Essay: applied cyclo-stratigraphy for the Middle East E&P industry

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Summary

The modeling of ordered sedimentary cycles through orbital forcing (cyclo-stratigraphy) could impact the Middle East E&P industry practices from regional exploration to reservoir engineering. The correlation of longer period cycles could detect thinning or disappearing reservoir intervals over structures. These terminations may be due to erosion or non-deposition, and used to guide exploration for stratigraphic traps. The correlation of shorter period cycles may be used to map the disappearance or diagenetic alteration of reservoir flow units between wells. The Permian and Mesozoic carbonates and evaporites that constitute the main Middle East hydrocarbon reservoirs and seals, manifest cycles at many scales, and are particularly suited for cyclo-stratigraphic analysis.

Introduction

Since the mid-19th century, stratigraphers have debated over the origin and predictability of sedimentary cycles—first in academia and then in the industry. GeoArabia inaugurated the 21st century with the publication of the first sequence stratigraphic framework of the Arabian Plate (Sharland et al., 2001), and an orbital forcing, computational model to match it (Matthews and Frohlich, 2002). These two studies focused on third-order cycles that generally were deposited in a few million years (my). These cycles are typically about 50–100 m thick, and generally attributed to orbital forcing and glacio-eustasy.

In the Middle East, the boundaries of third-order cycles are commonly observed on seismic lines. Quite often, however, geologists and engineers observe much thinner sedimentary cycles and reservoir flow units. These can range in thickness from millimeters to several centimeters; but more commonly several tens of centimeters to tens of meters. This essay suggests that these higher-order cycles are probably also caused by orbital forcing and associated climatic changes. By analyzing this orbital beat, the Middle East industry may gain completely new E&P insights.

For readers who are not familiar with the subject matter, pages 740–743 give a useful introduction to the fundamental aspects of cyclo-stratigraphy, as well as the causes of periodic and non-periodic sedimentary cycles.

Hanifa sedimentary cycles: a typical outcrop example

The best place to start is usually in the outcrop where the rocks can be studied in detail. Near Riyadh, the Jurassic Hanifa Formation shows typical depositional cyclicity (Figures 1 and 2). This Formation is fairly uniform in thickness (115–128 m) and divided into two shallowing-upward depositional sequences that correspond to the Hawtah and Ulayyah members (Figure 1a). The age of the Formation is interpreted as Oxfordian–early Kimmeridgian (Vaslet at al., 1991), and so its deposition spanned about 3–6 my. The members are similar in thickness, and so each was probably deposited in about 1.5–3 my. These two cycles are likely to be third-order depositional sequences that are predicted to have a period of 2.0–2.8 my (Matthews and Frohlich, 2002).

Upon closer examination (Figure 1a–c), five higher frequency cycles—each some 10 to 20 m thick—can be seen within the lower Hawtah Member. Carbonate beds, up to a few meters thick, cap each of these thinner, shallowing-upward cycles. Further magnification (Figure 1c) reveals interbedded, claystone-carbonate sedimentary cycles—each only about 30 cm thick. These cycles probably reflect...
Hanifa Stratigraphy and Stacking of Depositional Cycles in Outcrop

a) Stratigraphy

Figure 1a: Stratigraphic sketch of the Hanifa Formation showing the Hawtah and Ulayyah members (modified after Vaslet et al., 1991). Each member might represent a third-order depositional cycle.

b) 10-20 m Shallowing-upward Cycles

Figure 1b: Hanifa outcrop. Higher-order shallowing-upward cycles in the Hanifa Formation are expressed as morphological ledges in outcrop. Each of these cycles was deposited in 300,000–600,000 years (location: south of Wadi Nisah, Saudi Arabia, 24°13′N, 46°41′E).

c) 2 m Bedding Bundles

Figure 1c: Overview of a higher-order shallowing-upward cycle in the Hawtah Member. Every 2 m cyclic modulations (bedding bundles) are manifested in this shallowing-upward cycle. Over this interval, the alternating claystone and carbonate beds change their relative thickness. These modulations could reflect time intervals of 75,000–300,000 years. (location: about 50 km WNW of Riyadh along the road from Al Uyaynah to Sadus).

d) 30 cm Claystone-Carbonate Cycles

Figure 1d: Well-developed 30-cm-sized cycles in the Hawtah Member. The cyclicity is expressed as alternating layers of clay and carbonate. Each cycle is estimated to be deposited in a time interval of about 7,500 to 20,000 years.
alternating climatic conditions. These thin cycles modulate into bedding bundles about 2 m thick (seen as variations in relative thickness of the layers in Figure 1c). A back-of-the-envelope-calculation summarized in Table 1, shows that the Hanifa cycles and orbital forcing periods are comparable (Matthews and Frohlich, 2002). This is very encouraging as it suggests that with detailed orbital forcing modeling a match may be possible.

Hanifa reservoir flow units in Berri field

Some 400 km northeast of Riyadh, the giant Berri field produces oil from the Hanifa reservoir. Here the Hanifa Formation is about 235 m thick (nearly double the Riyadh outcrop thickness). The reservoir is developed in the upper 150 m of the Formation, and also consists of many sedimentary cycles (Figure 2; modified after McGuire et al., 1993).

Based on 32 cores and 142 logs, McGuire et al. (1993) interpreted a sequence stratigraphic model for this reservoir. They concluded that compared to lithostratigraphy, sequence stratigraphy is a superior tool in characterizing reservoir flow units. For example, they showed that the water flood can be restricted below well-cemented sequence boundaries thereby leaving bypassed oil in the overlying layers. In earlier lithostratigraphic reservoir characterization models these sequence boundaries were not interpreted as bounding reservoir zones.

McGuire et al. (1993) interpreted about 30–40 sedimentary cycles (their so-called fifth-order parasequences) in the Hanifa reservoir. Some of these cycles do not extend beyond the field (Figure 2a), whereas others form a thick ramp-margin wedge to the south. On average these sedimentary cycles are about 4–5 m thick. This average cycle thickness, extrapolated for the entire 235-m-thick Hanifa Formation, implies about 50–60 sedimentary cycles were deposited in 3–6 my. Once again, a quick calculation indicates that each of these sedimentary cycles was deposited in about 50–120 ky.

Hanifa cycles are not layer cake

As shown by McGuire et al. (1993), most of the Hanifa cycles in Berri field do not persist for more than some 10–20 km (Figure 2). They generally either downlap, onlap, or are truncated. They also interpreted a package of cycles that converged together as a ramp-margin wedge.

It seems likely that orbital forcing drove the Hanifa cycles in both Berri field and the Riyadh outcrops. These two far apart locations occupied different Late Jurassic paleoenvironments. The Hanifa in Berri field carries the overprint caused by paleogeography and topography at the ramp edge (Figure 2b), while the Riyadh Hanifa outcrop was part of an earlier broad interior platform. This indicates that cyclo-stratigraphic modeling software must match the data in space and time.

| Cycle | Lithostrat unit | Periodity | Sequence stratigraphy | Orbital forcing (Matthews and Frohlich, 2002) |
|-------|----------------|-----------|-----------------------|-----------------------------------------------|
| 2 cycles each 60 m | Hawtah and Ulayyah members | 1.5–3.0 my | 3rd order | 2.0–2.8 my |
| 5 cycles each 10–15 m | Hawtah member units | 300–600 ky | Higher order | Eccentricity 100–400 ky |
| 5–10 cycles each 2 m | Hawtah member subunits | 75–300 ky | Higher order | Tilt 40–54 ky |
| 10–15 cycles each 0.30 m | Hanifa member beds | 7.5–20 ky | Higher order | Precession 19–23 ky |
Figure 2a: N-S cross-section of the Hanifa Formation through Berri field in northern Saudi Arabia (modified after McGuire et al., 1993). McGuire et al. (1993) illustrate the difference between lithostratigraphic (blue line overlay) and sequences stratigraphic interpretation of the Hanifa reservoir. Their model had direct impact on the Berri field producing strategy through a better definition of flow units and the recovery of by-passed oil.

Figure 2b: Paleogeographic map of central and north-eastern Saudi Arabia at the end of the Oxfordian showing the Arabian Basin and Rimthan Arch (modified after McGuire et al., 1993). The Hanifa outcrops around Riyadh represent a more basinal setting, whereas the Hanifa Formation in Berri field was deposited on the southern flank of the Rimthan Arch.
Are the Hanifa cycles typical?

The well-preserved cyclicity of the Hanifa Formation is shared by most Middle East reservoirs (i.e. Permian-Triassic Khuff, Jurassic and Cretaceous reservoirs). In general, three factors that are related to the paleodepositional environment favor cyclo-stratigraphic analysis (Figure 3):

- continuous and prolonged uninterrupted marine sedimentation;
- uniform and comparable subsidence and sedimentation rates;
- high preservation potential with minimal reworking or erosion of sediments.

Most of the carbonate reservoirs of the Arabian Plate meet these ideal settings for the preservation of orbital forcing related cyclicity. The Plate occupied equatorial and low paleolatitudes during the Late Permian and Mesozoic that favored carbonate deposition. This resulted in long periods of uninterrupted deposition in shallow marine settings. As a broad continental shelf, the Plate subsided gently resulting in sufficient open space to accommodate most sedimentary input rates.

As seen for the Hanifa Formation, the depositional system persisted for long periods with only minor reworking near sequence boundaries. Moreover, the Permian–Mesozoic reservoirs crop out in extensive NS belts in central Saudi Arabia. In addition to the thousands of well bores with logging data, these belts offer a natural laboratory for quantifying the sedimentary cycles of the Arabian Platform.

![Depositional Continuity and Preservation Potential](image)

**Figure 3:** Continued deposition over a long period of time is the first requirement for observing cycles with different periodicities. The other requirement is geological preservation potential. On broad continental shelves and in the deep oceans, the rock record (shown as a core) will generally contain a complete record of the cyclicity. In continental and marginal marine positions, erosion, non-deposition and reworking of the sediment may record only a brief segment of the cyclic record. The Permian-Triassic Khuff and Mesozoic reservoirs of the Arabian Plate were mostly deposited on a continental shelf with a tropical climate and are therefore ideally situated to register the orbital beat. The predominantly continental Paleozoic formations, however, are not likely to serve this purpose.
Does cyclo-stratigraphy apply to the Paleozoic of the Arabian Plate?

Most Middle East Paleozoic reservoirs are continental clastics and represent highly discontinuous and intermittent deposition (Figure 3). Continental sedimentation is primarily driven by forces within the depositional environment, rather than external forces such as orbital forcing. The Middle East’s Paleozoic clastics are therefore unlikely candidates for catching the orbital beat.

Another factor that disfavors the modeling of the Paleozoic clastics is the high southern latitudes occupied by the Arabian Plate at that time. In particular, the effects of the two Paleozoic glaciations profoundly obscured the cyclostratigraphic signature in many regions of the Plate. The first glaciation was in the Late Ordovician–Early Silurian and affected most of the western Arabian Plate. The second occurred in the Late Carboniferous–Early Permian and reworked the sediments of southern Arabia. Sediments deposited shortly before and during these glaciations were affected by the repeated erosion and reworking caused by the advances and retreats of the ice sheets. Sedimentation is also controlled by glacial loading effects. Therefore sediments deposited adjacent to continental ice sheets and shortly after their retreat will not reflect absolute sea-level changes but rather relative local sea-level variations (see p.742–743).

What is the next step?

Scientific advances are usually produced by the interaction of empirical observations and theoretical models. This essay proposes that the Middle East should adopt the same strategy. Some geoscientists and engineers should continue to refine the empirical sequence stratigraphic framework of the Arabian Plate proposed by Sharland et al. (2001). At the same time, others should consider a systematic orbital forcing approach to model the observed framework (e.g. Matthews and Frohlich, 2002). By modeling and calibrating the higher period cycles (up to the 20 ky), the analysis could reveal stratigraphic traps and reservoir flow units. The following approach may prove to be a good start:

• Systematically focus on cyclicity in outcrop and boreholes in continuous Upper Permian and Mesozoic sections across the Arabian Plate.
• Establish criteria to identify cycles by using: (1) rock-based, such as lithology, thickness, chemical composition, mineralogy, etc.; (2) log-based, such as spectral gamma ray, high-resolution density, isotope, etc.; (3) biological-based, such as fossil content, diversity, size, etc.; and (4) high resolution seismic-based, such as unconformities, onlaps, etc.
• Apply probabilistic and statistical techniques (e.g. Markov, Fourier or similar analysis) to determine soundness of cyclic events. Look for the fundamental Milankovitch frequencies (19–23 ky, 40–54 ky, 100–400 ky, 2.0–2.8 my; Matthews and Frohlich, 2002).
• Identify potential time marker beds for the Arabian Plate. Date and correlate marker beds in absolute time. Date cyclic deposits above and below time marker beds.
• Integrate and combine the above with other dating methods (e.g. chemostratigraphy and magnetic reversals)

The systematic collection of cyclo-stratigraphic data could quickly enrich the empirical framework. This would provide the mathematicians and statisticians with a space-time data volume to model using orbital forcing. During this R&D program, it could be assumed that the regular orbital forces play the central role. However, other causes (chaotic, autocyclic, tectonic, etc.) need to be kept in mind. Some of these factors are explained on pages 741–743. Unmatched local signals could be attributed to local basins, and missing signals to local highs and growth. These may be welcome anomalies as they may clarify reservoir heterogeneities, or even establish stratigraphic traps.

Not all cycles are orbital - Allocycles vs Autocycles

Allocyclic sequences are caused by periodic forces representing regular time intervals that originate outside (allo in Latin) the geological environment, such as orbital forces.

Autocyclic sequences are governed by changes within (auto in Latin) the geological environment. For example, the lateral migration of a river channel may cause stacked and therefore cyclic-appearing channel sequences. These represent, more or less, random sedimentary events that do not occur at regular time intervals and are not caused by orbital forcing.
Tidal Laminae and Tidal Bundles: Short Sedimentary Cycles

The shortest sedimentary cycles are caused by the tides. Tides result from the orbital force of gravity between the Earth and Moon. Under favorable conditions the reoccurring 12-hourly tides as well as the fortnightly (2 weeks) neap and spring tides leave an imprint in the sedimentary record, like cross-laminae and tidal bundles. The photo on the right shows unconsolidated early 20th Century subtidal deposits in the Oosterschelde, Netherlands. Each centimeter- to decimeter-thick, silty and sandy cross-lamina was deposited in about six hours by the strong tidal ebb current. The thin clay layers represent the intervals of little or no water movement between the ebb and flood currents (about 15 to 60 minutes). During the weaker flood currents, covering a period of about six hours, small sand ripples climb upon the ebb foresets, resulting in millimeter thick, less continuous sandy layers in between two clay drapes. A neap-spring tidal bundle occurs every 14 days when tidal floods peak. They are reflected by the cyclical thinning and thickening of the cross-lamina.

Varves: Yearly Sedimentary Cycles

Sedimentary cycles are also deposited every year. The photo shows an example of Pleistocene lacustrine deposits (Yellowknife, Canada). The lighter part of each layer reflects the warm season, in which melt water of a glacier transports rock-flour into the lake. The darker layer was created in the colder season when the lake was probably covered by seasonal ice and no melt-water flowed into it. During this time the smaller clay particles settled out of suspension to the lake bottom. Seasonal variations e.g. influence organism growth in the sea. Millimeter-thick laminations, possibly related to seasonal weather changes, exist in the infra-Cambrian reservoirs of Oman (e.g. Athel Silicilites).
Cyclo-stratigraphy at a Glance

Orbital forcing produces periodic climatic changes that affect the environment of continents and oceans. These changes are interrelated and sometimes recorded as sedimentary cycles. For example, temperature and rainfall control vegetation cover on land, which in turn controls weathering and erosion. The vast majority of sedimentary cycles are preserved in marine deposits even when the main climatic effect was continental. For example, ice sheet build-ups and meltdowns that affect sea level are continental.

Periodic and Non-periodic Events

Besides orbital forcing, other phenomenon can affect climate and sea level. Non-periodic events, such as large meteorite impacts and major volcanism, can inject massive amounts of sulfur and dust into the stratosphere resulting in a drop of global temperature by several degrees. Orbital forcing calculations can be calibrated by major chaotic events. This graph shows the average time interval between chaotic events that can impact global climate. These may be short-lived and temporarily disrupt the orbital forcing cyclic signal. Direct evidence for chaotic events may include ash or rare-element concentrations. Indirect evidence may be the extinction or reduction in numbers of certain species. For example, the Cretaceous-Tertiary boundary is defined globally by a meteorite that hit the Earth about 65 million years ago. It formed the 180-km-wide Chicxulub crater in the Gulf of Mexico. The impact was so great that it dispersed Iridium that formed a thin layer globally. Meteorites that create a 10-km-wide crater hit the Earth on average every one to three million years.

For regional correlations across the Arabian Plate are the Habhab crater of Oman (Al-Hinai et al., 1997) and the Jabal Rayah crater in the Tabuk area of Saudi Arabia (Janjou et al.. 1996). In this issue of GeoArabia, Levell et al. describe another possible impact crater in Oman with a diameter of 2.5 km.
Relative and Absolute Sea-Level Change

Orbital forcing induces global sea-level changes that are recorded in the shallow marine and coastal sedimentary rocks as transgressions and regressions. Vertical land movements, however, can attenuate or even reverse global sea level trends in certain locations around the Earth. Some common causes of vertical land movement include tectonic uplift, thermal doming, and thinning or thickening of the continental crust (hot spots, subduction). Differentiating between relative (local) and absolute (global) sea-level changes is a challenge.

For example, when ice sheets advance over continents the global sea level may drop by about 50–100 m. This absolute sea-level change, however, is seen as a completely different relative change in different parts of the world.

Glacial isostacy - Figure a
The weight of an advancing ice sheet pushes down the land beneath it (in some cases over 1,000 m). In front of the advancing ice sheet, a forebulge develops that may be up to 100 m high. After the ice sheet melts, the forebulge collapses and the

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**Mattner and Al-Husseini**

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742
down-warped Earth’s crust rebounds. The land rebounds back to its original position in a period of some 10,000 years (possibly up to 100,000 years).

**Isostatic rebound - Figure b**
The effect of post-glacial rebound and forebulge collapse on relative sea-level change continues in North America today. The influence of the last ice age is still being measured at sea-level stations along the North American Atlantic coast. Local sea-level measurements converge on the present-day global sea-level rise of 2 mm per year in Florida, about 1,200 km away from the former ice-sheet edge (redrawn after Douglas and Peltier, 2002).

**Relative vertical land movement - Figure c**
The present-day glacial isostatic adjustment map is used to calibrate the global sea-level curve. Only the yellow colored regions have less than one millimeter of vertical land movement caused by glacial isostatic adjustment per year.

Surrounding these central figures (a–c) are eight plots of local sea level interpreted from geological indicators and dated by Carbon-14. Each plot shows the reconstruction of relative sea level over the past 21,000 years (redrawn after Douglas and Peltier, 2002). Locations close to present-day and Holocene continental ice sheets, show strong influence of glacial isostasy (Churchill in Canada, and Angermanalven in Sweden). More equatorial regions show little influence of glacial isostasy (Kuwait Bay and Barbados) and therefore closely reflect the absolute global sea-level influence by melting of the Pleistocene ice sheets.
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