AAPG BULLETIN

Sedimentology of a 'non-actualistic' Middle Ordovician tidal-influenced reservoir in the Murzuq Basin (Libya)

Marc Gil-Ortiz, Neil David McDougall, Patricia Cabello, Mariano Marzo, and Emilio Ramos

AAPG Bulletin published online March 1, 2019
doi: 10.1306/02151918138

Cite as: Gil-Ortiz, M., N. D. McDougall, P. Cabello, M. Marzo, and E. Ramos, Sedimentology of a 'non-actualistic' Middle Ordovician tidal-influenced reservoir in the Murzuq Basin (Libya), *(in press; preliminary version published online Ahead of Print* March 1, 2019*):* AAPG Bulletin, doi: 10.1306/02151918138.

Sedimentology of a 'non-actualistic' Middle Ordovician tidal-influenced reservoir in the Murzuq Basin (Libya)

Marc Gil-Ortiz[1,3], Neil David McDougall[1], Patricia Cabello[2,3], Mariano Marzo[2,3] and Emilio Ramos[2,3]

[1]Repsol Exploración S.A. c/Méndez Álvaro, 44, 28045 (Madrid, Spain)

[2]Departament de Dinàmica de la Terra i de l'Oceà. Facultat de Ciències de la Terra. Universitat de Barcelona, c/Martí i Franquès s/n, 08028 (Barcelona, Spain)

[3]Institut de Recerca Geomodels. Universitat de Barcelona, c/Martí i Franquès s/n, 08028 (Barcelona, Spain)

ACKNOWLEDGMENTS

Special thanks are due to the Libyan NOC, notably Bashir Garea and Khaeri Tawengi, partners Total, Equinor and OMV both for the technical support in this project and permission to publish the results. Special thanks are also due to Edward Jarvis of CGG-Robertson for discussions concerning the key core descriptions. Thanks are also to my colleagues Manuel Ron, Javier Buitrago, Mikel Erquiaga, Lamin Amh Abushaala and Mourad Bellik for introducing me to the project and their continuous help throughout the study. Special thanks to Eduard Remacha and Francisco Pángaro for constructive discussions in the field and in the office. Support from the Ministerio de Economía y Competitividad (Project Sedimentary Sediment Routing Systems: Stratigraphic Analysis and Models CGL2014-55900-P) and Generalitat de Catalunya

(2014SGR467) is gratefully acknowledged. Thanks to reviewers David Boote and Jonathan Redfern and also to the editors of the AAPG Bulletin for their constructive comments which have improved the content of this paper.

ABSTRACT

The subsurface of the highly productive Murzuq Basin in southwest Libya remains poorly understood. As a consequence there is a need for detailed sedimentological studies of both the oil-prone Mamuniyat Formation and Hawaz Formation reservoirs in this area. Of particular interest in this case, is the Middle Ordovician Hawaz Formation, interpreted as an excellent example of a 'non-actualistic', tidally influenced clastic reservoir which appears to extend hundreds of kilometers across much of the North African or Saharan craton. The Hawaz Formation comprises 15 characteristic lithofacies grouped into 7 correlatable facies associations, distributed in broad and laterally extensive facies belts deposited in a shallow marine, intertidal to subtidal environment. Three main depositional sequences and their respective systems tracts have also been identified. On this basis a genetic-based stratigraphic zonation scheme has been proposed as a tool to improve subsurface management of this reservoir unit. A 'non-actualistic' sedimentary model is proposed in this work with new ideas presented for marginal to shallow marine depositional environments during the Middle Ordovician in the northern margin of Gondwana.

Keywords: Hawaz Formation, 'non-actualism', shallow marine, marginal marine, ichnofacies

INTRODUCTION

For many years, the main Libyan petroleum province was the prolific Sirte Basin with a limited contribution from the Ghadames Basin (Berkine Basin in Algeria) (Hallet, 2002; Figure 1). However, since the mid-1990s, the Murzuq Basin has developed into a major oil and gas producing province. The Hawaz Formation constitutes one of the most important reservoirs in a number of producing fields in the central and northern part of the basin. The generally high reservoir quality (average 5-15% porosity and 0.1-150md permeability) and lateral continuity, characteristic of the Hawaz are key factors in the development and production of these accumulations. However, despite the well-documented potential of the Hawaz Formation, its subsurface character remains poorly understood.

To date, only a few sedimentological studies of this formation have been carried out and all are exclusively based on surface geology (Vos, 1981; Anfray and Rubino, 2003; Marzo and Ramos, 2003, personal communication; Ramos et al., 2006; Gibert et al., 2011). Other published works have focused on diagenesis (Abouessa and Morad, 2009; Abouessa, 2012) and trapping mechanisms (Franco et al., 2012). In addition, subsurface interpretations of the formation are based on inconsistent lithostratigraphic correlations unconstrained by a consistent sequence stratigraphic framework. As such there is no genetic or sequence stratigraphy-based zonation. This limited database highlights the necessity of providing a sequence stratigraphic framework based on a robust sedimentological model of the transitional to shallow marine Hawaz Formation.

As Dalrymple and Choi (2007) have highlighted, transitional tide-dominated and deltaic facies reflect the interaction of numerous terrestrial and marine processes in a very complex depositional environment. Any paleoenvironmental or stratigraphic interpretation of such transition zone successions requires a comprehensive understanding of the facies and facies associations. Hence, a comprehensive understanding of the facies changes through this transition zone is necessary in order to make proper paleoenvironmental and sequence-stratigraphic interpretations of the sedimentary successions. However, is it actually possible to compare these paleoenvironments with any 'actualistic' sedimentary model?

The limitations of the approach become apparent when the uniformitarian principle is extended to depositional environments in the most ancient geological record. In particular, the assumption that modern environments can provide analogues for all geological successions must be questioned (Nichols, 2017). It is broadly accepted that earth dynamics have changed considerably throughout geological history and accordingly, factors controlling sedimentation have changed also, such as a lack of flora stabilizing river banks, greenhouse vs icehouse periods defining coastal geomorphology, tidal ranges controlling facies belts or characteristic ichnofacies during a particular period of geological time. The analysis of some of these factors suggests that the facies succession of the Hawaz Formation reflects rather different depositional processes from those observed in modern environments. From this point forward we will use the term 'non-actualistic' to describe those processes affecting the geological signature of the Hawaz Formation which are difficult to compare with any modern depositional environment analogue.

Consequently, the main aim of this article is to present a sedimentological characterization of the Hawaz Formation based on a detailed lithofacies description and interpretation together with the development of a facies association classification. This forms the basis for an appropiate depositional model in accordance with plausible physical and chemical processes during the Middle Ordovician. In addition the overall analysis aims to build a genetically-based zonation through sequence stratigraphy which will improve reservoir management and provide tools for maximizing hydrocarbon recovery efficiency. Finally, it is intended that these sedimentological and stratigraphic models should be a well-documented subsurface analogue for clastic reservoirs in similar settings.

GEOLOGICAL SETTING

The structure and stratigraphy of the Murzuq Basin

The Paleozoic succession of the Murzuq Basin is an erosional remnant of a much more extensive regional succession extending along the northern margin of the Gondwana supercontinent (Davidson et al., 2000; Shalbak, 2015). Its present extent reflects several periods of uplift and unroofing during the late Paleozoic, Mesozoic and Cenozoic, which together are responsible for its modern architecture. As a consequence, the present-day basin geometry bears little relation to the broader and larger pre-existing sedimentary basin. The current basin is composed of a central Cretaceous depression bounded to the northwest by the Atshan arch, the Gargaf high to the north, and the Tibesti and Tihemboka highs on the southeast and southwest, respectively (Figure 1). These structural highs were formed by multiphase tectonic uplifts from the middle Paleozoic to Cenozoic, although the main periods of uplift and erosion occurred during the Pennyslvanian (late Carboniferous; Hercynian) and early Cenozoic (Alpine) orogenic cycles.

A series of geological events can be recognized in the stratigraphic record of the Murzuq Basin, some represented by basin-scale unconformities within the sedimentary infill reflecting the Pan-African, Caledonian and Hercynian orogenesis and the short Late Ordovician glacial event responsible for the Taconic or basal glacial erosional surface (Figure 2). Other unconformities that may be recognized within the sedimentary record are minor or belong to the younger Austrian or Alpine cycles, and consequently, they do not strongly affect the Paleozoic section directly in the central Murzuq Basin; although, they may have had strong implications in terms of overburden removal, source rock maturity and reservoir quality due to uplift and unroofing of Mesozoic series on the Paleozoic section (Boote et al., 2012).

The maximum sedimentary thickness in the present-day Murzuq Basin is about 4000 m (13,000 ft). Despite successive erosive episodes during several phases of uplift throughout the history of the basin, the maximum sedimentary thickness most probably never exceeded 5000 m (16,400 ft) (Davidson et al., 2000). The age of the infill ranges from Cambrian to Cretaceous, often covered by large Quaternary sand dunes in the central part of the basin. The sedimentary infill can be subdivided into four main units: 1) Cambrian–Ordovician, 2) Silurian, 3) Devonian–Carboniferous, and 4) Mesozoic (Figure 2).

The lower Paleozoic succession comprises the terrigenous Cambrian–Ordovician Gargaf Group consisting of at least five formations – from bottom to top: Hasawnah, Ash Shabiyat, Hawaz, Melaz Shuqran and Mamuniyat Formations (Figure 2). The lowermost Hasawnah Formation rests unconformably on the Precambrian basement and is composed of Cambrian to Lower Ordovician conglomeratic to sandy continental and shallow marine littoral deposits. The Hasawnah Formation is overlain, above a transgressive surface of erosion, by the shallow marine and preglacial Ash Shabiyat and Hawaz Formations, attributed respectively to the Lower and Middle Ordovician (Tremadocian-Sandbian). The Upper Ordovician succession, associated with a major glaciation, principally comprises the Melaz Shuqran and Mamuniyat Formations, locally overlain by a thin and somewhat enigmatic package known as the Bir Tlacsin. The former is most probably lower Hirnantian and predominantly mud-prone representing the period of the highest relative sea level during the Late Ordovician (McDougall and Martin, 2000) whereas the Mamuniyat Formation is a major Hirnantian sand-prone package.

The petroleum systems and the hydrocarbon production history of the Murzuq Basin

Early exploration in the Murzuq Basin focused upon surface structures. The first exploratory well was drilled in the northern Murzuq in 1955-56. Subsequently, a number of successful discoveries in the neighbouring Illizi Basin (southeastern Algeria) encouraged further exploration across the border. Three years later Exxon discoverd gas at Atshan region and Gulf tested oil at low rates from Ordovician sandstones. However, in 1958, industry attention shifted east with the discovery of a major oil accumulation in the Sirte Rift province and there was little further exploration of the Murzuq Basin for the next 20 years. During the late 1980s to 1990s, Rompetrol and later Repsol drilled up to 57 exploratory wells in the basin, all of which targeted Ordovician prospects. This exploratory activity resulted in many significant oil discoveries highlighting the rapidly growing potential of the basin.

The most recent hydrocarbons-in-place estimation for the Murzuq Basin is about 6 billion barrels (bbl) of oil and about 35 trillion cubic feet (TCF) of gas, which represent about 6.5% of the Libya's resources and 30% of the Libya's current oil production (Shalbak, 2015).

The main petroleum system in the Murzuq Basin comprises a basal Silurian (Tanezzuft) hot-shale source rock, Ordovician sandstone reservoirs and a thick Tanezzuft shale seal (Figure 2). A secondary petroleum system in the basin (noncommercial to date) is composed of the basal Devonian sandstones (BDS) as reservoirs and the intra-Devonian shales as the seal (Hallet, 2002; Shalbak, 2015), which also involves the basal Silurian hot-shale source rock (Fello et al, 2006; Hall et al, 2012).

The Ordovician sandstone reservoirs, associated with the primary petroleum system, are the Middle Ordovician Hawaz Formation and the Upper Ordovician Mamuniyat Formation, separated by a deeply incised unconformity related to the Late Ordovician glaciation. This succession was cut by north-northwest to west-flowing Hirnantian glaciers (Ghienne et al., 2003; Le Heron et al., 2004) eroding down into the Hawaz Formation to create a rugged landscape of paleovalleys and highs ('buried hills'). The valleys were partially infilled by the periglacial to subglacial Melaz Shuqran, Mamuniyat and Bir Tlacsin clastics and the residual topography subsequently buried by Tanezzuft shales. This sometimes sealed the Hawaz erosional highs to form paleotopographic traps with now reservoir significant volume of hydrocarbons (Figure 2).

The Hawaz Formation

In the subsurface of the northern Murzuq Basin, the Hawaz Formation is represented by a detrital succession of slightly more than 200 m (650 ft) thick, composed of fine-grained quartz arenites and subarkosic arenites, with subordinate sublithic arenites, similar to the equivalent succession exposed on the Gargaf High (Ramos et al., 2006).

Trace fossils are frequent and, locally, abundant enough to overprint most primary sedimentary structures (Ramos et al., 2006). Gibert et al. (2011), identify eleven ichnogenera, which exhibit a close relationship with both lithofacies and depositional paleoenvironments (facies associations). In broad terms, nearshore to shoreface facies are dominated by dense ‘pipe rock’ fabric formed by *Skolithos* and *Siphonichnus*. In contrast, storm-dominated heterolithic facies are characterized by horizontal deposit feeding *Cruziana* bioturbation.

Two main paleocurrent trends have been identified by Ramos et al. (2006): a) small-scale sedimentary structures including ripples and small sigmoidal cross-bedded sets, indicative of widely dispersed flow directions and b) large scale sedimentary structures suggesting a dominant flow towards the northeast and northwest but locally with bidirectional currents.

A number of sedimentary models have been proposed for the Hawaz Formation, but all within transitional to shallow marine setting. Vos (1981) suggested the outcrop succession represented a fan-delta complex. Other authors (i.e. Anfray and Rubino, 2003; Ramos et al., 2006) identified sedimentary structures indicative of strong tidal influence and the latter proposed a tide-dominated model with deposition in a mega-estuary or gulf where the morphology of the paleocoastline enhanced tidal action, especially during transgressive episodes, when the coastal embayment was flooded.

Measured porosity can reach up to 25.7% although values around 15 to 16% are the most frequent. Pore connectivity is good with pore throat diameters ranging from 0.1 μm to 64 μm (average 14.6 μm). Measured horizontal permeability values from core plugs may reach 900 to 1000 md (Shalbak, 2015) although most commonly average values in wells are around 0.2 to 150md. On the other hand, diagenetic alterations have also had an impact on reservoir quality as noted by Abouessa and Morad (2009). Specifically, the presence of higher amounts of feldspar, illite, a higher dickite to kaolinite ratio and more abundant quartz cement, compared with those sampled in outcrops, is possibly due to the longer residence time under deep burial conditions.

DATABASE AND METHODOLOGY

The present study was based on data from 36 wells located across the north central sector of the Murzuq Basin (Figure 3). This data included core descriptions, high-resolution image logs (FMI), gamma-ray (GR), sonic (DT), neutron porosity (NPHI) and density (RHOZ) wireline logs. The methodology followed consisted of:

1) Well data synthesis and standardization from the 36 wells by means of building well composite charts with the wireline logs available for each well.
2) Description and interpretation of the sedimentary facies based on 14 cored wells and FMI data. Conventional wireline logs were not used to define lithofacies at this stage as the typical thickness of most lithofacies units is below the vertical resolution of these tools. The resultant facies analysis was compared with previous outcrop descriptions from the northern Gargaf high by Marzo and Ramos (2003, personal communication), Ramos et al. (2006)

and Gibert et al. (2011) and used as an analogue for subsurface correlations.

3) Grouping the resultant lithofacies into facies associations, defined by cores and FMI logs, each with distinct wireline log profiles and stacking patterns. These log profiles were then used to identify facies associations in wells lacking core or FMI data.
4) Construction of a comprehensive depositional model defined by the lithofacies and facies associations identified in cores, FMI logs and conventional wireline log profiles.
5) Sequence stratigraphic analysis of the Hawaz Formation. Vertical changes in facies associations and their stacking patterns were used to identify correlatable stratigraphic genetic units. These units were then preliminary traced throughout the study area and used to define the sedimentary architecture of the Hawaz succession (Gil-Ortiz et al. personal communication).

SEDIMENTOLOGY OF THE HAWAZ FORMATION

Lithofacies

Fifteen Hawaz lithofacies were defined in the subsurface of the central Murzuq Basin based upon their lithology and internal fabric including sedimentary structures and bioturbation (Table 1). These include sandstones (S), muddy sandstones (MS), heterolithic sandstones (HS) and heterolithic mudstones (HM). These lithofacies have been compared with those outcropping in the Gargaf high as described by Marzo and Ramos (2003, personal communication) and Ramos et al. (2006), and complemented with valuable ichnofacies observations from outcrops described by Gibert et al. (2011). Each of the lithofacies is described and interpreted as follows:

Large scale cross-bedded sandstones (Sx1)

Fine-grained, well-sorted and cross-bedded sandstones with high-angle foresets (>15º) (Figure 4) characterized by a N-NW directed paleoflow derived from image log dip picking. Locally, mud drapes and rare mudstone intraclasts line set bases and foresets. There is no evidence of bioturbation. Typically, these sandstones form sets more than 50 cm (20 in) thick and cosets up to 10 m (33 ft) thick. The cross bedding is interpreted as a response to the migration of dune bedforms under conditions of net sedimentation. The mud-draped foresets reflect alternating periods of slack water in a tidal regime. The lack of detrital clays and bioturbation suggests moderate to high energy conditions, under which the fines were carried off in suspension. Equivalent lithofacies have been described by Ramos et al. (2006) in outcrops as large-scale, sigmoidal cross-bedded sandstones with occasional horizontal trace fossils (*Cruziana* ichnofacies).

Small to medium scale cross-bedded sandstones (Sx2)

Fine to medium-grained, well-sorted and cross-bedded sandstones characterized by low-angle (5º to 15º) foresets (Figure 4) again characterized by a N-NW directed paleoflow as suggested by image log interpretation. Planar lamination, current ripple cross lamination, mud drapes, and mudstone intraclasts also occur locally. The degree of bioturbation ranges from absent to weak with rare *Planolites*. It forms sets up to 50 cm (20 in) thick. The cross stratification and cross lamination record the migration of medium-scale dunes and ripples and megaripples, respectively, under the influence of unidirectional current flow. This lithofacies could also be interpreted as corresponding to toesets of the previous described large-scale cross-bedded sandstones (i.e. lithofacies Sx1). Most probably deposition occurred within a high energy tidally influenced environment. Equivalent lithofacies have been described by Ramos et al. (2006) outcropping as medium-scale, sigmoidal cross-bedded sandstones with occasional horizontal trace fossils (*Cruziana* ichnofacies).

Parallel-laminated sandstones (Sl)

Fine-grained sandstones with parallel lamination (<5º) (Figure 4). Bioturbation was not recognized (Figure 4). Organized in sets 10 to 100 cm (4 to 39 in) thick. It is interpreted to record sand deposition from nearshore currents under a moderate to high-energy, upper flow regime. A similar lithofacies has been described by Ramos et al. (2006) in outcrops as parallel-laminated sandstones with occasional parting lineation and very scarce bioturbation.

Cross-laminated sandstones (Sxl)

Fine-grained sandstones with low-angle cross-lamination (Figure 4). Climbing-ripple lamination and mud drapes are also occasionally present. In general, it is a nonbioturbated lithofacies, although sparse *Skolithos* were occasionally observed. Set thicknesses range from 10 to 140 cm (4 to 55 in). This lithofacies is interpreted as the deposits of storm events in a nearshore environment. When climbing ripples are present, a high rate of sedimentation under unidirectional flows is inferred. Similar lithofacies are described by Ramos et al. (2006) outcropping in the Gargaf high as low-angle, swaley (SCS) to hummocky cross-stratified sandstones (HCS).

Ripple cross-laminated sandstones (Sr)

Fine-grained very well sorted sandstones with ripple cross-lamination and locally intraclasts. Occasionally the current ripples display bimodal foreset directions. Bedset or coset thickness does not exceed 50 cm (20 in) whilst individual sets are up to 3 cm (~1 in) thick typically associated with very thin clay drapes (Figure 4). This is an unbioturbated lithofacies. The cross-lamination records the migration of current ripples under low to moderate velocity currents. The presence of clay drapes and the bimodal foreset directions, observed in some sets, would suggest deposition in a subtidal setting. Equivalent ripple cross-laminated sandstones with occasional horizontal trace fossils (*Cruziana* ichnofacies) have also been identified in outcrop by Ramos et al. (2006) characterized by a dominantly north-northwest paleoflow direction, locally bimodal towards south-southeast.

Massive sandstones (Sv)

Fine-grained, clean, generally well sorted sandstones with poorly defined planar lamination and cross-bedding (Figure 4). Locally, mud intraclasts and basal erosive surfaces were identified. This lithofacies is characterized by the absence of bioturbation. It is organized forming sets of 30 to 100 cm (10 to 39 in) thick. The massive appearance of this facies could be interpreted as the result of early postdepositional processes involving dewatering and partial fluidization suggestive of a high sedimentation rate in the depositional system. This lithofacies can be easily misinterpreted as Sx1 in cores when the clean nature of the sandstones, reflecting the lack of micas and fine sediment obscures the limits between cross-bed sets. The lack of detrital clays and micas in these sandstones suggests deposition in a relatively high-energy environment where fines were carried off in suspension. Equivalent lithofacies have been observed by Ramos et al. (2006) outcropping in the northern margin of the basin as apparently massive sandstones.

Burrowed cross-bedded sandstones (Sxb)

Clean, fine-grained sandstones displaying small to medium-scale cross bedding with local mudstone intraclasts. Moderate degree of bioturbation with *Skolithos* and *Siphonichnus* burrows (Figure 4). Typically organized in 30 to 200 cm (10 to 79 in) thick beds. The clean nature of the sandstones and the presence of mudstone intraclasts suggest moderate to high energy conditions in which fines were carried off in suspension. The cross-bedding records the migration of dune and bar bedforms whereas the vertical to oblique burrows suggest a shallow, high energy marine environment.

Burrowed cross-laminated sandstones (Sxlb)

Fine-grained, variably argillaceous and micaceous sandstones with low-angle cross-lamination and local mud laminae and mudstone intraclasts. This lithofacies is moderately bioturbated with an ichnofabric dominated by *Skolithos* and *Siphonichnus*, indeterminate burrows and meniscate backfilled burrows (Figure 4). The minimum thickness observed of this lithofacies is 70 cm (28 in). The moderately intense bioturbation, dominated by mainly vertical, suspension-feeding burrows suggests a shallow, high-energy subtidal environment. However, the mud laminae also reflect low-energy conditions. Thus, depending on the context, this lithofacies may have different interpretations ranging from a lower shoreface to an intertidal environment. The low-angle cross-lamination is interpreted as reflecting deposition from subtidal sand sheets or low relief sand bars.

Burrowed ripple cross-laminated sandstones (Srb)

Very fine- to fine-grained sandstones, locally argillaceous and micaceous characterized by current-ripple cross-lamination and planar lamination. A moderate degree of bioturbation characterizes this lithofacies (Figure 4), with an ichnofabric dominated by *Skolithos* (6 – 8 mm [0.24 – 0.31 in] diameter and maximum length of 30 cm [12 in]), *Siphonichnus* and local indeterminate burrows. This lithofacies forms packages 15 to 170 cm (6 to 67 in) thick. The fine grain size and the locally argillaceous composition of this lithofacies imply deposition in a relatively low energy environment. The cross-lamination records the migration of current ripples under conditions of net sedimentation and implies that the sand was transported by a unidirectional current of low to moderate velocity. The ichnofauna (mostly represented by vertical burrows) suggests a shallow marine environment dominated by suspension feeding benthonic fauna.

Burrowed sandstones with Siphonichnus (Sb)

Fine-grained well-sorted sandstones locally with mud laminae. This lithofacies is highly bioturbated, with an ichnofauna dominated by *Siphonichnus* burrows, locally up to 100 cm (39 in) in length, giving rise to a distinctive 'pipe rock' fabric. The minimum bed thickness appears to be about 20 cm (8 in), although bed boundaries are typically obscured by bioturbation (Figure 4); This lithofacies is volumetrically very abundant and continuous sections of up to 20 m (66 ft) have been identified in some wells. The occurrence of vertical burrows

(*Skolithos* ichnofacies) suggests a moderate- to low-energy, restricted to shallow-marine environment, and the presence of mud laminae (mud drapes) implies fluctuating energy levels. Equivalent lithofacies have been described by Ramos et al. (2006) in outcrops as thick-bedded, massive, bioturbated sandstones.

Burrowed sandstones with feeding ichnofauna (MSb)

Argillaceous fine-grained sandstones characterized by moderately intense bioturbation dominated by horizontal, deposit feeding burrows (Figure 4); notably *Teichichnus and Thalassinoides.* Individual beds range in thickness from 10 to 270 cm (4 to 106 in). The moderately high detrital clay content of these sandstones and the characteristic low-energy ichnofauna suggests a relatively protected depositional setting or open-marine conditions.

Sandy heterolithics (HS)

Interbedded very fine- to fine-grained sandstones and argillaceous siltstones (>50% sand content). This lithofacies displays flaser structures together with combined current and wave ripple cross-lamination and also planar lamination (Figure 4). There is only a limited amount of bioturbation with rare *Chondrites* and *Planolites* burrows. The thickness of this lithofacies ranges between 1 cm (0.4 in) sets up to an accumulated bedset thickness of 5 m (16 ft). The interbedding of sandstone and argillaceous siltstone implies fluctuating energy levels. Sands were transported and deposited by both unidirectional and oscillatory (wave-generated) flows. Unidirectional current flow was mostly of low to moderate velocity, resulting in the formation of current ripples. By contrast, the presence of cross-bedding (due to the migration of dune and bar bedforms) and mudstone intraclasts indicates higher current velocities. The presence of *Chondrites* indicates that burrowing took place under marine conditions; the remaining burrows, *Planolites* and indeterminate horizontal tubes, also suggest a marine environment. The low bioturbation index together with the local occurrence of *Chondrites* (generally considered to be characteristic of low oxygen conditions), suggests that oxygenation levels were low. Wave, current and combined-flow cross-lamination suggests sands were deposited during storm events below fair-weather wave base.

Burrowed sandy heterolithics (HSb)

Thinly interbedded very fine-grained, micaceous, argillaceous sandstone and micaceous, argillaceous siltstone (>50% sand content). Locally, the argillaceous siltstones display planar lamination and the sandstones current and wave ripple cross lamination. Bioturbation is moderately intense characterized by overprinted *Skolithos* and *Cruziana* ichnofacies (*Siphonichnus* burrows, with subordinate *Planolites* and indeterminate burrows) (Figure 4). Minimum bed thickness is 1 cm (0.4 in) whereas accumulated bedset thickness can reach 4 m (13 ft). The interbedding of sandstone and siltstone suggests fluctuating energy conditions, with the sandstones representing higher energy levels. The cross lamination within the sandstones records the migration of combined current and wave ripples under conditions of net sedimentation and low to moderate current velocities. The mixed assemblage of ichnofauna suggests the transition from a high-energy to a low-energy setting, from an open-marine inner shelf up to a lower shoreface setting. There is a variation of this lithofacies in the upper part of the Hawaz Formation, where the base of the sandy intervals occasionally displays rip-up mudstone clasts and a rhythmic alternation of thin, inclined, mud drapes and sandstones. In this case, the interpretation given to this lithofacies corresponds to inclined heterolithic stratification (IHS) associated with minor channels or tidal creeks in a restricted, sandy to mixed intertidal subenvironment.

Muddy heterolithics (HM)

Mudstones interbedded with micaceous argillaceous siltstone and very fine-grained sandstone (>50% clay content). The mudstone and argillaceous siltstone display planar lamination and lenticular bedding (current and wave rippled sand lenses). The sandstone contains current ripples and rare wave ripples (Figure 4). Individual lithofacies packages have a minimum thickness of 5 cm (2 in) but may reach an accumulated bedset thickness up to 3.5 m (11.5 ft). The sandstone beds and lenses represent energetic pulses in an overall low energy setting, where mud settled out of suspension. During the higher-energy pulses, sand was moved by both unidirectional and oscillatory (wave-generated) flows. The lack of burrows indicates anoxic conditions in a fairly distal marine setting or a restricted and stressed subenvironment, such as a tidal mudflat or lagoon.

Burrowed muddy heterolithics (HMb)

Argillaceous siltstone interbedded with minor fine-grained sandstone layers and sandstone laminae (>50% clay content). It is characterized by a variable degree of bioturbation with *Siphonichnus*, *Skolithos*, *Planolites* and indeterminate vertical burrows (Figure 4). Shrinkage cracks may occur locally. The minimum thickness of individual facies units is 7 cm (3 in) whilst the accumulated bedset thickness is up to 3.8 m (12.5 ft). The interbedding of argillaceous siltstone and very fine- to fine-grained sandstone suggests fluctuating energy conditions in an overall low-energy setting. The shrinkage cracks are probably related to variations in salinity and temperature when present. The depositional setting of this lithofacies varies from a relatively distal, inner shelf subenvironment to a restricted intertidal flat subenvironment.

Facies associations

The proposed scheme based on the previously described lithofacies establishes 7 facies associations designated as HWFA1 to HWFA7 assigned to proximal and increasingly distal environments (Figure 5).

HWFA1: Tidal flat

Facies association HWFA1 mainly consists of lithofacies Sxlb, MSb, Sb, HMb and HSb with subordinate Srb and Sv (Figure 5). The thickness of individual packages of this facies association is very variable, ranging from 30 to 60 m (100 to 200 ft), as a direct consequence of the downcutting associated with the Upper Ordovician glaciogenic unconformities. The GR log response varies significantly from 30 to 140 API units in a characteristic fining-upward succession . The intensity of bioturbation is moderate to very high; characterized by a mixed low diversity S*kolithos* and *Cruziana* ichnofacies assemblage indicative of a relatively high-energy environment grading towards a more protected and restricted low-energy setting. It is also characterized by an upwards-increasing detrital clay content typical of tidal flat environments. Furthermore, the low diversity of acritarch assemblages and the strong predominance of leiospheres, characteristic of a marginal-marine setting, identified in palynological studies of some wells, suggests a relatively protected tidal sand to mixed flat environment grading normally from the underlying HWFA3 or HWFA2 (see below). Some ichnogenera identified as *Planolites*, *Siphonichnus* and *Thalassinoides* strongly associated with tidal flat deposits (Gingras et al., 2012) also support this hypothesis, together with the common occurrence of clay drapes and flaser-lenticular bedding (Figure 6-A). The sporadic occurrences of individual massive to rippled sandstones levels (Sv and Srb) and the presence of rip-up mudstone clasts at the base of these units in the heterolithic intervals (locally associated with small synsedimentary faults) are interpreted in terms of bank collapse in tidal creeks on the sand flat. The same package in the Gargaf high was described as an upper shoreface wave dominated facies assemblage by Ramos et al. (2006) which probably would represent a beach to barrier island setting laterally equivalent to this facies association HWFA1.

HWFA2: Subtidal complex

Facies association HWFA2 is mainly composed of lithofacies Sx2, Sx1, Sxl, Sr, Sl and Sv with subordinate HM (Figure 5). It is organized into stacked packages 0.3 to 40 m (1 to 131 ft) thick. The basal contact of these packages is typically erosive, locally marked by the presence of mud clasts (Figure 6-B) and the GR response is both clean and blocky (GR values around 25 API units) locally marked by peaks (up to 65 API units) related to the presence of thin mud-drapes or concentrations of mica . These values are within the established range for micaceous sandstones which could have values of up to 80 API units (Rider, 2004). Bioturbation is scarce to absent, probably related to a very high sediment supply in a relatively short period of time. Paleocurrents, measured in this facies association from image log data, indicate a dominant trend towards the north-northwest with some bidirectionality, probably related to tidal effects as indicated by the mud drapes in lithofacies Sx1, Sx2 and Sr (Figure 6-C). However, an additional secondary trend has also been identified indicating flow toward the northeast. The reservoir quality of this facies association is the best of the entire Hawaz Formation with an average porosity of 11% and an average horizontal permeability of 125md.

Facies association HWFA2 is interpreted as an amalgamated complex of sand bars and dunes (slightly coarsening-upwards profile with Sx1, Sx2 and Sr lithofacies), and channel deposits (slightly finning-upwards profile with Sv, Sl and Sr lithofacies) influenced by the action of the tides. The interpretation is a laterally extensive fluvio-tidal to subtidal complex. Subordinate heterolithic intervals are also found intercalated with the cross-stratified sand bars, possibly related to periods of slack water and deposition in relatively protected lagoonal or interbar subenvironments. The features of this facies association are very similar to those described by Ramos et al. (2006) from the Gargaf high 100 km (62 mi) to the north. They are almost equivalent in depositional environment although in the subsurface of the northern Murzuq Basin HWFA2 would represent a shallower lateral equivalent with higher fluvial influence due to the general absence of bioturbation reflecting higher energy and sedimentation rates.

HWFA3: Abandoned subtidal complex

Facies association HWFA3 is primarily characterized by lithofacies Sxlb, Sxb, Srb, Sxl, Sv and Sx2 (Figure 5). It forms packages ranging in thickness from 0.6 to 12 m (2 to 40 ft). Facies packages are distinguished by a fining-upward succession of fine-grained sandstones represented by a distinctive upwards increase in the GR characterized by API values between 25 and 70. Bioturbation is moderate typically becoming more abundant towards the upper part of these successions with common *Skolithos* and *Siphonichnus* burrows.

This facies association is interpreted to represent the abandonment of the associated subtidal complex (HWFA2) after a general rise in relative sea level and a cessation or major decrease in sediment supply promoting colonization in a subtidal setting. It is quite common to find this facies association gradationally intercalated with the subtidal complex reflecting a transgressional trend in a relatively protected environment.

HWFA4: Middle to lower shoreface

Facies association HWFA4 is mainly composed of lithofacies Sr, Srb, Sxlb, Sxb, Sv, HSb (Figure 5). The thickness of individual packages ranges between 0.6 and 14 m (2 and 46 ft). The GR response is typically a serrate, coarsening–upwards succession with values ranging between 30 and 80 API units (Figure 9). Bioturbation varies from scarce to moderate. Overall packages of this facies association form clear coarsening-upwards successions with a characteristic *Skolithos* ichnofacies related to regressive sand belts prograding during highstand sea-level conditions (Gibert et al., 2011). On this basis, the interpretation proposed is of a low to moderate-energy, middle to lower shoreface setting prograding in a relatively high-energy subtidal environment.

HWFA5: Burrowed shelfal and lower shoreface

Facies association HWFA 5 mainly consists of lithofacies Sb, MSb and Sxlb (Figure 5). Thickness of individual packages ranges between 0.6 and 33 m (2 and 108 ft). The typical GR log response of this facies association is irregularly serrate with values between 30 and 80 API units , reflecting a relative increase in the detrital clay content. Bioturbation is moderate to very abundant tending to overprint and obscure all primary sedimentary structures (Figure 6-D).

This facies association is interpreted to have been deposited in a lower shoreface to shelf environment as suggested by the variably clean to argillaceous nature of the sandstones and ubiquitous bioturbation with a well-developed *Skolithos* ichnofacies.

HWFA6: Burrowed inner shelf

Facies association HWFA6 comprises lithofacies HMb and HSb (Figure 5). The minimum thickness of individual packages is around 30 cm (1 ft) whilst the maximum value is 15.8 m (52 ft). It may be considered as the distal equivalent of HWFA5 characterized by a spiky GR response characterized by notably higher values ranging from 60 to 120 API units . Bioturbation intensity is moderate, with an ichnofaunal assemblage dominated by the *Cruziana* ichnofacies.

This facies association is interpreted as having been deposited in a distal burrowed lower shoreface to inner shelf setting based on its heterolithic lithology, *Cruziana* ichnofacies (Figure 6-E) and the occurrence of combined current and wave ripples. This suggests a low-energy, open-marine environment in moderate water depths above storm wave base (SWB).

HWFA7: Shelfal storm sheets

Facies association HWFA7 is mostly composed of lithofacies HS and HM (Figure 5). The thickness of these facies packages ranges from 0.3 to 18 m (1 and 59 ft). It is characterized by a continuously high GR response with values of up to 150 API units or even higher . Where notably high GR peaks occur, these may represent local flooding events interrupting a rather shallower depositional sequence. This facies association has the lowest reservoir quality in the formation with an average porosity of around 5% and an average horizontal permeability of 0.2md.

It is interpreted to have been deposited in a distal shelf environment on the basis of a high detrital clay content and the occurrence of combined wave and current ripples (Figure 6-F). These suggest fluctuating energy levels in broadly very low energy environment between the fair-weather wave base (FWWB) and storm wave base (SWB). This is supported by the generally very low intensity of bioturbation, the occasional occurrence of *Chondrites* burrows and shrinkage cracks indicating deposition in a fairly distal, poorly oxygenated setting, perhaps associated with distal waning storm events capable of transporting sand to the open-marine shelf.

When core data was not available for several sections in the studied wells, image log data was key to characterize the seven facies associations previously mentioned (Figure 7).

‘NON-ACTUALISTIC’ SEDIMENTARY MODEL

Ever since James Hutton's key observations in the late eighteenth century, modified by the work of John Playfair and, critically, Charles Lyell's development of the concept of "uniformitarianism" in his Principles of Geology (1832), geologists have sought to explain ancient processes by reference to 'actualistic' processes in order to better understand the sedimentary record.

However, the Earth has changed significantly through geological history. Indeed, even from the early Paleozoic until present day, some processes and depositional environments simply cannot be directly compared, since conditions were significantly different. As Nichols (2017) certainly points out, if choosing a 'present' to be the 'key of the past' probably choosing the most recent 'present' is not the best idea.

After careful study of the Hawaz Formation and the sedimentary processes involved in its deposition, several significant concepts have been developed which require further discussion in this respect (Table 2):

1) The lack of fauna and specifically flora in subaerial conditions during the Middle Ordovician and more ancient times must have constituted a key controlling factor on depositional processes operating in marginal marine and coastal environments (Kenrick and Mitchell, 2015; Kenrick and Mitchell, 2016; Bradley et al., 2018). Firstly, vegetation constitutes a fixing element within the substrate allowing the stabilization of floodplains and the control of lateral river channel migration (Davies and Gibling, 2010; Davies et al., 2011; Gibling and Davies, 2012), generally lowering the energy and net sediment throughput of the environment. Whereas fluvial meandering systems can be considered a general pattern in continental to marine transitional zones for most present day cases (with the notable exception of

glacial-influenced settings or proximity to high relief source areas), the lack of vegetation in the Middle Ordovician would have almost certainly contributed to maintaining a high energy levels in the sedimentary system as far as the coastal plain, characterized by laterally extensive braided floodplains (Table 2).

The other remarkable aspect worthy of note is the effect of vegetation on the generation of clay minerals (Table 2). Many Precambrian to Ordovician clastic deposits are characterized by their low claystone or detrital clay content. One of the reasons for this may be the absence of vegetation and the resultant enhanced chemical weathering on land surfaces. The generation of clays by weathering was significantly less than at the present time, and therefore the availability of clays in the source areas, including potentially erodible rocks, was also less for the same reason. Other mechanisms for inputting a clay fraction into the depositional environment may be associated with hydrothermal processes, diagenesis or volcanic ash deposits; the latter has been identified by Marzo and Ramos (2003, personal communication) and Ramos et al. (2006).

This is indeed what we see in the upper part of the Hawaz Formation; typically comprising a package of sand prone tidal flat deposits with very few clear claystone intervals, accumulating in a restricted low-energy environment where, in a modern system, vegetation would fix finer sediments at the very top of this kind of depositional succession. Furthermore, the possibility of a clay input of volcanoclastic origin should not be ruled out as Ramos et al., (2006) highlight the presence of K-bentonite layers within the Hawaz Formation as observed in outcrops.

2) In line with Nichols (2017), the climate factor related to periods of greenhouse and icehouse is also key in understanding how coastal environments have evolved. Given that the last few million years of geological history are considered as an icehouse period, some processes related to the characteristic low relative sea levels are clearly not equivalent to those produced during greenhouse periods, as much of the Cambrian-Ordovician actually was. The relative sea level, during much of the Ordovician (at least until the onset of the Hirnantian glaciation), was probably tens of meters higher than at present time, which in the case study would represent a very extensive area of land flooded, across a very low relief cratonic margin (Table 2). Thus, confined estuary systems produced by incised valleys during sea-level drop are not expected in this setting. This discussion can be applied to the depositional model of the Hawaz Formation. As such, classical estuarine environments are inherently unlikely. Indeed, conventional lowstand systems tracts would be, in any case, extremely difficult to identify, as major erosive features related to sea-level drop would not be produced in this low gradient, cratonic transitional setting.
3) It is also relevant to our study that tidal range has not been constant through the whole of Earth's history. Tides are largely controlled by differential gravitational forces exerted between the Earth and the Moon, but the distance between both bodies has changed through time at a currently calculated rate of 3.8 cm/yr (1.5 in/yr) (Odenwald, 2018), entailing an average Earth-Moon distance of 367,000 km (228,000 mi) as opposed to 384,000 km (238,000 mi) today. Tidal-energy dissipation over time is thus a well-established process reflected in the increasing length of the day and

thus number of days per year. This appears to be a purely linear process reflecting the progressive slowing of Earth´s rotation and the associated outward spiralling of the Moon. Thus, a day in the Ordovician is calculated to have been 21 hours long and the year 414 days long. For our purposes it is also true that the potential sediment load of nearshore tidal currents together with their depositional effectiveness are related directly to the tidal range or maximum tidal height (Williams, 2000); itself controlled by global tidal forces, water depths and local topography. In general, therefore, we can assume notably higher tidal ranges and more powerful tidal currents during the deposition of the Hawaz Formation. Going further, we may also assume that in the case of the upper Hawaz Formation, for example, even very small variations in tidal range in such low gradient depositional environment would result in a significant increase in the areal extension of marginal or paralic, tidally influenced environments (Table 2).

4) Ichnofacies are usually related to sedimentary environments and, particularly in tidal settings, there are specific parameters such as salinity, depositional energy, sediment grain size and sedimentation rates that control fauna colonization (Gingras, et al., 2012). However, there are some ichnological assemblages, which may also have a chronostratigraphic value when looked at on the basis of bioturbation intensity and lateral extent. A very good example is the lower part of the Hawaz Formation and the underlying Lower Ordovician Ash Shabiyat Formation, which are characterized by their distinctive ‘pipe rock’ or high-density burrowed *Skolithos* ichnofabric. Similarly, the association of this suspension-feeding fabric, often overprinting a deposit feeding burrowing characterized by

common trilobite traces and thus a “true” *Cruziana* ichnofacies is distinctive. Some if not many or even all of the organisms responsible for these ichnofabrics are already extinct (Table 2). Thus, the occurrence of these ichnofacies in such a very low gradient, cratonic platform is highly unlikely in the present day.

After these comments, it is also worthwhile considering that the geomorphology of clastic coastal depositional environments is closely linked to the relative influence of waves and tides along the coastline (Harris and Heap, 2003), their evolution controlled by three main factors: sediment supply, physical processes (river currents, tidal currents and waves) and relative sea level variation (Dalrymple, 1992, Boyd et al., 1992; Dalrymple et al., 1992; Harris et al., 2002). Thus, taking all of this into account with and applying it to the study dataset in the area, a ‘non-actualistic’ depositional model is proposed for the Hawaz Formation based upon modern sedimentological criteria but constrained and adapted to Middle Ordovician environmental conditions (Figure 8).

It was a constantly evolving tide-dominated environment, evolving from a relatively open-marine setting characterized by mixed storm-tide-dominated deposition towards a more protected subtidal to intertidal setting on an embayed coastline. This promoted tides as the dominant controlling factor on sedimentation process, supported by the vertical arrangement or stacking of facies associations. It shows a lower shoreface to shelf environment with sandy storm sheet deposits present across much of the basin. Above this lower interval, a laterally extensive and fluvio-tidal to subtidal complex comprising of tidal channels and bars developed across the study area (Figure 8-A). The distal part of this subtidal complex eventually became abandoned as sea level rose creating a system of lagoons and barrier islands (not clearly identified in the subsurface) (Figure 8-B). Finally, prograding tidal flats developed during a relative high sea level stage (Figure 8-C).

From subsurface paleocurrent data it is apparent that the depositional system evolved from a coastal environment in the south-southeast to fully marine environments towards the north-northwest. The data show only limited dispersion defining a clear depositional trend from southeast to northwest with strong ebb current indicators. These data are in accordance with those of Ramos et al. (2006) from outcrops in the Gargaf high. Evidence of bidirectional current indicators in primary sedimentary structures is, however, hard to observe. Although the presence of this kind of feature would strongly support an important tidal influence, it is not always present in many tidal deposits. On the other hand, no evidence for a seasonally controlled river have so far been found in the succession which would help to preserve this type of reverse flow structure during periods of low fluvial regime (Dalrymple and Choi, 2007). However, the presence of clay drapes in most of the lithofacies described does strongly support an important tidal effect throughout the depositional system.

SEQUENCE STRATIGRAPHY AND ZONATION OF THE HAWAZ FORMATION

The purpose of this section is to recognize and correlate stratigraphic surfaces representing changes in depositional trends and to interpret the resulting stratigraphic units bounded by these surfaces.

The key bounding surfaces splitting genetic sedimentary packages were recognized using a material-based sequence stratigraphic approach (Embry, 2009). The defined surfaces are:

- **Maximum regressive surface**, where a conformable horizon marks a change from coarsening and shallowing upwards to fining and deepening upwards;
- **Maximum flooding surface**, where a conformable horizon marks a change from fining and deepening upwards to coarsening and shallowing upwards and is normally represented by the highest clay content in the succession;
- **Shoreline ravinement unconformity**, where a clear erosive surface is overlain by brackish marine deposits and which represents erosion in the stratigraphic unit produced by wave and tidal currents during an early transgressive stage just after a base level fall;
- **Regressive surface of marine erosion**, where in an overall regressive succession there is a clear change in depositional trend with shelfal deposits abruptly overlain by prograding shoreface deposits. As suggested by Embry (2009), this last surface, is not a suitable surface for correlation due to its highly diachronous nature, so has not been used as a main bounding surface for our sequence stratigraphic framework. However, locally it may be of use in explaining trend changes in the facies succession observed in some wells.

Several low-order and numerous high-order sequences can be recognized in the stratigraphic record of the Hawaz Formation (Figure 9) but, after analyzing the evolution or stacking of the facies associations in each well it is possible to erect a simplified scheme with three major depositional sequences (DS1-3) and

5 Hawaz reservoir zones (HWZ1-5) each defined by key correlatable genetic, material-based surfaces (Figure 9).

The top of the Ash Shabiyat Formation is marked by a sharp or slightly more gradational shift from the blocky, low GR response, characteristic of this formation, to a notably more spiky or serrate GR response typical of much of the lower Hawaz. This shift is interpreted not only as a maximum regressive surface but also as a sequence boundary. As such it is a compound surface and might be considered in terms of marine erosion as a ravinement which marks the base of the depositional sequence 1 (DS1) (Figure 9).

The overlying HWZ1 is broadly transgressive in character, comprising stacked fining-upwards parasequences (including a regionally distinctive and extensive abandoned subtidal complex) capped by a regional flooding surface (Figure 9), and finally a cleaning-upwards, progradational parasequence or parasequence set.

The boundary between HWZ1 and HWZ2 is marked in all the wells by an abrupt change in lithology to more argillaceous facies recording a marked deepening in the basin. This is an excellent and consistent correlatable surface but is not fully genetic as the maximum flooding surface of the DS1, only rarely coincides with the lithological change and is instead typically picked a short distance above the shift at the highest GR peak in the well (Figure 9).

The maximum flooding surface defines the onset of the highstand systems tract (HST) of DS1, which coincides completely with the zone HWZ2. This can often be divided into two subzones (HWZ2a and HWZ2b) separated by a regressive surface of marine erosion (Figure 9), created by the cut of waves and tides in the lower shoreface during the regression of the shoreline. This surface separates a dirty sandy package from a cleaner sandy package within a coarsening-upwards parasequence or parasequence set as suggested by the GR response and facies analysis. However, this surface is not easily recognizable in all wells and has not been used as a regional correlative surface due to its probable diachronous nature.

The HST of DS1 is truncated by an erosive surface interpreted as a shoreline ravinement unconformity (Figure 9) generated by the action of wave and tidal currents during an early transgressive stage just after a base level fall and probably enhanced by an allocyclic trigger mechanism, perhaps tectonics related. This surface would also be a sequence boundary and would correspond with the onset of the depositional sequence 2 (DS2) and the base of zone HWZ3, the main reservoir section of the Hawaz Formation. The facies association immediately overlying this key boundary is usually HWFA2 (Subtidal complex), considered to represent an early transgressive systems tract (TST) equivalent to zone HWZ3. Locally, this zone shows minor higher frequency flooding surfaces mostly composed of heterolithics (Figure 9). These flooding surfaces could be interpreted as condensed lagoonal deposits, but the lack of biostratigraphic data in this sand-prone package suggests we should treat this hypothesis with caution, although the presence of these sub-environments should not be rejected. Tidal inlet storm deposits or inclined heterolithic stratification (IHS) could also be a plausible option, considering the broad general subtidal setting of this zone.

The boundary between zones HWZ3 and HWZ4 is marked by a change in depositional environment from a subtidal to intertidal setting. This boundary would be close to the maximum flooding surface after which the tidal flat would prograde infilling the available space (bay infilling) under a forced regression pattern, whereas further to the north barrier island deposits (observed in Gargaf outcrops by Ramos et al., 2006) would most likely have limited the connection to the open sea.

Zone HWZ4 comprises stacked fining-upwards parasequences, mainly formed by tidal sand to mixed flat deposits cut by tidal creeks (Figure 9). Similar processes have been highlighted by Desjardins et al. (2012) in the lower Cambrian Gog Group of the Canadian Rocky Mountains where tidal flats are forced to regress in response to falling sea level in tide-dominated settings.

Above zone HWZ4, the depositional trend changes again and GR values begin to decrease in response to increasingly abundant cleaner sand deposits. There is no evidence of sharp changes either in lithology, or in conventional log responses suggesting there is no major unconformity. However, some subtidal packages are preserved sometimes at the very top of the Hawaz Formation which would denote a new transgression. Thus, the boundary between HWZ4 and HWZ5 is considered to be a compound maximum regressive surface and sequence boundary which would constitute the beginning of a rarely preserved depositional sequence 3 (DS3) (Figure 9). Zone HWZ5 is often eroded and overlain by the Upper Ordovician formations or the base of the Silurian.

DISCUSSION

Following Boyd et al. (1992) and Dalrymple et al. (1992), clastic coastal depositional environments are classified on a ternary diagram summarizing the main factors (rivers, waves and tides) controlling the geomorphology of linear shorelines, deltas or estuaries. This is a very useful and powerful tool in 'actualistic' or 'near-actualistic' systems, but in many cases it might be hard to apply to very ancient coastal to shallow marine depositional systems, notably those of the Precambrian to lower Paleozoic due to major differences in Earth surface dynamics. Nevertheless, while some of these ancient depositional systems lack obvious modern analogues, some features remain comparable with modern environments. A detailed interpretation from subsurface cores and logs highlights the major depositional and paleogeographic factors responsible for the Middle Ordovician Hawaz Formation of the northern Murzuq Basin. The resultant seven correlatable facies associations (HWFA1 to HWFA7) and the robust sequence stratigraphic framework suggest that the Hawaz Formation was deposited in an intertidal to subtidal environment prograding from south to north. The facies associations and their linked ichnogenera suggest that water depths are unlikely to have exceeded several tens of meters (hundreds of feet), with the sea floor above storm wave base at most locations.

Considering the significant areal extent, not only of the Hawaz Formation across the Murzuq Basin but also its lateral equivalents, in both Kufra and Illizi Basins, which lack the key unburrowed cross-bedded sandstones (McDougall et al., 2008; McDougall et al., 2011) typical of the subtidal complex described in this work, it is clear that deposition occurred in and on the margins of an epeiric sea characterized by a very low bathymetric relief and very broad facies belts tracts. Dalrymple and Choi (2007) suggest fluvio-tidal transition zones may range in-width up to hundreds of kilometers (hundreds of miles) in low-gradient settings as would indeed be the case for the northern margin of Gondwana during the Middle Ordovician. In such environments small changes in relative sea level would be sufficient to cause major lateral shifts in facies belts. These small changes occurred during a greenhouse period with relatively high global sea levels. There is no evidence of incised valley systems within the Hawaz succession suggesting global sea level remained relatively high through its deposition. As such, lowstand systems tract facies could not be observed either in the Gargaf high outcrops (Anfray and Rubino, 2003), or in the subsurface of the Murzuq Basin.

During the initial stages of sea-level rise (TST), coastal areas were slowly flooded, producing subtidal sedimentation associated with fluvial discharge along embayed coastlines, presumably due to flooding of braided fluvio-tidal systems, whereas during stages of high sea levels (HST), the shoreline migrated seaward, resulting in the progradation of tidal-wave influenced strand plains, beaches, or deltas associated with gentle lobate to linear coasts. The embayed morphology of coastal areas was probably enhanced by tectonism, which controlled the size and subsidence of the basin, generating a large-scale depressed area, elongated in an approximately north-south direction (Klitzsch, 2000). Such a large-scale embayment characterized by a very low gradient probably increased tidal power (Ramos et al., 2006).

The vertical stacking of the facies association packages was principally controlled by eustasy, as suggested by the presented zonation. However, there are other secondary factors which almost certainly acted to control the evolution of sedimentation in these coastal and shallow-marine environments, notably subsidence and sediment supply (Dalrymple, 1992; Dalrymple et al., 1992; Walker and Plint, 1992; Johnson and Baldwin, 1996).

Given that this environment was characterized by a very low gradient it is possible that sedimentation was controlled by a pre-existing paleorelief expressed as complex lobate to linear shoreline. The low gradient of this depositional system impeded the development and identification of well-defined clinoforms both in outcrops and in seismic images. What is evident is the significant influence of tidal processes in these deposits with a preferential paleocurrent direction towards the north-northwest according to both outcrop (Ramos et al., 2006) and FMI data from wells showing some bi-directional current indicators in some cases. In addition there is also strong evidence for a secondary paleocurrent dispersal system flowing towards the northeast which requires further study.

Several depositional models have been proposed for the Hawaz Formation. Vos (1981) suggested a fan-delta complex as the more likely setting, whilst other authors including Ramos et al. (2006) have argued for deposition within a mega-estuary or tidal gulf setting. The current study strongly suggests that the Hawaz Formation cannot be compared with any present day coastal environment. The clear tidal influence observed in the system and the vertical stacking of facies associations highlight the evolution of a shallow marine environment from a subtidal to an intertidal setting accompanied by parallel evolution of ichnofacies and fossil content (Figure 10).

The presence of some ichnogenera such as *Chondrites* in heterolithics from the most distal facies associations HWFA6 and HWFA7, compared to those deposited in the most proximal association HWFA1, suggests that a different setting for the lower (DS1; HWZ1-2) and upper (DS2-3; HWZ3-5) parts of the Hawaz Formation should be considered. Gibert et al. (2011) concluded that the restricted and uncommon ichnofacies assemblage in the upper part of the Hawaz was not clear. A mixed *Cruziana* and *Skolithos* ichnofacies has been observed both in the subsurface and in outcrops, the latter showing many excellent examples of trilobite traces (Ramos et al., 2006 and Gibert et al., 2011). Some authors have realized that, although trilobite tracks typical of the *Cruziana* ichnofacies are usually regarded as indicators of open-marine offshore to nearshore settings, their presence in heterolithic facies can no longer be taken as an absolute indicator of deposition in subtidal settings in the early Paleozoic and indeed they may have been notably more common within intertidal deposits than currently envisioned (Mángano et al., 2014). The 'non-actualistic' sedimentary model presented in this study incorporates this observation so that the *Cruziana* ichnofacies is also considered a common characteristic element of shallow tidal flat settings (Figure 10).

CONCLUSIONS

Where encountered in the subsurface of the northern Murzuq, the Hawaz Formation is represented by a clastic succession mainly comprising fine- to locally medium-grained quartzarenites and subarkosic arenites, with subordinate sublithic arenites, up to 210 m-thick (690 ft-thick). Fifteen major lithofacies, comprising sandstones and heterolithics have been recognized and grouped into seven correlatable facies associations. These include: (1) Tidal flat (HWFA 1), (2) Subtidal complex (HWFA 2), (3) Abandoned subtidal complex (HWFA 3), (4) Middle to lower shoreface (HWFA 4), (5) Burrowed shelfal and lower shoreface (HWFA5), (6) Burrowed inner shelf (HWFA 6) and (7) Shelfal storm sheets (HWFA7), all deposited within the framework of an intertidal to subtidal setting.

There is a clear relationship between facies and reservoir quality for the Hawaz Formation. The best reservoir quality sandstones are those comprising facies association HWFA2 (subtidal complex) with an average porosity of 11% and horizontal permeability of 125md and general absence of thick mud drapes and interlayered claystones.

The depositional model for the Hawaz Formation cannot be compared with an 'actualistic' sedimentary analogue due to the major differences stemming from: a) the absence of fauna and especially flora in subaerial environments which directly determines coastal dynamics; b) the difference in relative sea level and its control on erosion in shallow marine settings together with the low gradient depositional setting which promoted very wide facies belts compared to most present day moderate to high gradient depositional systems; c) the difference in tidal ranges reflecting the progressive change in the distance between the Earth and the Moon, and finally; d) the characteristic ichnofacies observed in the Hawaz are not present in modern environments.

The Hawaz Formation can be divided into three main depositional sequences (DS1-3), each with characteristic systems tracts bounded by key surfaces: maximum regressive surface, maximum flooding surface and unconformable shoreline ravinement surface.

Based upon this systems tracts architecture, a genetic zonation composed of 5 zones has been proposed (HWZ1 to HWZ5). This new stratigraphic zonation should serve as a useful tool to improve the management in oil production from the Hawaz Formation. The Hawaz Formation extends laterally hundreds of kilometers (hundreds of miles) away from the study area forming an excellent regional reservoir across the Murzuq and southern Ghadames (Berkine) Basins and, to a lesser extent, as the laterally equivalent unit III in the Illizi Basin. The facies schemes, depositional model and zonation framework proposed here should also be applicable to existing or potential Hawaz reservoirs elsewhere within this larger region.

REFERENCES

Abouessa, A., 2012, Diagenetic properties of Hawaz Formation, Murzuq Basin, Libya. In: M.J. Salem, M.T. Elbakai & Y. Abutarruma (eds), *The Geology of Southern Libya*. Earth Sc. Soc. of Libya, Tripoli, v. 1, p. 47-82.

Abouessa, A. and Morad, S., 2009, An integrated study of diagenesis and depositional facies in tidal sandstones: Hawaz Formation (Middle Ordovician), Murzuq Basin, Libya. *J. Petrol. Geology*, v. 32, pp. 39-66.

Anfray, R. and Rubino, J-L., 2003, Shelf Depositional Systems of the Ordovician Hawaz Formation in the Central Al Qarqaf High. In: Salem, M.J. & Oun, K.M (Eds) The Geology of Northwest Libya II. Gutenberg Press,Malta, p. 123-134.

Aziz, A., 2000, Stratigraphy and hydrocarbon potential of the Lower Paleozoic succession of License NC-115, Murzuq Basin, SW Libya, in M. A. Sola and D. Worsley, eds., Geological exploration in Murzuq Basin: Amsterdam, Elsevier Science, p. 349–368.

Boote, D.R.D, Dardour, A., Green, P. F., Smewing, J. D., Van Hoeflaken, F., 2008, Burial and Unroofing History of the Base Tanezzuft 'Hot' Shale Source Rock, Murzuq Basin, SW Libya: New AFTA Constraints from Basin Margin Outcrops (abs.). Paper presented at the 4th Sedimentary Basins of Libya Symposium: the Geology of Southern Libya, 17-20 November, Tripoli, Libya.

Boyd, R., Dalrymple, R., Zaitlin, B. A., 1992, Classification of clastic coastal depositional environments: Sedimentary Geology, v. 80, p. 139–150.

Bradley, G., Redfern, J., Hodgetts, D., George, A. D., Wach, G. D., 2018, The applicability of modern tidal analogues to pre-vegetation paralic depositional environments. Sedimentology, v. 65, p. 2171-2201.

Dalrymple, R. W., 1992, Tidal depositional systems, in R. G. Walker and N. P. James, eds., Facies models. Response to sea level change: Waterloo,Geological Association of Canada, p. 195–218.

Dalrymple, R. W., Zaitlin, B. A., Boyd, R., 1992, Estuarine facies models: Conceptual basis and stratigraphic implications: Journal of Sedimentary Petrology, v. 62, p. 1130–1146.

Dalrymple, R. W. and Choi, K., 2007, Morphologic and facies trends through the fluvial-marine transition in tide-dominated depositional systems: A schematic framework for environmental and sequence-stratigraphic interpretation. Earth –Science Reviews, v.81, p.135-174.

Davidson, L., Beswetherick, S., Craig, J., Eales, M., Fisher, A., Himmali, A., Jho, J., Mejrab, B., Smart, J., 2000, The structure, stratigraphy and petroleum geology of the Murzuq Basin, southwest Libya, in M. A. Sola and D. Worsley, eds., Geological exploration in Murzuq Basin: Amsterdam, Elsevier Science, p. 295–320.

Davies, N. S. and Gibling, M. R., 2010, Cambrian to Devonian evolution of alluvial systems: The sedimentological impact of the earliest land plants. Earth Science Reviews, v. 98, p. 171-200.

Davies, N. S., Gibling, M. R., Rygel, M. C., 2011, Alluvial facies evolution during the Palaeozoic greening of the continents: case studies, conceptual models and modern analogues. Sedimentology, v. 58, p. 220-258.

Desjardins, P.R., Buatois, L. A., Pratt, B. R., Mángano, M. G., 2012, Forced Regressive Tidal Flats : Response to Falling Sea Level in Tide-dominated Settings. Journal of Sedimentary Research, v. 82, p. 149-162.

Embry, A., 2009, Practical Sequence Stratigraphy. Canadian Society of Petroleum Geologists, 79 p.

Fello, N.; Lüning, S.; Storch, P.; Redfern, J., 2006, Identification of early Llandovery (Silurian) anoxic palaeo-depressions at the western margin of the Murzuq Basin (southwest Libya), based on gamma-ray spectrometry in surface exposures. *GeoArabia*, v. 11, p. 101-118.

Franco, A., Perona, R., Dwyianti, R., Yu, F., Helal, S., Suarez, J., Ali, A., 2012, NC186 Block, Murzuq Basin: Lessons Learned from Exploration. In: M.J. Salem, I.Y. Mriheel & A.S. Essed (eds.), The Geology of Southern Libya. Earth Sc. Soc. of Libya, Tripoli, v. 2, p. 37-50.

Ghienne, J.-F., Deynoux, M., Manatschal, G., Rubino, J.-L., 2003, Palaeovalleys and fault-controlled depocentres in the Late-Ordovician glacial record of the Murzuq Basin (central Libya). Comptes Rendus Geoscience, v. 335, p. 1091–1100.

Gibert, J.M., Ramos, E., Marzo, M., 2011, Trace fossils and depositional environments in the Hawaz Formation, Middle Ordovician, western Libya. Journal of African Earth Sciences, v. 60, p. 28–37.

Gibling, M. R. and Davies, N. S., 2012, Palaeozoic landscapes shaped by plant evolution. Nature Geoscience, v. 5, p. 99-105.

Gingras, M. K., MacEachern, J. A., Dashtgard, S. E., 2012, The potential of trace fossils as tidal indicators in bays and estuaries. Sedimentary Geology, v. 279, p. 97-106.

Hall, P.B., Bjorøy, M., Ferriday, I.L., Ismail, Y., 2012, Murzuq Basin Source Rocks. *In*: M.J. Salem, I.Y. Mriheel & A.S. Essed (eds) *The Geology of Southern Libya*. Earth Sc. Soc. of Libya, Tripoli, v. 2, p. 63-84.

Hallet, D., 2002, *Petroleum geology of Libya*: Amsterdam, Elsevier, 503 p.

Harris, P. T., Heap, A. D., Bryce, S. M., Porter-Smith, R., Ryan, D. A., Heggie, D. T., 2002, Classification of Australian clastic coastal depositional environments based upon a quantitative analysis of wave, tidal, and river power: Journal of Sedimentary Research, v. 72, p. 858–870.

Harris, P. T. and Heap, A. D., 2003, Environmental management of clastic coastal depositional environments: inferences from an Australian geomorphic database. Ocean & Coastal Management, v.46, p. 457-478.

Johnson, H. D. and C. T. Baldwin, 1996, Shallow clastic seas, in H. G. Reading, ed., Sedimentary environments: Processes, facies and stratigraphy: Oxford, Blackwell Science, p. 232–280.

Kenrick, P. and Mitchell, R. L., 2015, The origins of land plants communities. The rise and fall of photosynthate: Evolution of plant/fungus interactions from paleobotanical and phylogenomic perspectives Symposium.

Kenrick, P. and Mitchell, R. L., 2016, The early fossil record of land plants and their environment. 38th New Phytologist Symposium – Colonization of the terrestrial environment 2016, Bristol.

Klitzsch, E. H., 2000, The structural development of the Murzuq and Kufra basins- Significance for oil and mineral exploration, in M. A. Sola and D. Worsley, eds., Geological exploration in Murzuq Basin: Amsterdam, Elsevier Science, p. 143–150.

D. P. Le Heron, O. Sutcliffe, K. Bourgig, J. Craig, C. Visentin, R. Whittington, 2004, Sedimentary architecture of Upper Ordovician tunnel valleys, Gargaf Arch, Libya: implications for the genesis of a hydrocarbon reservoir GeoArabia, v. 9, p. 137-160.

Lyell, C., 1832. Principles of Geology vol.II, John Murray, London.

Mángano, M. G., Buatois, L. A., Astini, R., Rindsberg, A. K., 2014, Trilobites in early Cambiran tidal flats and landward expansion of the Cambrian explosion. Geology, v.42, p. 143-146.

McDougall, N. and Martin, M., 2000, Facies models and sequence stratigraphy of Upper Ordovician outcrops in the Murzuq Basin, SW Libya. *In*: M.A. Sola & D. Worsley (eds). *Geological Exploration in Murzuq Basin*. Elsevier, Amsterdam, p. 223-236.

McDougall, N. D., Gerard, J., Wloszczowski. D., and Sharky, K., 2008, Ordovician Plays on the Arabian and Saharan Platforms: A Comparison; Poster & Abstract; for AAPG International Conference & Exhibition; Cape Town, South Africa.

McDougall, N.D., Bellik, M and Jauregui, J. M..2011, Sedimentology and sequence stratigraphy of the Ordovician section in the Gassi-Touil-Gassi Chergui-In Amedjane area. Poster & Abstract; 5th Algerian Oil & Gas Energy Week, Oran, Algeria.

Nichols, G., 2017, Challenging orthodoxy: is the Present the Key to the Past? The Sedimentary Record, v. 15, no. 3, p 4-9.

Odenwald, S., 2018, Spacemath@NASA, https://spacemath.gsfc.nasa.gov/ (accessed Fefbruary 2, 2018).

Ramos, E., Marzo, M., Gibert, J.M.de, Tawengi, K.S., Khoja, A.A., Bolatti, N.D., 2006, Stratigraphy and sedimentology of the Middle Ordovician Hawaz Formation (Murzuq Basin, Libya). AAPG Bulletin, v. 90, p. 1309–1336.

Rider, M., 2004, *The Geological Interpretation of Well Logs*. Rider – French Consulting Ltd.

Shalbak, F., 2015, *Paleozoic petroleum systems of the Murzuq Basin, Libya*. Universitat de Barcelona, 203p.

Vos, R. G., 1981, Sedimentology of an Ordovician fan delta complex, western Libya: Sedimentary Geology, v. 29, p. 153–170.

Walker, R. G. and A. G. Plint, 1992, Wave- and storm-dominated shallow marine systems, in R. G. Walker and N. P. James, eds., Facies models. Response to sea level change: Waterloo, Geological Association of Canada, p. 219–238.

Williams, G. E., 2000, Geological constraints on the Precambrian history of Earth's rotation. Reviews of Geophysics, v. 38, no. 1, p. 37–59.

AUTHORS VITAE

Marc Gil Ortiz ~ Marc Gil Ortiz is currently working as a Clastic Sedimentologist in the Stratigraphy and Sedimentology Team of Repsol Exploración. He is a member of the Geomodels Research Institute and researcher of the University of Barcelona where currently he is also doing his PhD. His research is mainly focused on clastic sedimentology, sequence stratigraphy and the relationships between tectonics and sedimentation.

Neil David McDougall ~ Neil McDougall was awarded his Ph.D in geology at the University of Liverpool in 1988. Since then he has worked as a Senior Sedimentologist for Robertson Research and as a Clastic Sedimentologist Advisor for Repsol Exploración. He has studied clastic reservoirs in various basins worldwide with a special focus on the Lower Paleozoic of Libya and Algeria.

Patricia Cabello ~ Patricia Cabello is a lecturer at the University of Barcelona and is a member of the Geomodels Research Institute and the Research Group of Geodynamics and Basin Analysis. She received her Ph.D. from the University of Barcelona in 2010. Her research is mainly focused on the characterization of reservoirs and outcrop analogues.

Mariano Marzo ~ Mariano Marzo is a professor of stratigraphy at the University of Barcelona. His research interest focuses on the application of clastic sedimentology, sequence stratigraphy, reservoir modelling, and basin analysis to the exploration and production of hydrocarbons. He has been involved in several research projects funded by oil companies in southern Europe, the North Sea, South America, and northern Africa.

Emilio Ramos ~ Emilio Ramos was awarded his Ph.D. in geology at the University of Barcelona in 1988. Since then, he has held a post as a lecturer in basin analysis and petroleum geology at the same university. He has worked on several research projects on sedimentology and basin analysis in Spain, North Africa, Antarctica, and South America.

FIGURES AND TABLE CAPTIONS

Figure 1. – Geological map of Libya showing the main sedimentary basins. The Murzuq Basin is bounded by the Atshan arch to the northwest, the Gargaf high to the north, the Tihemboka high to the southwest and the Tibesti high to the southeast. The area of interest represented in Figure 3-A is highlighted in the red box. Modified from Marzo and Ramos (2003, personal communication).

Figure 2. – A) Stratigraphic chart summarizing the stratigraphic column for the Murzuq Basin highlighting the main stratigraphic units (1= Cambro-Ordovician; 2= Silurian; 3= Devonian-Carboniferous; 4= Mesozoic) and major basin-scale unconformities. B) Wheeler diagram showing lithostratigraphic to chronostratigraphic relationships of the Ordovician and Lower Silurian succession in the area of study. C) Seismic line showing the typical geomorphological signature of the Ordovician succession in form of paleohighs ('buried hills') and paleovalleys. Silur. = Silurian; Dev. = Devonian; Carbonif. = Carboniferous; Perm. = Permian; Q = Quaternary. The main petroleum systems elements are also represented in Figure 2-A and B.

Figure 3. – (A) Satellite image of the northern Murzuq Basin highlighting the study area (red box). (B) Study area showing the position of the wells. Find highlighted the wells with core data available and, in white, the wells from figures 4, 6, 7, 9 and 10. Note the distance between the studied area in the subsurface and the western Gargaf high where the outcrops studied by Ramos et al. (2006), referred to in this paper, are located.

Figure 4. – Core sections (90cm [35 in] length approx.) of the main lithofacies identified in this study. Sx1= Large scale cross-bedded sandstones; Sx2 = Small to medium scale cross-bedded sandstones; Sl = Parallel-laminated sandstones; Sxl = Cross-laminated sandstones; Sr = Ripple cross-laminated sandstones; Sv = Massive sandstones; Sxb = Burrowed cross-bedded sandstones; Sxlb = Burrowed cross-laminated sandstones; Srb = Burrowed ripple cross-laminated sandstones; Sb = Burrowed sandstones with Siphonichnus; MSb = Burrowed sandstones with feeding ichnofauna; HS = Sandy heterolithics; HSb = Burrowed sandy heterolithics; HM = Muddy heterolithics; HMb = Burrowed muddy heterolithics. See the location of the corresponding wells (B, C, D, E, F and G) in Figure 3-B.

Figure 5. – Summary of facies associations and interpreted depositional settings. Description includes typical core sections and thickness ranges. See also the main lithofacies composing each facies association and the location of detailed features shown in Figure 6. Interpretation in terms of depositional environment is also included. In addition, summary conventional core analysis (CCA) porosity (Ø) and permeability (K), data for every facies association and average gamma-ray values are also shown. The last column shows the

sequence stratigraphic interpretation plus the location of each association within the depositional model of the Figure 8. Sx1= Large-scale cross-bedded sandstones; Sx2 = Small- to medium-scale cross-bedded sandstones; Sl = Parallel-laminated sandstones; Sxl = Cross-laminated sandstones; Sr = Ripple cross-laminated sandstones; Sv = Massive sandstones; Sxb = Burrowed cross-bedded sandstones; Sxlb = Burrowed cross-laminated sandstones; Srb = Burrowed ripple cross-laminated sandstones; Sb = Burrowed sandstones with Siphonichnus; MSb = Burrowed sandstones with feeding ichnofauna; HS = Sandy heterolithics; HSb = Burrowed sandy heterolithics; HM = Muddy heterolithics; HMb = Burrowed muddy heterolithics. TST = transgressive systems tract; HST = highstand systems tract;

Figure 6. – Detailed close-up views of some characteristic sedimentary structures and fabrics of the Hawaz Formation in core. A) Mud-draped (flaser) lamination (arrows) in HWFA1 tidal flat facies association from well E. B) Mudstone rip-up clasts (arrows) from fluvio-tidal to subtidal channels of HWFA2 subtidal complex in well F. C) Clay-draped current ripples (small arrows) from HWFA2 subtidal complex from well C. Notice the direction of the paleocurrent flow leftwards (horizontal arrow). D) Burrowed sandstones with characteristic *Skolithos* ichnofacies of the HWFA5 burrowed shelfal and lower shoreface facies association in well E. E) Characteristic view of the HWFA6 burrowed inner shelf deposits from well D. F) Clay-draped combined flow ripples (small arrows) from HWFA7 shelfal storm sheets in well D. Notice the direction of the paleocurrent flow rightwards in the upper part and bidirectional in the lower part of the image (horizontal arrows). See the location of the corresponding wells (C, D, E and F) in Figure 3-B.

Figure 7. – Representative sections of slabbed cores (40cm [~16 in]) for each facies association and a typical high-resolution formation microimager (FMI) image (3m [~10 ft] long) showing their main characteristics. From top left to bottom right: HWFA1 tidal flat, HWFA2 Subtidal complex, HWFA3 abandoned subtidal complex, HWFA4 middle to lower shoreface, HWFA5 burrowed shelfal to lower shoreface, HWFA6 bsponding wells (A, C, D and E) in Figure 3-B.

Figure 8. – Evolutionary sedimentological model for the deposition of the Hawaz Formation. A) Early transgressive systems tract highlighting embayments; B) Late transgressive systems tract; C) Highstand systems tract. The main facies associations are represented in the sketches. The sketches are purely conceptual but consistent with observed trends in the study area but not geographically tied to well data. Mean sea level = msl.

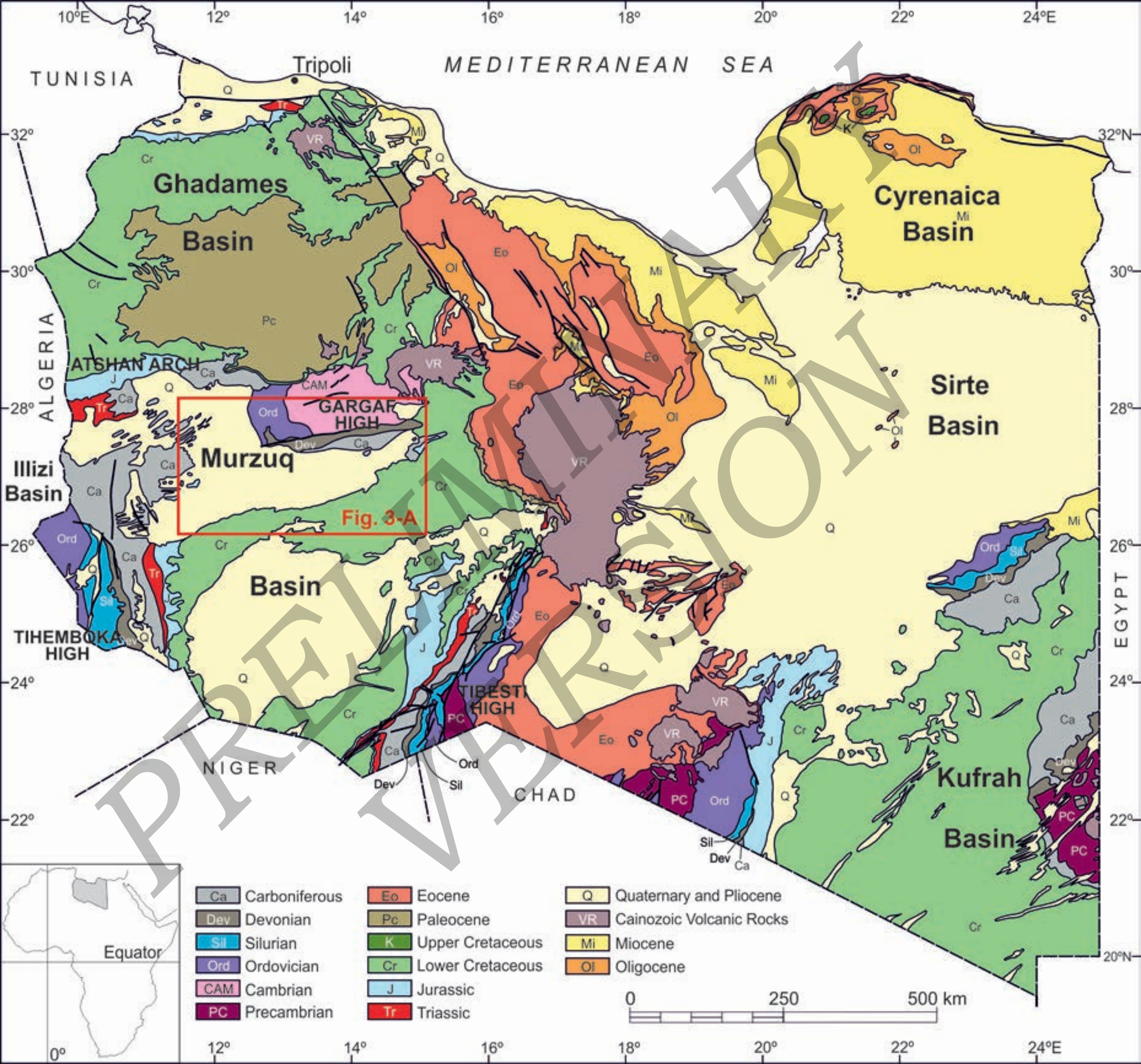
Figure 9. – Composite section of a well showing a synthetic stratigraphic column of the Hawaz Formation, the wireline log responses, the suggested zonation for the reservoir based on the facies associations and sequence stratigraphic framework. The Transgressive and Regressive stacking patterns

are represented on the figure together with the 3 main depositional sequences. See the location of the corresponding well (B) in Figure 3-B.

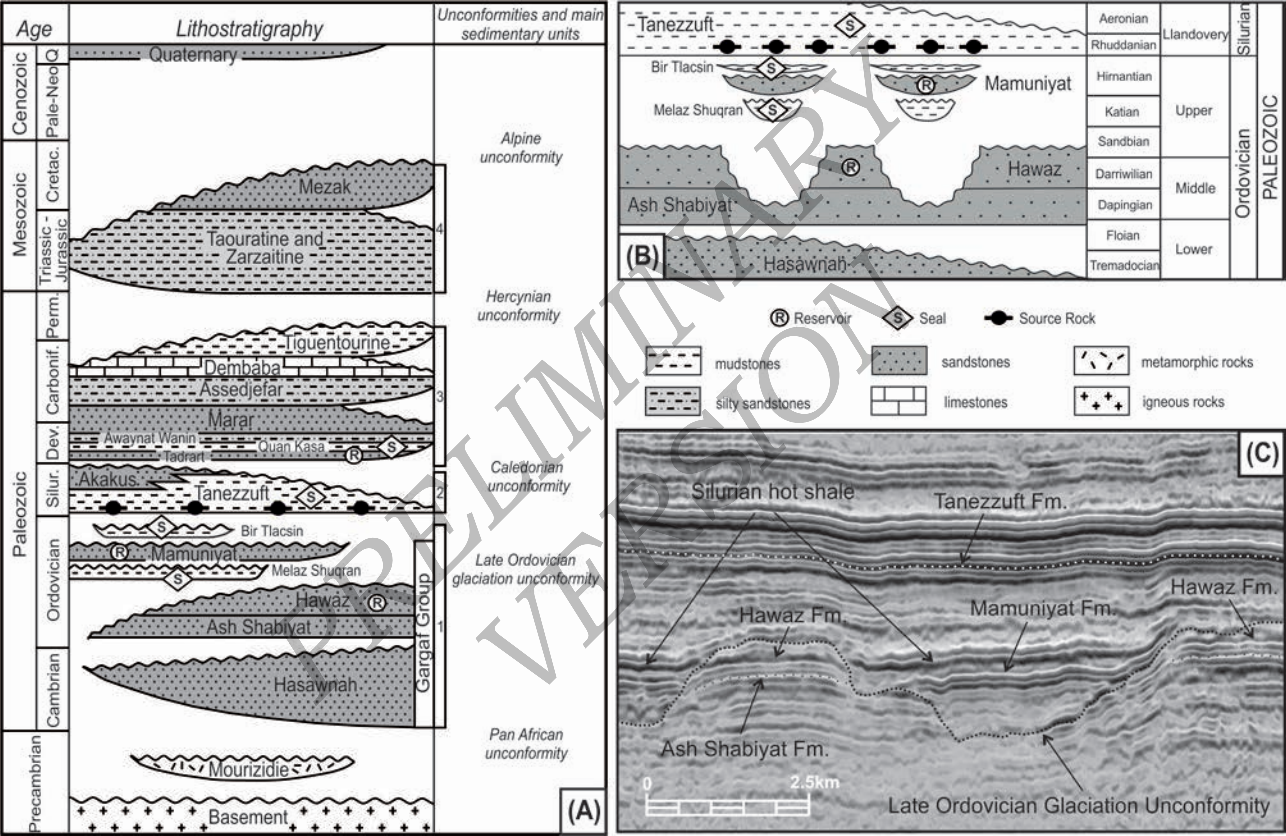
Figure 10. – Three-dimensional conceptual sketch of a coastal tidal-influenced environment analogue to the Hawaz Formation deposition during a highstand systems tract stage, grading from a braided coastal plain environment in the most proximal part of the sedimentary system to intertidal and subtidal environments and lower shoreface to inner shelf settings. Note the clear relationship between the ichnofacies assemblage and the energy of the depositional environment. From left to right: (A) mixed *Cruziana* and *Skolithos* ichnofacies assemblage with characteristic vertical suspension feeder burrows of *Skolithos* (Sk) overprinting an ichnofabric comprising horizontal deposit feeders and miners such as *Thalassionides* (Th) and *Planolites* (Pl) associated with tidal flat deposits; (B) characteristic *Skolithos* 'Pipe Rock' ichnofacies with typical *Siphonichnus* (Si) burrows from lower shoreface to burrowed shelfal deposits; (C) Mixed *Cruziana* and *Skolithos* ichnofacies assemblage, from burrowed inner shelf sediments with characteristic *Teichichnus* (Te), *Thalassinoides* (Th) and *Skolithos* (Sk) burrows; (D) heterolithic mudstones belonging to the most distal storm deposits with *Chondrites* (Ch) burrows characteristic of the distal *Cruziana* ichnofacies. See the location of the corresponding well (E and D) in Figure 3-B.

Table 1. – Lithofacies scheme for the Hawaz Formation.

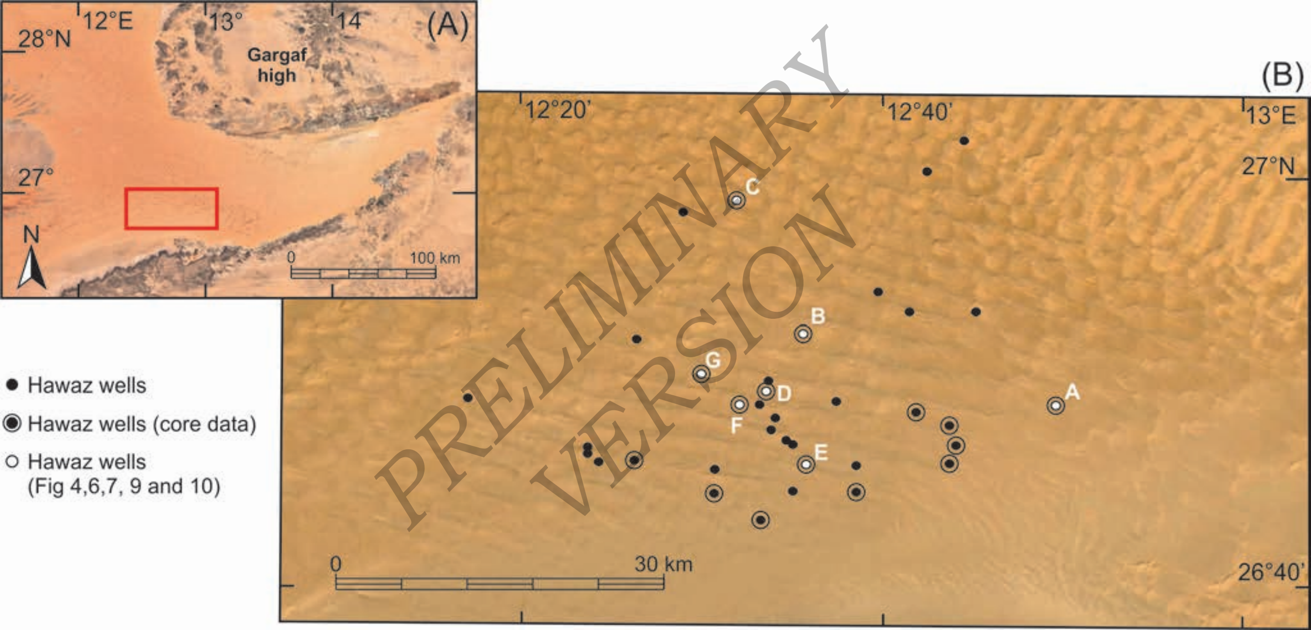
Table 2. – Comparative table between key 'actualistic' (Present) and 'non-actualistic' (early Paleozoic and older) main processes or controlling factors affecting the geological signature of tidal-influenced successions in the geological record.

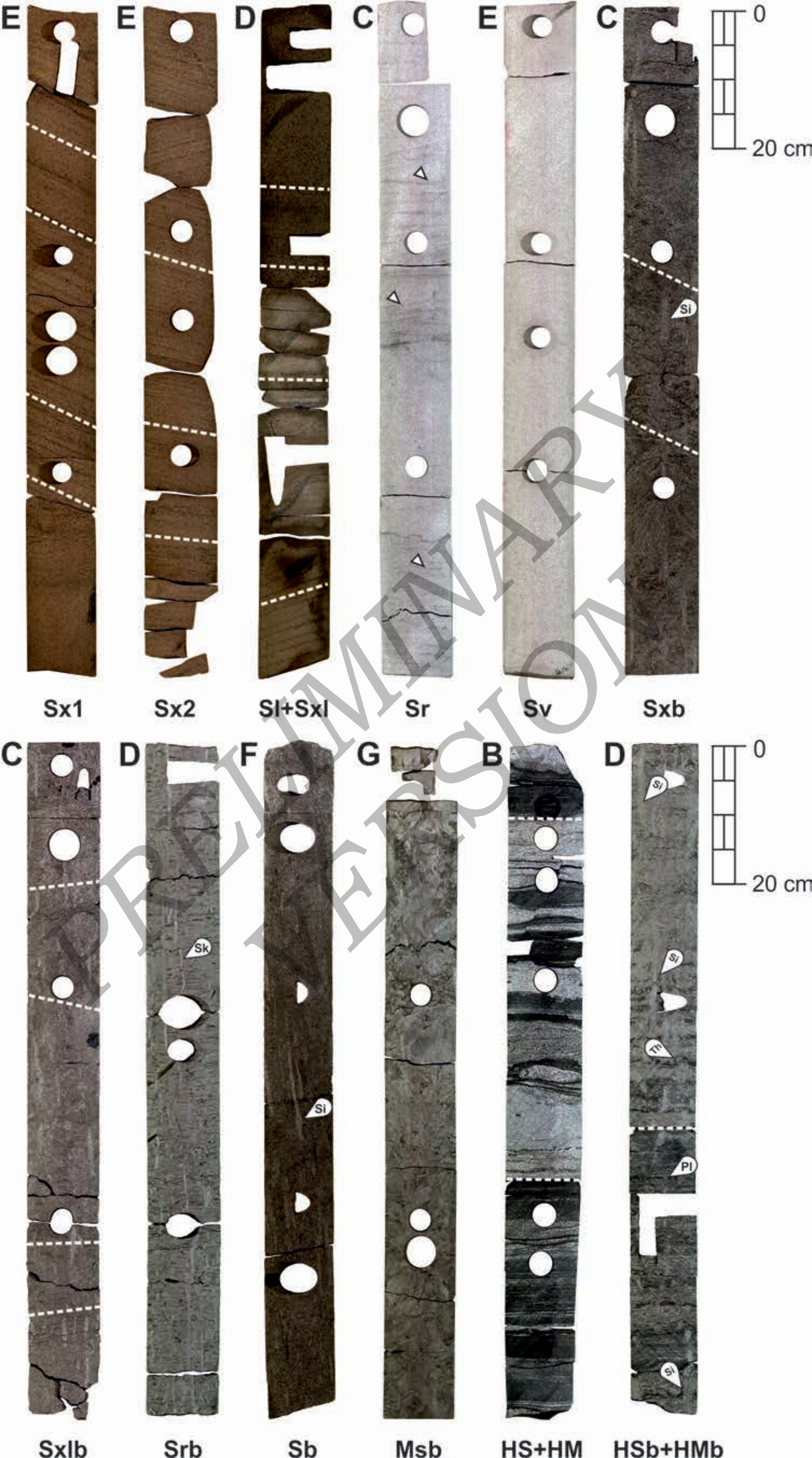


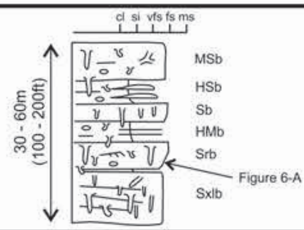
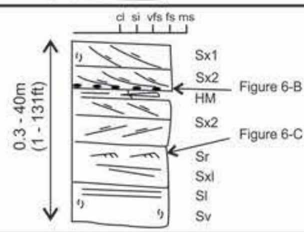
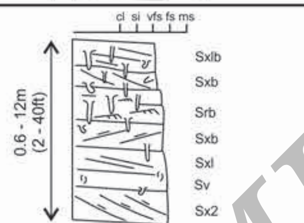
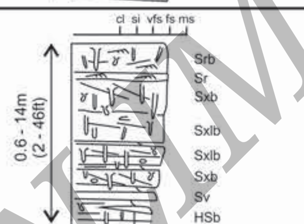
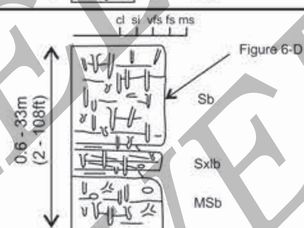
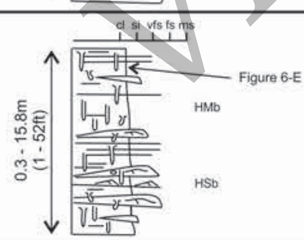
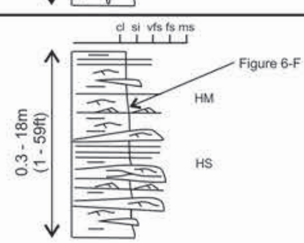
TUNISIA
Tripoli
MEDITERRANEAN SEA
ALGERIA
EGYPT
NIGER
CHAD
Ghadames
Basin
ATSHAN ARCH
GARGAF HIGH
Murzuq
Basin
Illizi Basin
TIHEMBOKA HIGH
TIBESTI HIGH
Cyrenaica Basin
Sirte Basin
Kufrah Basin
Fig. 3-A
Equator
10ºE 12º 14º 16º 18º 20º 22º 24ºE
32ºN 30º 28º 26º 24º 22º 20ºN
0º
Ca Carboniferous
Dev Devonian
Sil Silurian
Ord Ordovician
CAM Cambrian
PC Precambrian
Eo Eocene
Pc Paleocene
K Upper Cretaceous
Cr Lower Cretaceous
J Jurassic
Tr Triassic
Q Quaternary and Pliocene
VR Cainozoic Volcanic Rocks
Mi Miocene
Ol Oligocene
0 250 500 km



Age
Lithostratigraphy
Unconformities and main sedimentary units
Cenozoic
Q
Pale-Neo
Quaternary
Mesozoic
Cretac.
Triassic - Jurassic
Mezak
Taouratine and Zarzaitine
Alpine unconformity
Paleozoic
Perm.
Carbonif.
Dev.
Silur.
Ordovician
Cambrian
Tiguentourine
Dembaba
Assedjefar
Marar
Awaynat Wanin
Quan Kasa
Tadrart
Akakus
Tanezzuft
Bir Tlacsin
Mamuniyat
Melaz Shuqran
Hawaz
Ash Shabiyat
Hasawnah
Gargaf Group
Hercynian unconformity
Caledonian unconformity
Late Ordovician glaciation unconformity
Precambrian
Mourizidie
Basement
Pan African unconformity
4
3
2
1
(A)
Tanezzuft
Bir Tlacsin
Melaz Shuqran
Mamuniyat
Hawaz
Ash Shabiyat
Hasawnah
(B)
Aeronian
Rhuddanian
Llandovery
Silurian
Hirnantian
Katian
Sandbian
Upper
Darriwilian
Dapingian
Middle
Floian
Tremadocian
Lower
Ordovician
PALEOZOIC
Reservoir
Seal
Source Rock
mudstones
silty sandstones
sandstones
limestones
metamorphic rocks
igneous rocks
(C)
Silurian hot shale
Tanezzuft Fm.
Hawaz Fm.
Mamuniyat Fm.
Hawaz Fm.
Ash Shabiyat Fm.
0
2.5km
Late Ordovician Glaciation Unconformity

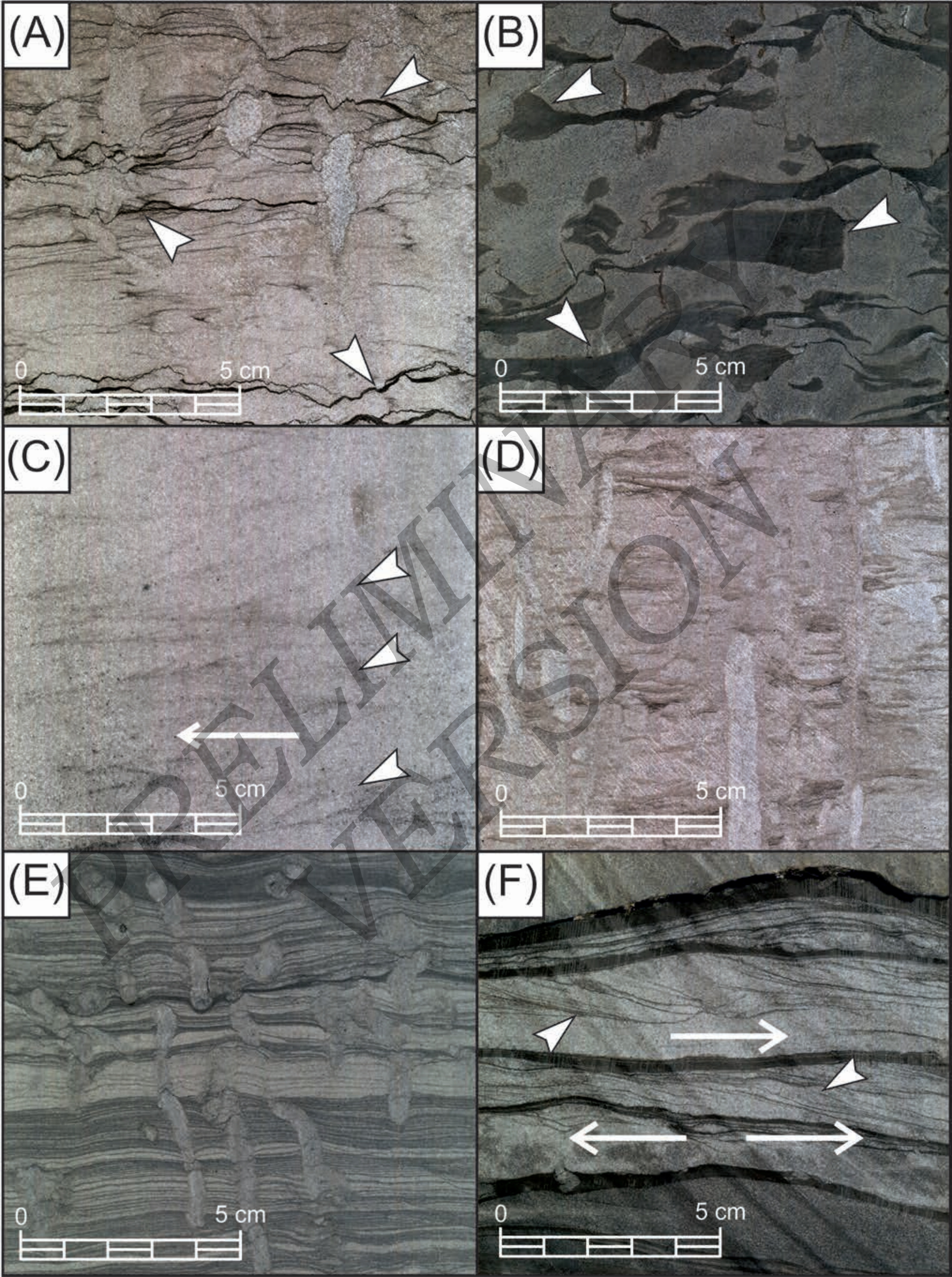

(A)
12°E
13°
14
28°N
27°
Gargaf
high
N
0
100 km
(B)
12°20'
12°40'
13°E
27°N
26°40'
C
B
G
D
F
E
A
0
30 km
Hawaz wells
Hawaz wells (core data)
Hawaz wells
(Fig 4,6,7, 9 and 10)


E
E
D
C
E
C
0
20 cm
Si
Sx1
Sx2
Sl+Sxl
Sr
Sv
Sxb
C
D
F
G
B
D
0
20 cm
Sk
Si
Si
Si
Tr
Pl
Si
Sxlb
Srb
Sb
Msb
HS+HM
HSb+HMb

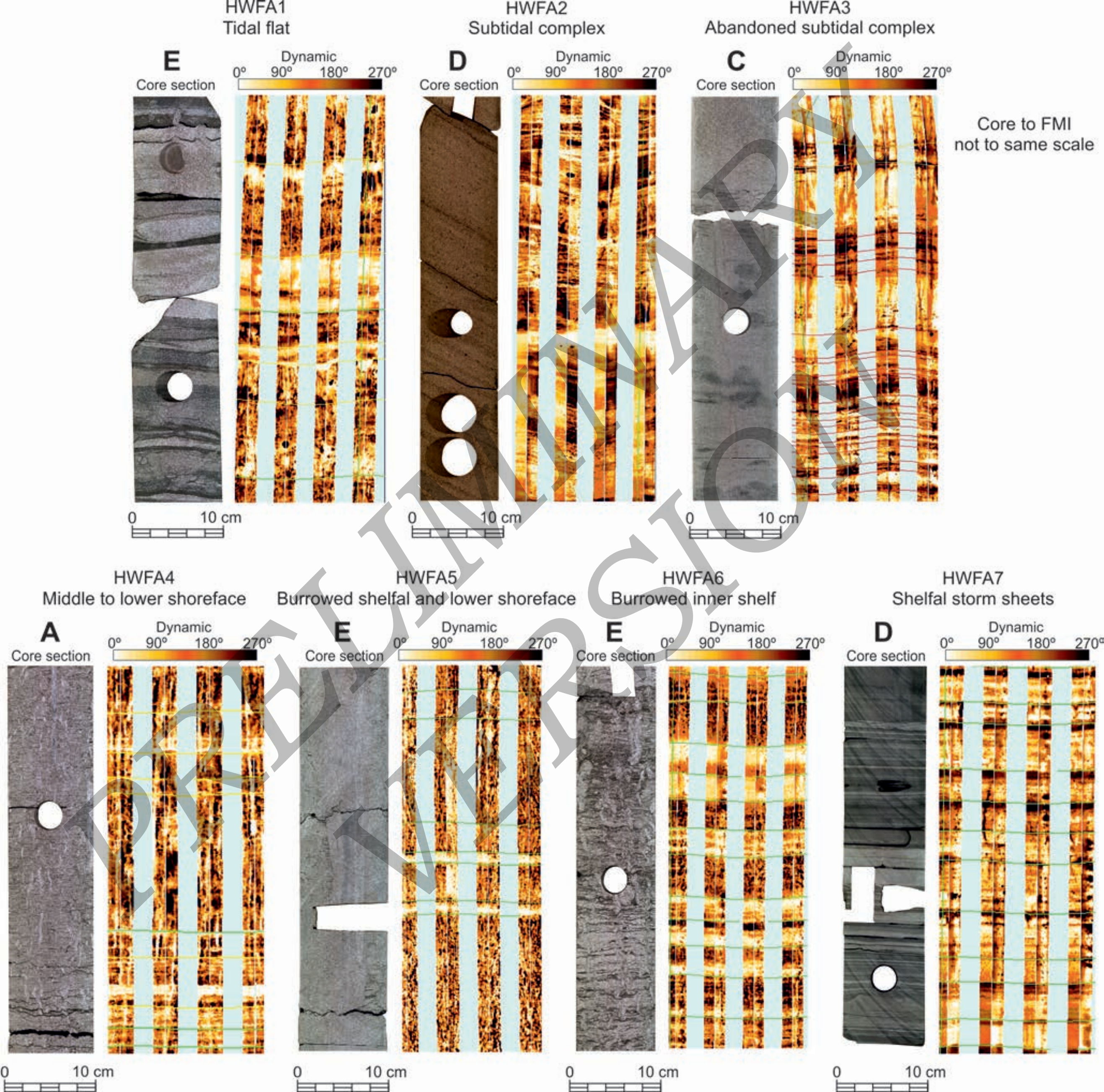
Depositional setting	Facies association	Description (Typical section with lithofacies & thickness ranges)	Interpretation	CCA average Ø / K Gamma Ray	Systems Tracts in Figure 8
FORESHORE Intertidal zone	**HWFA1** Tidal flat		Tidal sand to mixed flat deposited during high relative sea levels in an embayed tidal-influenced setting	13% / 30.4md 30 - 140 API	HST (Figure 8-C)
MIDDLE SHOREFACE Subtidal zone	**HWFA2** Subtidal complex		Amalgamated complex of sand bars, dunes and channel deposits deposited in a fluvio-tidal to subtidal setting	11% / 125md 25 - 65 API	Early and late TST (Figure 8-A & B)
	HWFA3 Abandoned subtidal complex		Distal equivalent of the subtidal complex product of the abandonment of previously active subtidal channels	14% / 152md 25 - 70 API	Early and late TST (Figure 8-A & B)
LOWER SHOREFACE below MFWB	**HWFA4** Middle to lower shoreface		Prograding middle to lower shoreface related to regressive sand belts during highstand sea level conditions	14% / 56md 30 - 80 API	HST (Figure 8-C)
	HWFA5 Burrowed shelfal and lower shoreface		Deposition in a relatively protected to more open lower shoreface to inner shelf setting	14% / 3.5md 30 - 80 API	Early TST, late TST and HST (Figure 8-A, B & C)
INNER SHELF above MSWB	**HWFA6** Burrowed inner shelf		Deposition in an open-marine inner shelf setting	9% / 0.2md 60 - 120 API	Late TST and HST (Figure 8-B & C)
	HWFA7 Shelfal storm sheets		Distal mixed sand to mud rich deposits product of waning storm events in an open-marine shelf setting	5% / 0.2md 80 - 160 API	Early TST, late TST and HST (Figure 8-A, B & C)

Parallel stratification/lamination; Through cross-stratification; Mud rip-up clasts; Current ripples; Horizontal deposit feeding burrows

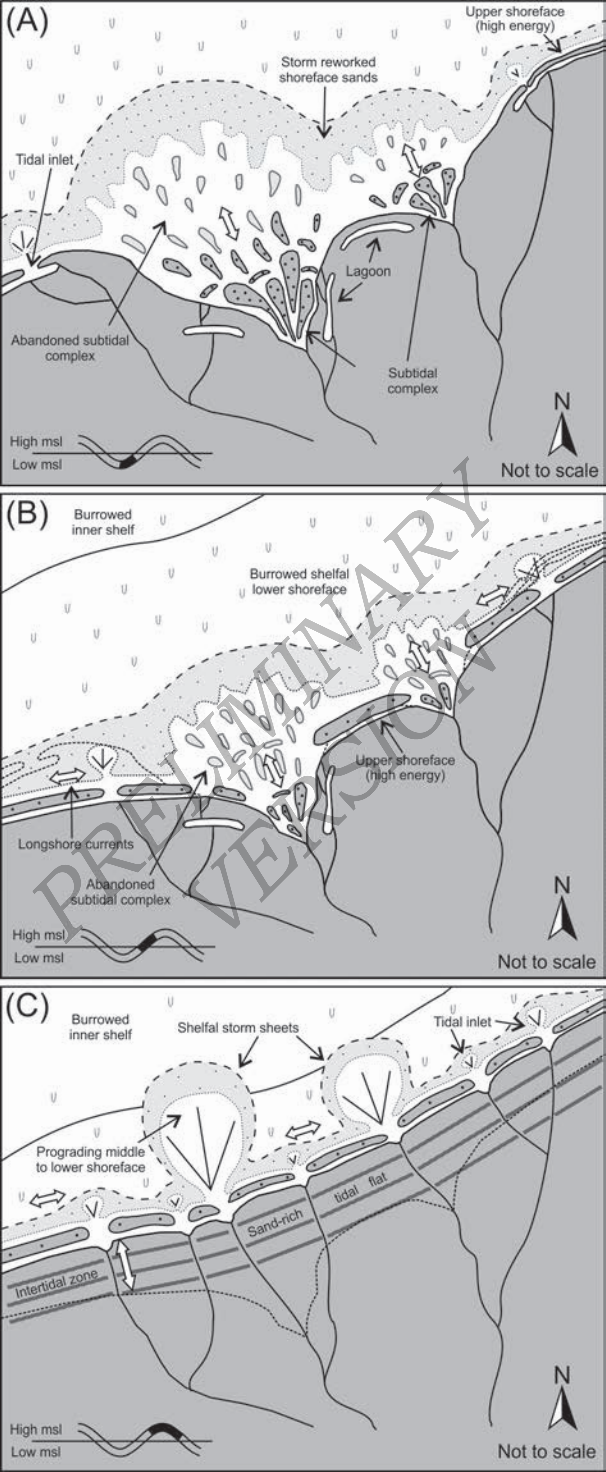
Planar cross-stratification/lamination; Hummocky/Swaley cross-stratification; Fluid scape structures; Combined current and wave ripples; Vertical suspension feeding burrows



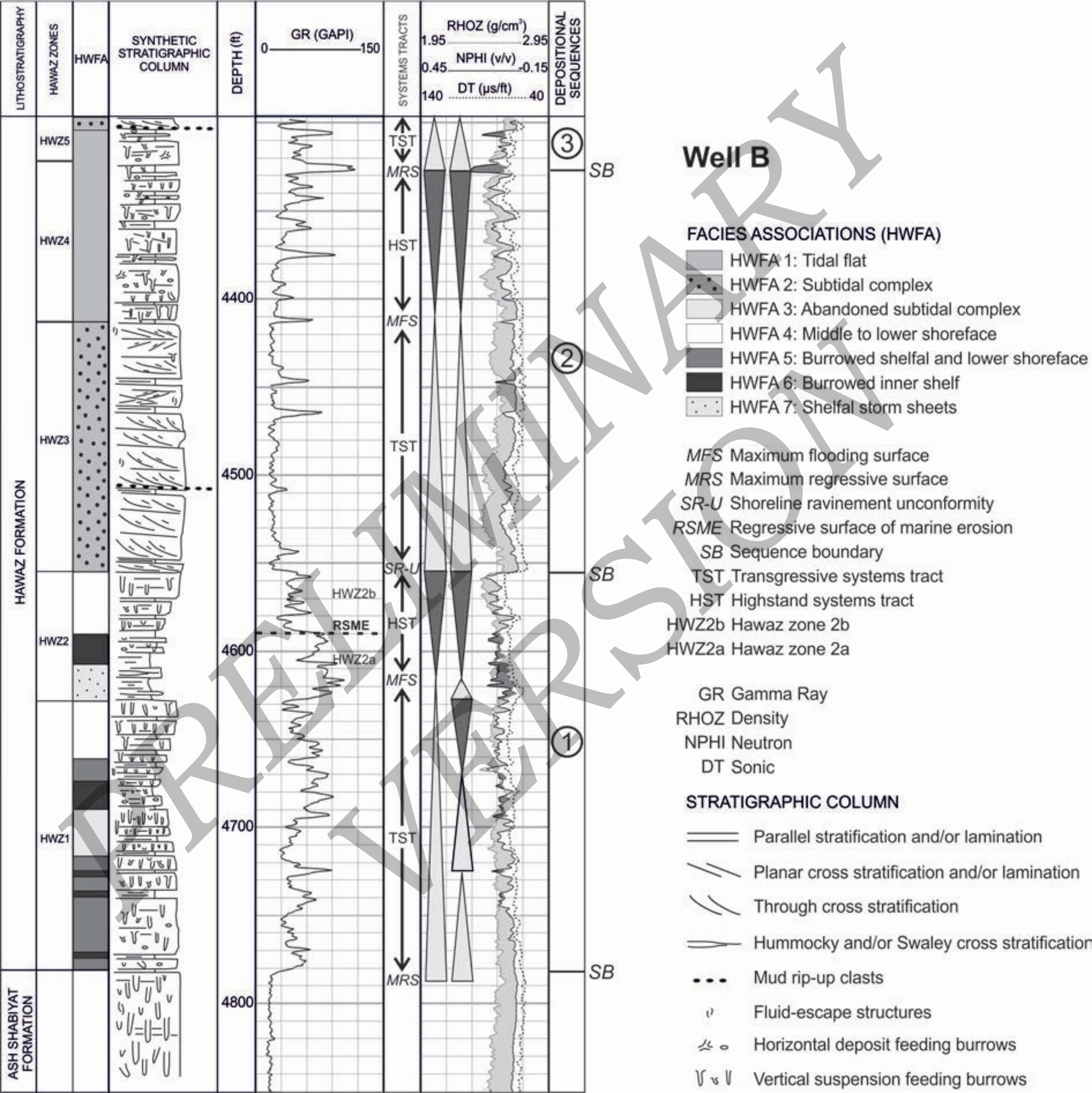
(A)
0
5 cm
(B)
0
5 cm
(C)
0
5 cm
(D)
0
5 cm
(E)
0
5 cm
(F)
0
5 cm

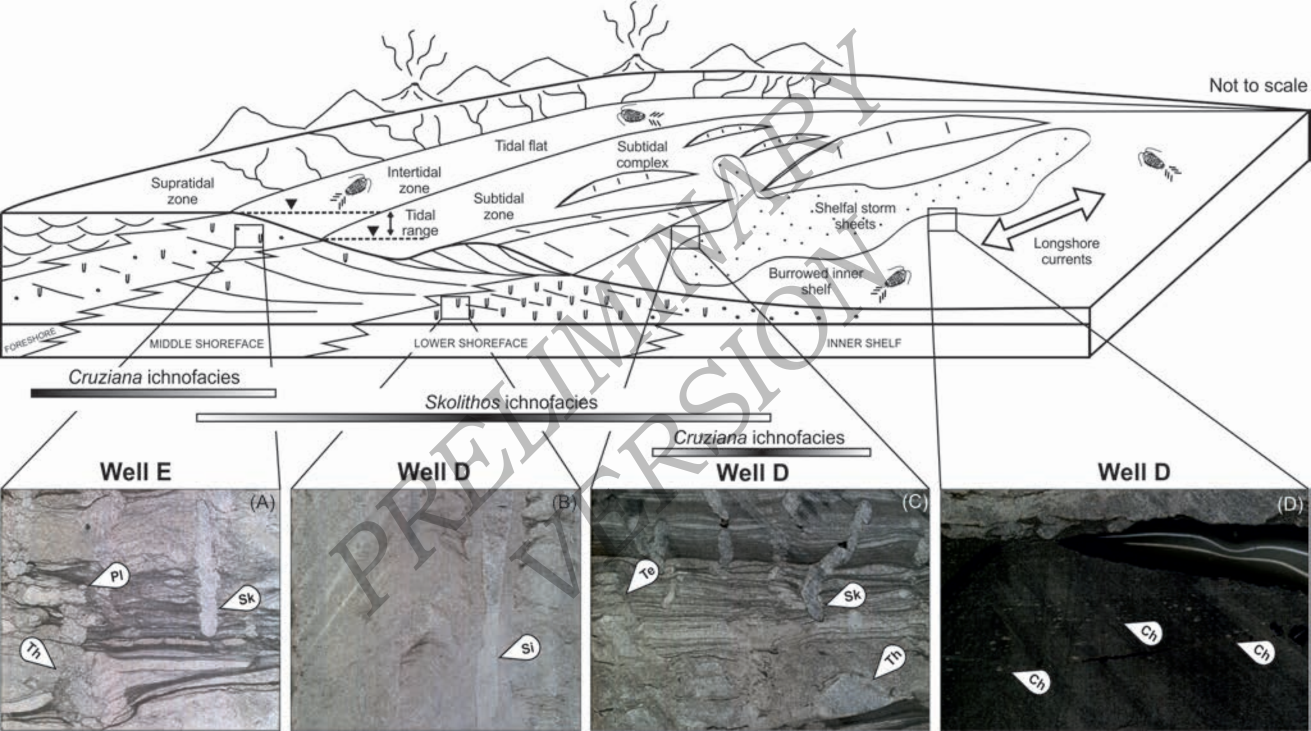


HWFA1
Tidal flat
E
Core section
Dynamic
0° 90° 180° 270°
0 10 cm
HWFA2
Subtidal complex
D
Core section
Dynamic
0° 90° 180° 270°
0 10 cm
HWFA3
Abandoned subtidal complex
C
Core section
Dynamic
0° 90° 180° 270°
0 10 cm
Core to FMI
not to same scale
HWFA4
Middle to lower shoreface
A
Core section
Dynamic
0° 90° 180° 270°
0 10 cm
HWFA5
Burrowed shelfal and lower shoreface
E
Core section
Dynamic
0° 90° 180° 270°
0 10 cm
HWFA6
Burrowed inner shelf
E
Core section
Dynamic
0° 90° 180° 270°
0 10 cm
HWFA7
Shelfal storm sheets
D
Core section
Dynamic
0° 90° 180° 270°
0 10 cm



(A)
Upper shoreface (high energy)
Storm reworked shoreface sands
Tidal inlet
Lagoon
Abandoned subtidal complex
Subtidal complex
High msl
Low msl
N
Not to scale
(B)
Burrowed inner shelf
Burrowed shelfal lower shoreface
Upper shoreface (high energy)
Longshore currents
Abandoned subtidal complex
High msl
Low msl
N
Not to scale
(C)
Burrowed inner shelf
Shelfal storm sheets
Tidal inlet
Prograding middle to lower shoreface
Sand-rich tidal flat
Intertidal zone
High msl
Low msl
N
Not to scale


LITHOSTRATIGRAPHY
HAWAZ ZONES
HWFA
SYNTHETIC STRATIGRAPHIC COLUMN
DEPTH (ft)
GR (GAPI)
0
150
SYSTEMS TRACTS
RHOZ (g/cm³)
1.95
2.95
NPHI (v/v)
0.45
-0.15
DT (μs/ft)
140
40
DEPOSITIONAL SEQUENCES
HAWAZ FORMATION
ASH SHABIYAT FORMATION
HWZ5
HWZ4
HWZ3
HWZ2
HWZ1
4400
4500
4600
4700
4800
HWZ2b
RSME
HWZ2a
TST
MRS
HST
MFS
TST
SR-U
HST
MFS
TST
MRS
3
2
1
SB
SB
SB
Well B
FACIES ASSOCIATIONS (HWFA)
HWFA 1: Tidal flat
HWFA 2: Subtidal complex
HWFA 3: Abandoned subtidal complex
HWFA 4: Middle to lower shoreface
HWFA 5: Burrowed shelfal and lower shoreface
HWFA 6: Burrowed inner shelf
HWFA 7: Shelfal storm sheets
MFS Maximum flooding surface
MRS Maximum regressive surface
SR-U Shoreline ravinement unconformity
RSME Regressive surface of marine erosion
SB Sequence boundary
TST Transgressive systems tract
HST Highstand systems tract
HWZ2b Hawaz zone 2b
HWZ2a Hawaz zone 2a
GR Gamma Ray
RHOZ Density
NPHI Neutron
DT Sonic
STRATIGRAPHIC COLUMN
Parallel stratification and/or lamination
Planar cross stratification and/or lamination
Through cross stratification
Hummocky and/or Swaley cross stratification
Mud rip-up clasts
Fluid-escape structures
Horizontal deposit feeding burrows
Vertical suspension feeding burrows



Not to scale
Tidal flat
Subtidal complex
Intertidal zone
Supratidal zone
Subtidal zone
Tidal range
Shelfal storm sheets
Longshore currents
Burrowed inner shelf
FORESHORE
MIDDLE SHOREFACE
LOWER SHOREFACE
INNER SHELF
Cruziana ichnofacies
Skolithos ichnofacies
Cruziana ichnofacies
Well E
Well D
Well D
Well D
(A)
(B)
(C)
(D)
Pl
Sk
Th
Si
Te
Sk
Th
Ch
Ch
Ch

Sandstones (S)	Nonburrowed	Sx1: Large-scale cross-bedded sandstones
		Sx2: Small- to medium-scale cross-bedded sandstones
		Sl: Parallel-laminated sandstones
		Sxl: Cross-laminated sandstones
		Sr: Ripple cross-laminated sandstones
		Sv: Massive sandstones
	Burrowed (b)	Sxb: Burrowed cross-bedded sandstones
		Sxlb: Burrowed cross-laminated sandstones
		Srb: Burrowed ripple cross-laminated sandstones
		Sb: Burrowed sandstones with Siphonichnus
		MSb: Burrowed sandstones with feeding ichnofauna
Sandy Heterolithics (HS)		HS: Sandy heterolithics
		HSb: Burrowed sandy heterolithics
Muddy Heterolithics (HM)		HM: Muddy heterolithics
		HMb: Burrowed muddy heterolithics

Processes / Controlling factors	Actualistic (Present)	Non-Actualistic (Early Paleozoic and older)
Land flora	Vegetation in continental to transitional environments helps to stabilize river banks limiting channel shifting, changing river style from braided to meandering in low gradient systems	The lack of vegetation in subaerial conditions led to the development of high energy fluvial systems (mainly braided style) characterised by rapid channel shifting of rivers even in very low gradient systems
	Chemical weathering and related clay generation.	Lack of clay generation by induced chemical weathering due to the absence of vegetation in subaerial environments. Clay-size particles alternatively sourced from volcanic ash, hydrothermalism, diagenesis, etc.
Greenhouse / Icehouse	Incision of valleys during sea level fall in recent icehouse periods and subsequent development of estuarine environments with marine transgressions. Fluvial sediments are common in proximal parts of the systems and related hyperpycnal deposits in more distal settings during lowstand stages.	Epeiric seas in large cratonic basins during greenhouse periods developing areally extensive paralic environments. Very difficult to identify lowstand deposits due to very limited incision in proximal environments. Very low gradients imply major paleoshoreline shifts with only limited relative sea level rises
Tidal range	Lower tidal range caused by tidal energy dissipation due to larger distance between the Earth and the Moon with time. Maximum known current tidal range is about 12m (40ft)	Higher tidal range due to the reduced distance between the Earth and the Moon (unknown maximum tidal range in the early Paleozoic).
Ichnofacies	Broader and more diversified ichnofacies at present times. Characteristic *Skolithos* and *Cruziana* ichnofacies found in Hawaz Formation have different signature due to the presence of different fauna in present depositional environments.	Characteristic, often low diversity, mix of *Skolithos* and *Cruziana* ichnofacies is largely confined to the early Paleozoic, often occurring in the form of ichnofabrics characterised by a distinctive ‘pipe rock’ texture and trilobite traces.