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Stratigraphy and Operational Palynology of the Devonian System in Saudi Arabia

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ABSTRACT

Surface and subsurface Devonian rocks of Saudi Arabia are correlated using a combination of palynology and sequence stratigraphy. Recent exploratory drilling in eastern Saudi Arabia has confirmed that sweet gas and condensate-bearing Devonian strata are preserved on the flanks of high-relief Hercynian structures such as Ghawar field. This Devonian succession is composed of three homogeneous litho-stratigraphic units, the Tawil, Jauf and Jubah formations that cannot be imaged seismically nor readily discerned with conventional wireline logs.

An operational palynological zonation was consequently devised based on first down-hole occurrences (i.e. extinctions) of encountered palynomorphs. This zonation was calibrated with the standard European spore zonations of Streel et al. (1987) and Richardson and McGregor (1986), and further controlled by mega-fossil data from outcrops in northwestern Saudi Arabia. Six palynozones, and four subzones, have been recognized. A particularly reliable late Early Devonian zone is based on the acme of an endemic *Leiosphaeridia* species. This palynosubzone coincides stratigraphically with the upper part of the gas-bearing Jauf Reservoir.

INTRODUCTION

Saudi Aramco is conducting a new phase of deep exploratory drilling in the Ghawar field, eastern Saudi Arabia (Figure 1). The objective is to evaluate the non-associated gas potential of Palaeozoic siliciclastics below the vertically and laterally extensive Upper Permian carbonates of the Khuff Formation. Wender et al. (1998) provide a synthesis of the exploration data and Palaeozoic (pre-Permian) hydrocarbon geology of the Ghawar Area. Devonian strata, located at subsurface depths of some 12,000 feet (ft) to 17,000 ft, have become a prime exploration target because of the recognition of a quality, sweet-gas reservoir within the Lower to Middle Devonian Jauf Formation.

In the Eastern Province of Saudi Arabia, seismic reflectors within the Devonian strata are poorly-defined as a consequence of large-scale lithofacies homogeneity. Well prognoses, therefore, can be somewhat speculative, especially in areas of sparse well control or structural complexity. Stratigraphic control during drilling is therefore mandatory. An operational palynological zonation has been developed and has proven to be an invaluable tool for identification of stratal units and, furthermore, is so far the only effective method of monitoring stratigraphy during drilling prior to the running of wireline logs.

In the course of recent exploration, palynological studies have identified the youngest Devonian strata (Famennian) so far recognised in Saudi Arabia. Furthermore, a laterally persistent chrono-stratigraphic marker has been resolved that is fortuitously located at the top of the Jauf Reservoir and is an invaluable aid to recognition and correlation of the reservoir.

This paper reviews the Devonian stratigraphic and structural setting in the eastern Ghawar Area and its relationship to the type sections of the Devonian in the outcrops of northwestern Saudi Arabia. Additionally, it outlines the operational palynological zonation that is in current use and the basis of its age control in terms of independent palaeontological data derived from outcrop and correlations with the standard Devonian spore-based zonations that have been developed for Western Europe and North America.

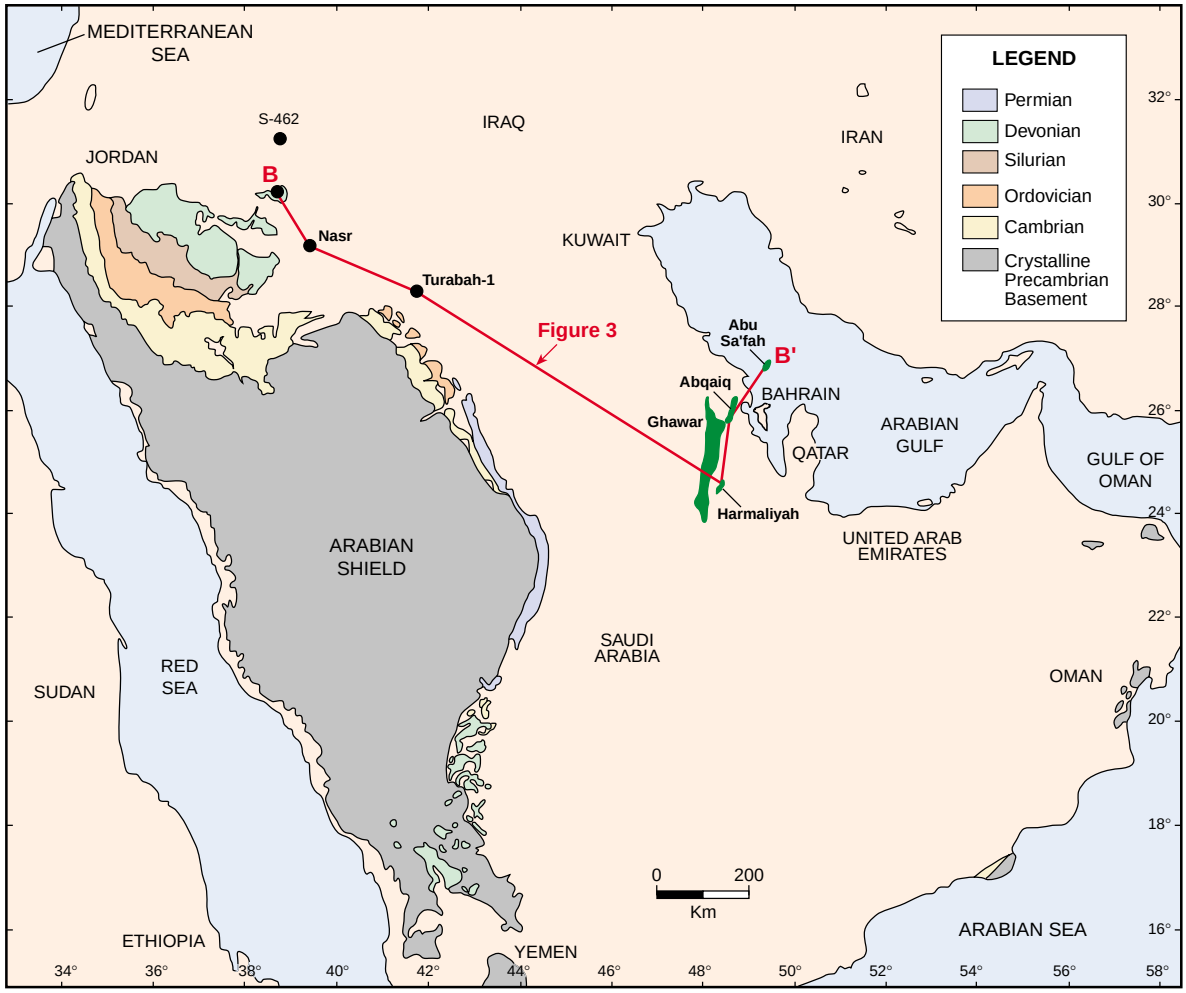

Figure 1: Palaeozoic outcrop map of Saudi Arabia. B-B' shows the location of the regional Devonian cross-section shown in Figure 3.

STRATIGRAPHY

Devonian sedimentary rocks of North Africa and the Middle East comprise a generally coarsening-upwards, progradational sequence along the passive margin of northeastern Gondwana that commenced in the Silurian and culminated in the Upper Devonian times.

In Saudi Arabia, Devonian sedimentary rocks are only known to be exposed in the southwestern and northwestern parts of the country, adjacent to the exposed Arabian Shield (Figure 1). These rocks were first described and named by Aramco geologist E. L. Berg in 1944 from the northwestern outcrops. The stratigraphy was later formalised by Steineke et al. (1958) and amended in Powers et al. (1966) and Powers (1968). Powers originally divided the Devonian into the Lower Devonian Tawil Formation and the Lower to Middle Devonian Jauf Formation. In 1988, Meissner et al. defined the Middle to Upper Devonian Jubah Formation (Figure 2).

Three formations are now recognised in the type outcrop area of northwestern Saudi Arabia. In order of succession, these are the Tawil, Jauf, and Jubah formations which reflect shifts in sedimentation from siliciclastics to mixed siliciclastics and carbonates and a return to siliciclastics. The alternating siliciclastic and carbonate units of the mid part of the succession subdivide the Jauf Formation into five members, with the uppermost member being transitional between the carbonate and siliciclastic units (Figure 2).

Exploration drilling has extended the known distribution of the Devonian into subcrop not only in the northwest but also in eastern Saudi Arabia. The Eastern Province succession reflects a different depositional regime (? sub-basin) in that the shallow-marine carbonate members of the Jauf Formation are replaced entirely by siliciclastics (Figure 3). The succession consists predominantly of sandstones with minor silty / shaly intercalations that represent a continental to marginal marine, fluvio-deltaic, depositional system. Notwithstanding this, the same litho-stratigraphic nomenclature has been extended to the Eastern Province though the formations are less readily differentiated litho-stratigraphically, even with the aid of wireline logs. Likewise, an absence of significant impedance contrast renders seismic an ineffective stratigraphic tool through the Devonian. Palynostratigraphy is thus essential for maintaining consistency in correlations amongst well sections.

The top of the Devonian is almost invariably eroded by either pre-Khuff or pre-Unayzah (Permo-Carboniferous) unconformities, particularly on structural highs such as the Ghawar Structure. More section is preserved away from these highs, notably to the east. A recent easterly well on the Harmaliyah structure penetrated 2,300 ft of Devonian section that includes the youngest Devonian (late Famennian) so far substantiated in Saudi Arabia. In the offshore Arabian Gulf the succession passes, seemingly conformably, into the Lower Carboniferous.

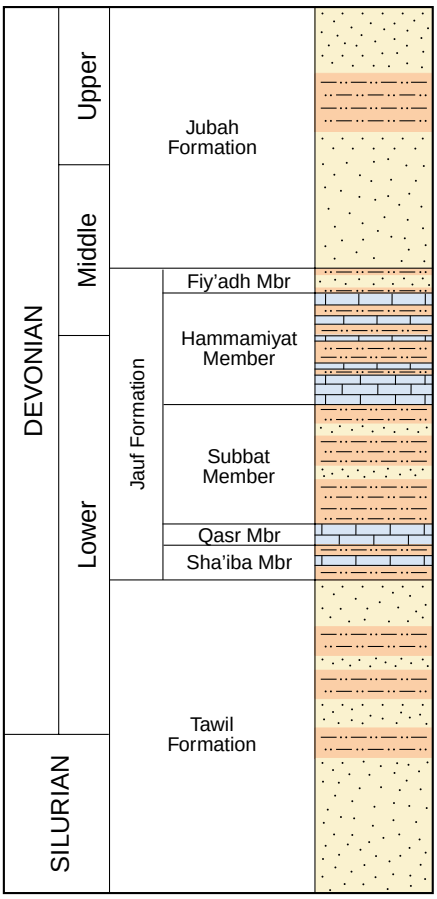

Figure 2: Generalized Devonian stratigraphic section of northwestern Saudi Arabia.

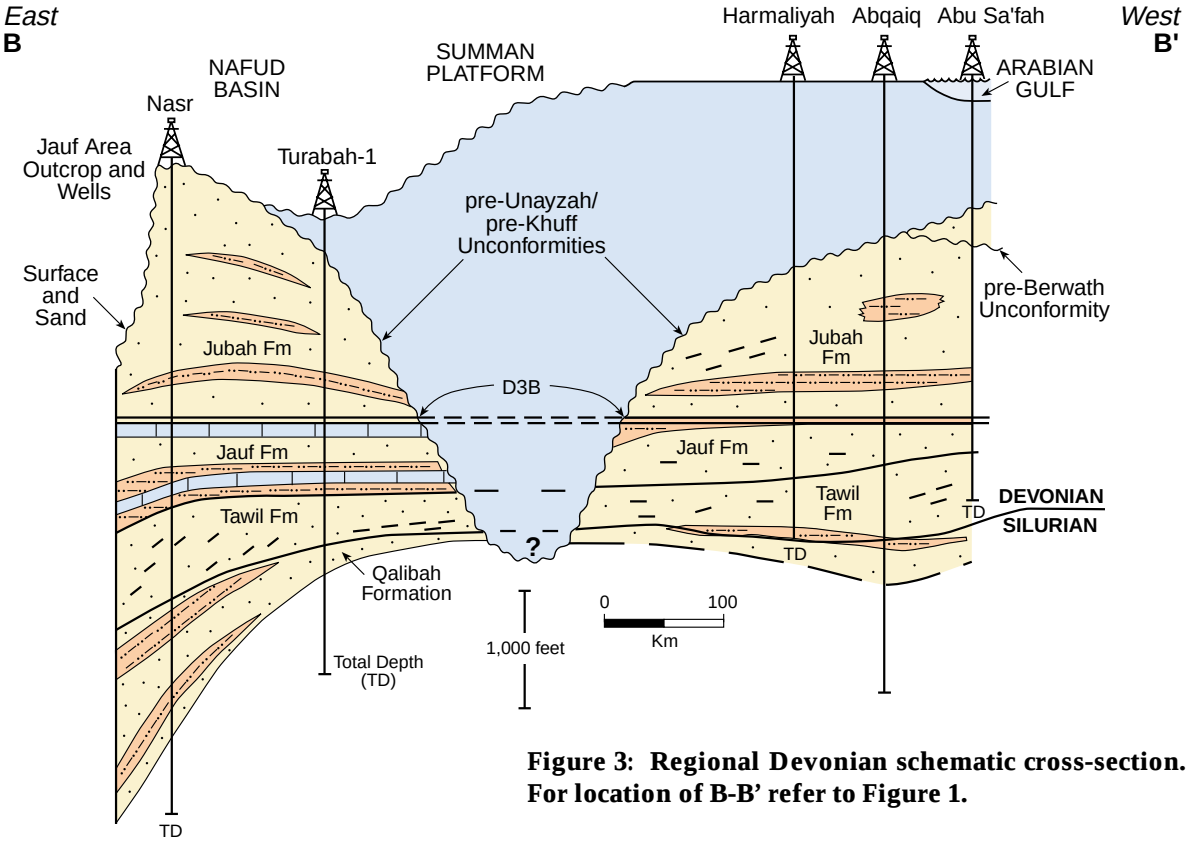

Figure 3: Regional Devonian schematic cross-section. For location of B-B' refer to Figure 1.

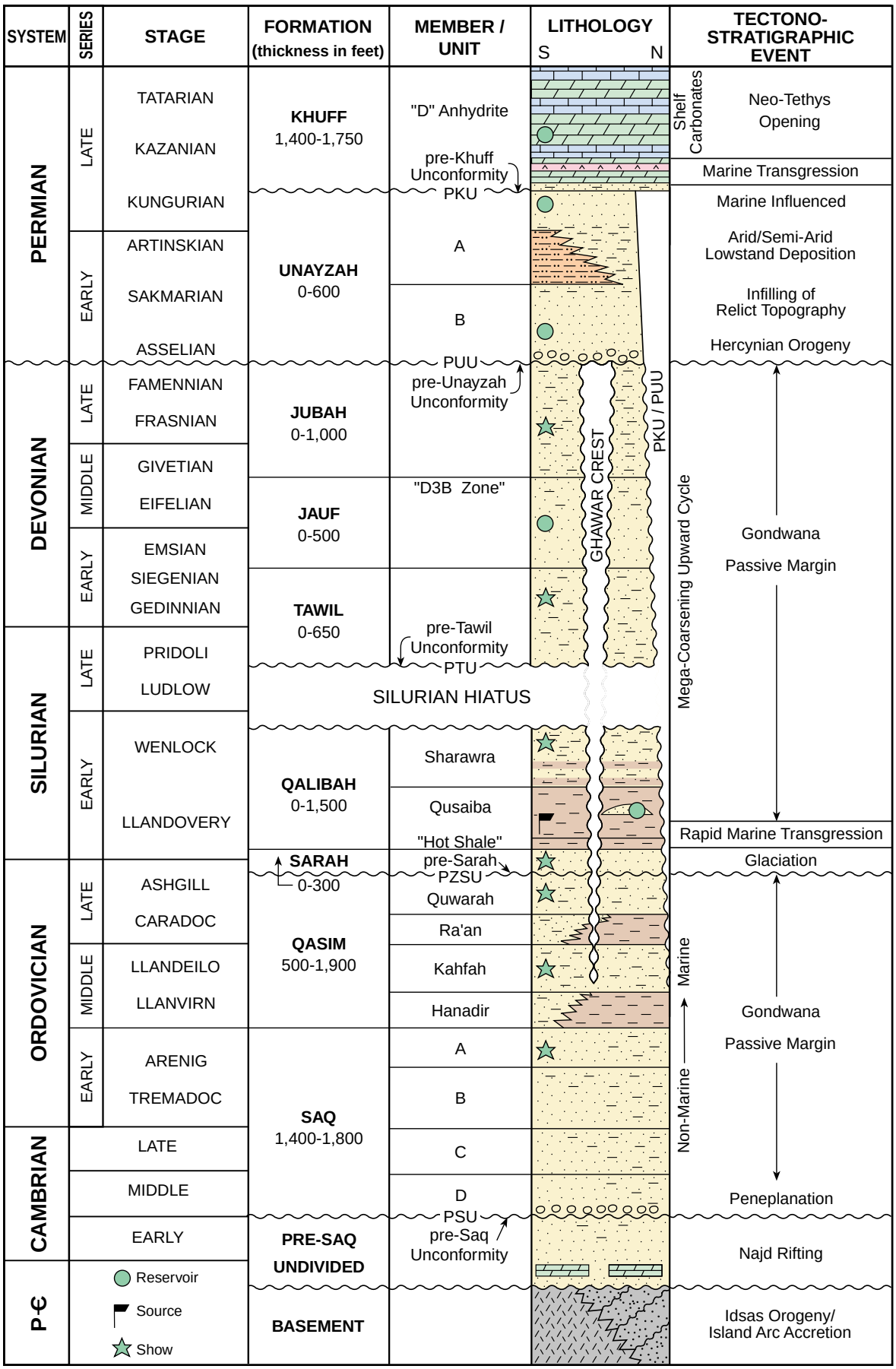

Figure 4: Generalized Palaeozoic stratigraphic column of the Ghawar Area (after Wender et al., 1998).

The Tawil Formation extends down-section into the upper Silurian (Ludlow-Pridoli) where it disconformably overlies Wenlock and older sediment of the Qalibah Formation (Figure 4). The contacts between the Tawil, Jauf, and Jubah formations appear to be conformable.

EASTERN AREA PETROLEUM GEOLOGY

The Ghawar anticlinorium contains the world's largest oil field. The field is approximately 260 kilometers (km) in length and the oil is reservoired primarily in Jurassic carbonates of the Arab-D Formation. Exploration for non-associated gas initially concentrated on deeper objectives on the crestal portions of Ghawar and mainly targeted carbonate reservoirs of the Upper Permian Khuff Formation. Early successes highlighted also the potential of the pre-Khuff siliciclastic section, notably Early to Middle Devonian sandstones of the Jauf Formation, as reservoirs for sweet gas. Figure 4 is a generalized stratigraphic column for the Paleozoic of the Ghawar Area.

Recent acquisition of higher-fold seismic data over Ghawar has shown the deep structure to be much more complex than previously realized. Structural mapping indicates that Ghawar is composed of a series of horst and tilted fault blocks arranged in a general north-south direction. The predominant north-south faults are high-angle and basement-involved. The major faults originated in the Late Carboniferous Hercynian Orogeny and have been rejuvenated in the Triassic and Late Cretaceous. Some of the faults show as much as 3,000 feet of displacement at the pre-Khuff level. Deep erosion occurred over the crest of Ghawar as a result of the Hercynian Orogeny, effectively removing the Devonian over much of Ghawar. Figure 5 shows a pre-Unayzah Unconformity (PUU) subcrop map, which depicts the surface geology of the Ghawar Area following the Hercynian Orogeny (Wender et al., 1998).

Recent exploration drilling, therefore, has focused on combination structural-stratigraphic traps on the eastern flank of Ghawar, as well as low relief structural closures such as Harmaliyah. Here the Jauf and younger Devonian sediments have been downfaulted and preserved beneath the Hercynian Unconformity (Figure 6). The Jauf consists of marginal marine sandstones with preserved porosities as high as 30%. The source rock for the gas and condensate is considered to be the basal "hot shales" of the Lower Silurian Qusaiba Member of the Qalibah Formation (Figure 4; McGillivray and Husseini, 1992; Mahmoud et al., 1992).

STRATIGRAPHIC PALYNOLOGY

The Devonian Period was a time of rapid evolution for land plants. Major events were the appearance of leaves, heterospory, secondary growth, and the emergence of seeds (Gensel and Andrews, 1984). This evolution was reflected also by rapid developmental changes and increasing complexity of miospore morphology through the Devonian. A notably major and globally significant palynological event occurred in the late Emsian when assemblages of small, simply-structured and sculptured trilete miospores (e.g. *Ambitisporites* Hoffmeister 1959; *Emphanisporites* McGregor 1961) diversified to include zonate, cavate, and complexly-ornamented genera such as *Samarisporites* Richardson 1965, *Grandispora* Hoffmeister, Staplin and Malloy 1955, and *Hystrichosporites* McGregor 1960 (see Kemp, 1972, p. 120).

In Saudi Arabia this change made it relatively easy for earlier workers to separate the Early to early Middle Devonian Jauf Formation from the late Middle to Late Devonian Jubah Formation. Hemer and Nygreen (1967) described four assemblages from such a succession in S-462 (Figure 1), a well to the northeast of the Devonian outcrop. Although this study demonstrated the existence of additional Devonian section in the subsurface, their zonation has proven to be impractical to apply more widely as it is based on seemingly endemic, poorly-defined species. The underlying Tawil Formation, however, is sandy and thus usually barren of palynomorphs with only rare occurrences of Late Silurian to Early Devonian assemblages.

As a result of the palynological investigation associated with the recent exploration program, palynofloras from all stages of the Devonian are now known to be represented in Saudi Arabia (Plates 1 and 2). To provide stratigraphic control for exploration, an operational palynological zonation was devised utilising data generated both by in-house staff and outside consultants. It comprises six zones

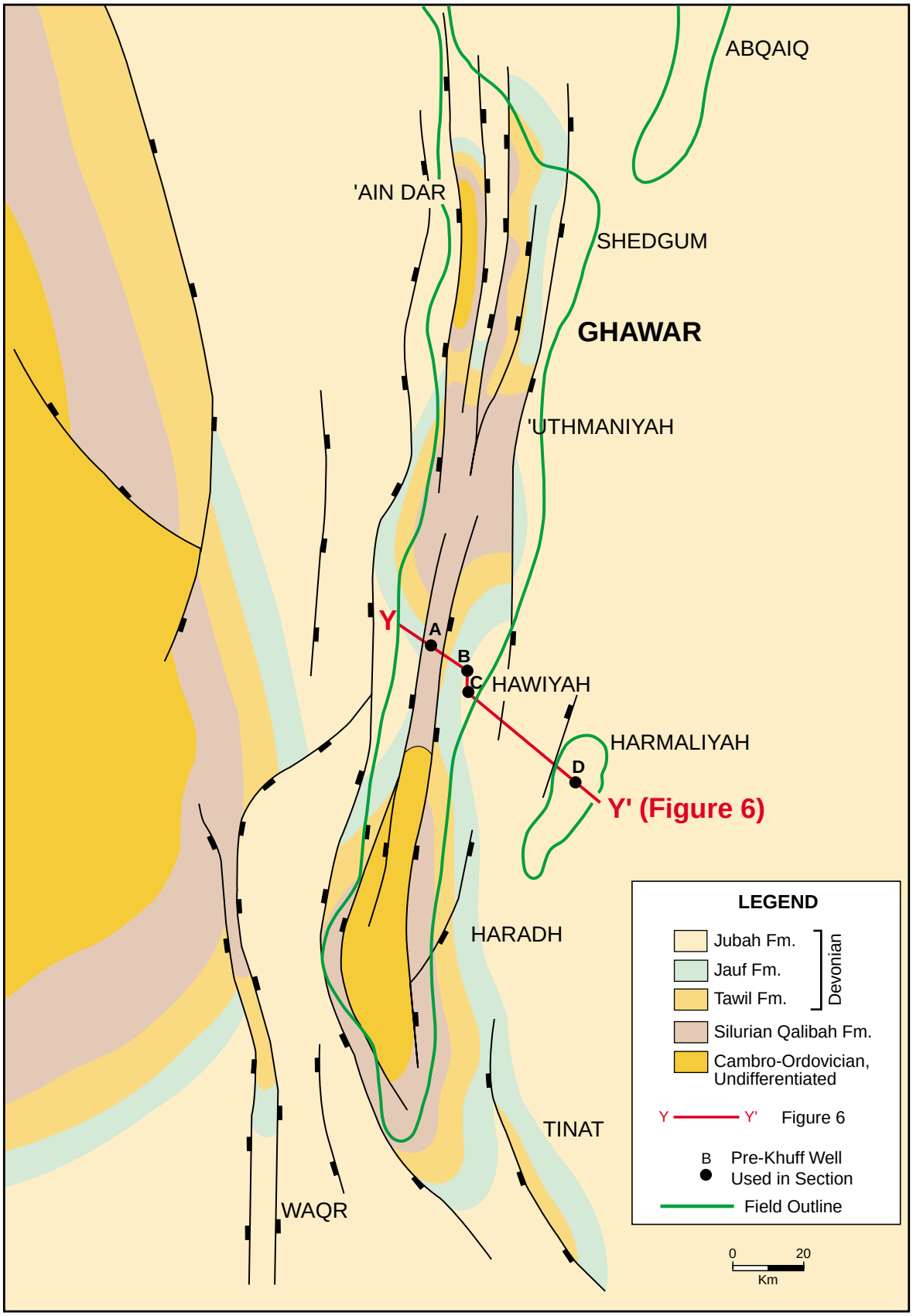

Figure 5: Pre-Unayzah subcrop map of the Ghawar Area. Y-Y' shows the location of the structural cross-section in Figure 6 (after Wender et al., 1998).

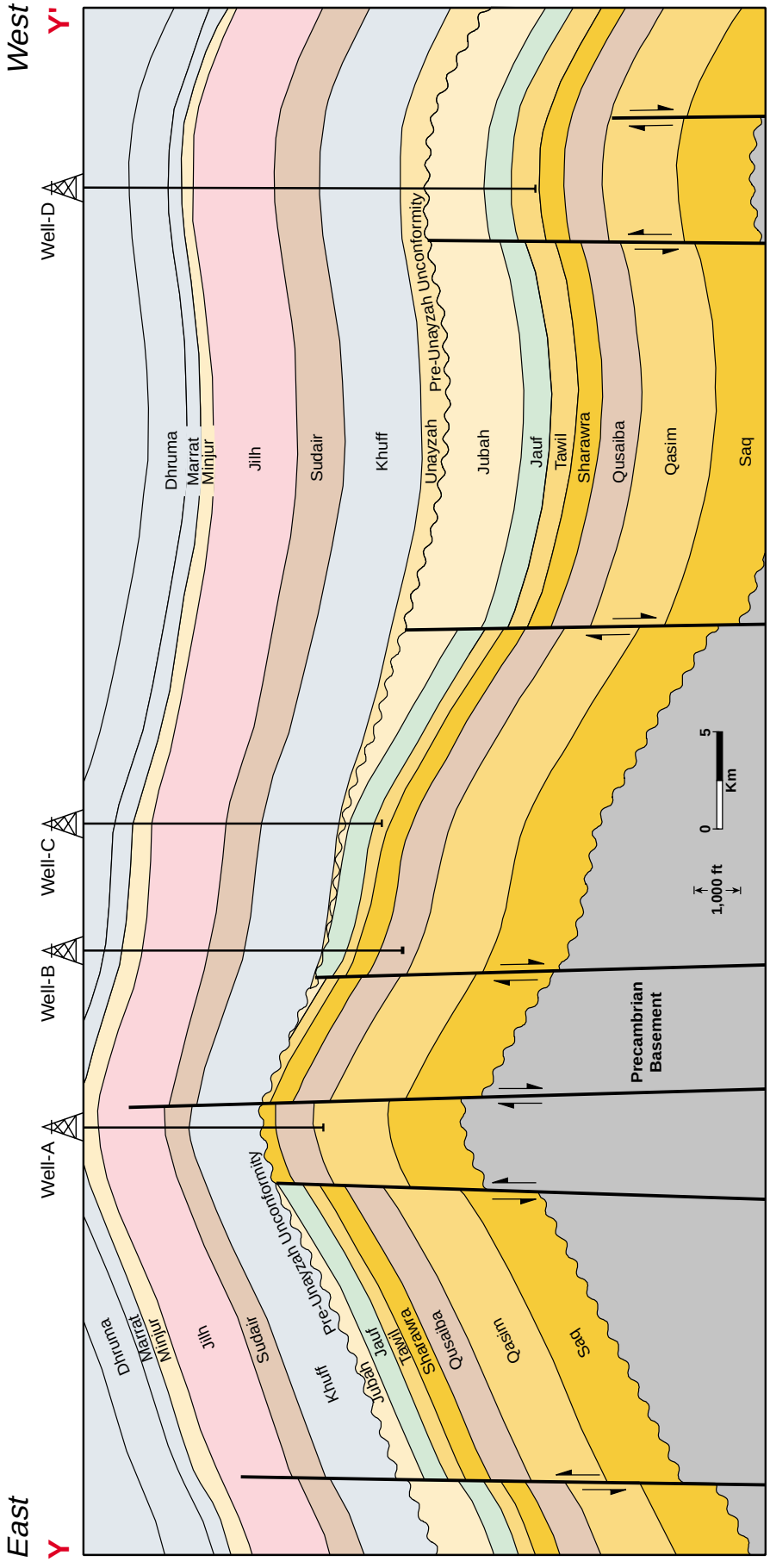

Figure 6: Schematic structural cross-section of the Ghawar Area. For location of Y-Y' refer to Figure 5 (after Wender et al., 1998).

and four subzones and is based primarily on first down-hole taxon occurrences (i.e. extinctions) of index miospore species (Figure 7). Exceptions are the D3B Palynozone which is a partial acme biozone and Palynozones D2 and D3 that are defined by the first common down-hole occurrences (co-occurrence in the case of D2) of designated taxa. The development of the Devonian zonation has been painstaking since the distribution and abundance of spores is inconsistent. In most well sections, extensive barren sandy intervals are sporadically interspersed with thin shale beds containing rich to impoverished palynofloral suites. Furthermore, in the Ghawar Area, because of considerable burial depths, the spores are dark brown to black, near to totally opaque, and thus difficult to identify.

Most detailed and precise published Devonian zonations rely largely on first evolutionary occurrences of spore species. Although 'first appearances' are subject to heterochroneity, resulting from ecological, hydro-dynamic and large-scale geographical controls for example, they tend to be inherently more reliable, and thus have become better known, than 'last appearances' (i.e. extinctions). As stated by Richardson and McGregor (1986, p. 3): "Upper stratigraphical limits (disappearances) may have been affected by such factors as persistence of relict floras, or redeposition, and so are given less weight in the definition of zonal boundaries." In subsurface operations, however, a zonation based on first down-hole occurrences is more practicable as it circumvents contamination by cavings in ditch cutting samples. It provides palynostratigraphic data in a timely manner for operational decisions since only the top, and not the base, of a zone needs to be penetrated to confirm its identity. The application of a zonation based on first down-hole occurrences, however, requires vigilance for possible reworking.

To attain age control the zonation (Figure 7) was calibrated against established European / North American spore zonations of Streel et al. (1987; Ardenne-Rhenish Biozonation) and Richardson and McGregor (1986). The reason that these zonations are applicable to North Africa and Saudi Arabia stems from the fact that the proto-Tethyan Ocean was not a significant barrier to plant migration and thus the whole region was embraced within the Western Gondwana-Southern Euramerica Phytogeographic Province (Streel and Loboziak, 1996).

The zonation has also been calibrated against available marine-faunal and plant-fossil age data derived from the outcrops of northwestern Arabia (e.g. Boucot et al., 1989; Forey et al., 1992). Some of the more age-diagnostic data comes from trilobites and conodonts associated with the uppermost Sha'iba and Qasr members (lower Jauf Formation) that indicate a Pragian to early Emsian age. Somewhat less definitive data based on brachiopods suggest a late Emsian age for the Hammamiyat Member (upper part of the Jauf Formation). The palynological scheme, derived from subsurface data, complements and adds to these data and, furthermore, is in itself more readily and widely applicable for correlations within Saudi Arabia.

Although the distribution and abundance of spores varies both stratigraphically and regionally throughout the Devonian System of Saudi Arabia, the devised zonation has nevertheless proven to be an invaluable tool in furnishing stratigraphic control for exploration and development. Neither the zonation nor its age calibration is presumed to be complete or final. Modifications are anticipated as new data come to hand from continuing exploration and as previously drilled sections are re-evaluated. The following is a discussion of each of the zones in current use, arranged in descending order.

Palynozone D0

Palynozone D0 has been documented recently from the uppermost portion of the Jubah Formation penetrated deep in a well in the Harmaliyah field (Figure 1). This biozone is based on the highest occurrence of *Retispora lepidophyta* (Kedo) Playford 1976, a worldwide marker species for the Late Famennian (Strunian). Other stratigraphically important miospores such as *Auroraspora macra* Sullivan 1968, *Hymenozonotriletes explanatus* (Luber) Kedo 1963, *Vallatisporites pusillites* (Kedo) Dolby and Neves 1970, and *Grandispora famenensis* (Naumova) Streel 1974, further characterize the zone and facilitate international correlation. The zone correlates well with palyno-assemblages of this age in many localities worldwide but its biostratigraphic significance is best appreciated by correlation with the LE Interval Zone (Streel et al., 1987) and upper part of the *pusillites-lepidophyta* Zone (Richardson and McGregor, 1986) of the comprehensive, spore-based zonations established for Western Europe and North America (Plate 1). The proximity of the Old Red Sandstone Continent to Gondwanaland during the Late Devonian explains the fact that North America, Europe, North Africa and Saudi Arabia share 80% of

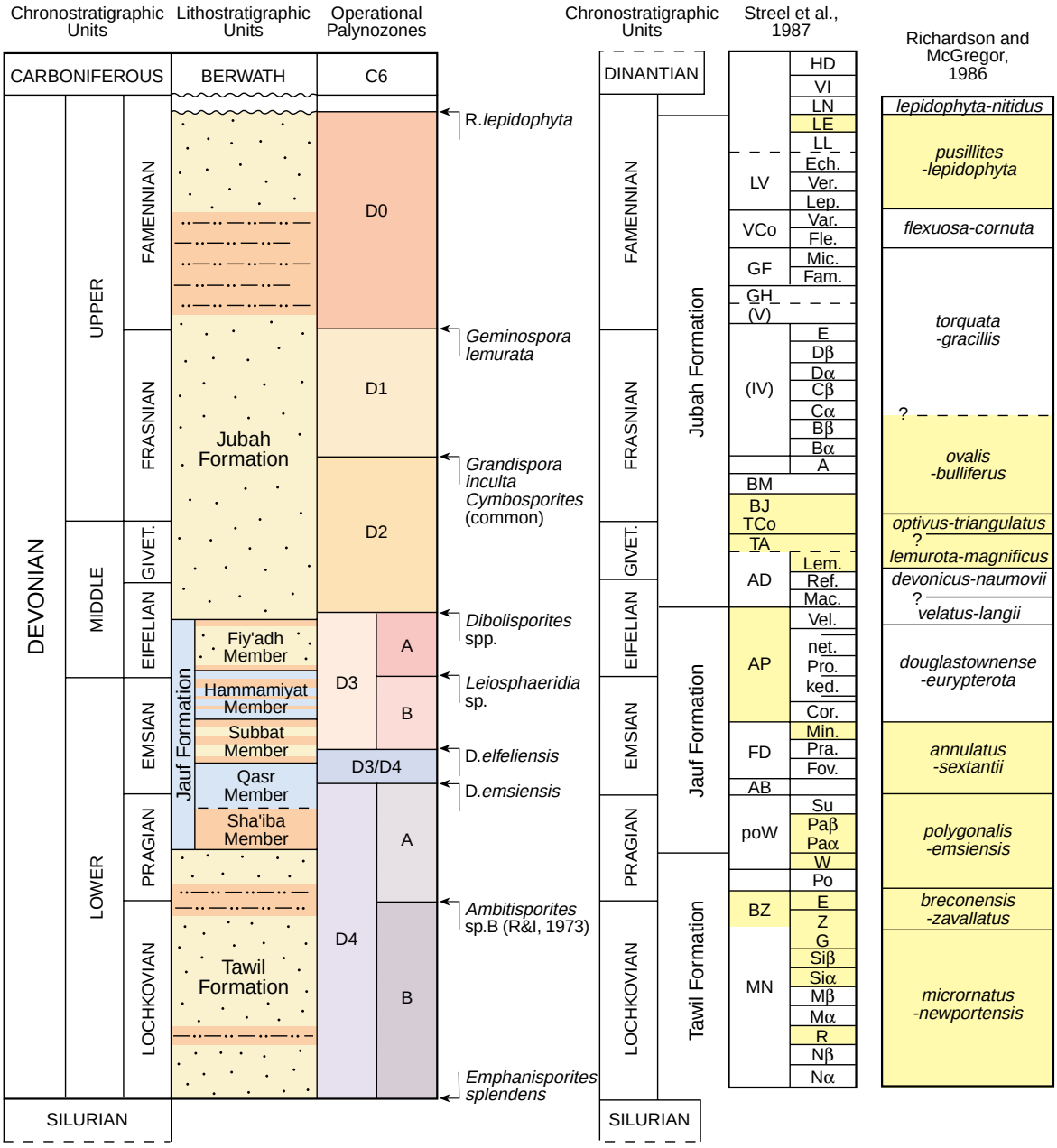

Figure 7: Devonian palynostratigraphic scheme of Saudi Arabia compared with the standard European zonations of Streel et al. (1987), and Richardson and McGregor (1986).

their Late Devonian genera of marine invertebrates and plant miospores (Figure 8). The base of the zone is defined by the first down-hole appearance of *Geminospora lemurata* (Balme) Playford 1983. An interval immediately below D0 and above D1 has so far been found to be non-palyniferous. A discovery of palyno-assemblages from this level would undoubtedly lead to subdivision of the zone. The D0 Palynozone identifies the youngest sedimentary rocks of the Jubah Formation so far penetrated in Saudi Arabia.

Palynozone D1

Palynozone D1 is defined by the interval from the highest occurrence of the index species *Geminospora lemurata* to the highest co-occurrence of prominent *Grandispora inculta* Allen 1965 and *Cymbosporites* spp. *Geminospora lemurata* is a well-recognised cosmopolitan zonal marker species. In the European succession its first evolutionary appearance corresponds to the base of Interval Zone Lem within the

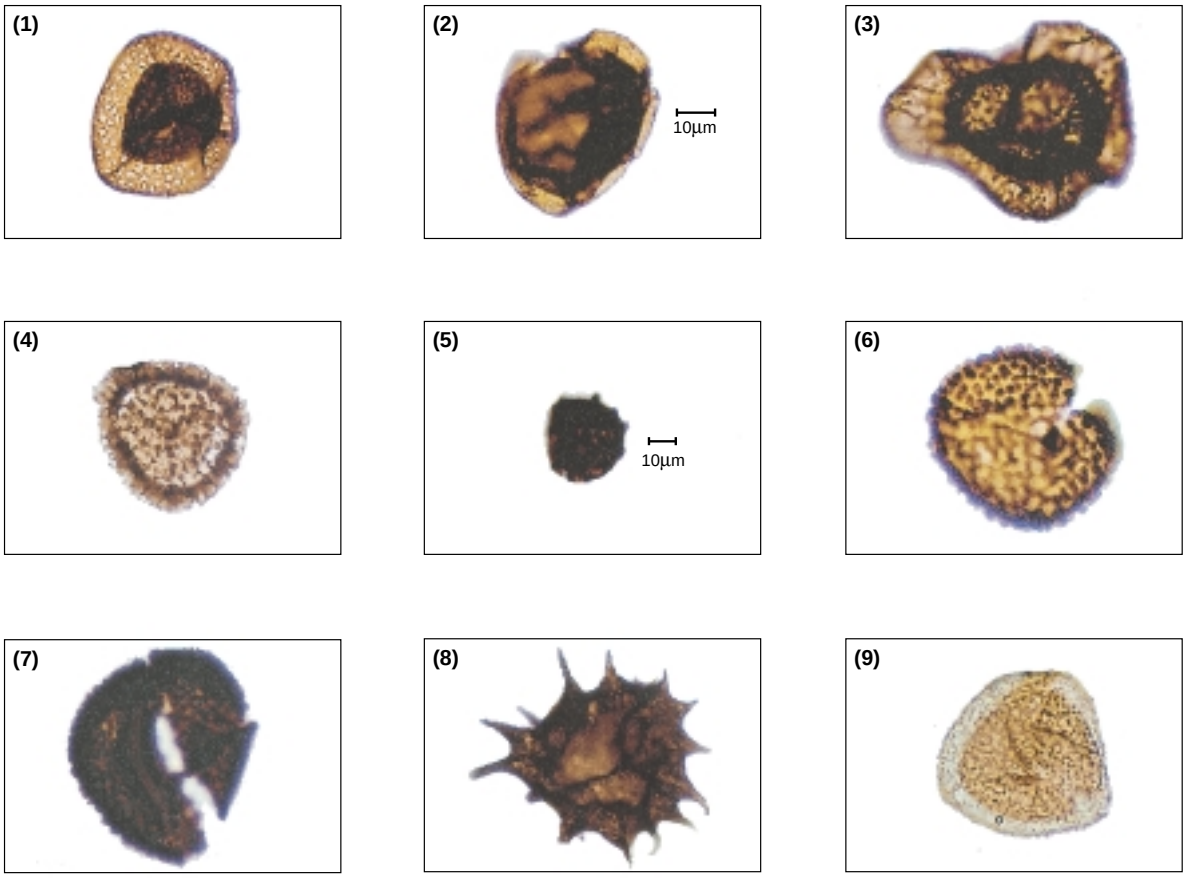

Plate 1: Late Devonian (Famennian) miospores from the D0 Palynozone which is equivalent to the *lepidophyta-explanatus* of Streel et al. (1987). All magnifications are x420, unless otherwise indicated. This assemblage was recovered from the uppermost part of the Jubah Formation of a Harmaliyah well. (1) *Retispora lepidophyta* (Kedo) Playford 1976, (x170) the marker species of Palynozone D0; (2) *Auroraspora macra* Sullivan 1968; (3) *Indotriradites explanatus* (Luber) Playford 1970; (4) *Vallatisporites pusillites* (Kedo) Dolby and Neves 1970; (5) ? *Pustulatisporites* sp. (x170); (6-7) *Grandispora famenensis* (Naumova) Streel 1974; (8) *Ancyrospora* sp.; (9) *Grandispora* sp.

AD Oppel Zone (*Acinosporites acanthomammillatus-Densosporites devonicus*). Loboziak et al. (1991) have reported the first occurrence of *G. lemurata* within the *ensensis-obliquimarginatus* Conodont Zone which was proposed by the Subcommission on Devonian Stratigraphy to define the base of the Givetian Stage (see Loboziak and Streel 1995, p.110). In Saudi Arabia the Lem biozone has been documented by Loboziak and Streel (1995) from the middle and upper parts of the Jubah Formation in the well Turabah-1. The first down-hole occurrence of *G. lemurata* occurs in the upper part of the Jubah Formation. Various records for the highest occurrence (extinction) of *Geminospora lemurata* favour this event to have taken place at the Famennian - Frasnian boundary (Richardson and McGregor, 1986; Loboziak et al., 1988; Loboziak and Streel, 1989; Loboziak et al., 1992).

Palynozone D2

Palynozone D2 is defined as the interval from the highest, prominent co-occurrence of *Grandispora inculta* and *Cymbosporites* spp. to the highest common occurrence of *Dibolisporites* spp.. The highest reported occurrences of *G. inculta* from North Africa and Brazil are from the early Frasnian European BJ Oppel Zone (Streel et al., 1990; Loboziak et al., 1988; Loboziak and Streel, 1989; Loboziak et al., 1992). Some of the stratigraphically more important and distinctive miospores from the zone are *Samarisporites triangulatus* Allen 1965, *Cymbosporites cyathus* Allen 1965, *C. catillus* Allen 1965, and *Grandispora libyensis* Moreau-Benoit 1980. *Grandispora* spp. are normally common. The D2 Palynozone occurs consistently in the mid and lower Jubah Formation of both northwestern and eastern Saudi

Figure 8: Distribution of selected Late Devonian (Famennian) miospores. Base map modified from Scotese and McKerrow (1990).

Arabia. A recently recovered palynoflora of this palynozone from the basal Jubah Formation contains *Camarozonotriletes concavus* Loboziak and Streel 1989, *Grandispora riegelii* Loboziak and Streel 1989, *G. gabesensis* Loboziak and Streel 1989, and *G. incognita* (Kedo) McGregor and Camfield 1976. The palynoflora equates with late Efelian, lower AD Oppel Zone (pre-*lemurata*) of Streel et al. (1987).

Palynozone D3

Palyno sub-zone D3A is defined as the interval from the highest abundant occurrence of *Dibolisporites* spp. to the highest inception of *Dibolisporites eifeliensis* (Lanninger) McGregor 1973. The palynozone is divisible into two subzones designated as D3A and D3B.

Palynosubzone D3A: This subzone is defined by the interval between the highest abundant occurrence of *Dibolisporites* spp. and the top of a mono-specific leiosphaerid acritarch acme. The subzone is characterised by a prominence of *Dibolisporites* spp. and includes the species *Dibolisporites* cf. *gibberosus* (Naumova) Richardson 1965, *Dibolisporites* cf. *echinaceus* (Richardson) McGregor 1973, *Acinosporites acanthomammilatus* Richardson 1965, and rare specimens of *Acinosporites apiculatus* (Streel) Streel 1967. Such an assemblage suggests that the subzone is no older than late Emsian. Since *Samarsiporites* Richardson 1965 (e.g. *S. eximius* (Allen) Loboziak and Streel 1989) makes its evolutionary appearance within the subzone, correlation with the lower part of the Western European AP Oppel Zone can be drawn, suggesting a late Emsian-earliest Eifelian age. The palynozone spans the lowermost Jubah to upper Jauf formations in both northwestern and eastern Saudi Arabia.

Palynosubzone D3B: The top of the D3B Palynosubzone is marked by the sudden abundance of a monospecific leiosphaerid. As far as is known the species is not described and is endemic to the Arabian Peninsula. It is a simple, psilate sphaeromorph with a diameter range of 25-45 micrometers (µm); a somewhat thickened, rigid wall gives rise to distinctive broad compressional folds, a feature that enhances recognition of the species. Although the top of the subzone is picked at the top of the acme the species does appear to range, in low numbers, partly into the overlying subzone. Because of cavings phenomenon the base of the acme cannot be readily discerned from cuttings samples. In cored sections the acme zone ranges in thickness from five to sixty feet. The first evolutionary appearance of the D3B leiospheres is uncertain but may be near coincident with the base of its acme. The base of the D3B Palyno subzone (and D3 Palynozone) is not based on the leiosphaerid but the first down-hole appearance of *Dibolisporites eifeliensis* (Lanninger) McGregor 1973.

The acme zone is remarkable for its lateral continuity and in poorly-palyniferous sections is more reliably preserved than any of the other palynozones. Its significance to exploration activities is further enhanced in that it is normally associated with siltstones and shales that cap the Jauf Reservoir, although in some instances it occurs within the upper part of the reservoir itself. In its wide geographic extent, but constrained stratigraphic range, the seemingly near isochronous, event is thought to reflect peculiar environmental conditions associated with a marine transgression. Associated spores are few, probably reflecting the restricted environment, and mostly include species of *Dibolisporites* Richardson 1965 and *Apiculiretusispora* (Streel) Streel 1967. In northwest Saudi Arabia the sub-zone is associated with the marine Hammamiyat and ?Subbat members of the Jauf Formation and includes rare specimens of the acritarch ?*Polyedryxium pharonis* Deunff 1961, and chitinozoan *Angochitina capillata* Eisenack 1937. Unusual monotypic assemblages within the upper Jauf Formation have been noted also amongst the marine invertebrate fauna (Boucot et al., 1989, p. 549) within the exposed upper section of the Jauf Formation of northwestern Saudi Arabia.

According to A.J. Boucot (1989), "A remarkable feature, especially of the marine part of the Jauf Formation, is the repeated occurrence of faunally unique beds. The extreme of this situation is seen in the presence of numerous beds where the fossil content is monotypic (a single, low-diversity community, or even a single species community). . . . . The fossil content of these peculiar, low diversity and single species beds may possibly reflect unusually subtle paleoenvironmental fluctuations that are rarely seen in the geologic column. Extraordinary explanations seemed called for. An extraordinarily stable, extraordinarily gently-dipping, extraordinarily extensive platform area as the dominant paleogeographic feature might be at least a partial clue to the control producing such fossil occurrences."

The exact age of the D3B Palyno subzone remains equivocal. Loboziak and Streel (1995) assigned samples from the interval in Turabah-1 to the European FD Oppel Zone of Early Devonian, Emsian, age. *Dibolisporites eifeliensis*, however, whose extinction marks the base of the zone, is known to range into the early Eifelian (Richardson and McGregor, 1986; Moreau-Benoit, 1989). It may be that the environmental conditions associated with the D3B event locally limited the upper range of *D. eifeliensis* and the subzone in fact ranges into the Emsian. As noted earlier invertebrate fossil evidence from nearby surface exposures support a late Emsian age for the equivalent stratigraphic interval.

Palynozone D3/D4

Palynozone D3 / D4 is defined as the interval zone from the highest occurrence of *Dibolisporites eifeliensis* to the highest occurrence of *Dictyotiletes emsiensis* (Allen) McGregor 1973. On these criteria a late Emsian to early Eifelian age range is indicated since the former species became extinct in the early Eifelian and the latter in the late Emsian (Richardson and McGregor, 1986). Rare occurrences of *Verrucosisporites polygonalis* Lanninger 1968 from the lower part of the zone, however, favour an Emsian age as this species is considered to have its extinction within the late Emsian (Richardson and McGregor, 1986). It may be that the upper part of the stratigraphic range of species such as *D. emsiensis* is locally restricted because of peculiar environmental conditions that prevailed at the level of the D3B Palynosubzone. Other commonly occurring taxa within the D3 / D4 Palynozone include species of *Apiculiretusispora*, many of which resemble *A. brandtii* Streel 1964. The zone spans the lower section of the Jauf Formation of both northwestern and eastern Arabia.

Palynozone D4

Palynozone D4 is defined as the interval zone from the highest occurrence of *Dictyotiletes emsiensis* to the highest occurrence of *Emphanisporites splendens* Richardson and Ioannides 1979. The zone is divisible into two subzones, viz. D4A and D4B.

Palynosubzone D4A: The base of Palynosubzone D4A is marked by the highest occurrence of *Ambitisporites* sp. B Richardson and Ioannides 1973 which indicates the middle Siegenian (=early Pragian). Palynosubzone D4A, therefore, has a possible early Pragian to late Emsian age span. *Emphanisporites micronatus* Richardson and Lister 1969, where present in the zone, indicates an age no younger than mid Emsian. *Apiculiretusispora brandtii* and *Tholisporites chulus* (Cramer) McGregor 1973 are common accompanying species within the subzone. Palynosubzone D4A has been documented in samples from the lower part of the Jauf Formation of northwestern Saudi Arabia and upper part of the Tawil Formation in eastern Saudi Arabia.

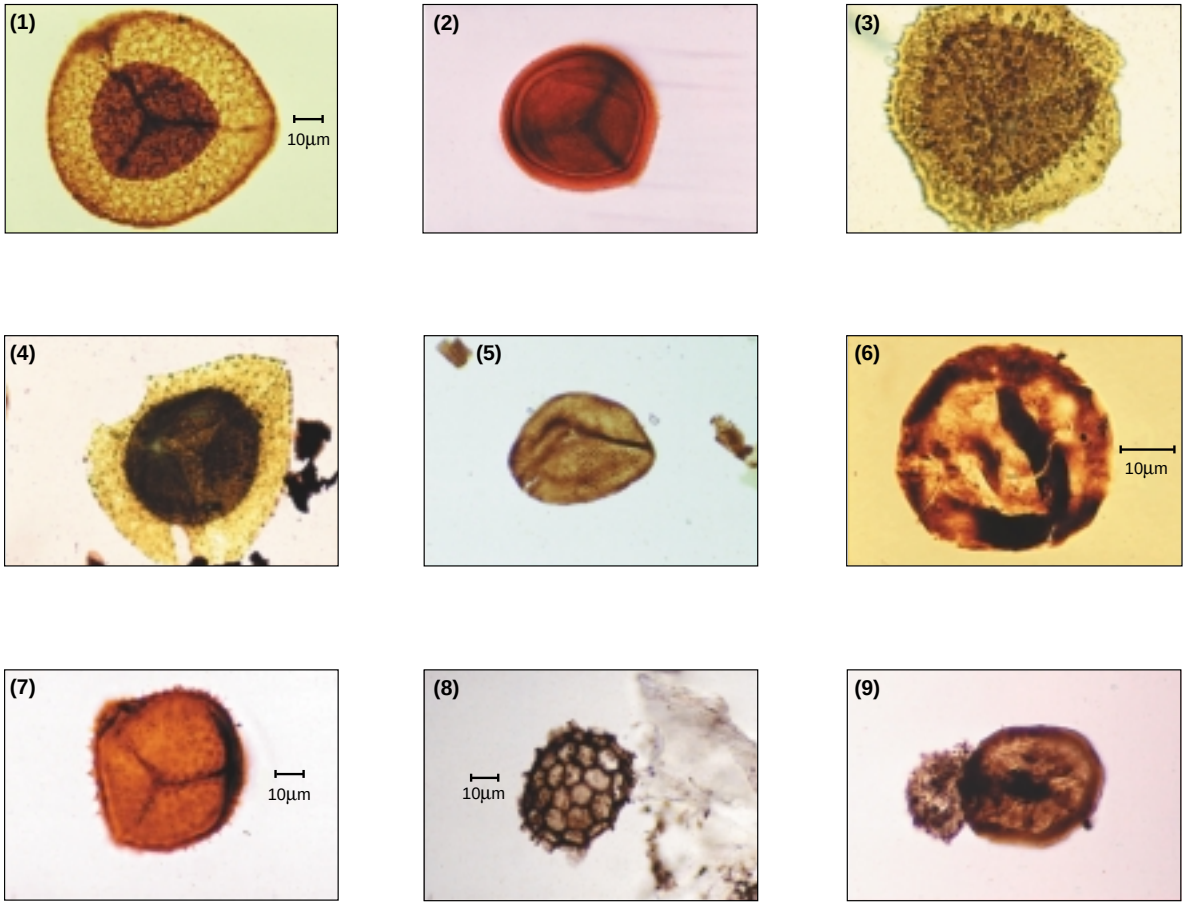

Plate 2: Marker Devonian miospore species from various wells in Saudi Arabia. All magnifications are x420. (1) *Retispora lepidophyta* (Kedo) Playford 1976, the marker species of D0; (2) *Geminospora lemurata* (Balme) Playford 1983, the marker species for Palynozone D1; (3) *Grandispora libyensis* Moreau-Benoit 1980, an index species from Palynozone D2; (4) *Grandispora* sp., recovered from Palynozone D2; (5) *Dibolisporites* sp., recovered from Palynozone D3; (6) *Leiosphaeridia* sp., the marker species for Palyno sub-zone D3B; (7) *Dibolisporites eifeliensis* (Lanninger) McGregor 1973, the marker species to Palynozone D3/D4; (8) *Dictyotriletes emsiensis* (Allen) McGregor 1973, the marker species to Palyno sub-zone D4A; (9) *Ambitisporites* sp. B Richardson and Ioannides 1973, the marker species of Palyno sub-zone D4B.

Palynosubzone D4B: The D4B Palynosubzone is defined as the interval between the first down-hole appearance of *Ambitisporites* sp. B and that of *Emphanisporites splendens*. Commonly occurring accessory species include *Quadrisporites granulatus* (Cramer) Cramer and Diez 1972 and *Laevolancis divellomedium* (Chibrikova) Burgess and Richardson 1991. Assemblages from this subzone have been described by Steemans (1995) and are considered to be of Pridoli (Late Silurian) to early Pragian age. The subzone characterizes the mid to upper parts of the Tawil Formation.

CONCLUSIONS

The developed Devonian palynostratigraphic zonation provides a primary tool for correlating the northwestern Devonian type section with the subsurface Devonian rocks of eastern Saudi Arabia. It comprises six zones and four subzones, which are based on first down-hole occurrences (i.e. extinctions) of index miospore species or acme intervals of selected taxa. This zonation has proven to be an invaluable tool in furnishing stratigraphic control during drilling operations.

The shaly / silty facies of Palyno subzone D3B in the eastern province is a temporal equivalent to the Hammamiyat Member of the Jauf Formation of northwestern Saudi Arabia. It is usually associated with the cap rock or the upper part of the sweet gas and condensate Jauf Reservoir. A late Early Devonian (late Emsian) age is suggested by both palynological and invertebrate fossil evidence. Moreover the event seems to reflect peculiar paleo-environmental conditions that are possibly related to transgression on a broad shelf.

Latest Devonian (Fammenian) sediments are documented here for the first time from the upper part of the Jubah formation in a well in the Harmaliyah field, and thereby indicate that a complete Devonian succession is represented in Saudi Arabia.

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