PREFACE

GeoArabia Special Publication 3 presents the most complete and detailed Arabian Plate Carboniferous, Permian and Early Triassic stratigraphic analysis to be compiled in recent years. It documents in one publication the characteristic lithologies and chronostratigraphy of key component formations that represent this period of almost one hundred million years.

Why select the Carboniferous, Permian and Early Triassic for this study? Why be concerned about the accuracy of Palaeozoic time correlations when many of the petroleum fields have already been discovered and documented with detailed seismic and well control? The answers to these two questions are equally vital in assessing the future oil and gas exploration opportunities in the Arabian Plate.

In the first instance, the Carboniferous, Permian and Lower Triassic systems of the Middle East contain a substantial concentration of the world's oil and gas reserves. The Permian-Triassic carbonate reservoirs alone are estimated to contain about 15-20% of the world's non-associated gas reserves, which include the Khuff reservoirs in the super-giant North Dome/South Pars and Ghawar fields (Figures 1 and 2). Below the Khuff carbonates, the Carboniferous-Permian Al Khlata, Gharif and Unayzah clastic reservoirs contain billions of barrels of oil, gas and condensate reserves. All these reservoirs range across the southern Arabian Plate, a region of about one million square kilometres, with discovered oil and gas fields in Bahrain, Iran, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. Additional exploration efforts are likely to add more reserves throughout the region.

The answer to the second question: "why chronostratigraphy?" is more complex. Ever since the unanticipated discovery and near blow-out of Khuff gas in the Saudi Arabian Dammam field in 1940, the geological understanding of Palaeozoic reservoirs has been a challenge. On one hand, their localised geometry is the outcome of complex local and regional tectonic events that bear little resemblance to the overlying Mesozoic reservoirs. This complexity has been documented by detailed seismic delineation and development drilling, but remains to be fully exploited as an exploratory tool. Dramatic variations in lateral reservoir development and lithology provide many opportunities for conceptual stratigraphic traps. Because these play concepts are to some extent theoretical, detailed stratigraphic studies are a pre-requisite for evaluating the probability of their actual occurrence.

The Permian-Carboniferous formations consist primarily of glacio-fluvial and eolian clastics that were deposited along the flanks of major palaeostructures. Syn-depositional and post-depositional structural growth and basin development, compounded by erosional processes and post-depositional diagenesis, make these reservoirs a complex geological puzzle to unravel.

In contrast to the Permian-Carboniferous clastics, the Permian-Triassic formations are more laterally continuous and represent a cyclic sequence of carbonates and evaporites deposited in a shallow-marine shelf environment. While the deposition of these facies was controlled by the palaeotopography of platform configuration, their initial reservoir properties also incorporate the imprint of early diagenesis associated with regular intervals of subaerial exposure. Deep burial and additional diagenesis, along with some faulting and fracturing, resulted in further reservoir changes and ultimately created a complex patchwork of high-permeability zones, in close vertical and horizontal juxtaposition to tight zones, within the same oil and gas reservoirs.

Knowing where the well-developed reservoirs may be present in such formations, as well as where they may have radical changes in reservoir properties, is a complex exploration challenge. Furthermore, determining how to correlate and segregate such reservoir zonations, both regionally and across giant oil and gas fields, is virtually impossible without an adequate time-correlative framework. Inevitably, chronostratigraphy is a pre-requisite for the effective exploration and development of such complex reservoirs.

Crucially, while the Carboniferous, Permian and Early Triassic formations represent a period of important reservoir development within the region, their exploitation can only be achieved through the reliable understanding of their chronostratigraphy on a regional basis. This book is the first stage to developing that understanding.

Hydrocarbon fields, Arabian Plate

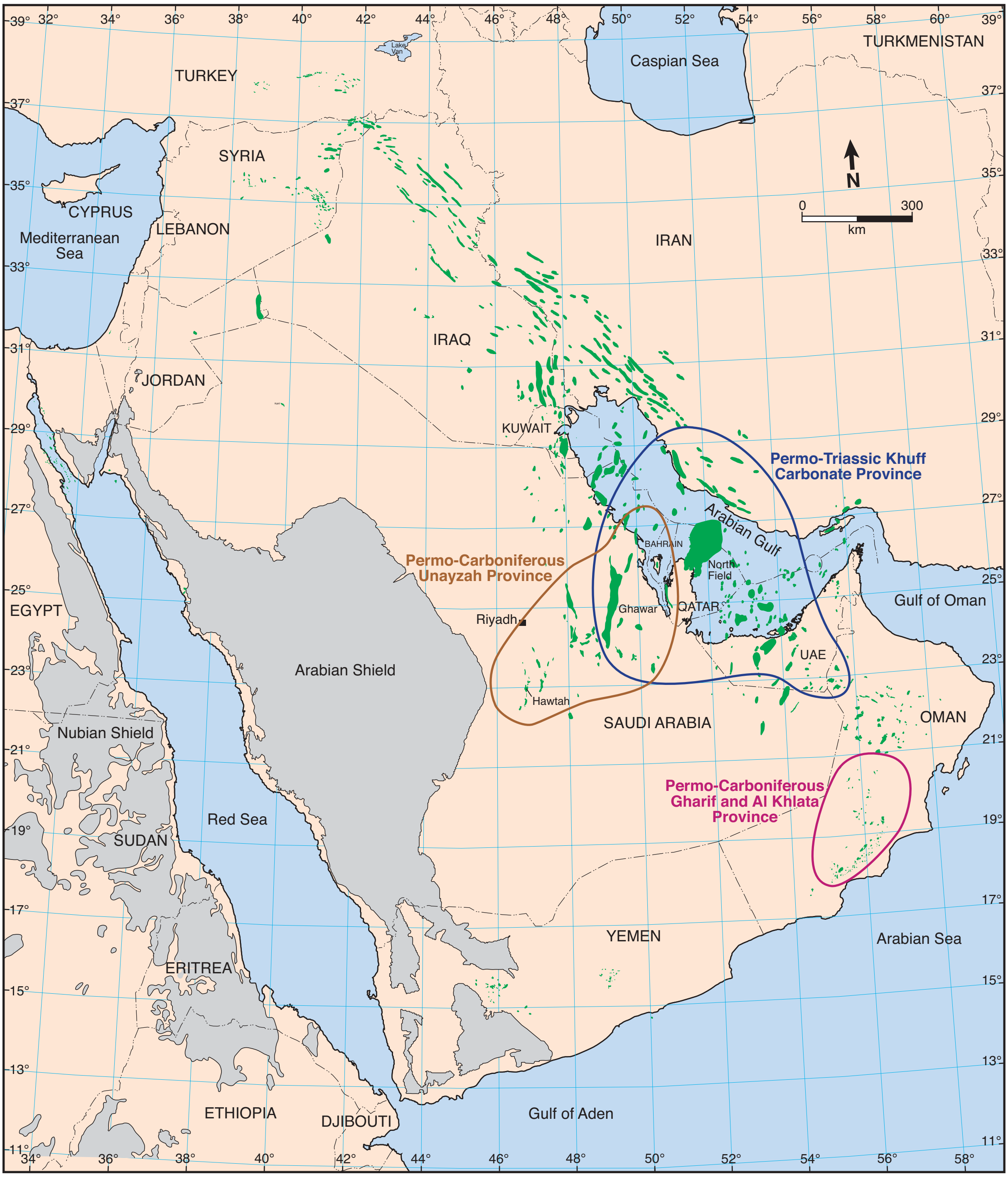


Figure 1: The fields of the Arabian Plate are shown together with the provinces where the Carboniferous, Permian and Lower Triassic reservoirs contain hydrocarbons. The Permo-Triassic carbonates house the Khuff gas reservoirs including the giant North Dome/South Pars field in Qatar and Iran. The Khuff Formation passes laterally to the Permian Dalan and Triassic Kangan formations in Iran. The Permo-Carboniferous clastics contain oil and gas in Oman (Al Khlata and Gharif formations), and Saudi Arabia (Unayzah Formation).

Selecting and Reviewing Time-Representative Formations

Within the Arabian Plate region, the options for selecting locally defined and documented formations that represent a complete record of the Carboniferous to Middle Permian are very limited (Figure 2). Early Carboniferous time is not represented in many areas of the southern Arabian Plate, but a few wells in Saudi Arabia offer a glimpse of the Lower Carboniferous Berwath Formation and overlying formations.

The first paper in this publication (Al-Husseini, 2004) reviews the available stratigraphic record of the Berwath and overlying Unayzah formations, the nature of the intervening pre-Unayzah unconformity, the regional style of the mid-Carboniferous tectonic event, and the ensuing third Arabian Plate glaciation (AP G3). The mid-Carboniferous tectonic event and the associated pre-Unayzah unconformity are set at about 327-311 Ma, and time-correlated to a stratigraphic break in the mid-Carboniferous time (Namurian and early Westphalian stages of Tethys, or Serpukovian-Bashkirian stages of Russia).

The Late Carboniferous and Early Permian times are represented by the glaciogenic Al Khlata Formation of Oman. Osterloff et al. (2004a, this publication) show the Al Khlata lithostratigraphic members and biostratigraphic assemblages to form four regional depositional sequences, which characterise this geological time frame. To correlate these stratigraphic units across the Arabian Plate and create a unified Carboniferous-Permian sequence, Stephenson (2004, this publication) utilises the Oman-Saudi Arabia Palynozones (OSPZ of Stephenson et al., 2003) to tie the Al Khlata Formation to the time-equivalent Unayzah C and B members. These chronostratigraphic correlations thus bridge 1,500 kilometres in the geological record from the interior of Oman to northwest Saudi Arabia (Figures 1 and 2). They provide a firm time-correlative framework from which subsequent local and regional palaeogeographies can be interpreted.

The remainder of the Permian and Early Triassic time in the Arabian Plate region is most completely represented in the subsurface of Oman by the Gharif and Khuff formations. Osterloff et al. (2004b, this publication) define an Oman ‘reference region’ of about 100,000 square kilometres that can be used to calibrate future studies in other parts of the Arabian Plate. These authors identify and correlate nearly twenty mappable chronostratigraphic units and depositional sequences in the Lower Permian to Lower Triassic succession. In particular, the complex transition from the continental Gharif clastics to Khuff carbonates is vividly shown in both subsurface (Osterloff et al., 2004b), and in outcrop (Angiolini et al., 2004, this publication).

Geological Time Correlation beyond the Arabian Plate Region

Integrating Arabian Plate biostratigraphic studies with the standard International Commission on Stratigraphy (ICS) chronostratigraphic framework remains a challenging task. Arabian fossil assemblages, including palynomorphs, plants and shelly macrofauna, tend to be provincial. This makes it difficult to relate them to stratotype biostratigraphy, sometimes erected in sections thousands of kilometres away in different palaeoclimatic zones. Crucially also, relevant palaeontological data is lacking from some of the newer stratotypes established in North America and China, so that comparisons cannot be made; an example is the lack of palynological data from the Guadalupian Series of the Permian of Texas.

Historically, biostratigraphic assemblages from the Middle East were correlated to the ‘traditional’ chronostratigraphic stages in northwest Europe (for the Carboniferous) and the Russian Platform (for the Permian), hence the use in older literature of terms like ‘Tatarian’ and ‘Namurian’ which are now not standard. Similarly some stratigraphers have preferred to use local chronostratigraphic stage names based in the Tethys region, such as ‘Murgabian’. In order to prevent confusion only the standard nomenclature is used in this book, but where necessary these terms are related, using the most modern correlation available, to older terms that are still in use elsewhere or that appear in older literature (e.g.

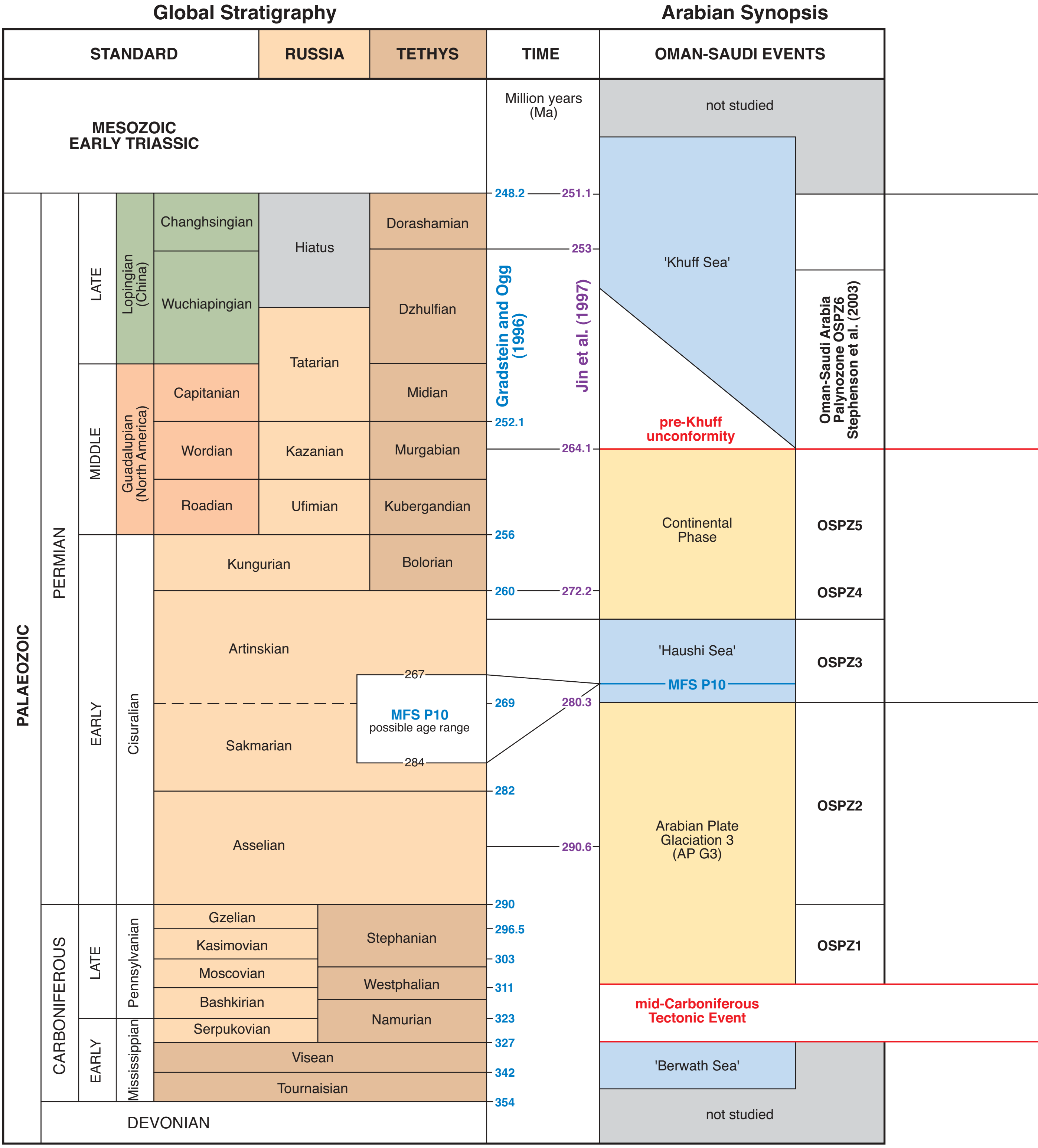
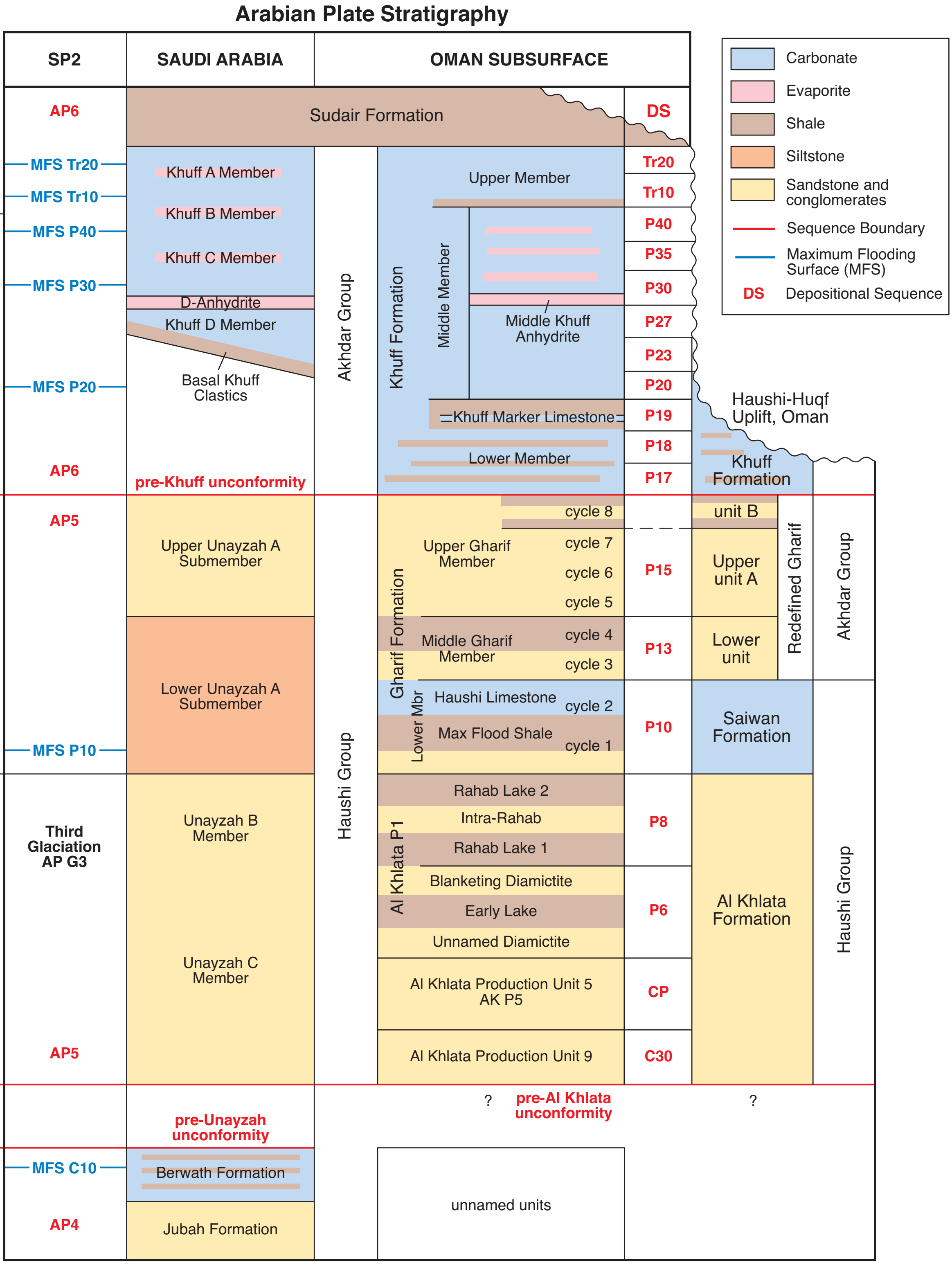


Figure 2: The standard Permian scale proposed by the International Commission on Stratigraphy (after Jin et al., 1997) is divided into Early (Cisuralian of Russia), Middle (Guadalupian of North America), and Late periods (Lopingian of China). The Carboniferous scale is shown after Gradstein and Ogg (1996), and consists of Early (Mississippian) and Late (Pennsylvanian); and the stages of Tethys and Russia. The time calibrations of Gradstein and Ogg (1996) and Jin et al. (1997) are shown in million years (Ma; note time scale is not drawn linearly). These two scales were published just one year apart but differ by as much as 11 million years in the calibration of the Sakmarian and Artinskian stages. The Carboniferous-Early Triassic stratigraphy of Arabia is represented by rock units in Oman and Saudi Arabia, and summarised in the Arabian Synopsis. These units are shown in chronostratigraphic position in relationship to the Oman-Saudi Arabia palynozones (OSPZ1-OSPZ6, Stephenson et al., 2003;



Stephenson, 2004, this publication). The seven Maximum Flooding Surfaces (MFS) and Arabian Plate Megasequences AP4, AP5 and AP6 of Sharland et al. (2001) are shown as SP2 (GeoArabia Special Publication 2). These are complimented by corresponding depositional sequences (DS), and accompanied by intermediate sequences in Oman subsurface (Osterloff et al., 2004a, b, this publication) and surface (Angiolini et al., 2004, this publication). A mid-Carboniferous tectonic event is correlated to the pre-Unayzah unconformity and a break between the Berwath Formation and Unayzah C Member (Al-Husseini, 2004, this publication). The third glaciation of Arabia (AP G3) is Late Carboniferous and Early Permian in age, but may have started in mid-Carboniferous. The uncertainty in calibrating the chronostratigraphy of rock units is shown using MFS P10. It may be late Sakmarian or/and early Artinskian, and its age may range between 284-267 Ma.

Figure 2). Recently, attempts have been made (e.g. Stephenson et al., 2003) to integrate Arabian Plate biostratigraphy for certain parts of the column and relate new biozones directly to the ICS standard scale, thus bypassing obsolete chronostratigraphic terms.

Application of Sequence Stratigraphy

'Global' stratigraphic sequences (e.g. Haq et al., 1988; Ross and Ross, 1988) are difficult to correlate to the Arabian upper Palaeozoic. However, the locally-focused Arabian Plate Maximum Flooding Surfaces (MFS of Sharland et al., 2001) and associated Depositional Sequences (DS) can be recognised. These sequences are abbreviated by system (Tr for Triassic; P for Permian; and C for Carboniferous), followed by a number to indicate the chronostratigraphic position (e.g. DS P10 is older than DS P13, and so forth). This concise alphanumeric nomenclature is suitable for inclusion in geological cross sections and logs, and indicates relative stratigraphic position without reference to further information; it is therefore convenient for explorationists and other non-stratigraphic specialists.

Lithostratigraphic, Chronostratigraphic and Biostratigraphic Challenges

Several rock units in this book have contradictory definitions in the literature and published geological maps. Where possible these issues are clarified, but not explicitly resolved. In this book, the definitions of the subsurface Berwath, Unayzah and Wajid formations are updated and placed for the first time in a regional framework (Al-Husseini, 2004, this publication).

Next, the Omani subsurface Al Khlata, Gharif, and Khuff (Osterloff et al., 2004a, b), and surface Saiwan, redefined Gharif and Khuff formations (Angiolini et al., 2004) are reviewed, and placed in the context of biostratigraphic zones and chronostratigraphic markers. The surface-to-subsurface correlation of these formations is tentatively presented in these papers, although the names of the encompassing groups (Haushi and Akhdar groups) remain mismatched between subsurface and outcrop (Figure 2).

Permian biostratigraphy is discussed in detail by Angiolini et al. (2004), Osterloff et al. (2004b) and Stephenson (2004). In particular, the fossil assemblages, interpreted stages and age of the first post-glacial Permian marine flooding surface MFS P10, and the onset of the Khuff transgression with DS P17 are reviewed, and shown in photographic plates.

Identifying a reliable chronostratigraphic marker and confidently correlating it across formations, however, should not be misconstrued to imply accurate dating in absolute time (million years before present: Ma). The first post-glacial MFS P10 provides an example of stage and age uncertainty. MFS P10 was picked by Sharland et al. (2001) within the subsurface Lower Gharif Member, and the equivalent outcropping Saiwan Formation. These authors placed MFS P10 in the upper Sakmarian stage, and dated it at 272 Ma using the geological scale of Gradstein and Ogg (1996). The ICS, however, favours the time scale of Jin et al. (1997) that dates the late Sakmarian at about 284 Ma. These two scales were published only one year apart, but carry a difference of 11 million years for the top Sakmarian!

Further uncertainty is caused by the stage assignment of MFS P10. It could be: (1) upper Sakmarian based on brachiopod and cephalopod fossils (Angiolini et al., 2004); (2) lower Artinskian based on palynomorph assemblages (Osterloff et al., 2004a); or (3) both upper Sakmarian and lower Artinskian (Stephenson, 2004). Thus the age of MFS P10 could be late Sakmarian (284-272 Ma) and/or early Artinskian (278-267 Ma), depending on biostratigraphy and the adopted time scale (Gradstein and Ogg, 1996; or Jin et al., 1997). This illustration shows the level of uncertainty for MFS P10 (one-half a stage, and 17 million years) and highlights the need for caution associated with using state-of-the-art biostratigraphic and chronostratigraphic calibrations.

Concluding Remarks

The outlook for sustained oil, gas and condensate exploration in the Arabian Plate region is proving more certain than ever. This is driven by the increasing global demand for hydrocarbon resources, the established record of Palaeozoic discoveries within the Arabian region, and the limited opportunities in competing basins elsewhere in the world.

In order to commercialise these potential resources, however, they must be discovered and developed in the most cost-effective manner. In this sense, and in spite of the many advances in geoscientific technology, chronostratigraphy continues to stand out as the most powerful tool in exploration. Fundamental research and development in regional chronostratigraphy can be exploited to provide timely insights into the complex geology of the Arabian Palaeozoic formations. The accurate timing of tectonic events, and the reliable correlation of key horizons across the Arabian Plate, will lead to better predictions of basin development, migration histories, and the emplacement of commercial hydrocarbons. More focused predictive geological models of petroleum systems can then be used to direct search patterns, and sustain exploration successes.

This process can advance with the integration of local data and geological interpretations (some from released proprietary studies) into one publication that incorporates the state-of-art interpretation of regional geological observations. It is in this spirit that *GeoArabia Special Publication 3* attempts to consolidate and integrate the publicly accessible stratigraphic studies of the Carboniferous, Permian and Early Triassic into one chronostratigraphic framework.

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Moujahed Al-Husseini, PhD
Editor-in-Chief, GeoArabia