GeoArabia, v. 19, no. 1, 2014, p. 163-168
Gulf PetroLink, Bahrain

LETTER TO THE EDITOR

Khuff Sequence Stratigraphy

Thank you for publishing in 2010 to 2013 the series of papers on the chronostratigraphy and sequence stratigraphy of the Khuff Supersequence in the Arabian Plate (Koehrer et al., 2010, 2012; Al-Husseini and Koehrer, 2013; Bendias et al., 2013; Haase and Aigner, 2013; Walz et al., 2013), and the stratigraphic note on the lithostratigraphic position of the top Khuff-equivalent in Al Jabal al-Akhdar (Baud and Richoz, 2013). These papers provide an important framework for geoscientists working on the middle Permian–Lower Triassic stratigraphy in the Middle East and elsewhere.

I have several comments regarding the nomenclature and positions of sequence boundaries that are summarized in the proposed reference section in Al Jabal al-Akhdar (Al-Husseini and Koehrer, 2013) and briefly discussed in the editorial of GeoArabia's v. 18, no. 3 (2013, p. 13).

In regards to nomenclature, I support giving the same name to sequences and their lower sequence boundaries: (1) Khuff Sequence Boundary at the base of the Khuff Supersequence, (2) Sequence Boundary KS4 at the base of Khuff Sequence KS4, and (3) Sudair Sequence Boundary at the base of the Sudair Formation.

Khuff Sequence Boundary

The term "Khuff Sequence Boundary", abbreviated "Khuff SB", is defined in Oman as the Gharif/Khuff formation boundary. It is taken at the base of the lowermost Khuff-equivalent carbonates in Al Jabal al-Akhdar, corresponding to the boundary between the lower and upper Saiq members or the top of the Saiq Basal Clastics. The boundary between deposits assigned to the Khuff Formation (carbonates) and the Unayzah Formation (siliciclastics) is considered diachronous throughout Saudi Arabia. The lower part of Khuff Sequence KS6 carbonates of offshore Saudi Arabia and the UAE are interpreted by Strohmenger et al. (2002) to be time equivalent to so-called Khuff Clastics and/or Upper Unayzah siliciclastics (Unayzah-A reservoir) of onshore Saudi Arabia, with the Khuff Sequence Boundary cross-cutting lithologic boundaries.

Sequence Boundary KS4

The term "Sequence Boundary KS4", abbreviated as "SB KS4", separates Khuff sequences KS5 from overlying KS4. This boundary is taken in Al-Husseini and Koehrer (2013) at the top of a regionally correlative anhydrite marker bed known as the "Khuff-D Anhydrite" in Saudi Arabia, "Khuff Middle Anhydrite" or "Khuff Median Anhydrite" in Oman, UAE, etc. I fully agree that there is a major exposure surface (sequence boundary) at the top of the Median Anhydrite or slightly above the lithological anhydrite/carbonate boundary.

An alternative position for SB KS4 might be at the base of the Khuff Median Anhydrite. The reason for this position is based on relative sea level. The Median Anhydrite is dominated by subaqueous (shallow subtidal) anhydrite-after-gypsum. It therefore was deposited in slightly deeper marine conditions compared to the underlying upper KS5 carbonates that were deposited in an intertidal setting. I therefore interpret the Median Anhydrite as an early transgressive deposit/sequence. It would be useful to know, what occurs in the slope and basinal environments during the KS4 lowstand.

Sudair Sequence Boundary

The term "Sudair Sequence Boundary", abbreviated as "Sudair SB", is correlated to the Khuff/Sudair formation boundary in the Arabian Plate. With the terrestrially influenced Sudair prograding over the Khuff carbonate platform from west to east, the top Khuff is expected to be highly time transgressive, and therefore not easy to pick (especially in the east).

Christian Strohmenger
christian.j.strohmenger@exxonmobil.com

REPLY

Thank you for your appreciation of the series of papers dealing with the Khuff sequences that appeared in GeoArabia 2010–2013. Your letter raises several important issues that require further clarifications.

Adopting common nomenclature and precise definitions for sequences and their associated surfaces is an important first step that should apply to boundaries, maximum flooding surfaces, orders, etc. The proposed reference section of the Khuff Supersequence at outcrop in Al Jabal al-Akhdar may not necessarily apply throughout the Middle East. In this outcrop Al-Husseini and Koehrer (2013) interpret four "third-order" transgressive-regressive sequences, from base-up: KS6, KS5, KS4 and combined KS3-KS1. This differs from the interpretation of some other authors that interpret seven Khuff sequences in the UAE and Musandam Peninsula (e.g. Strohmenger et al., 2000). Ultimately a regional correlation based on chronostratigraphic data is required.

Regarding the three issues raised by Strohmenger.

Khuff Sequence Boundary

In Al Jabal al-Akhdar, in Al-Husseini and Koehrer (2013), we pick the Khuff SB as the surface that separates the oldest marine deposits of KS6 from the underlying terrestrial siliciclastics (Basal Saiq Clastics). We interpret this surface to pass to the correlative Sub-Khuff Unconformity (pre-Khuff unconformity), which in Central Saudi Arabia separates the mixed clastics and carbonates of the Ash Shiqqah Member of the Khuff Formation from the Unayzah Formation (Vaslet et al., 2005). In subsurface Saudi Arabia, it separates the Basal Khuff Clastics (BKC) or Khuff E member from the underlying Unayzah Formation (Al-Jallal, 1995).

The Sub-Khuff Unconformity in Central Saudi Arabia is interpreted as a stratigraphic gap corresponding to a hiatus that spans ?late Roadian–Wordian (Stephenson et al., 2003; Vaslet et al., 2005). In the Huqf outcrop in Oman it passes to a sequence boundary that separates the Wordian Khuff Formation from the underlying fluvial-estuarine Gharif Formation (Osterloff et al., 2004). Again, a regional correlation from Oman to Central Saudi Arabia would help address this issue.

Sequence Boundary KS4

Insalaco et al. (2006) pick SB KS4 at the top of the Nar Member of the Dalan Formation in Iran, and describe it as "a strong exposure (with pedogenetic features) and subsequent erosive surface with clasts of eroded evaporites present within the subsequent transgressive lags". They add that the Nar Member represents deposition "in sabkhas, shallow coastal salinas and hypersaline lagoons, with occasional floodings resulting in carbonate deposition. There is also an overall evolution from hypersaline lagoons to coastal salina and finally sabkhas and sabkharised salinas. The Nar Member in this region represents a semi-enclosed saline depression prior to the deposition of the Upper Khuff."

The exposure of the top of the Nar Member represents the lowest relative sea level in the Dalan Formation and ends a sequence of up to 250 m of anhydrite and dolomite cycles in central Fars in Iran (Esrafili-Dizaji and Rahimpour-Bonap, 2003). Indeed the Fars Member may represent Khuff Sequence KS5 in its entirety. The top of the Nar Member is correlated to the tops of the Khuff D Anhydrite in Saudi Arabia and Khuff Median Anhydrite in Oman (Al-Jallal, 1995; Sharland et al., 2001; Konert et al., 2001).

The correlation of Khuff Sequence KS5 in Al Jabal al-Akhdar in Koehrer et al. (2010, 2012) to the Nar Member in Iran is also based on biostratigraphic control in KS5 (e.g. *Shanita amosi*). The correlations between outcrop (Al Jabal al-Akhdar) and subsurface (Yibal Field), published in Walz et al. (2013), allow delineating the LOD of *Shanita amosi* with the interval of the Khuff Median Anhydrite in the subsurface (however, the Median Anhydrite is thin and mainly nodular in subsurface Yibal).

The interpretation of evaporites in terms of sequence stratigraphic position has been a matter of geologic debate for decades. The Khuff example forms no exception and indeed provides different interpretation possibilities. Key to correctly interpret these deposits is the analysis of

the sedimentological nature of the evaporites and their interbedded sediments. Thickly-bedded, aggradational stacks of mainly laminated, often basin-center evaporites (e.g. anhydrite, halite) that are laterally highly extensive are most likely deposited and preserved during the early transgressive systems tract of sequences (e.g. Moore and Wade, 1992; Smith et al., 2004) as they rely on rising sea-level, providing accommodation space, and large volumes of seawater.

In contrast, sabkha/salina-type (mainly nodular) evaporites, which are interbedded with peritidal to shallow subtidal sediments, like the Nar Member and the Khuff Median Anhydrite in subsurface Oman, are commonly deposited during the late highstand system tract of sequences on platform tops (e.g. Elrick and Read, 1991). They are laterally more heterogenous, possibly confined to subtle topographic lows and partly eroded on topographic highs, like the Al Jabal al-Akhdar region in Oman. In these outrops, the Median Anhydrite is not present and the basal part of the KS4 is dominated by massive grainstones, making it diffucult to think of a lateral, early transgressive evaporitic equivalent bearing in the mind the extensive layer-cake type appearance of gross depositional environments within the Khuff Formation.

In our view, a transgressive model for the deposition of Median Anhydrite may not be required to explain its sedimentological nature as well as its lateral heterogeneity across the Middle East region.

Sudair Sequence Boundary

In Central Saudi Arabia, the uppermost Khuff Formation consists of evaporites, including salt, deposited in a salina (Ziegler, 2001). These evaporites were encountered in the SHD-1 borehole *below* the terrestrial shales that define the lowermost part of the Sudair Formation. The SHD-1 evaporites correlate to the uppermost Khuff Formation in subsurface Saudi Arabia (Al-Jallal, 1995). We therefore interpret the deposition of the uppermost Khuff as a highly restricted evaporitic basin, similar to the one associated with the Nar and Khuff Median Anhydrite.

The influx of the Sudair shales on top of the Khuff carbonates and evaporites marks a new depositional regime. It reflects a climatic switch from arid to pluvial conditions. The boundary between the Sudair and Khuff formations can be correlated across Saudi Arabia (Al-Jallal, 1995) and Oman (Osterloff et al., 2004; Koehrer et al., 2010, 2012; Pöppelreiter et al., 2011; Baud and Richoz, 2013) to southwest Iran, where it passes to the boundary between the carbonates of the Kangan Formation and overlying shales of the Aghar Member of the Dashtak Formation (Insalaco et al., 2006), reflecting a major, second-order sequence or orbiton boundary (Al-Husseini and Koehrer, 2013).

In summary, we believe that formally naming and defining these sequence boundaries in key reference sections is a first step. The second step is to determine if they can be correlated with confidence at the scale of the Arabian Plate, and eventually at a global scale.

Bastian Koehrer
bastian.koehrer@wintershall.com

Moujahed Al-Husseini
geoarabi@batelco.com.bh

REFERENCES

Al-Husseini, M.I. and B. Koehrer 2013. Chrono- and sequence-stratigraphy of the Mid-Permian to Early Triassic Khuff sequences of the Arabian Plate. GeoArabia, v. 18, no. 3, p. 103-130.

Al-Jallal, I.A. 1995. The Khuff Formation: Its regional reservoir potential in Saudi Arabia and other Gulf countries; depositional and stratigraphic approach. In M.I. Al-Huseini (Ed.), Middle East Petroleum Geosciences Conference, GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 103-119.

Baud, A. and R. Sylvain Richoz 2013. Permian–Triassic Transition and the Saiq/Mahil Boundary in the Oman Mountains: Proposed correction for lithostratigraphic nomenclature. GeoArabia, v. 18, no. 3, p. 87-98.

Bendias, D., B. Koehrer, M. Obermaier and T. Aigner 2013. Mid-Permian Khuff Sequence KS6: Paleorelief-influenced facies and sequence patterns in the Lower Khuff time-equivalent strata, Oman Mountains, Sultanate of Oman. GeoArabia, v. 18, no. 3, p. 135-178.

Elrick, M. and J.F. Read 1991. Cyclic ramp-to-basin carbonate deposits, Lower Mississippian, Wyoming and Montana: A combined field and computer modeling study. Journal of Sedimentary Petrology, v. 61, p. 1194-1224.

Esrafili-Dizaji, B. and H. Rahimpour-Bonap 2013. A review of Permo-Triassic reservoir rocks in the Zagros area, SW Iran: Influence of the Qatar-Fars Arch. Journal of Petroleum Geology, v. 36, no. 3, p. 257-279.

Haase, M.L. and T. Aigner 2013. High-resolution anatomy of a grainstone package in Khuff Sequence KS4, Oman Mountains, Sultanate of Oman. GeoArabia, v. 18, no. 4, p. 17-44.

Insalaco, E., A. Virgone, B. Courme, J. Gaillot, M. Kamali, A. Moallemi, M. Lotfpour and S. Monibi 2006. Upper Dalan Member and Kangan Formation between the Zagros Mountains and offshore Fars, Iran: Depositional system, biostratigraphy and stratigraphic architecture. GeoArabia, v. 11, no. 2, p. 75-176.

Koehrer, B., M. Zeller, T. Aigner, M. Poeppelreiter, P. Milroy, H. Forke and S. Al-Kindi 2010. Facies and stratigraphic framework of a Khuff outcrop equivalent: Saiq and Mahil formations, Al Jabal al-Akhdar, Sultanate of Oman. GeoArabia, v. 15, no. 2, p. 91-156.

Koehrer, B., T. Aigner, H. Forke and M. Pöppelreiter 2012. Middle to Upper Khuff (Sequences KS1 to KS4) outcrop-equivalents in the Oman Mountains: Grainstone architecture on a subregional scale. GeoArabia, v. 17, no. 4, p. 59-104.

Konert, G., A.M. Al-Afifi, S.A. Al-Hajri and H.J. Droste 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate. GeoArabia, v. 6, no. 3, p. 407-442.

Moore, C.H. and W.J. Wade 1992. The role of evaporites in the sequence stratigraphic framework of carbonate platforms (abs.). American Association of Petroleum Geologists Annual Meeting Program, v. 1, p. 90-91.

Osterloff, P., A. Al-Harthy, R. Penney, P. Spaak, G. Williams, F. Al-Zadjali, N. Jones, R. Knox, M.H. Stephenson, G. Oliver and M.I. Al-Husseini 2004. Depositional sequence of the Gharif and Khuff formations, subsurface Interior Oman. In M.I. Al-Husseini (Editor), Carboniferous, Permian and Early Triassic Arabian Stratigraphy. GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, p. 83-147.

Pöppelreiter, M.C., C.J. Schneider, M. Obermaier, H.C. Forke, B. Koehrer and T. Aigner 2011. Seal turns into reservoir: Sudair equivalents in outcrops, Al Jabal al-Akhdar, Sultanate of Oman. GeoArabia, v. 16, no. 1, p. 69-108.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate sequence stratigraphy. GeoArabia Special Publication 2, Gulf PetroLink, Bahrain, 371 p., with 3 charts.

Smith, L.B., G.P. Eberli and M. Sonnenfeld 2004. Sequence-stratigraphic and paleogeographic distribution of reservoir-quality dolomite, Madison Formation, Wyoming and Montana. American Association of Petroleum Geologists Memoir 80, p. 67-92.

Stephenson, M.H., P.L. Osterloff and J. Filatoff 2003. Palynological biozonation of the Permian of Oman and Saudi Arabia: Progress and challenges. GeoArabia, v. 8, no. 3, p. 467-496.

Strohmenger, C.J., R.H.S. Alway, R.W. Broomhall, R.F. Hulstrand, A. Al- Mansoori, A.A. Abdalla and A. Al-Aidarous 2002. Sequence Stratigraphy of the Khuff Formation Comparing Subsurface and Outcrop Data (Arabian Plate, U.A.E.). Paper presented at 10th Abu Dhabi International Petroleum Exhibition and Conference (SPE #78535), 11 p.

Vaslet, D., Y.-M. Le Nindre, D. Vachard, J. Broutin, S. Crasquin-Soleau, M. Berthelin, J. Gaillot, M. Halawani and M.I. Al-Husseini 2005. The Permian-Triassic Khuff Formation of central Saudi Arabia. GeoArabia, v. 10, no. 4, p. 77-134.

Walz, L., T. Aigner and B. Koehrer 2013. Khuff sequence KS5 outcrop equivalents in the Oman Mountains, Sultanate of Oman: Variations to the simple "layer-cake" stratigraphy. GeoArabia, v. 18, no. 4, p. 179-218.

Ziegler, M.A. 2001. Late Permian to Holocene paleofacies evolution of the Arabian Plate and its hydrocarbon occurrences. GeoArabia, v. 6, no. 3, p. 445-504.