions in two facies associations (FA) that are conformably interbedded. Facies association 1 (FA1) includes sediment deposition in aeolian and continental, groundwater table-related environments such as aeolian dunes (facies 1), dry and damp aeolian interdunes (facies 2 and 3), ephemeral and perennial stream deposits (facies 4 and 5), and palaeosols (facies 6). Facies association 2 (FA2) reflects sedimentation in shallow-marine, tidally influenced environments and includes punctuated occurrences of tidal flats and sheltered shallow bay deposits (facies 7 and 8) displaying a brackish-water trace fossil assemblage. This suite exhibits a diminutive, highly stressed mixture with structures reflecting an impoverished *Skolithos* Ichnofacies and *Cruziana* Ichnofacies associated with tidal flat deposits displaying synaeresis cracks, lenticular bedding, low-angle and wavy lamination, flaser bedding, reactivation surfaces, carbonaceous double mud drapes, current ripples and tubular tidalites.

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5.2.1 Chapter 3: A model for marginal-marine and aeolian interactions and their resulting ichnofossil suite

• Aeolian sedimentation and trace fossil associations presented in Chapter 3 are significant because they provide evidence for shallow-marine, tidally influenced and aeolian processes in the Unayzah Group during deposition of the Tinat Member of the Nuayyim Formation. More importantly, documenting marine and aeolian interactions and their resulting ichnofossil suite can be used 1) to build integrated sedimentological and ichnological facies models and 2) to characterize the resulting trace fossil association in this particular interactive setting that can be used to identify similar successions elsewhere in the rock record.

5.3 Chapter 4: Trace-fossil faunas and sedimentary environments in the paleosols of the Tinat Member

• Chapter 4 documents a complex mosaic of facies that include paleosol horizons for the Tinat Member. Therein, sedimentation took place mainly in a continental setting dominated by aeolian processes that resulted in dunes, interdunes, ephemeral stream deposits terminating with regional development of paleosols. Facies, ichnofacies and palynological analysis presented in Chapter 4, suggest an arid to semi-arid setting with biogenic activity in the form of continental fauna and plants in deposits associated with pedogenetical alteration in paleosol horizons. Therein, burrowing exhibits elements of the *Scoyenia* Ichnofacies in beds with sparse to abundant bioturbation.

5.3.1 Chapter 4: Trace-fossil faunas and their utility in genetic stratigraphy in continental settings.

• Paleosols formed at the top of the Tinat Member of the Nuayyim Formation are interpreted be the result from tectonic uplift and subaerial exposure by the exhumation of previously buried substrates. Thereby, leading to the formation of burrowed palimpsest surfaces associated with pedogenically altered substrates at the end of Unayzah deposition prior to the onset of the Khuff Formation. Progressive thermal updoming is interpreted to have occurred during the latest portion of the Unayzah Group sedimentation cycle in the Arabian Plate culminating in the regional "Pre-Khuff unconformity" at the top of this megacycle recognized in this study by biogenically-demarcated diastems.

• Ichnological and sedimentological observations outlined in Chapter 4 are significant because they: (1) refine existing interpretations of the paleoenvironmental history in the study area; (2) document diastems marking breaks in sedimentation; and (3) outline several soil-forming cycles that allowed the establishment of a trace fossil suite with continental affinities, thus demarcating the end of an entire sedimentation cycle. The recognition and delineation of burrowed horizons associated with paleosols provides a tool to understand the tectono-stratigraphic evolution of similar successions in the rock record. More importantly, it provides an example of the utility of trace fossil analysis in genetic stratigraphy in continental settings.

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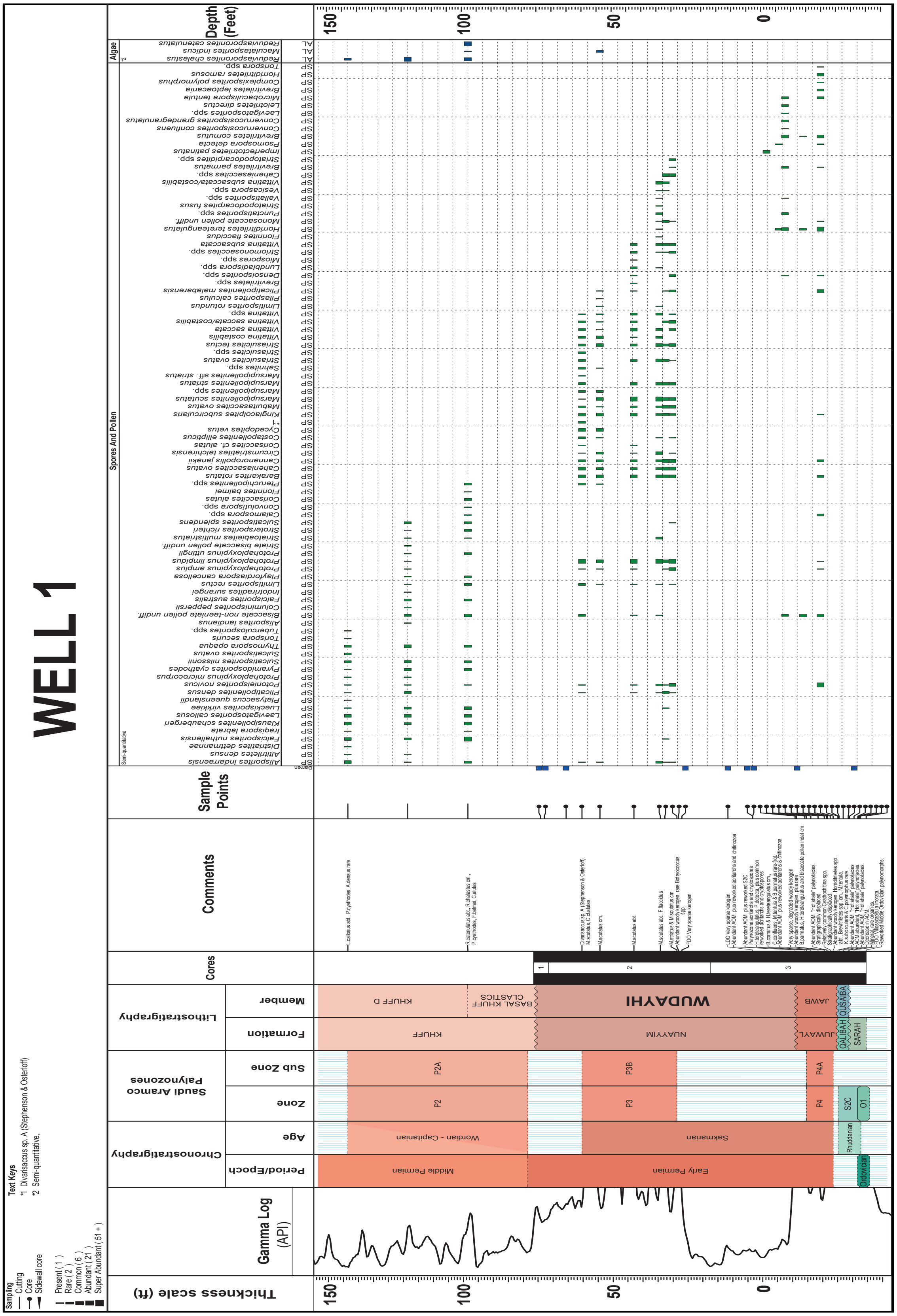
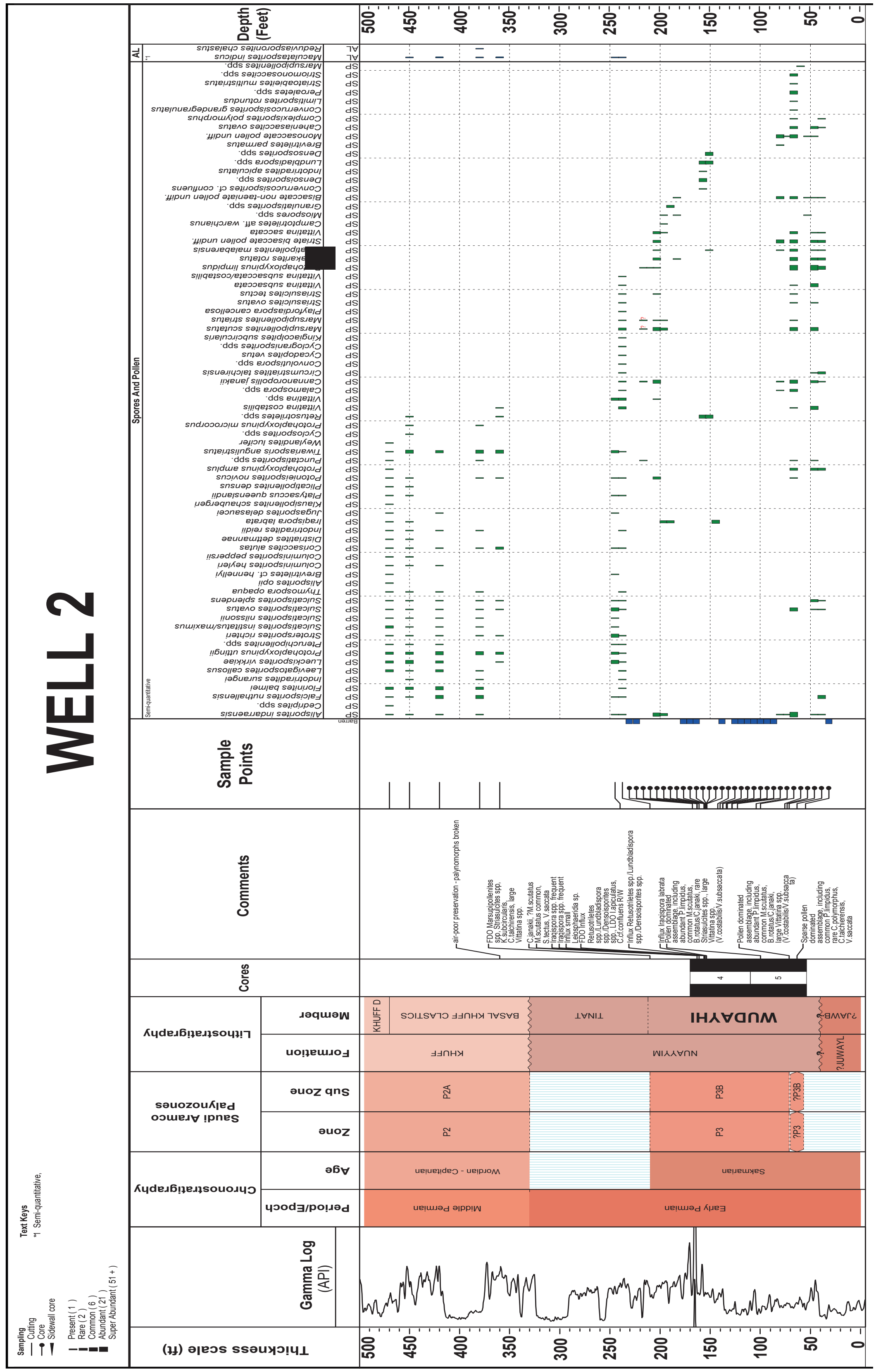
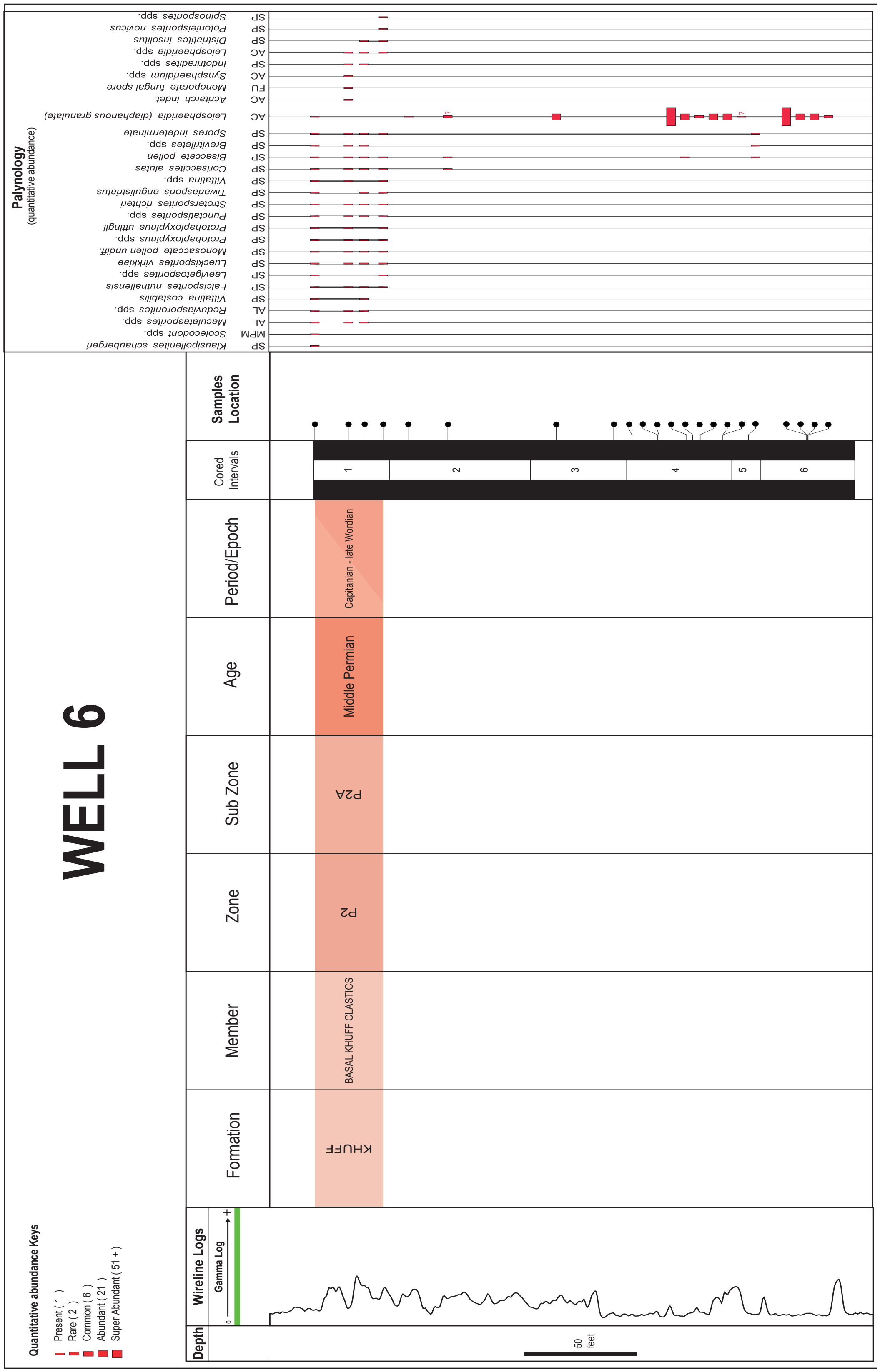
Appendixes – Supplementary Material



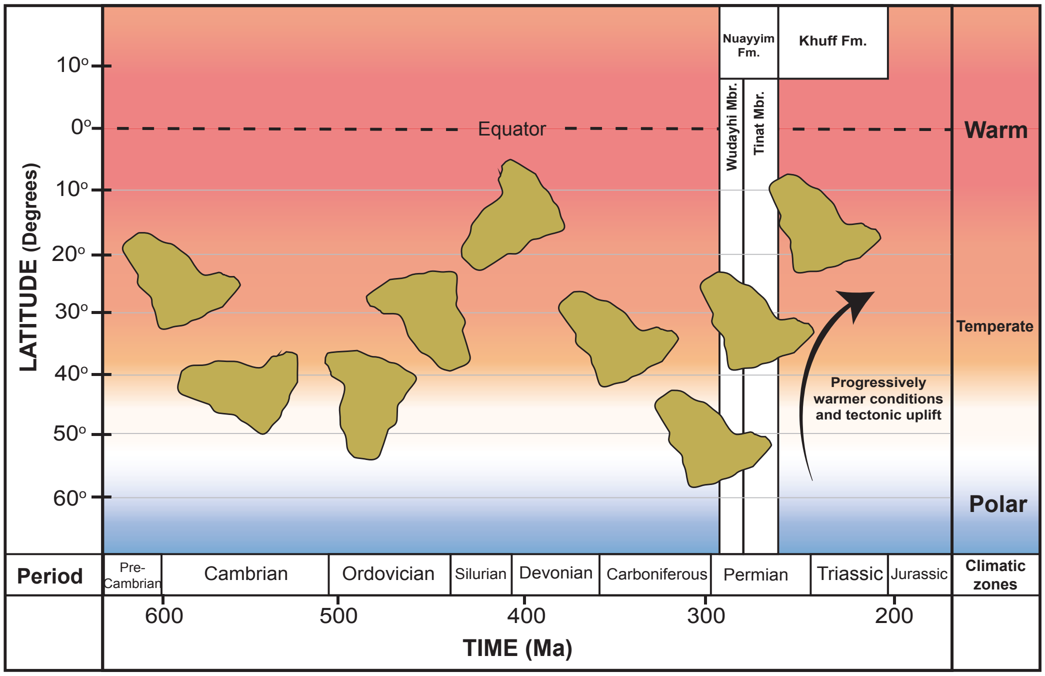
Appendix 1–*Supplementary material*. Palynological determinations from Chapter 2, Well-1



Appendix 2–*Supplementary material*. Palynological determinations from Chapter 2, Well-2.



Appendix 3–*Supplementary material*. Palynological determinations from Chapter 3, Well-6, and Chapter 4, Well-1



Appendix 4–*Supplementary material*. Evolution of the orientation and paleolatitude positions of the Arabian Plate during the Palaeozoic. Annotated is the onset of deposition of the Nuayyim Formation and its Wudayhi and Tinat members. Note the location of the Arabian Peninsula at the time of deposition of the Tinat Member (Early Permian; Artinskian to Kungurian) suggesting increasingly arid conditions as also inferred from palynological assessments.