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Sequential Stratigraphy of Outcropping Strata Equivalent to Arab-D Reservoir, Wadi Nisah, Saudi Arabia

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ABSTRACT

Two outcrops in Wadi Nisah of Central Saudi Arabia expose sedimentary successions of the Jubaila and Arab formations which are stratigraphic equivalents of the Arab-D reservoir in Ghawar field. These carbonate exposures consist of lithofacies and stacking patterns similar to the succession found in Arab-D reservoir. Nineteen vertical sedimentary cycles were identified by collectively evaluating disconformable relationships, textural characteristics, and lithofacies assemblages. These, in turn, define 3 depositional cycle types: (1) stromatoporoid, (2) skeletal bank, and (3) thinning-upward.

The lateral distribution of lithofacies within the stromatoporoid cycle shows that stromatoporoid grainstones form organic buildups flanked by burrowed mud-dominated carbonates. Stromatoporoid banks locally exhibit thickness increases of about 3 meters (10 feet) over a horizontal distance of 500 meters (1, 700 feet). Conversely, the five foot-thick skeletal grainstone capping the skeletal bank cycle forms a continuous sheet exceeding 2 kilometers (1.2 miles) in width. Thinly bedded carbonate sand units within the thinning-upward cycle exhibit pronounced lateral discontinuity. Beds pinch out against topographic highs formed by stromatoporoid buildups over distances of less than a hundred meters (328 feet).

Results of the outcrop stratigraphic analysis enable visualization of lateral and vertical stratigraphic relationships and potential fluid-flow pathways. This study demonstrates that outcropping cycles and their lithofacies components have several important implications for ongoing subsurface reservoir characterization and modeling of the Arab-D. Firstly, cycle definition identifies stratigraphic units whose bounding surfaces describe envelopes that constrain the interwell distribution of lithofacies. Secondly, the lithofacies define geometries for the interwell distribution of petrophysical characteristics. Thirdly, the understanding of lateral relationships of these carbonates aids in reservoir simulation modeling.

INTRODUCTION

The Arab-D carbonates represent the most prolific oil producing interval in the world. Yet, the reservoir architecture remains problematic. Although in most Arab-D reservoirs there are extensive wireline logs and core data that constrain the vertical stratification of the reservoir, these wells are spaced one to two kilometers apart. Therefore with the exception of rare horizontal borehole or high-resolution three-dimensional seismic data, information is largely missing about lateral stratigraphic relationships. This presents a significant problem for stratigraphers and engineers because the poorly constrained lithofacies and permeability architecture are critical variables for understanding subsurface flow and recovery. Two and three-dimensional information from large-scale outcrop equivalents of the Arab-D reservoir would allow an examination of the spatial distributions of lithofacies and petrophysical properties within an unequivocal stratigraphic framework.

Upper Jurassic units equivalent to the Arab-D reservoir section occur in a curved outcrop belt in the Tuwaiq Mountains of Central Saudi Arabia (Figure 1). Roads and wadis provide easy access to Jurassic sections. Although many cuts expose laterally extensive sequences equivalent to various portions of the Arab-D reservoir, only a few outcrops display sections equivalent to the upper Arab-D reservoir. These exposures provide a unique opportunity to detail the lateral stratigraphic and petrophysical architecture in three dimensions. Information gained from these studies may be applied as an additional component to enhance the reservoir characterization in the subsurface. Here we present the stratigraphic description of strata equivalent to the Arab-D reservoir in two Wadi Nisah sections (Figure 1).

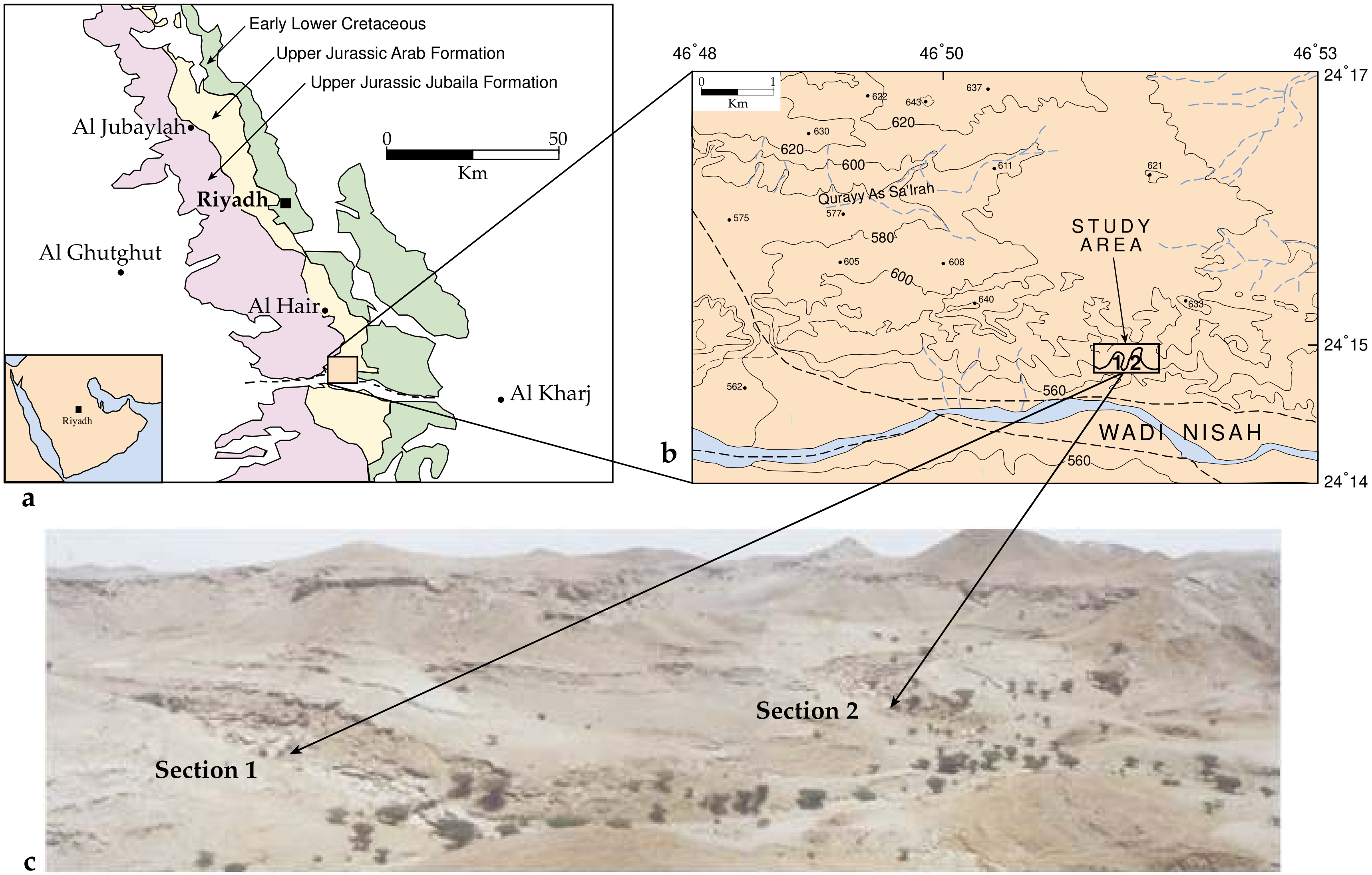


Figure 1: (a) Geologic map of Jurassic outcrop belt in Riyadh area showing the location of Study Area (modified after Sharief, 1991). (b) Topographic map showing location of the two measured sections in two small wadis along north side of Wadi Nisah (contour interval 20 meters, modified after Ministry of Petroleum and Mineral Resources (1983a, b)). (c) Looking northeast toward the escarpment, the two diverging wadis that expose the Jubaila and Arab formations can be seen in the middle of the photograph.

Okla (1986) carried out the first petrographic investigation of rocks from the two Wadi Nisah sections. He mainly concentrated on the microfacies characteristics of the entire Upper Jurassic outcrop belt. Furthermore, his published rock descriptions of measured sections at Wadi Nisah were far too generalized, and lacked the lithostratigraphic framework that facilitates comparison with subsurface data. In this paper, we emphasize the small-scale cycle stratigraphy as the basis for laterally distributing lithofacies and petrophysical characteristics.

The value of this outcrop study is to provide a stratigraphic model that can be used by geologists and engineers to enhance description of the three-dimensional volume of the Arab-D reservoir using one-dimensional (borehole) data. The model incorporates the expression of relative sea level changes, lateral distribution of lithofacies and paleocurrent indicators recognized in outcrop. Specifically, it details the stratal characteristics and vertical expression of genetically related lithofacies packages and compares them to a typical subsurface reservoir equivalent section.

METHODS

Two Wadi Nisah exposures (Figure 1) provide the basis for interpreting the depositional and stratigraphic dynamics of strata equivalent to the Arab-D reservoir. Both sections are incomplete. They expose strata equivalent only to the upper half of the Arab-D reservoir section. We measured sections on a bed by bed basis at both locations. Thin platy beds of the uppermost Arab-D are exceptions to this approach. These typically form scree slopes whose thickness we measured with a hand level and Jacob's staff. We sequentially numbered beds or groups of beds from the bottom to top. The identification of individual beds is clearly subjective and also is a function of weathering. In general, we chose to assign individual numbers (1-18) to laterally continuous beds throughout the lower part of each section, whereas the laterally discontinuous, thin, platy beds were numbered in groups.

Textural descriptions are from Dunham's (1962) classification except for a modification of grainstone. Aramco uses the term mud-lean packstone to describe a grain-supported carbonate that has a mud content between 1 to 10 percent. We follow this usage here even though Swanson (1981) expanded the allowable mud content for a grainstone from 1 to 10 percent with Dunham's full consent.

To categorize the reservoir equivalent Arab-D section, we used a modified version of the Meyer and Price (1993) and Mitchell et al. (1988) lithofacies classifications. The modified classification scheme incorporates lithofacies unique to the outcropping sections, but retains shared categories to provide a lithostratigraphic tie with the subsurface. An analysis of vertical and lateral sequences forms the basis for interpreting interaction of sedimentation and relative sea level changes in the formation of depositional cycles.

STRATIGRAPHY

Outcrop studies can provide important stratigraphic guidelines about the spatial distributions of lithofacies in Arab-D oil reservoirs. However, the success of such endeavors depends on two keys. First is the ability to make reasonable correlations between surface exposures and subsurface strata. Second is the recognition of comparable depositional patterns.

The outcropping Jubaila Formation does not correlate directly with the Jubaila Formation as we presently define it in the subsurface (below base of Arab-D Reservoir). Review of original definitions of formations (Bramkamp and Steineke, 1952; Steineke et al., 1958) demonstrate that the outcropping Jubaila Formation is correlative with the lower portion of the Arab-D reservoir.

The following excerpt from Powers (1968) clarifies the stratigraphic relationship between the Jubaila and Arab-D formations as compared with the "Arab-D reservoir".

> *The Arab-D reservoir was originally defined on the presence of productive oil and is therefore not strictly a part of formal stratigraphic nomenclature. However, because of its distinctive lithology and nearly isochronous character over a broad area, it has subsequently been used, almost without exception, in a stratigraphic sense independent of its fluid content.*

> *The contact between the Arab and Jubaila formations in terms of the outcrop sequence falls near the middle of the Arab-D reservoir. Accurate identification of this boundary has proved of considerable importance for it divides the reservoir into two parts each with a decidedly different lithogenetic character and reservoir behavior.*

The originally defined Jubaila Formation top in the subsurface of the Ghawar field (Figure 4 of Steineke et al., 1958) occurs 100 feet below the C-D anhydrite. This places the top of the Jubaila, using present Arab-D reservoir terminology, at approximately the top of reservoir Layer-8 within Zone 2-B (Figure 2).

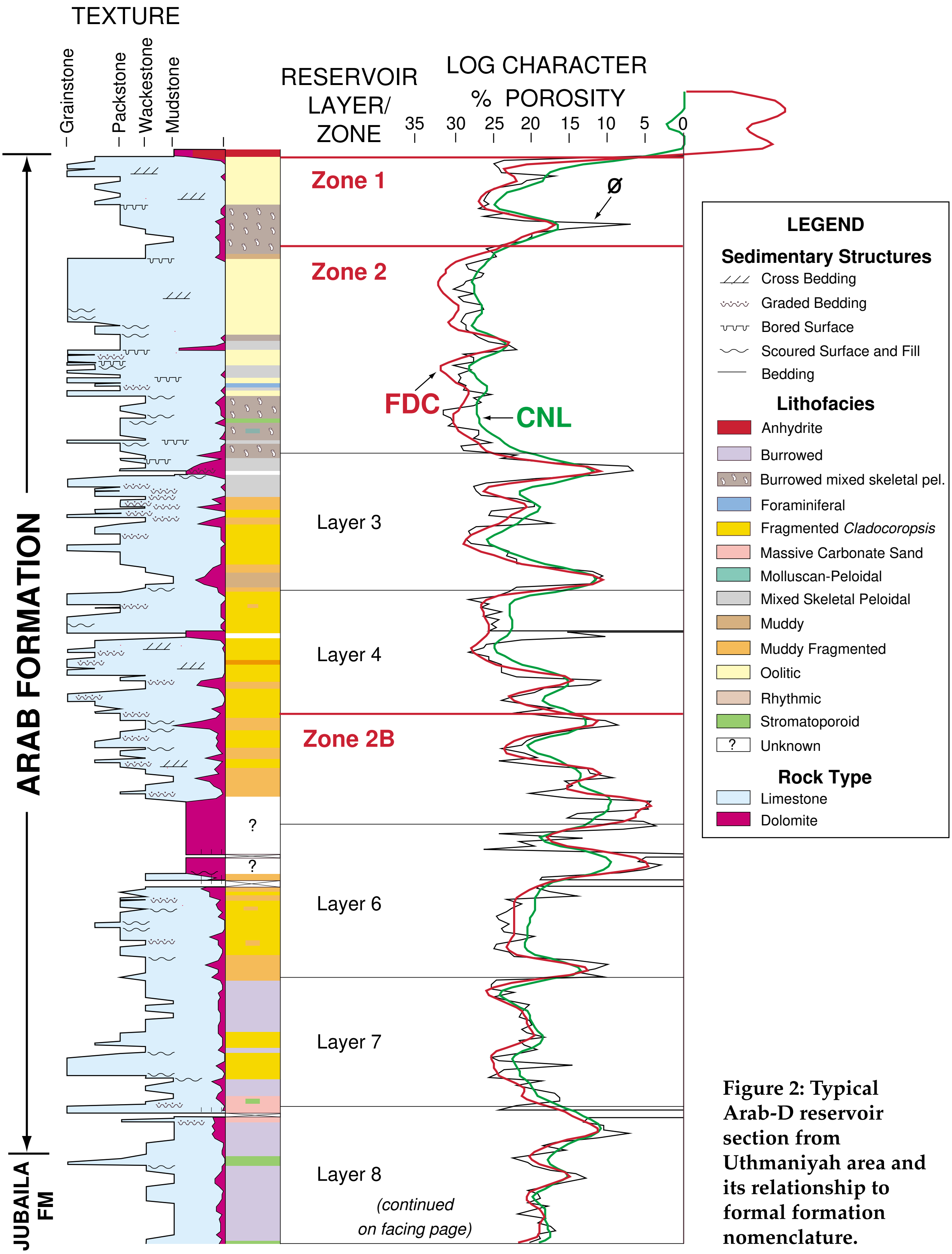
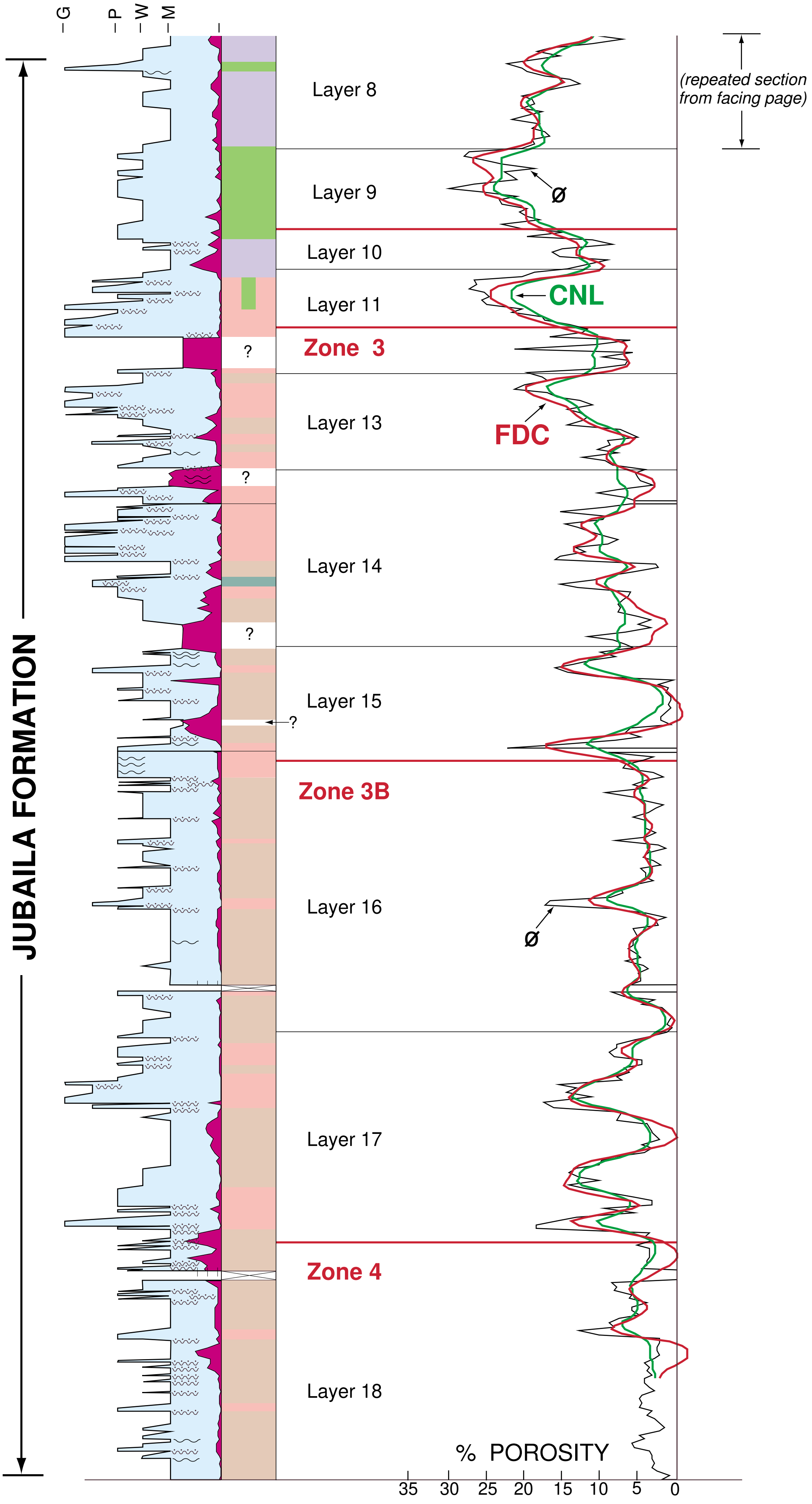


Figure 2: Typical Arab-D reservoir section from Uthmaniyah area and its relationship to formal formation nomenclature.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JUBAILA FORMATION
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This correlation shows that the lower portion of Arab-D reservoir Zone 2-B, Zone 3-A, and Zone 3-B correlate with what was originally defined as Upper Jubaila in the subsurface. Over the years, original formation definitions and boundaries were lost in the reservoir while they remained unchanged in outcrop. The correlation chart from Powers (1968) shows the historical evolution of the Jubaila and Arab-D terminology (Figure 3).

Although there is a nomenclature problem with detailed outcrop to reservoir correlation, we do not advocate a change in the general present-day lithostratigraphic reservoir definitions. However, recognizing and understanding the correct correlations is extremely important for the following reasons:

(1) clears up potential confusion on outcrop correlation with subsurface reservoir facies,
(2) demonstrates that the lower part of Arab-D reservoir Zone 2-B, and entire Zones 3-A and 3-B exist in outcrop and they are referred to as the Jubaila formation,
(3) explains why it is difficult in the reservoir to pick the boundary between reservoir Zone-4 and the Jubaila, since this contact falls within what was originally defined as the Jubaila Formation,
(4) ties original depositional interpretations (Steineke, et al., 1958; Bramkamp and Steineke, 1952; etc.) to equivalent reservoir facies,
(5) elucidates the fact that early published reservoir work utilized different definitions of the Jubaila and Arab-D as compared with the reservoir definitions of today (Figure 4), and
(6) forms the basis for constructing a regional Arab-D stratigraphic framework.

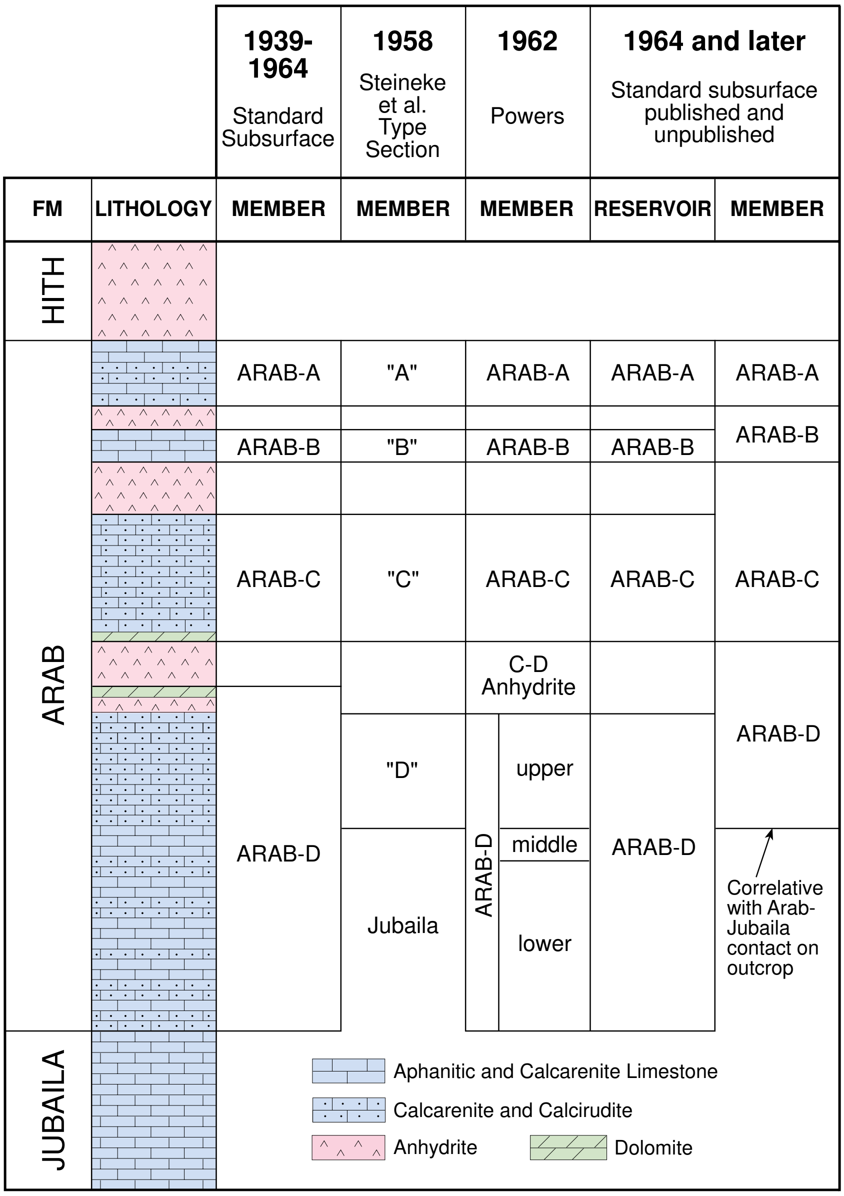


Figure 3: Historical evolution of Arab and Jubaila formation lithostratigraphic nomenclature as shown by Powers (1968).

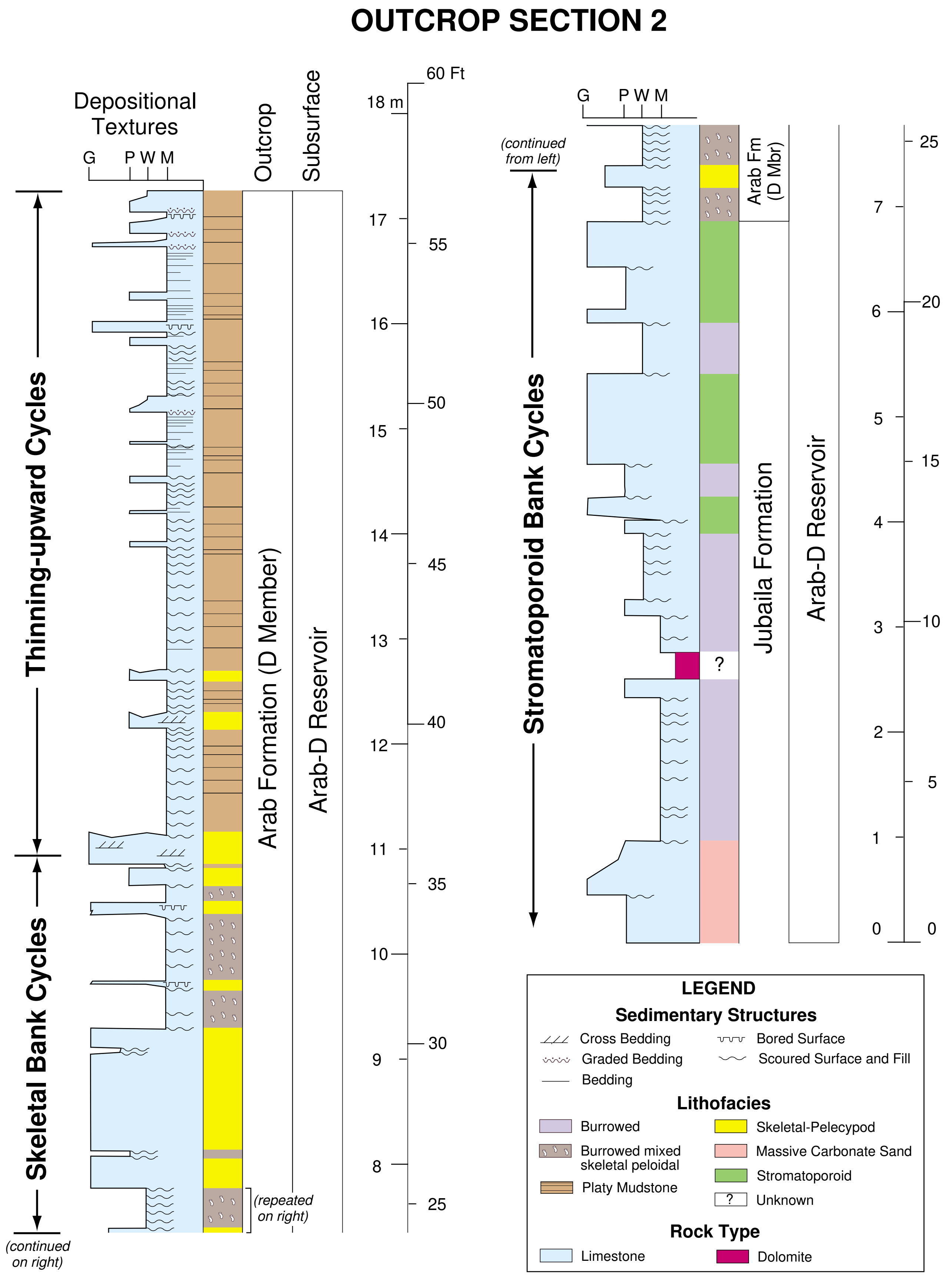


Figure 4: Lithologic log of Section 2 showing the relationships between formal and informal stratigraphic nomenclature applied to outcrop and subsurface reservoir unit.

Outcrop Lithofacies Characteristics

Figure 5 illustrates the distribution of six lithofacies described for outcropping strata in the two measured sections. It shows the lithofacies stacking order proceeds upward from massive carbonate sand through burrowed, stromatoporoid, burrowed mixed skeletal, skeletal-pelecypod to platy mudstone. The upward progression of lithofacies is punctuated by the repetative stacking of two or three facies types. Lithofacies are predominantly mud-dominate. Only the stromatoporoid and skeletal-pelecypod lithofacies have grain-supported depositional textures. Both lithofacies occur primarily in the middle part of the depositional succession.

Massive Carbonate Sand

With only one occurrence at the base of section two, this lithofacies is not well represented or exposed. A tentative characterization based exclusively on outcrop observations suggest it is a grain-dominated interval composed of amalgamated beds. Each bed contains graded intraclasts and skeletal elements that rest on a sharply scoured base. Individual graded beds appear to range from a few centimeters up to half a meter (1.5 ft) in thickness. Their basal erosion surfaces locally cut into the muddy, burrowed caps of underlying beds.

***Interpretation**:* Observed depositional and textural features of this lithofacies suggest event deposition below effective wave base. Not enough of the lithofacies was observed in the immediate study area to make a definitive interpretation, but the features noted compare well with those observed elsewhere. It compares to the couplet (micritic and bivalve-coated grain-intraclast lithofacies) observed in the lower Arab-D massive carbonate sand interval (Meyer and Price, 1993). These similarities between outcrop and subsurface depositional features and stratigraphic position support the proposed interpretation.

Burrowed

This lithofacies is a very distinct burrow mottled, buff, muddy limestone that contains scattered stromatoporoid heads. It typically weathers to a blue gray color in outcrop. Both vertically and laterally, this lithofacies is associated with stromatoporoid packstones and grainstones. Vertical contacts between burrowed and stromatoporoid units are typically gradational over a scale of inches. Faunal components are the same as the stromatoporoid lithofacies but are low in abundance.

***Interpretation**:* Faunal components and the mudstone to wackestone textures suggest this lithofacies formed in a low energy, open marine environment. Stratigraphic relationships and faunal similarities with the stromatoporoid lithofacies suggest the burrowed lithofacies could form in either quiet water conditions below wave base and seaward of the stromatoporoids, or in a protected position within or behind the stromatoporoid banks.

Stromatoporoid

Stromatoporoid units occur as medium to very thick beds, 0.2-3 m (0.5-10 ft), dominated by bulbous, decimeter size stromatoporoid heads. Corals represent a subordinate constituent that may locally exceed stromatoporoids in abundance but are completely absent in places. Red algae are rare. Locally, large (>2 cm), thick-shelled bivalves are abundant.

Packstone and wackestone form the textures where these units are transitional with the burrowed lithofacies. Grainstones, with a framework of onchoids and intraclasts, predominate toward the tops of individual stromatoporoid beds. Other faunal components include foraminifers, bivalves, echinoderms, calcareous algae (both red and green) and rare *Cladocoropsis*.

***Interpretation**:* Faunal frameworks formed by in situ stromatoporoid and rare coral skeletons suggest this lithofacies represents an open marine belt of stromatoporoid banks. An upward change from a mud- to grain-dominated matrix within the buildups indicates a catch-up bank growth. Stromatoporoid buildups appear to have colonized muddy low energy substrates and grown upwards until they reached active wave base.

Burrowed Mixed Skeletal Peloidal

Pale blue burrow-mottled beds of skeletal-peloidal wackestones occur interbedded with the grain-supported skeletal-pelecypod units. Their bases generally form a sharp textural transition from underlying skeletal-pelecypod grainstones whereas gradational contacts mark transitions into overlying grain-supported, skeletal-pelecypod units. Horizontal stylolites obscure bedding planes and locally follow burrows.

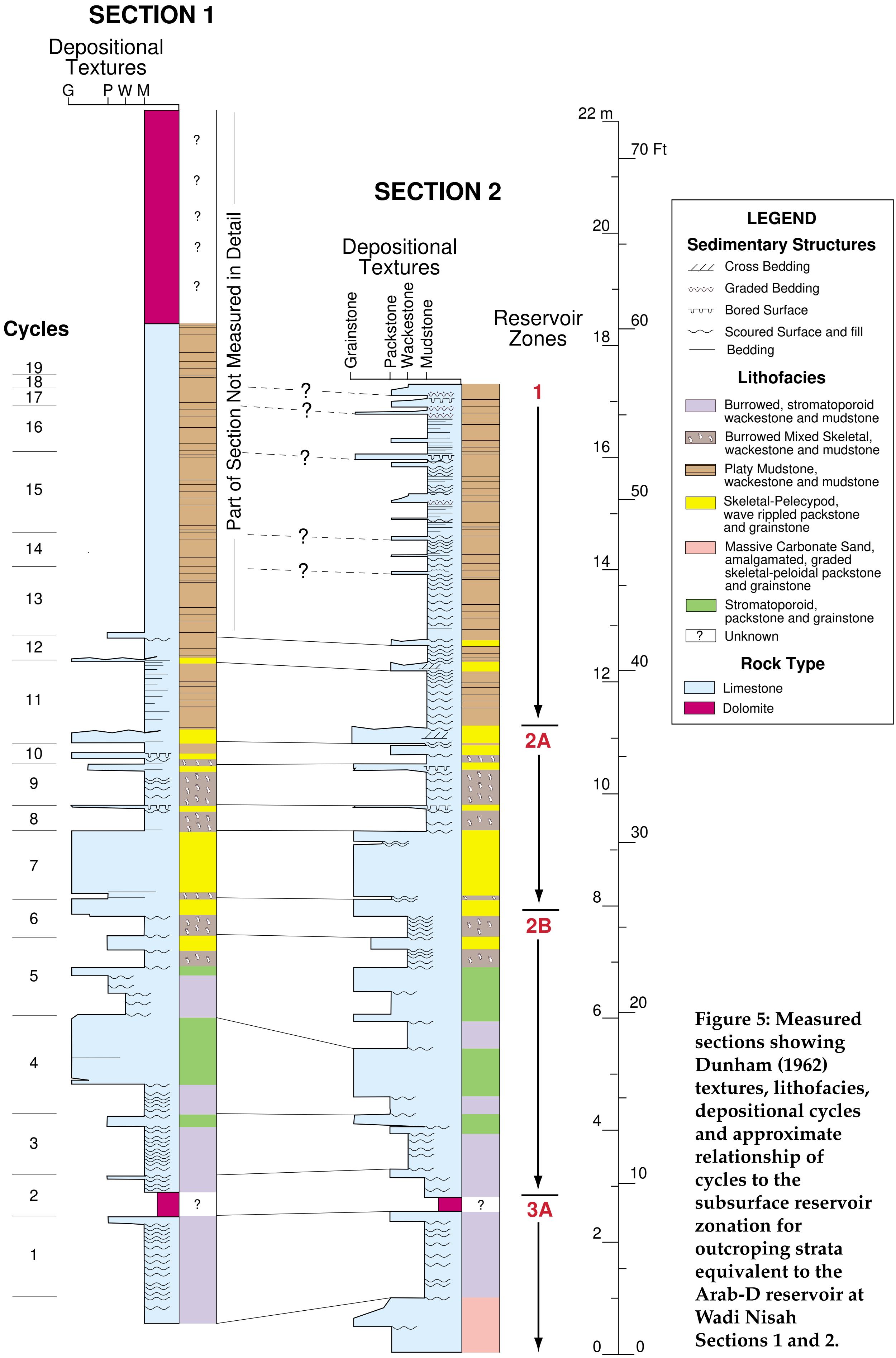


Figure 5: Measured sections showing Dunham (1962) textures, lithofacies, depositional cycles and approximate relationship of cycles to the subsurface reservoir zonation for outcroping strata equivalent to the Arab-D reservoir at Wadi Nisah Sections 1 and 2.

A mixed assemblage of sparse bioclasts and peloids typifies this lithofacies. The skeletal grains and peloids represent end-member components of this lithofacies and can occur in any ratio relative to each other. In some instances a mixed skeletal assemblage, peloidal grains, or any combination of these components may dominate the mixed skeletal-peloidal lithofacies. A specific grain type does not dominate the mixed skeletal assemblage. Instead, the skeletal assemblage contains a collection of bivalves, foraminifers, dasycladacean algae, red algae, and more rarely echinoderms, corals, gastropods, ostracodes, and brachiopods.

Interpretation: Stratigraphic relationships together with faunal components imply this lithofacies represents an offshore submarine environment. Wave and current aggitation was low in the environment as indicated by abundant mud-dominated textures. This lithofacies and the burrowed lithofacies are similar. In fact, they may represent the same lithofacies if the stromatoporoid distribution is patchy and does not form a continuous belt. The differentiation of these two lithofacies was based on stratigraphic position and the presence of scattered stromatoporoids within the burrowed lithofacies. Stratigraphically the burrowed mixed skeletal peloidal lithofacies was restricted to a position overlying the stromatoporoid lithofacies, whereas the burrowed lithofacies occurred lower in the section below the stromatoporoids. In actuality, these may represent more onshore (burrowed mixed skeletal) and offshore (burrowed) equivalents of the same lithofacies if not differentiated into separate environments by a continuous stromatoporoid belt. Additional field work focused on lateral tracing of beds should answer this question.

Skeletal-Pelecypod

Medium to very thick beds (0.15 to 2 m; 0.5 to 6 ft) of skeletal-pelecypod grainstone and packstone characterize this lithofacies. These occur below and interbedded with the platy carbonate lithofacies. Their bases may be sharp with erosional scours and include intraclasts, or they may be gradational with the underlying wakestone of the burrowed mixed skeletal-peloidal lithofacies. Most massive beds appear unstratified. Thin units locally preserve wave ripple stratification and have sheet-like geometries throughout the outcrop area. Beds of the skeletal-pelecypod lithofacies commonly contain small, dark pelecypod valves and peloids. Grain size varies from medium to coarse sand.

Interpretation: Wave ripples, stratigraphic relationships, and microfacies characteristics suggest this lithofacies accumulated as a skeletal bank in a subtidal, high energy setting. Stratigraphic association of the skeletal-pelecypod lithofacies with peritidal carbonates places the skeletal bank in a marginal marine setting seaward of tidal flats.

Platy Mudstone

Very thin beds of pale blue-gray lime mudstone distinguish this lithofacies. These exhibit a variety of peritidal stratification signatures, but faunal components are scarce. Intraclasts and small bivalves are locally abundant as shell beds whereas high-spired gastropods form a subordinate component.

Weathering reduces this well-bedded lithofacies to scree slopes littered with large plates of limestone. The platy mudstone is well represented. It forms a substantial (8 m or 25 ft) stratigraphic interval transitional between thick Arab-D grainstones and an overlying collapse breccia composed mostly of Arab-C carbonates. Carbonate brecciation and collapse occurred in conjunction with extensive Arab-D evaporite dissolution.

This interval of platy carbonates features three main types of stratification: millimeter laminations, limestone flat-pebble conglomerates, and fining upward layers.

In finely laminated carbonates, the individual laminae may be either flat, slightly crenulated, domed or locally mudcracked. Rare crinkly laminated carbonates with either flat or domed configurations resemble the "cryptalgal limestones" of Aitken (1967), James (1980) and Meyer (1979). By analogy to features in modern intertidal and supratidal carbonate environments (Shinn, 1983), we interpret these sedimentary structures as stromatolites.

Beds characterized by flat-pebble conglomerate stratification contain lime intraclasts that typically are flat and laminated with sparse burrows. Intraclast range from 1 to 10 cm (0.5-4 in) in diameter and locally exhibit evidence of grading or pebble imbrication. Based on their lensoid or sheet-like geometry such layers may represent either channel lag deposits or supratidal storm layers (Shinn, 1983).

Fining-upward layers typically are graded and contain quartz-rich, peloidal or skeletal components. Individual layers range up to a decimeter in thickness. Burrows which penetrate laminated tops on some of these layers locally contain a fine quartz and carbonate sand. Similar structures noted in modern and ancient deposits have been attributed by Shinn (1983) as storm deposits in tidal flat environments.

***Interpretation**:* A paucity of faunal elements, the prevalence of flat pebble limestone conglomerates, and the presence of stromatolites are consistent with a peritidal environment. Physical rather than biologic processes prevailed as shown by the preserved laminae and lack of bioturbation. The virtual absence of an in situ fauna reflects a high stress environment. Collectively these features and their stratigraphic relationship to overlying collapse breccia whose origin relates to anhydrite dissolution (Sharief et al., 1991) is consistent with a tidal flat origin.

Vertical Sequences

Stratification motifs, textural characteristics and lithofacies associations exhibit arrangements that collectively describe nineteen repetitive or distinctive vertical successions. Thirteen were correlated between the two measured sections (Figure 5). These sedimentary modules in turn distill into three cycle types: stromatoporoid, skeletal bank, and thinning-upward.

A group of stromatoporoid-bearing carbonate beds, that represent the burrowed and stromatoporoid lithofacies, forms the stromatoporoid cycle (Figure 6). This coarsening upward cycle occurs in the basal part of the succession in both measured sections. The cycle consists of four to eight limestone beds that increase in thickness toward the top. It passes upwards from burrowed wackestones rather abruptly into thick stromatoporoid bearing packstones that grade upwards into oncolitic grainstones with a framework of cobble-size bulbous stromatoporoids.

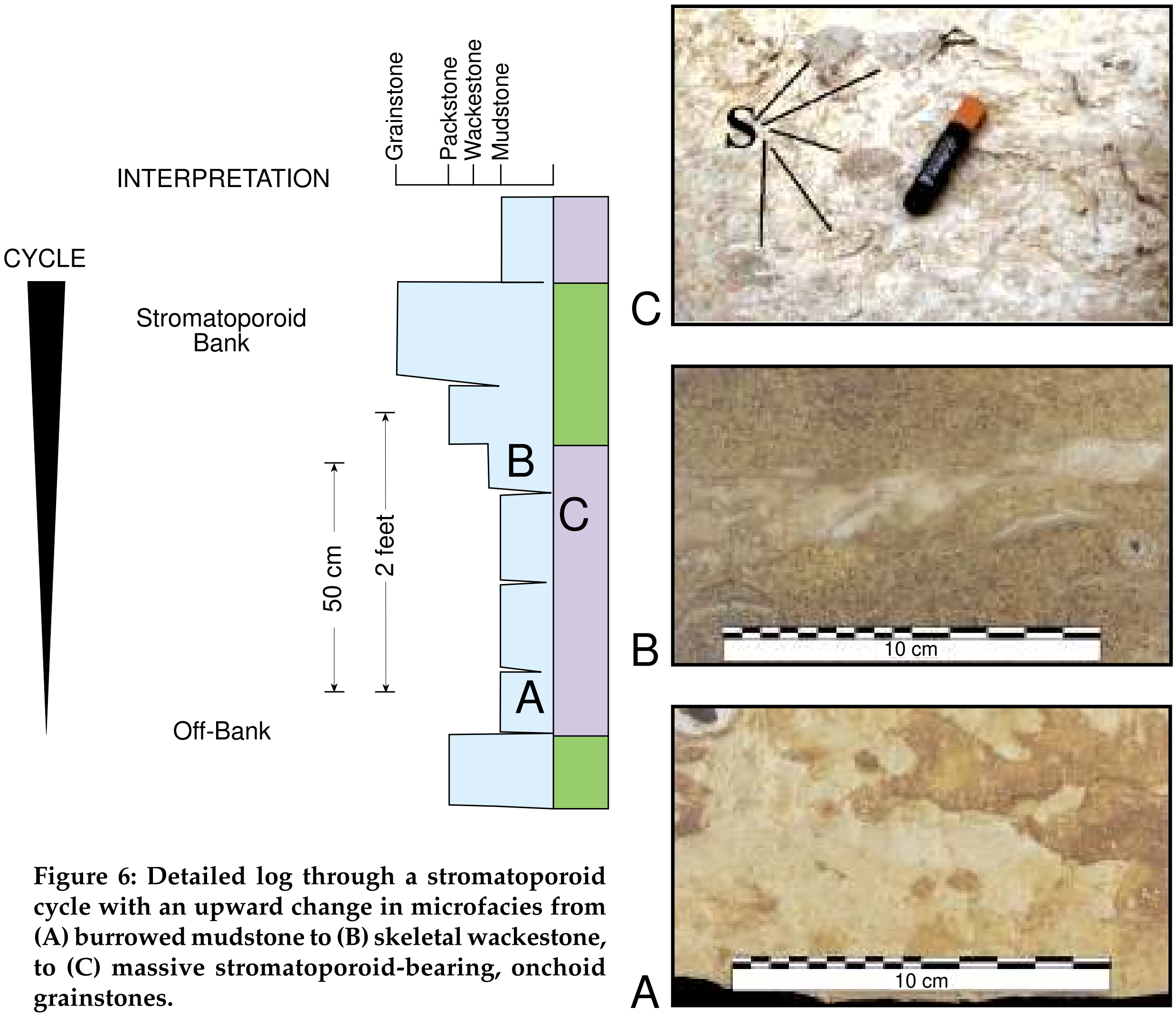


Figure 6: Detailed log through a stromatoporoid cycle with an upward change in microfacies from (A) burrowed mudstone to (B) skeletal wackestone, to (C) massive stromatoporoid-bearing, onchoid grainstones.

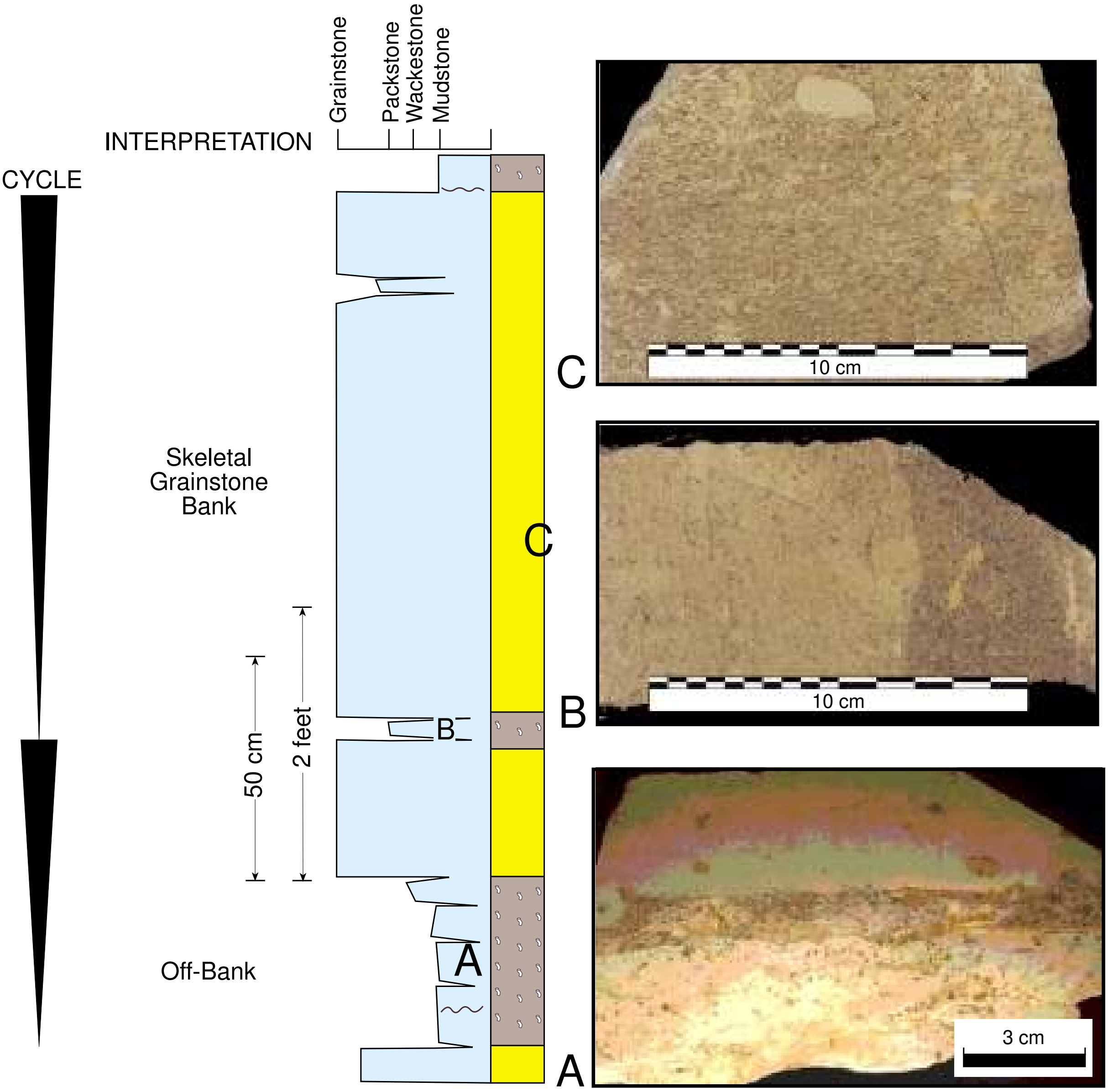


Figure 7: Detailed log through two skeletal bank cycles showing progressive upward change from (A) a burrowed mud-dominated carbonate to (B) a skeletal wackestone or packstone, to (C) a massive skeletal grainstones rich in pelecypods. See Figure 2 for color legend.

Skeletal Bank Cycle

This coarsening upward cycle varies from the stromatoporoid cycle because of the difference in faunal components. The skeletal bank cycle features an upward transition from nodular lime mudstone to a massive skeletal grainstone (Figure 7). Nodular limestones that form the basal part of the cycle form 0.3 meter (1 ft) thick units that are interbedded with transitional skeletal packstone beds. Burrowing combined with pressure solution contribute to the nodular character of the basal section. The basal part grades upward into a massive skeletal grainstone through a thin packstone transition zone. Bored and oyster-encrusted hardgrounds locally punctuate the tops of the capping skeletal grainstones. The uppermost skeletal bank cycle differs from other cycles in this set by the addition of an overlying thinly laminated and muddy lithofacies. This lithofacies marks the transition into the overlying thinning-upward cycles and is interpreted as continued shallowing into tidal flat deposition.

Thinning-upward Cycle

The thinning-upward cycle (Figure 8) is a shoaling-upward succession dominated by muddy carbonates whose bed thickness decreases upward. Unlike the other two cycle types, this cycle generally thins

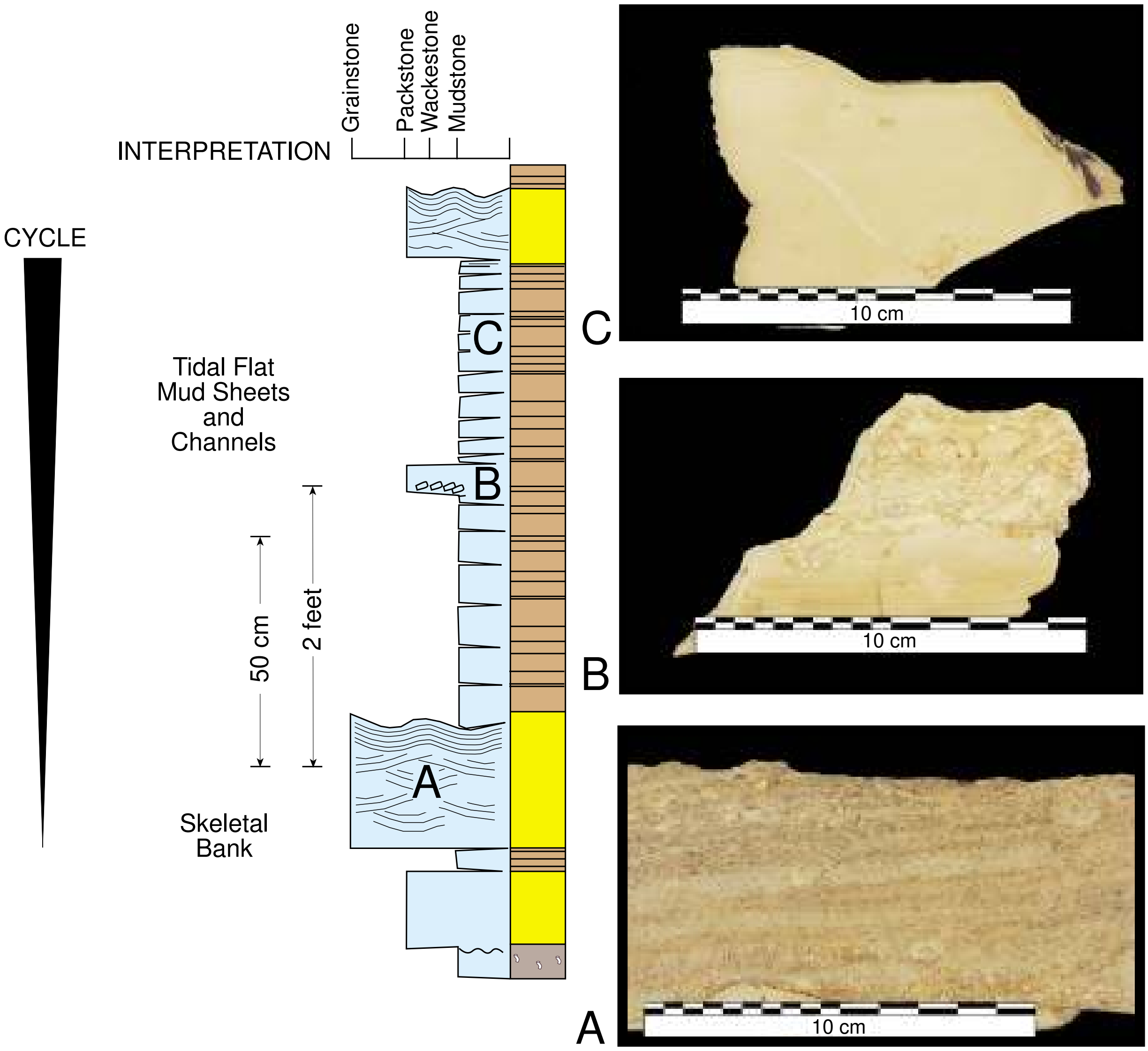


Figure 8: Detailed log through a thinning-upward cycle. Note upward changes from (A) subtidal grainstone with wave ripples into (B) channeled tidal flat mud sheets with intraclasts and finally into (C) a mudstone with sparse burrows containing a fill of pelloids and quartz sand. See Figure 2 for color legend.

upward but some cycles exhibit no upward change in grain size. It occurs above the skeletal bank cycles and is characterized by a progressive thinning of beds upwards. Its basal bed typically consists of a wave-rippled packstone to grainstone rich in quartz sand or burrowed skeletal wackestone. These pass upwards abruptly through an interval of laminated or unlaminated wackestones with local intraclast packstone lenses into laminated mudstones.

Vertical Arrangement of Cycles

Both outcrop sections display similar cycle stacking patterns (Figure 5). Their basal sequence features a stacked succession of five stromatoporoid cycles. Nodular wackestone of the skeletal sand cycle succeeds the grainstones at the top of the uppermost stromatoporoid cycle. The contact between cycles five and six is planar and sharp (Figure 5). Similarly, a sharp contact exists at the top of cycle 10, the uppermost skeletal bank cycle. This skeletal grainstone cycle, capped by thinly bedded and laminated wackestone or mudstone is succeeded by three thinning-upward cycles. The thickness of each thinning-upward cycle decreases as does the wave-ripple cross-laminated skeletal grainstone that forms their base. Bedding becomes variable in the uppermost portion of the thinning-upward cycles that cap the sections, but the absence of more than one lithofacies makes recognition of additional cycles problematic.

Lateral Facies Changes

Lateral continuity of lithofacies is based on detailed analysis and interpretation of the two sections in this study area and on general reconnaissance data from additional sections. We regard the overall vertical succession to represent a gradually shallowing up sequence. Lateral juxtaposition of lithofacies is inferred from vertical relationships for the most part, although some (stromatoporoid and burrowed) are visible in the field. Our lateral lithofacies model is tentative and will be refined with additional work.

The general lateral lithofacies model of outcropping reservoir equivalent Arab-D strata is that of near shore skeletal limestones passing offshore into burrowed and stromatoporoid limestones (Figure 9). Details of lateral lithofacies relationship are evident within individual cycles along a transect parallel to depositional dip. Lithofacies types grade continuously into one another as illustrated by the distribution of depositional textures (Figure 9). Seaward of the massive skeletal limestone zone occurs a prominent belt of burrowed and stromatoporoid limestones. The nearshore belt of massive carbonates consists of skeletal grainstones and packstones dominated by pelecypods and includes areas of peloidal grainstones. Further offshore, packstones prevail as mud increases and the skeletal content and depositional energy decrease. Still further offshore burrowed mudstones or skeletal wackestones with local stromatoporoid buildups predominate. In the stromatoporoid buildups, onchoid and skeletal grainstones or packstones form the matrix between stromatoporoid heads. In general, the grainstone matrix is more common toward the top of stromatoporoid buildups.

Paleocurrent Indicators

Orientation of sand waves and imbricated flat-pebble conglomerates serve as paleocurrent indicators. When evaluated together, our data suggest a general seaward direction to the east and landward direction to the west (Figure 10). This interpretation agrees with regional paleogeographic reconstructions of the Jurassic shelf. More extensive measurements of these outcropping paleocurrent indicators over a broader geographic area would allow a detailed reconstruction of the paleoshoreline. This would enhance our understanding of shoreline variability and consequently the degree of heterogeneity of nearshore depositional lithofacies.

In Wadi Nisah, the symmetrically developed sand waves typically have wavelengths of 80 centimeters with heights of 5 to 7 centimeters. A number of sand wave orientations were measured at two different localities approximately 5 kilometers apart (Figure 10). At both localities the sand wave crests were consistently oriented N5°W. Assuming wave crest orientations parallel or slightly oblique to shoreline would allow a bi-directional interpretation of on-shore/offshore either toward the east or toward the west. However, imbricated flat-pebble conglomerates, measured at locality 2, consistently dipped to the east and suggest a unimodal current direction toward the west (Figure 10). We interpret these imbricates as forming along shoreline as a result of wave energy dissipating across a tidal flat; consequently onshore would be toward the west. These two data sets, based on sedimentary structures, corroborate previous onshore/offshore interpretations based on regional data.

OUTCROP SUMMARY

Our current observations of the two Arab-D sections offer the following instructive insights:

(1) Reservoir equivalent outcrop strata exhibits features of a highly cyclic nature.

(2) Six lithofacies (platy mudstone, skeletal-pelecypod, burrowed mixed skeletal, stromatoporoid, burrowed, massive carbonate sand) make-up the cyclic vertical successions in outcrop.

(3) The three cycle types represented by their vertical lithofacies or bedding stacking pattern are: Thinning-upward, Skeletal, and Stromatoporoid.

(4) Nineteen cycles, recognized on the basis of general parasequence recognition criteria, characterize the reservoir equivalent outcrop sections.

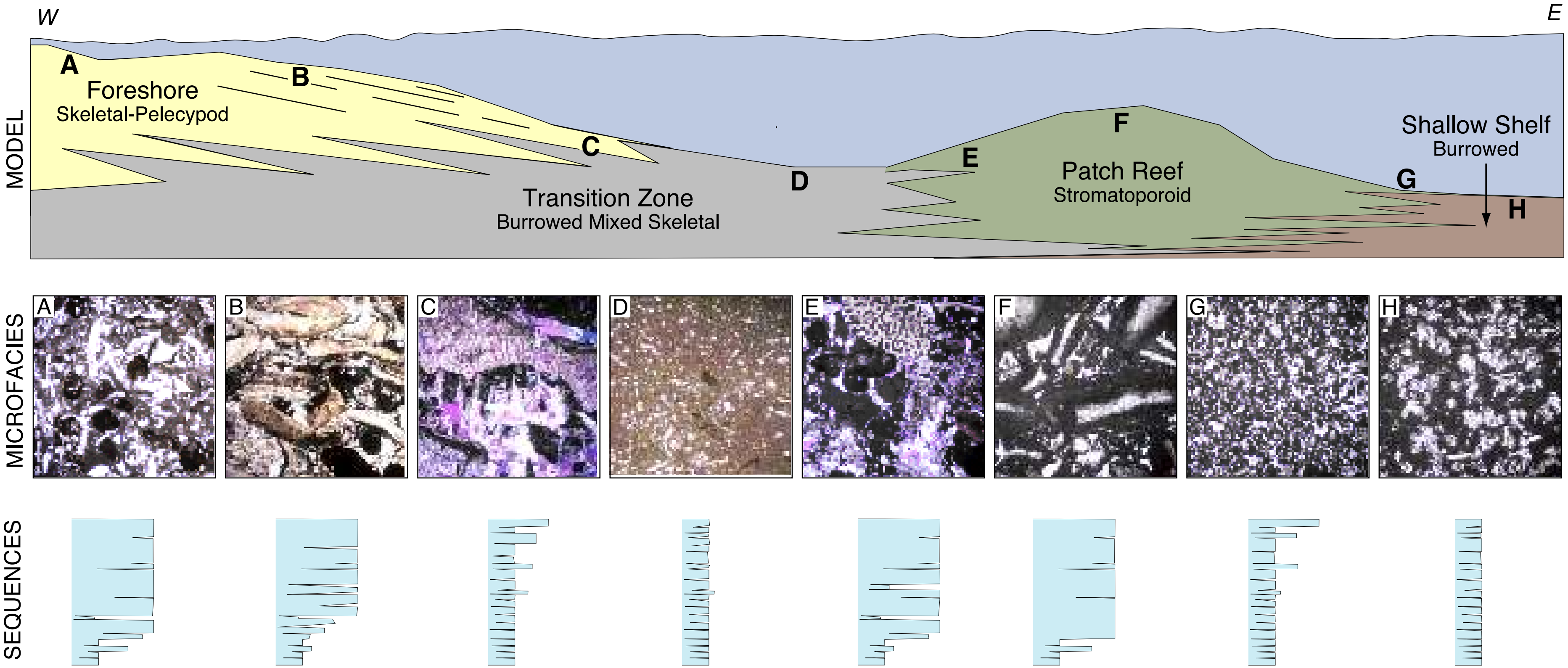


Figure 9: Transect through submarine portion of skeletal-stromatoporoid ramp complex showing facies distribution along depositional dip for one shallowing upward cycle in strata equivalent to the Arab-D reservoir. Note in vertical sequences that stratified mud-dominated carbonates (D) replace the shallow ramp near shore complex as it wedges out basinward. Massive stromatoporoid beds occur within the basinal muddy sequence. Photomicrograph F shows the oncolitic grainstone matrix of stromatoporoid beds. Photomicrographs C and D were taken with polarized light and gypsum plate, all others were taken with plane polarized light. Depositional model is schematic reconstruction only for the skeletal-stromatoporoid ramp and therefore drawn without a horizontal or vertical scale.

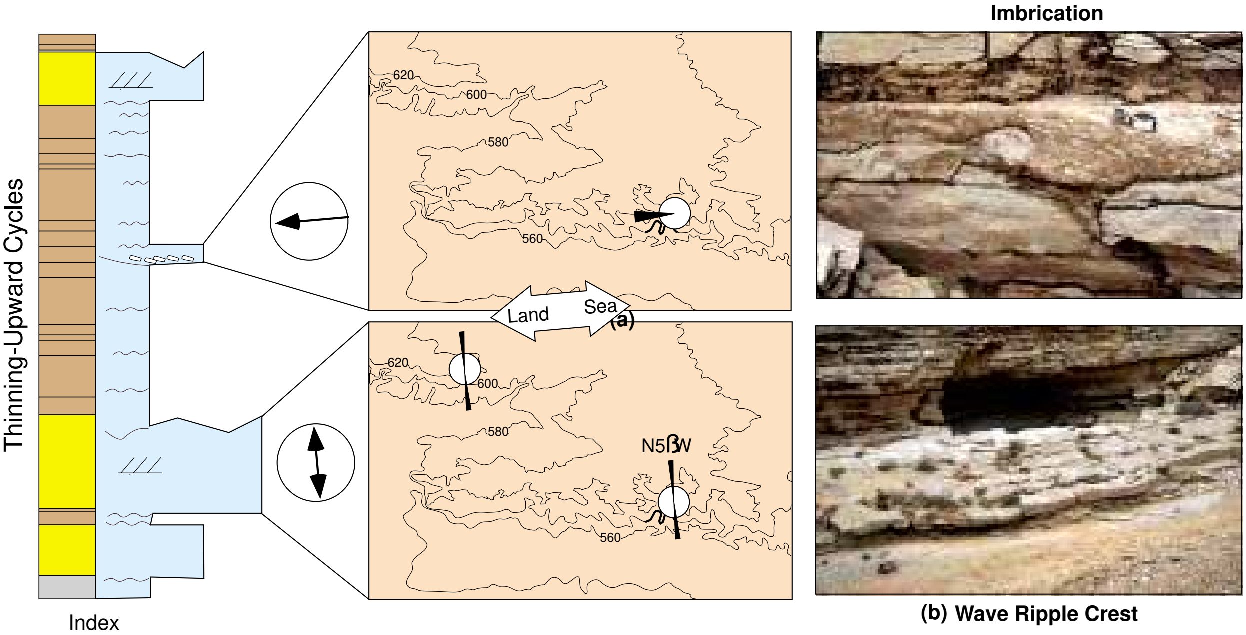


Figure 10: Orientation diagram of sand waves and imbricated flat-pebble conglomerates. (a) Imbricated flat-pebble conglomerates. These dip to the east and suggest a unimodal current direction toward the west. (b) Symmetrically developed sand waves typically have wavelenghts of 80 cm with heights of 5 to 7 cm. At two localities the sand wave crests were consistently oriented N5°W.

(5) Individual beds of the Skeletal-Pelecypod lithofacies show minor thickness increases in a seaward direction between the two measured sections.

(6) The stromatoporoid lithofacies forms organic buildups whose lateral thickness changes up to 10 feet over distances of a few hundred meters. Comparison between sections shows the stromatoporoid lithofacies progressively increases in thickness in a seaward direction.

(7) Strike directions of carbonate sand ripples suggest the shoreline trended N5°W at this location.

(8) Flat-pebble conglomerates have eastward dipping imbrications that are perpendicular to the strike of sand ripples. This suggests the Arab-D shoreline was to the West.

(9) Some grain-supported intervals within the thinning-upward cycles pinch out over the paleotopographic high of the underlying stromatoporoid bank.

OUTCROP-SUBSURFACE COMPARISON

Lithostratigraphy

Significant similarities and differences occur between the outcropping strata that is equivalent to the subsurface Arab-D reservoir section. In general, outcrops display sections lithostratigraphically equivalent to all of reservoir Zones 1 and 2 and uppermost part of Zone 3A (Figure 11). Specific stratigraphic similarities between outcrop and reservoir include:

(a) shared lithofacies types include: stromatoporoid, burrowed, burrowed mixed skeletal peloidal, and laminated,
(b) stromatoporoid and burrowed lithofacies successions are comparable to those found in reservoir Zone 2B,
(c) overall upward textural trend from muddy to grainy and back to muddy, and
(d) dolomite horizon occurs in a position similar to that of the layer 12 dolomite at the top of reservoir Zone 3A, i.e. near the base of the stromatoporoid unit.

Stratigraphic differences observed between outcrop and reservoir include:

(a) interval thickness between stromatoporoid lithofacies and the anhydrite is only half that of subsurface
(b) greatly expanded thickness of platy lithofacies in the outcrop,
(c) outcrop lithofacies changes include: absence of *Cladocoropsis*, fragmented *Cladocoropsis*, mixed skeletal peloidal, and oolitic lithofacies; presence of skeletal-pelecypod lithofacies.

We collected and drilled core plugs in 27 large samples to determine if the lithofacies retained any distinguishing petrophysical characteristics. Figure 11 shows porosity and permeability plots for measurements made on twenty seven outcrop samples. Low petrophysical values characterize all lithofacies (Table 1). These measurements together with thin-section analysis confirm our outcrop observation and support conclusions drawn by Sharief et al. (1991) in his investigation on the diagenesis of the Arab Formation. Namely, extensive blocky calcite cementation which effectively plugged porosity (Figure 9).

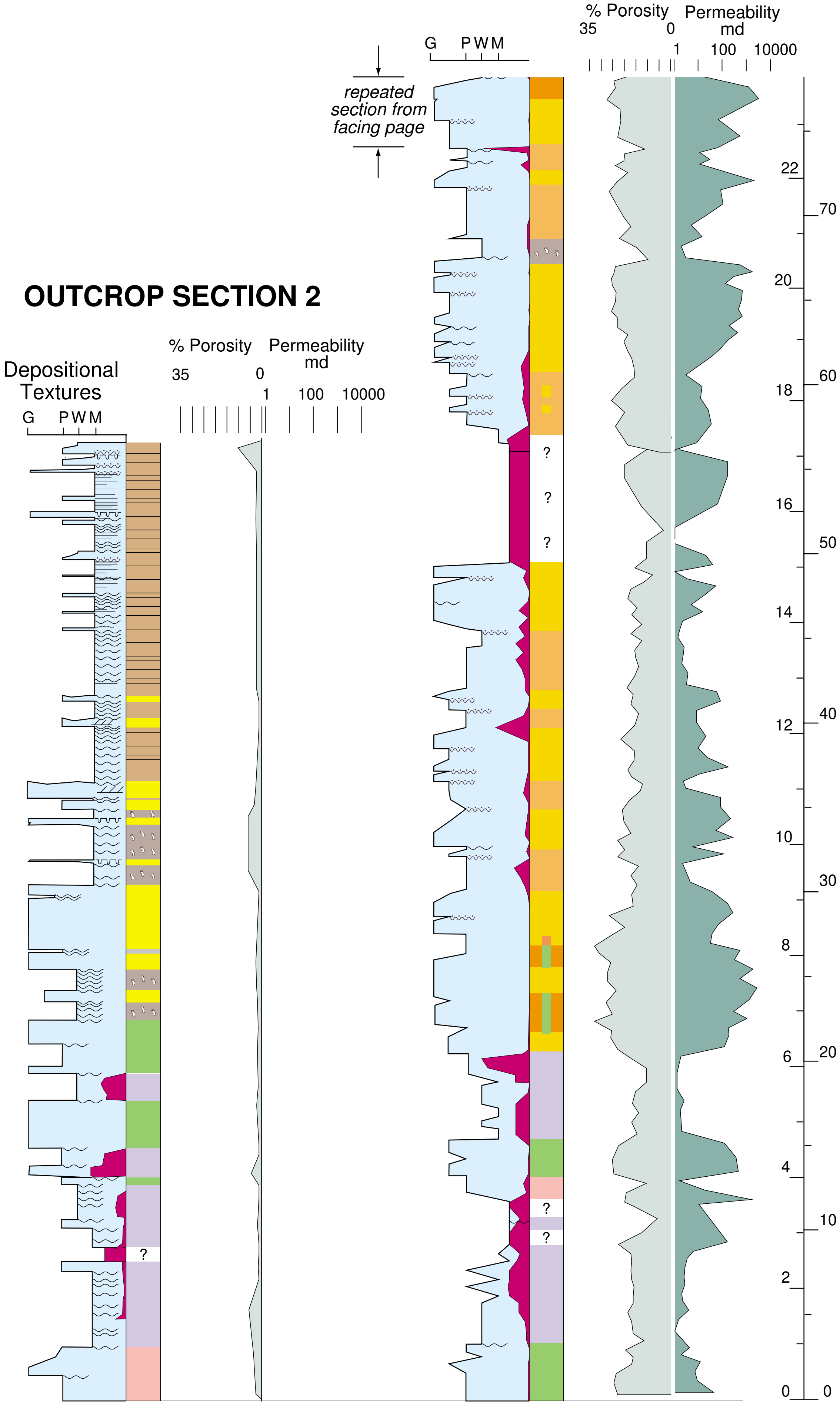
Table 1
Porosity and Permeability Measurements on Core Plugs

Sample #	Lithofacies Porosity	%Perm.	md
AD-1-WN	SP	1.3	0
AD-2-WN	SP	4.7	0
AD-3-WN	SP	1.9	0
AD-4-WN	BMS	4.6	NT
AD-5-WN	BMS	4.6	0
AD-7-WN	SP	1.5	0
AD-8-WN	BMS	1	0
AD-9-WN	SP	0.7	0.1
AD-10-WN	S	0.4	0
AD-11-WN	S	0.6	0
AD-12-WN	B	0.3	NT
AD-13-WN	S	1	0
AD-17-WN	B	3.3	0
AD-19-WN	B	0.3	0
AD-20-WN	S	0.6	0
AD-23-WN	S	0.3	0
AD-25-WN	B	4.2	0.1
AD-26-WN	MS	2.2	0
AD-27-WN	MS	1.3	3.9
AD-30-WN	PM	1	0
AD-31-WN	PM	1	NT
AD-32-WN	PM	1.3	0.3
AD-33-WN	PM	0.9	NT
AD-34-WN	PM	8.9	NT
AD-35A-WN	PM	0.7	NT
AD-35B-WN	PM	0.1	0.1
AD-38-WN	PM	0.6	0.1

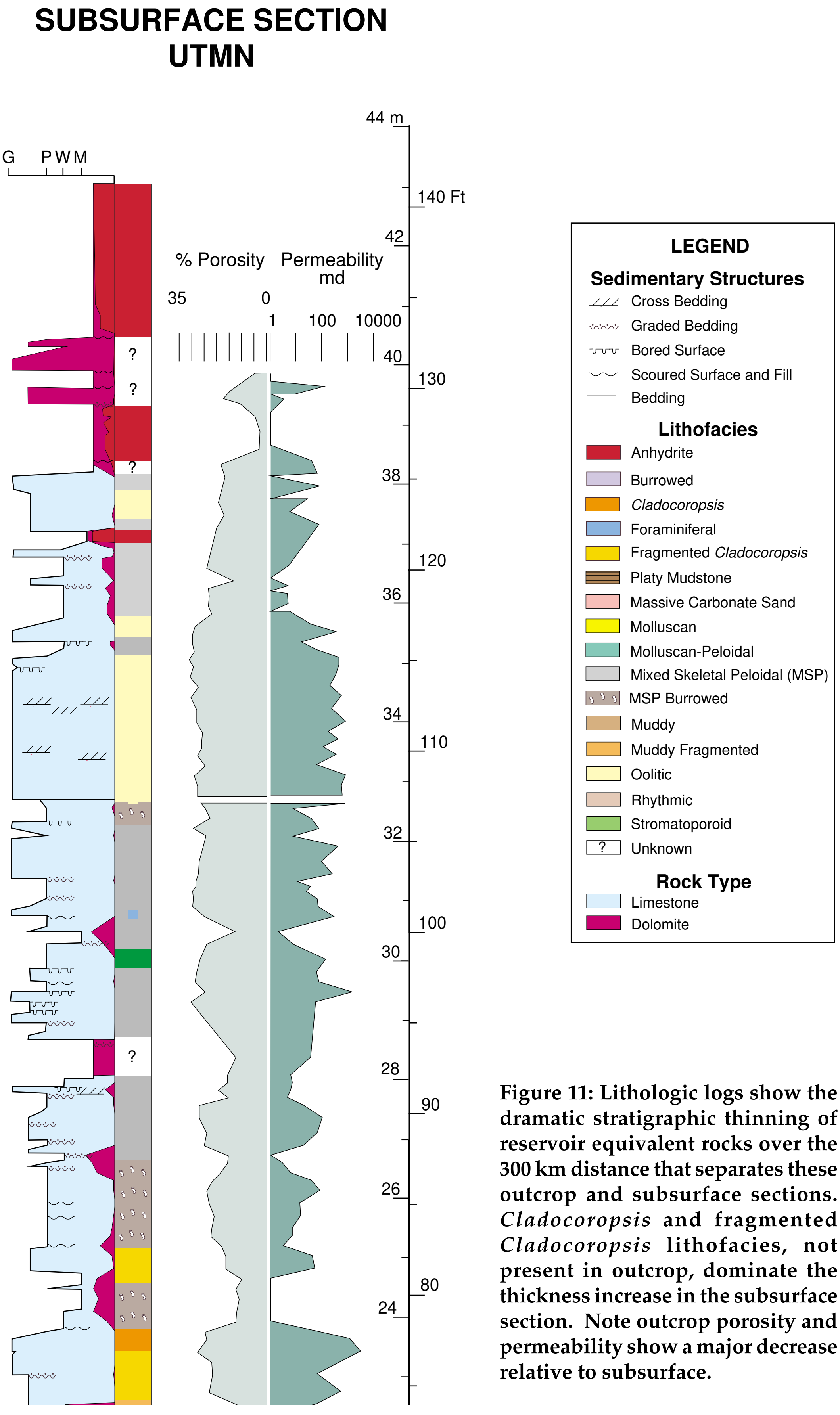
Note: Plugs were drilled from outcrop samples. Lithofacies MS=massive sand, B=burrowed, S=stromatoporoid, BMS=burrowed mixed skeletal, SP=skeletal pelecypod, PM=platy mudstone

OUTCROP IMPLICATIONS FOR SUBSURFACE ANALYSIS

The physical characterization and correlation of outcropping lithofacies and cycles have implications for interwell subsurface correlation. They include:



OUTCROP SECTION 2



(continued from facing page)

Figure 11: Lithologic logs show the dramatic stratigraphic thinning of reservoir equivalent rocks over the 300 km distance that separates these outcrop and subsurface sections. *Cladocoropsis* and fragmented *Cladocoropsis* lithofacies, not present in outcrop, dominate the thickness increase in the subsurface section. Note outcrop porosity and permeability show a major decrease relative to subsurface.

(1) Stratigraphic cycles form envelopes for distributing lithofacies in three dimensions.
(2) The lateral pinchout of thinly bedded carbonate sand beds in thinning-upward cycles over topographic highs implies poor effective horizontal permeability at a reservoir simulation scale.
(3) Horizontal stylolites and abrupt vertical changes from mud- to grain-dominated lithofacies indicate low vertical permeability and corresponding high horizontal to vertical matrix permeability ratios.
(4) Petrophysical studies on outcrops equivalent to the Arab-D reservoir provide no direct useful results for subsurface reservoirs because pervasive meteoric diagenesis gives all lithofacies very similar petrophysical properties.
(5) Lateral discontinuities in lithofacies distribution within stromatoporoid and skeletal bank units, provide valuable information regarding their geometry and anisotropy for reservoir characterization studies on lithofacies equivalents.

CONCLUSIONS

This study demonstrates that: (1) nineteen upward-shoaling depositional cycles, represented as a stacked succession of three different cycle types, characterize the reservoir equivalent outcrop sections; (2) vertical lithofacies or bedding motifs identify the stromatoporoid cycle, skeletal cycle, and thinning-upward cycle as three basic types; (3) six lithofacies (platy mudstone, skeletal-pelecypod, burrowed mixed skeletal, stromatoporoid, burrowed, massive carbonate sand) make-up the cyclic vertical successions in outcrop; (4) directions of carbonate sand ripples suggest a N5°W paleoshoreline trend whereas eastward dipping imbrications of flat-pebble conglomerates suggests the Arab-D shoreline was to the West at the Wadi Nisah study area; (5) stromatoporoid and skeletal-pelecypod lithofacies progressively increases in thickness in a seaward direction; (6) lateral thickness changes reach up to 10 feet over distances of a few hundred meters in the stromatoporoid banks; (7) local stratigraphic pinchouts occur over the paleotopographic high of an underlying stromatoporoid bank; (8) these outcrop sequences are lithostratigraphically equivalent to Arab-D reservoir Zones 1 and 2 and the uppermost part of 3A; (9) outcrop sections have similar gross textural trends and lithofacies as those observed in the subsurface; and (10) the lithostratigraphy of outcrops differ in that the section extending downward from the top of the Arab-D carbonates to the stromatoporoid horizon is only half as thick, lacks *Cladocoropsis*, fragmented Cladocoropsis, mixed-skeletal-peloidal, and oolitic lithofacies, and has a greatly expanded platy mudstone lithofacies interval.

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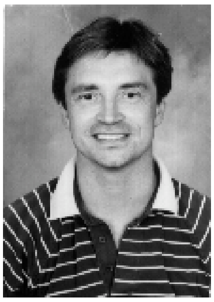

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