

Seismic stratigraphy and subsidence history of the United Arab Emirates (UAE) rifted margin and overlying foreland basins

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Introduction

Rifted continental margins form in response to continental breakup and the creation of new ocean basins. Heating and thinning of the continental lithosphere at the time of rifting causes a localized subsidence and the accumulation of syn-rift sediments (e.g., McKenzie 1978; Buck et al. 1999; Lavier and Manatschal 2006). Towards the ending of rifting, the heated and thinned margin cools and post-rift sediments accumulate.

The emplacement of large, loads on a rifted margin has major implications for its thermal and mechanical evolution. This is particularly well seen at margins that have been subject to large orogenic loads. For example, the emplacement of Semail Ophiolite in the northern Oman mountains onto the Arabian rifted margin moved the post-rift sedimentary sequences (e.g., Upper Jurassic source rocks) from relatively shallow to deep depths and into the oil window in response of formation of a foreland basin (Ali and Watts 2009).

Foreland basins develop by lithospheric flexure in front of migrating thrust and fold loads (e.g., Price 1971; Beaumont 1981). They are usually “wedge-shaped” in cross-section and are infilled by sediments that have mainly been derived from the adjacent thrust and fold belt. The foreland basin is separated from the orogenic belt by a major advancing thrust front and from the cratonic interior by a peripheral bulge (e.g., Karner and Watts 1983;

DeCelles and Giles 1996). There is evidence that the bulge may migrate across a foreland basin, both towards and away from the thrust and fold belt, and that they may, in some cases, act as a localised sediment source. For example, Patton and O’Connor (1988) suggest that in the case of the northern Oman foreland basin that the flexural bulge migrated across the foredeep towards the craton.

Foreland basins comprise a distinct stratigraphic ‘architecture’, usually involving onlap as clastic clinofold wedges move out across the basin and then offlap as the depositional centre migrates in towards the surface and buried loads and the basin fills. Forward modelling studies have shown that the patterns of onlap and offlap are mainly controlled by the rate of migration of the thrust and fold belt, the flexural response of the underlying basement, and the rate of sediment flux into the basin (e.g., Jordan 1981; Flemings and Jordan 1989; Sinclair et al. 1991).

The United Arab Emirates (UAE) is underlain by a deep sedimentary basin which comprises a lower rifted passive margin sequence and upper foreland basin (Aruma and Pabdeh) sequences. Previous studies (e.g., Patton and O’Connor 1988; Robertson 1987a, b; Boote et al. 1990; Warburton et al. 1990; Ali et al. 2008; Ali and Watts 2009) suggest that the UAE foreland basin developed by flexural loading of an underlying rifted continental margin. The rifted margin sequence (that includes Araej, Sila, Thamama and Wasia Groups) comprise predominantly shelf carbonates with minor deposits of evaporites and clastics that formed during the Late Permian to Late Cretaceous following breakup of the Arabian Plate and Cimmerian Terrane as well as the formation of Tethyan oceanic crust (e.g., Glennie et al. 1973; Searle 1988b; Ruban et al. 2007) (Figs. 6.1 and 6.2). The lower foreland basin (or Aruma basin) sequence comprises mainly deep-marine mudstones of the Fiqa and Juweiza formations that formed in the Late Cretaceous (Late Coniacian to Campanian) during ophiolite emplacement and thrust and fold loading onto the previously rifted continental margin. The upper foreland basin (Pabdeh basin) is infilled by shales, marls and limestones that formed as a result of the

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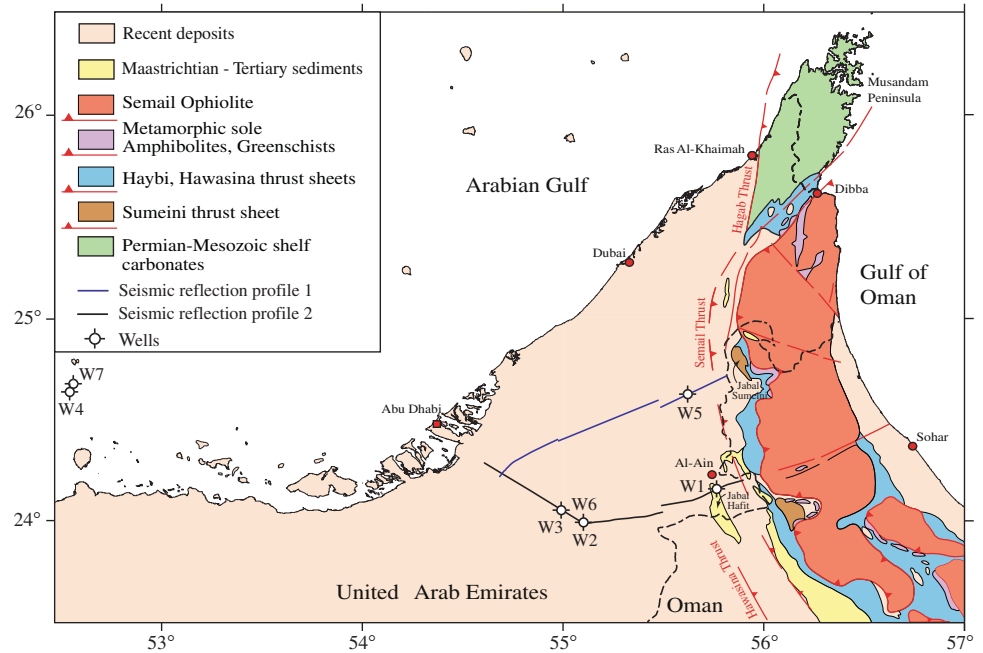
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Fig. 6.1 Simplified regional geological map of the United Arab Emirates and northern Oman mountains, modified from Searle (2007). The thick *black* and *blue* lines and *open circles* show the location of the seismic reflection profiles and exploratory wells used in this paper



Mid-Tertiary uplifting and thrust-culminating Musandam shelf carbonates (Searle 1988a).

Backstripping techniques have proved a powerful technique with which to quantify the tectonic subsidence and uplift of rift-type and foreland basins (e.g., Watts and Ryan 1976; Lin and Watts 2002; Corfield et al. 2005). However, although there have been a number of stratigraphic studies of the rifted margin sequences that are exposed in the north-eastern UAE and northern Oman mountains (e.g., Glennie et al. 1973, 1974; Robertson 1987b; Searle 1988a, Dunne et al. 1990; Rabu 1993; Styles et al. 2006; Searle 2007; Searle and Ali 2009), there have been few quantitative studies of their subsidence and uplift history. As a result, we know little about the thermal and mechanical properties of the Tethyan rifted margin. One problem has been that the exposures are deformed and so it is difficult to restore their thickness. The best record of the subsidence and uplift history, we believe, is in the relatively undeformed rifted margin sequences that underlie the UAE foreland basin.

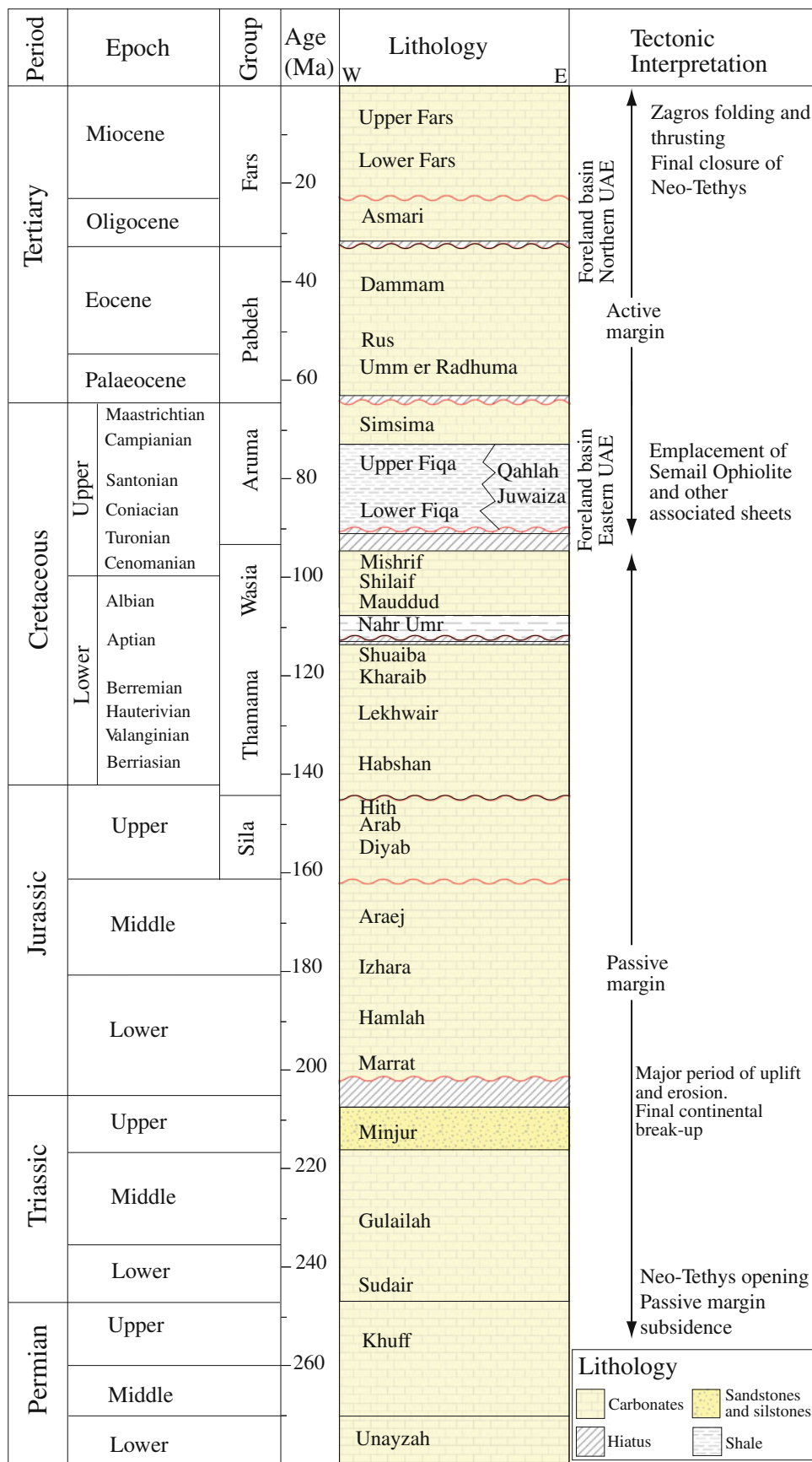
Recently, Ali and Watts (2009) deduced the crustal structure of the northern Oman mountains and UAE foreland basin from the thermal modelling of exploration wells and flexure and gravity modelling of both surface and subsurface (i.e. buried) loads. However, the thermal modelling was based on exploration wells that did not reach the syn-rift sequence of the Late Permian Tethyan margin. The main aim of this paper is, therefore, to use seismic reflection profiles and deep exploratory wells together with modern basin analysis techniques, to determine the tectonic subsidence and uplift history of the Arabian rifted margin and overlying foreland basins. The basin is of tectonic

significance because it formed by ophiolite obduction and Musandam culmination in the northern Oman mountains and flexural loading of the underlying Tethyan rifted margin.

Geological Setting

In the Late Carboniferous and Early Permian the Arabian Plate formed part of the Pangea Supercontinent (e.g., Sharland et al. 2001; Konert et al. 2001; Ruban et al. 2007; Muttoni et al. 2009). Hercynian Unconformity separates the Early Carboniferous (Berwath Formation) and older sediments from the overlying Permian Khuff and Unayzah deposits. In Middle to Late Permian (between 270 and 260 Ma), the Neo-Tethys opening began between the Cimmerian continental blocks (Central Iranian Plate and Lut Block) in the north and the eastern margin of the Arabian Plate in the south (e.g., Glennie et al. 1974; Searle and Graham 1982; Blendinger et al. 1990; Bechennec et al. 1990; Searle et al. 2004; Ruban et al. 2007). By the Late Permian a vast stable shelf carbonate platform was established along the whole northeast Arabian plate margin extending along the entire Zagros and Oman mountain region (Glennie et al. 1973). The mainly carbonate platform that developed on a rapidly subsiding Arabian Plate is represented by the Khuff and equivalent formation, Saiq Formation and Lower Mahil Member in Oman outcrops (Konert et al. 2001; Al-Husseini and Matthews 2010).

Fig. 6.2 Summary stratigraphic column of the UAE foreland basin. Modified from Ali and Watts (2009)



The earliest rifting deposits are dated as Early Permian in the Jabal Qamar exotic in the Dibba Zone, UAE and mid-Permian (Saiq Formation) around the Al Jabal al Akhdar and Saih Hatat shelf carbonate culminations (Searle 2007). Furthermore, the earliest sedimentary rocks in the slope facies Sumeini Group in the Jabal Sumeini (Maqam Formation) are Late Permian to Early Triassic (Watts and Garrison 1986; Watts 1990), equivalent to the Khuff-Saiq Formation on the autochthonous shelf. In addition, the oldest radiolarian cherts in the proximal basin facies (Hamrat Duru Group; Hawasina Complex) are also Late Permian (De Wever et al. 1988; Cooper 1990).

Middle to Late Permian volcanic units related with Tethyan opening are exposed in Oman and UAE in association either with platform carbonates (Saiq Formation) or with shallow to deep marine sediments (Hamrat Duru Series). For example, in the Saih Hatat area in central Oman mountains the initiation of the Neo-Tethys rifting is manifested by two volcanic horizons (Sq1 and Sq2v), comprising mildly alkaline volcanic flows and rhyolitic tuffs, which intrude the Middle-Upper Saiq Formation (Searle 2007). Furthermore, outcrops (Jabal Qamar, Bih and Hagil) in the north-eastern UAE, close to the northern Oman mountains provide additional information for the mid-Late Permian evolution of the Neo-Tethys and the rifted passive Arabian continental margin (Robertson et al. 1990; Maurer et al. 2009).

The stable carbonate platform lasted for over 160 Myrs years throughout the Triassic (Sudair, Gulailah and Minjur Formations), Jurassic (Marrat, Hamlah, Izhara Formations and Sila Group), Early Cretaceous (Thamama Group) and Aptian-Cenomanian (Wasia Group), as the margin subsided slowly due to post-rift thermal subsidence (Sharland et al. 2001; Ziegler 2001). However, the Late Triassic time was marked by emergence of the platform which lead to the deposition of continental sandstone and siltstone beds of Minjur Formation. This formation is only present in onshore Abu Dhabi but absent in offshore Abu Dhabi which indicates a major period of uplift and erosion at the end of the Triassic period (Alsharhan and Kendall 1986). The controls were probably structural uplift related to final continental break-up of Gondwana, combined with the globally recognized sea-level fall (Haq et al. 1988; Robertson and Searle 1990; Robertson et al. 1990) that left large areas of Arabian Plate exposed to lateritic weathering.

By the end of the mid-Cretaceous, the region was a mature carbonate-dominated rifted margin in an expanding Tethys ocean basin. However, the stable sedimentation ended abruptly at the end of the Cenomanian, 93.5 Ma, when SW-directed ophiolite started and the northeastern margin of the Arabian Platform was subjected to compressional deformation. This involved the emplacement of Sumeini, Hawasina, Haybi and Semail Ophiolite thrust

sheets on top of the Tethyan shelf carbonates (Glennie et al. 1973; Lippard et al. 1986; Searle 1988b). The Sumeini, Hawasina and Haybi complexes are distal time equivalent units to the Middle Permian to Cenomanian autochthonous shelf carbonates exposed around Jabal Al-Akhdar and the Musandam Peninsula (Glennie et al. 1973, 1974; Searle et al. 1983, 2004; Searle 2007). The Semail Ophiolite complex is a thick (an up to 8–15 km) thrust sheet comprising Cenomanian oceanic crust and upper mantle. The emplacement of thrust sheets was completed by ~70 Ma (Early Maastrichtian) (Searle 2007).

The stacking of the obducted thrust sheets caused loading, flexural subsidence and partial erosion of the underlying passive margin shelf carbonates (Wasia Group). This resulted in the development of the foreland basin (the Late Cretaceous Aruma basin) and a peripheral bulge at the western edge of the obducted allochthonous units (Robertson 1987a; Patton and O'Connor 1988).

The Aruma foreland basin was infilled by an up to 4.3 km thick Turonian-Campanian sediments, which rapidly increase in thickness towards the northeast (Glennie et al. 1973; Robertson 1987b). The bulk of the Aruma Group in the UAE is deep-marine mudstones of the Fiqa and Juwaiza Formations (Coniacian to Campanian age) reaching a maximum thickness of over 1,800 m in the well W4 and 1,015 m in well W5. Seismic sections across the foreland show the Hawasina thrust tips extending up into the Fiqa Formation (Warburton et al. 1990; Boote et al. 1990; Ali et al. 2008). In several places the top of the allochthonous and neo-autochthon units are marked by the Qahlah Formation comprising reddish lateritic siltstones and conglomerates that contain pebbles of ophiolite. These laterite horizons overlap the mantle sequence harzburgites along the western edge of the ophiolite south of Dibba zone (Searle and Ali 2009).

Following final emplacement of Semail Ophiolite, shallow-marine sedimentation resumed during the Middle-Late Maastrichtian. The Aruma foreland basin sequence and allochthonous units are overlain by the Late Maastrichtian rudist-bearing limestones of Simsima Formation (Glennie et al. 1973; Skelton et al. 1990; Searle and Ali 2009). The margin remained stable until Oligocene time through the deposition of the successive transgressive Paleocene-Eocene Pabdeh Group (Umm Er Radhuma, Rus, Damam and Asmari Formations) and the Oligocene Asmari Formation (Nolan et al. 1990; Skelton et al. 1990).

Compressional deformation resumed during Late Oligocene–Miocene time after a period of stable carbonate sedimentation and is recorded by deposition of the Early Miocene to Pliocene evaporitic deposits of the Fars Group. The Tertiary deformation is evident in the frontal fold and thrust belt of northwestern Oman mountains and adjacent foreland basin, where it produced large-scale folding and

the probable reactivation of deep-seated basement faults (Ali et al. 2008; Boote et al. 1990; Dunne et al. 1990). In Musandam Peninsula, 3.5 km thick sheet of Musandam shelf carbonates was folded and thrust about 15 km westwards along the Hagab thrust giving rise to the huge domal Musandam culmination (Searle 1988a, b; Searle et al. 1983). This deformation is interpreted as the beginning of the Zagros phase of continent–continent collision when the Musandam shelf collided with the central Iran continental block (Ricateau and Riche 1980; Searle 1988a, b; Searle 1988a; Searle et al. 1983).

A second later foreland basin, the Pabdeh basin, was developed in front of the rapidly uplifting and thrust-culminating Musandam shelf carbonates (Searle 1988a; Robertson et al. 1990). Pabdeh Group (Paleocene–Oligocene) consists of deep marine shales, marls and limestones. The Pabdeh basin extends in extreme eastern Abu Dhabi where it has much higher carbonate content (Alsharhan and Nairn 1995). However, the basin dies out to the south of the Musandam and is not present in the central Oman foreland (Searle 1988a).

The stratigraphy of the UAE foreland basin and the northern Oman mountains is summarized in Fig. 6.2.

Seismic Stratigraphy of the Rifted Margin and Overlying Foreland Basins

Two composite regional seismic reflection profiles that have total lengths of 101 km (Profile 1) and 146 km (Profile 2) respectively, were used to determine the subsurface structure of Tethyan rifted margin, frontal thrust/fold belt and foreland basins of the UAE. Profile 1 runs from west of Jabal Sumeini in the border between UAE and Oman with a northeast–southwest orientation towards the UAE foreland basin (Fig. 6.1). Profile 2 traverses across the UAE foreland basin between Al-Ain in the east and Abu Dhabi in the west (Fig. 6.1). The seismic profiles were part of large seismic surveys acquired and processed in the 1980s and early 1990s for hydrocarbon exploration activities in the area.

The quality of seismic profiles is reasonably good except in the eastern part where the quality of some of the seismic lines is poor due mainly to the geological complexity of the area. The seismic profiles reveal the sedimentary structure of the basin, but do not distinguish the syn-rift sequence from the post-rift sequence or the underlying basement. Moreover, the wells W4 and W5 only appear to penetrate the post-rift sequence. However, wireline logs (gamma ray, resistivity and sonic) combined with well reports provided information on subsurface geology at the well location including lithology and physical properties of formations. As a result, well-to-seismic ties and the lateral continuity of seismic horizons allowed identification of five regionally

mapable stratigraphic sequences (Fig. 6.3). These are: (1) Late Permian–Jurassic shelf carbonates, (2) Cretaceous shelf carbonates (Wasia and Thamama Groups), (3) Late Cretaceous foreland basin (Aruma Group), (4) Early–Mid Tertiary foreland basin (Pabdeh Group) and (5) Late Tertiary (Fars Group) sequences. All sequences are tied to wells W4 and W5 (Fig. 6.3). In addition each sequence was delineated on the basis of its seismic character, reflector terminations (e.g. onlap, top lap, downlap and truncation) and structural style, including prominent reflectors, continuity and amplitude (e.g., Mitchum et al. 1977).

Late Permian–Jurassic Shelf Carbonates

The deepest sequence corresponds to the syn-rift and post-rift stratigraphic units of Late Permian to Jurassic shelf carbonates. The top of the sequence exhibits laterally continuous weak reflector. Internally the sequence exhibits high-amplitude, continuous to discontinuous reflectors although some of the reflectors may be due multiples. The crystalline basement cannot be imaged due to either thick syn-rift and post rift sediment or contamination of multiples. However, we estimate that the shelf carbonate sequences comprise at least 4 km [2.0 s Two-Way Travel Time (TWT)] of syn-rift and post-rift sediments. Wireline logs show low gamma ray (~ 15 API) and neutron porosity ($\sim 2\%$) responses with some spikes close to the top of the sequence.

The seismic profiles (Figs. 6.4 and 6.5) suggest the presence of major thrust faults that cut through the entire shelf carbonates and overlying foreland basin sequences as well as low-displacement reverse faults that offset the top of the sequence (Fig. 6.4).

Cretaceous Shelf Carbonates (Thamama and Wasia Groups)

The top of the Mesozoic shelf carbonates (top of Wasia Group) is a laterally continuous strong reflector that can be easily traced across the profiles. Internally the sequence exhibits high-amplitude, continuous to discontinuous reflectors. Wireline logs through the sequence indicate low gamma ray (10–15 API) and low neutron porosity (2–4%) with sharp changes of porosity at Wasia Group. In some seismic sections, the top of the sequence show diffuse top lap and truncations with low angle geometry to overlying Lower Fiqqa reflectors which may correspond to the regional Late Turonian Wasia–Aruma break (Fig. 6.5). Moreover, Profile 2 suggests the presence of fault blocks that generally step up towards the mountain front with a low-displacement normal faults that offset the top of the sequence. Boote et al. (1990) and Ali and Watts (2009)

Fig. 6.3 Seismic reflection profile in the immediate vicinity of well W4 showing well-to-seismic tie. Location of the well in shown in Fig. 6.1. Total depth (TD) of the well is 4,724 m, Late Triassic Gulailah Formation. Information used for well-to-seismic tie includes biostratigraphic ages, lithologies, gamma ray log. Also shown is the porosity versus depth curve resampled porosity derived from neutron porosity log

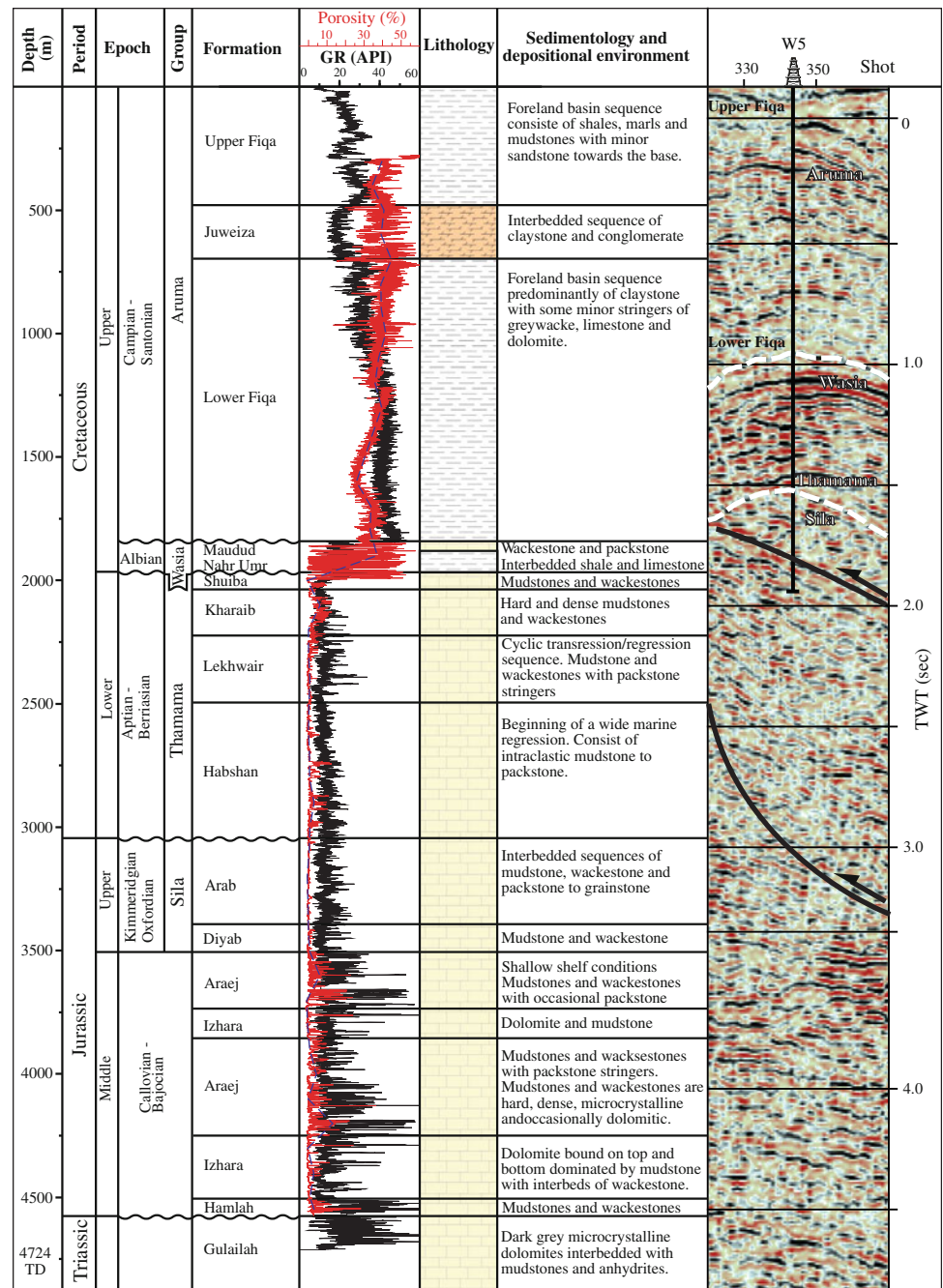
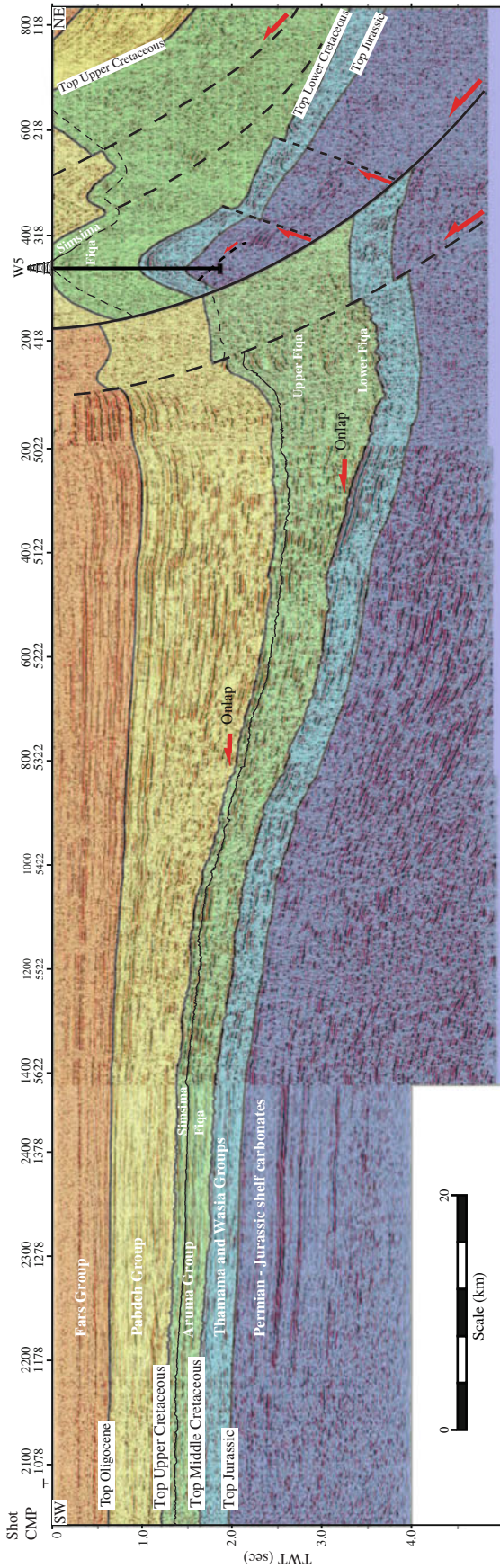
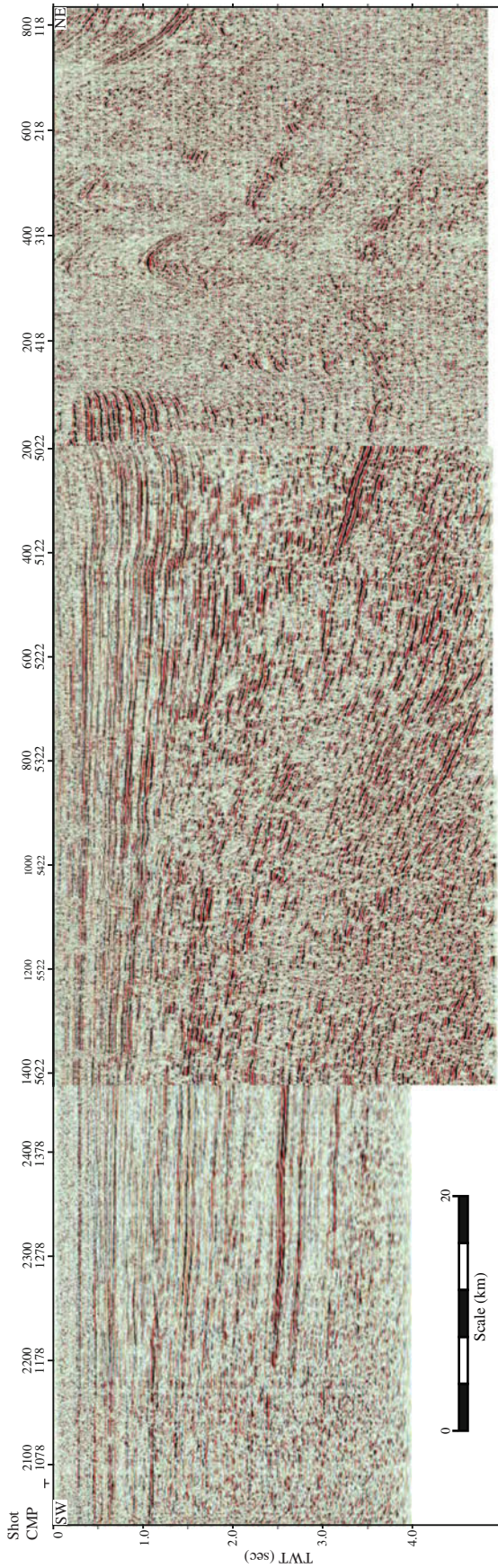


Fig. 6.4 a Uninterpreted northern composite regional seismic reflection profile (Profile 1) across the UAE foreland basin (for location see Fig. 6.1). A vibrator source and split spread geometry were used for all of the seismic lines. The CDP distance range from 12.5 to 45 m and the fold range from 48 to 160. Standard processing steps were used. However, for some lines FK filter, multiple suppression filters and

DMO were applied. **b** Interpreted seismic reflection profile showing the UAE foreland basins and the underlying rifted margin sequences. Note the progressive onlap of the Fiqa on the Late Cretaceous shelf carbonates which delineates the transition from an extensional rifted margin setting to a compressional foreland basin setting. The exploratory well W4, is shown along the profile



interpreted these observations as the result of a period of plate margin uplift and erosion caused by the development of a peripheral bulge during the initial phases of emplacement of the allochthons.

Late Cretaceous Foreland Basin (Aruma Group) Sequence

The base of Aruma foreland basin sequence is a prominent, readily traceable reflector of high amplitude and medium continuity across most of the study area, marking the contact between the Late Cretaceous foreland basin sequence of Aruma Group and rifted margin sequence of Wasia Group (Figs. 6.4 and 6.5). In wireline logs this contact shows an abrupt decrease from ~ 50 to 20 API in gamma ray and immediate drop from ~ 35 to 10 % in neutron porosity response.

The sequence is wedge shaped with a maximum thickness of ~ 4 km (2.0 s TWT) towards the east close to the thrust front, except around well W4 where the sequence has been partially eroded. The thickening of the sequence to the northeast of Profile 1 is probably due to tectonic thickening. To the east the sequence displays internal seismic reflections showing a variable amplitude, discontinuous, low-frequency, low-vertical spacing as well as chaotic pattern. To the west, sequence gradually onlaps onto the underlying rifted margin sequence to the west, where it exhibits low-amplitude sub-parallel reflectors. We refer to this sequence as the Fiqa Formation which forms most of the foreland basin sequence infill deposits (Glennie et al. 1974; Glennie et al. 1973; Robertson 1987b). The seismic data suggest that the lower part of the Fiqa was deposited immediately after the development of the foreland basin as a response to loading of the Semail Ophiolite and its associated thrust sheets. In contrast, the upper part of the Fiqa sequence was deposited during the final stages of the emplacement of the allochthonous units (Ali et al. 2008). The flexural bulge is obscured as it is covered by at least 2 km of sediment, possibly because of an increase in accommodation space due to dynamic effects associated with the subduction of the Arabian plate beneath the Central Iran plate.

The upper section of the sequence is characterised by prominent high-amplitude, continuous reflector suggesting

a conformable contact to the underlying Fiqa Formation. This is interpreted as a shallow-marine carbonate that was deposited as the margin subsided and was transgressed during the Late Maastrichtian. The section is most likely to represent the Simsim and Qahlah formations which are exposed along the western flanks of northern Oman mountains (Skelton et al. 1990; Searle and Ali 2009).

Early-Middle Tertiary Foreland Basin (Pabdeh Group) Sequence

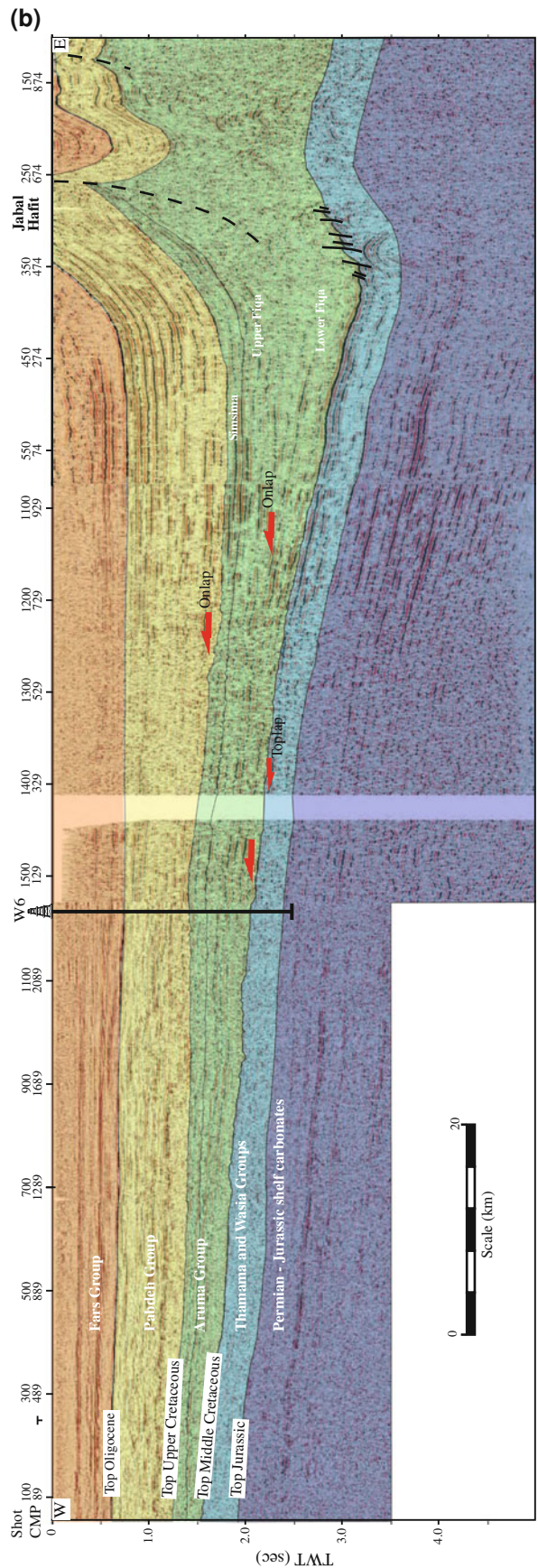
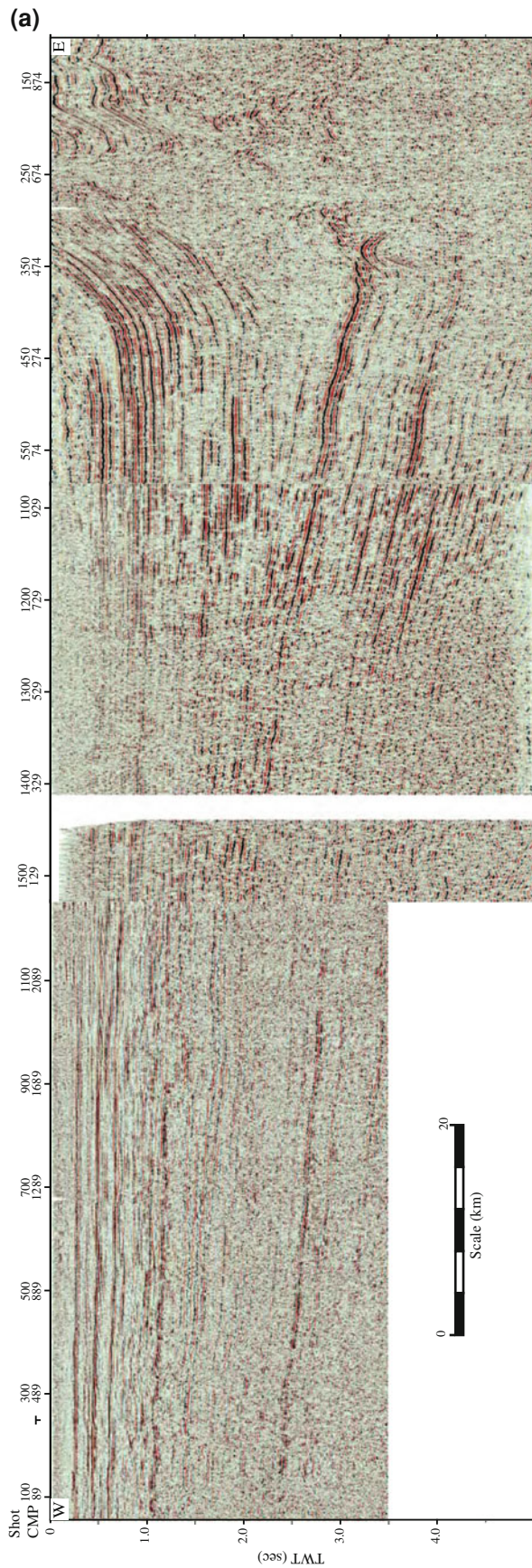
The Early-Middle Tertiary (Pabdeh Group) sequence is characterized by highly deformed concordant reflections to the east. To the west the sequence is characterized by high-amplitude, continuous, sub-parallel reflectors. Internally the sequences display strong amplitude, continuous, parallel reflectors that can be mapped throughout the seismic section. The bottom section of sequence is disconformable with the Aruma Group and is characterized by high-amplitude, continuous reflectors. The top of the sequence is laterally continuous, high to moderate amplitude reflector.

The sequence is overall wedge shaped with a maximum thickness of ~ 3 km (1.5 s TWT) to the east of the northern profile (Profile 1). To the west, its reflection terminations indicate onlap geometries onto the underlying Aruma Group while gradually pinching out further westwards. Towards frontal thrust front (around well W4 and Jabal Hafit) the thickness of the sequence decreases dramatically due to the post-Oligocene uplift which caused erosion of large parts of the mountain belt. Moreover, the thickness of the sequence decreases from north to south (from maximum thickness of ~ 1.5 s TWT in the east of Profile 1 to ~ 1.0 s TWT east of Profile 2). The Pabdeh Group is thicker west of Musandam Peninsula, however the sequence does not extend further to the south in the central Oman (Searle 1988a).

The stratigraphy of the Pabdeh Group clearly indicates that a second, later foreland basin developed during mid-Tertiary times. The basin probably formed as a result of lithospheric flexure in front of the rapidly uplifting and thrust-culminating Musandam shelf carbonates at the beginning of the Zagros phase of continent–continent collision when the Musandam shelf first collided with the central Iran continental block (Searle 1988a, b; Searle et al 1983).

Fig. 6.5 **a** Uninterpreted southern composite regional seismic reflection profile (Profile 2) across the UAE foreland basin (for location see Fig. 6.1). A vibrator source and split spread geometry were used for all of the seismic lines. The CDP distance range from 12.5 to 45 m and the fold range from 48 to 160. Standard processing steps were used. However, for some lines FK filter, multiple suppression filters

and DMO were applied. **b** Interpreted seismic reflection profile showing the UAE foreland basins and the underlying rifted margin sequences. Note the progressive onlap of the Fiqa on the Late Cretaceous shelf carbonates which delineates the transition from an extensional rifted margin setting to a compressional foreland basin setting. The exploratory well W4, is shown along the profile



Late Tertiary (Fars Group) Sequence

This sequence exhibits strong amplitude, continuous, sub-parallel reflectors that can be mapped throughout the seismic section. In the west the thickness of this sequence is consistent throughout the seismic section, whereas to the east its thickness increases and reaches approximately ~ 2 km (1.0 s TWT) in Profile 1. The increase in thickness may be related to the continuous subsidence of the Pabdeh foreland basin due to the culmination of the Hagab thrust sheet in the Musandam Peninsula. Towards the extreme east on the frontal thrust belt the sequence is totally absent particularly in Profile 1, due to the post-Oligocene uplift and erosion.

Structural Style of the Frontal Fold and Thrust Belt

Folding and thrusting dominate the structural style of the eastern part of the seismic profiles. The seismic profiles support the surface geology, which shows at least two major phases of deformation, a Late Cretaceous phase developed in the east resulting from the emplacement of the Oman mountains thrust sheets, and a Tertiary deformation phase resulting from the culmination of the Musandam thrust sheet (e.g., Searle 1988a; Searle and Ali 2009). Moreover, the seismic sections suggest that the Tertiary compressional event induced the thrusting of Late Permian-Mesozoic shelf carbonates and the folding of the Late Cretaceous and Tertiary sedimentary cover.

The seismic Profile 2 shows evidence of small-offset normal faults that cut through the shelf carbonates and die-out in the unconformable foreland basin sequence (Fiqa Formation). These faults are probably related to the flexural bending of the shelf carbonate sequence in response to the crustal loading during the initial phases of emplacement of the allochthons (Boote et al. 1990; Warburton et al 1990; Ali et al. 2009).

Seismic Profile 1 shows that foreland basin sequences (Aruma and Pabdeh Groups) are cut by relatively high-angle west verging thrusts that are associated with a series of tight folds. Most of these thrusts extend deeper and offset the carbonate platform. These faults appear to merge and detach within the lower part of Late Permian—Mesozoic shelf carbonate sequence as indicated by the series of imbricate thrusts. In contrast, Profile 2 suggests the presence of a WSW-dipping high-angle east verging thrust fault underlying the tight fold of Jabal Hafit that cut through the foreland basin sequence and overlying sequences. The thrust appears to detach within the lower part of the Aruma sequence or along the top of the shelf carbonates.

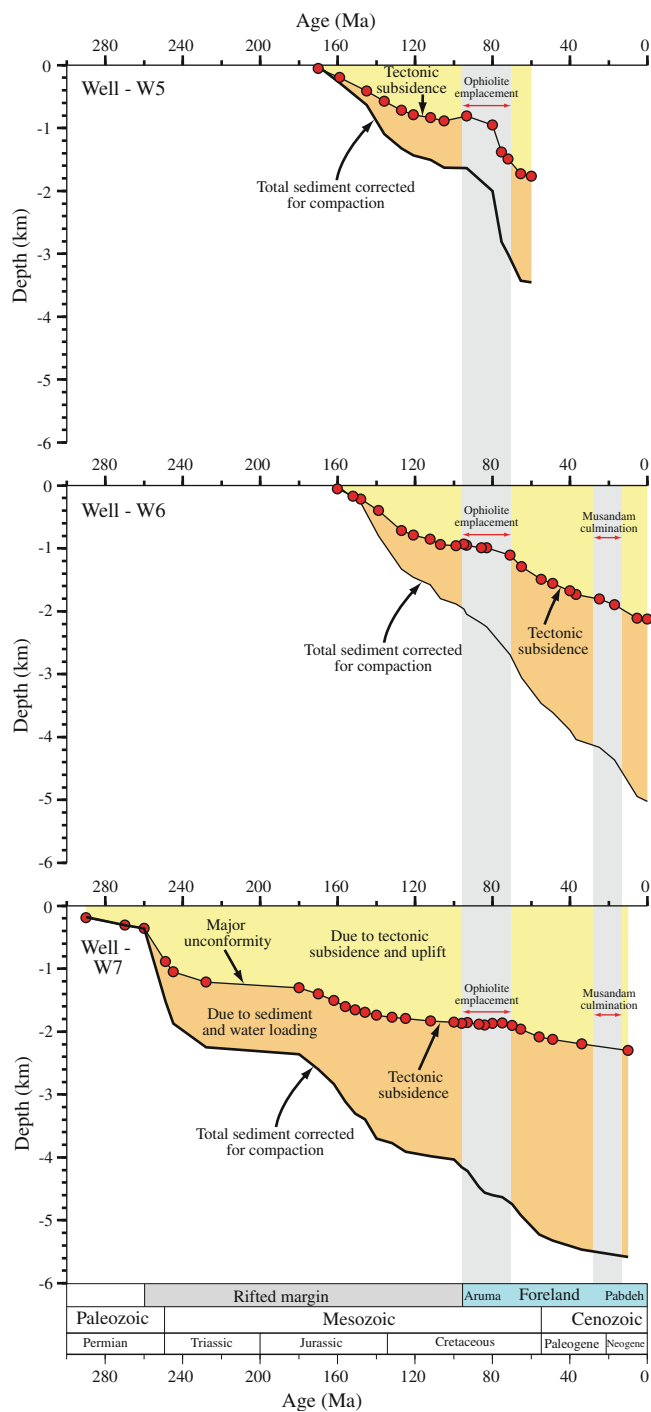
The most prominent thrust is illustrated in Profile 1 and cuts through the entire Late Permian-Mesozoic shelf carbonates and show listric shape flattening into a basal detachment (Fig. 6.4). The thrust causes large-scale uplift on the hanging wall of the thrust (>2.0 s TWT) and juxtaposition of shelf carbonates onto Aruma Group. Major subsidence is also observed on the south-western side of the major thrust where the shelf carbonates are at ~ 3.5 s TWT. Significant subsidence is also seen on the north-eastern side of the uplift. In addition, the profile suggests the presence of low-displacement back thrusts that offset the top of Thamama-Wasia sequence but do not continue upward into the overlying Aruma sequence. The precise timing of thrusting and folding is debatable. However, the seismic sections show that most of thrust faults extend tip lines up into the Pabdeh and Fars Groups showing that timing of slip extended up to the post- Oligocene–Miocene and continue till present day. Moreover, in the northern UAE and west of the Musandam peninsula these thrusts are sealed by the flat-lying Miocene Mishan Formation marls and clays (Michaelis and Pauken 1990). Therefore, our interpretation is consistent with many other studies (e.g., Boote et al. 1990; Ricateau and Riche 1980; Searle et al. 1983; Searle 1988b; Searle 2007), which correlated the thrusting and folding that resulted in the foreland basins of the UAE with the collision of Arabia with Central Iran along the Zagros Suture which started in the Late Oligocene with indentation of the Musandam peninsula and initiation of the Hagab thrust.

Backstripping, Subsidence and Uplift History of the Rifted Margin

Backstripping is a powerful tool for quantify the tectonic subsidence and uplift history of a sedimentary basin (e.g., Watts and Ryan 1976). The technique, which corrects the stratigraphic record for the effects of compaction, water depths, and sea-level changes (e.g., Steckler and Watts 1978), determines the depth-to-basement in the absence of sediment and water loading, and hence isolate the unknown tectonic driving forces responsible for the rift basin subsidence. By comparing this depth to predictions of thermal models it is possible to constrain the amount of thinning and, hence heating, of a margin during rifting.

The subsidence analysis performed in this study is based on biostratigraphic data from three exploration wells across the UAE foreland basins (Fig. 6.1). We label the wells W4, W5 and W6 in order to distinguish them from wells W1, W2 and W3 that were analysed by Ali and Watts (2009). Well W4 is located to the east over the thrust and fold belt along seismic Profile 1. Well W5 is located in the deep,

Fig. 6.6 Backstripping of biostratigraphic data from wells W4, W5 and W6 showing the total sediment accumulation together with the backstripped tectonic subsidence and uplift. Note that the early part of the backstrip curves are concave-up and resembles the tectonic subsidence curves of rifted margins. Well W4 suggests two phases of accelerated subsidence separated by major unconformity between 220 and 180 Ma. We interpret the inflection points at ~90 and ~25 Ma as due to orogenic loading. Also, note that the effects of orogenic loading are more clearly seen in well W4 than in well W6 due to its proximity to the thrust front



flexed, part of the basin, along seismic Profile 2, about 90 km east of Abu Dhabi city. Well W6 is located to the west near crest of the flexural bulge in the border between UAE and Qatar. Wells W4 and W5 penetrated foreland basin sequences (Aruma and Pabdeh Groups) and upper part of the post-rift sequences, whereas well W6 penetrated syn-rift sediments (Khuff and Unayzah Formations). The wells were selected in order to determine the history of Late

Permian rifting of Tethyan Ocean as well as the compressional deformation resulted the foreland basins in the UAE.

Figure 6.6 shows the tectonic subsidence curves resulting from the backstripping analysis at each of the wells. The tectonic subsidence was computed assuming densities of water, sediment grains, and mantle of 1,030, 2,670, and 3,330 kgm⁻³, respectively, and an Airy model of isostasy. A correction for compaction was calculated using porosity-depth

relationships based on neutron porosity logs of each well (Fig. 6.3). The water depth is a difficult problem. Whilst the rift margin sequences were deposited in a shallow-water carbonate shelf facies ($< \sim 20$ m), the palaeobathymetry of the foreland basin sequence is unknown. We have therefore assumed a zero water depth for each stratigraphic sequence. Finally, the resulting tectonic subsidence and uplift were corrected for the effect of sea-level change using the smooth global curve of Watts and Steckler (1979), which has been shown by Miller et al. (2005) to be representative of the long-term, sea-level curve during the Mesozoic and Cenozoic. For the Upper Palaeozoic and Lower Mesozoic sequences we used sea-level curves of Sahagian and Jones (1993) and Haq and Al-Qahtani (2005).

Figure 6.6 shows that the sediment accumulation at wells W4, W5 and W6 can be divided into two parts: one represents the contribution of sediment and water loading, the other the unknown tectonic *driving* subsidence and uplift. The tectonic subsidence curves show clearly one episode of rifting. There is evidence in W6, however, of a second phase of rifting. The curves also illustrate the flexural bulge and subsidence associated with ophiolite emplacement. In summary, the tectonic subsidence and uplift curves show five main features:

Late Permian to Late Triassic Rifting Phase

The most striking feature of the backstrip at well W6 is the fast initial and then slowing subsidence. The curve shape resembles the typical concave-up profile of a rifted basin and so we interpret it as representative of the fast initial syn-rift subsidence followed by exponential post-rift thermal subsidence of the Tethyan rifted margin that underlies the UAE foreland basins. The tectonic subsidence suggests that the rifting started on Late Permian (260 Ma) with syn-rift duration of about 15 Ma. The subsidence phase is interpreted to be related to the initial opening of Tethyan Ocean. This subsidence phase agrees well with the Middle to Late Permian volcanic rocks which are exposed in Oman and UAE and associated either with platform carbonates or with shallow to deep marine sediments which suggests that the main rifting of Neo-Tethys took place in the middle Permian to Late Permian [e.g., Searle and Graham 1982; Blendinger et al. 1990; Rabu 1993; Robertson and Searle 1990; Bechennec et al. 1990; Searle et al. 2004].

Late Triassic to Early Jurassic Uplift

The tectonic subsidence curve show a period of slower subsidence or uplift during Late Triassic to Early Jurassic

times. This episode coincides with emergence of the platform and a period of a pronounced long-term sea-level lowstand, caused by eustatic fall in sea-level and by an uplift of the margin related to final continental break-up of Gondwana (Robertson et al. 1990). This resulted in a major period of non-deposition and partial erosion of the Triassic sediments. For example, during the Late Triassic, the Qatar-South Fars Arch was actively uplifted, leading to non-deposition and erosion of Minjur Formation in western offshore areas of Abu Dhabi and most parts of Qatar (Alsharhan and Kendall 1986; Alsharhan and Nairn 1994). Hence, the Late Triassic formation of Minjur and Early Jurassic formation of Marrat are missing in well W6.

Early Jurassic to Late Cretaceous Rifting Phase

The tectonic subsidence curve of well W6 indicates renewed phase of rifting at ~ 180 Ma (Early Jurassic). This second rift episode continued throughout the Late Cretaceous times in response to the opening of the Tethyan Ocean.

Late Cretaceous Uplift Followed by Increase Subsidence

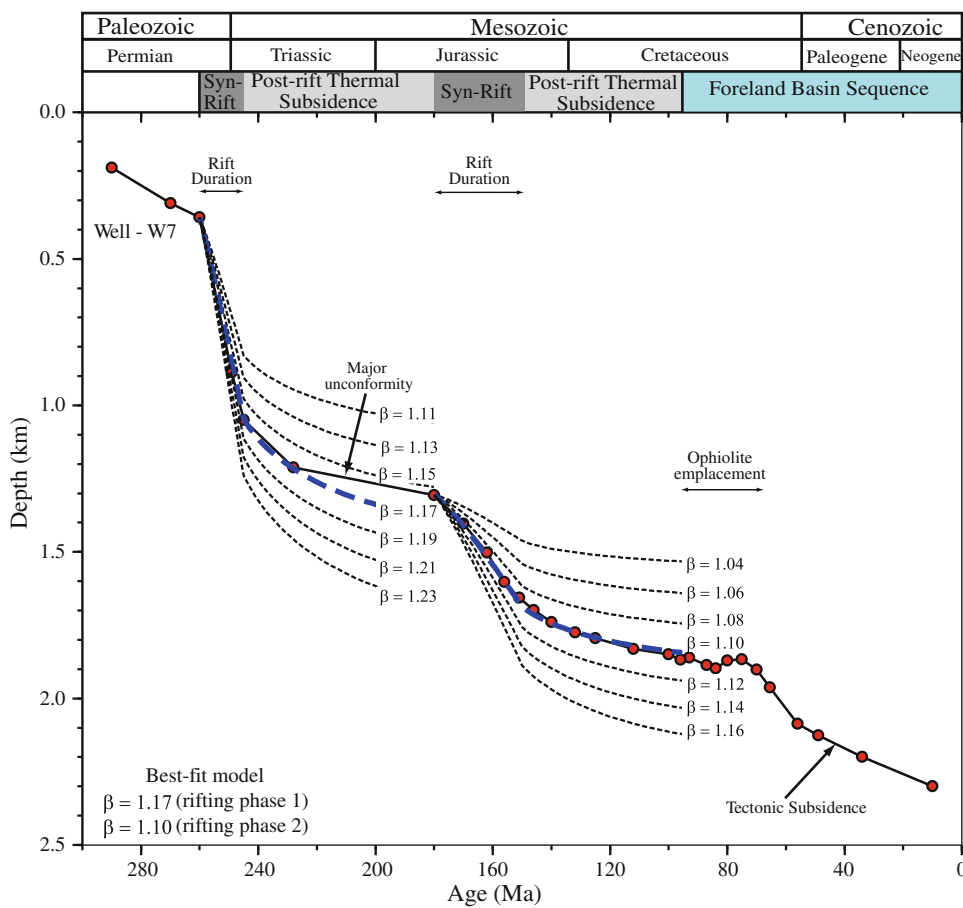
We see a significant uplift particularly wells located close to the thrust front (Wells W4 and W5) in the Late Cretaceous followed by an extremely rapid subsidence. The tectonic subsidence suggests that the uplift migrated through time from east to west. In well W4 the uplift started at ~ 90 Ma whereas in wells W6 the uplift began ~ 10 Ma later. We attribute the uplift and subsidence to a flexural bulge that developed on the Arabian plate ahead of the Semail Ophiolite load. Rapid subsidence occurred in well W4, whereas other wells indicate gentle subsidence after thrusting ceased and the foreland basin was filled.

There is a suggestion from the backstrip curves that the increase in tectonic subsidence at ~ 80 Ma is greater in well W4 than it is in well W5. This result is not unexpected because well W4 is located nearer to the ophiolite load than well W5. Well W6 (Fig. 6.1), however, is located further away and therefore the ophiolite-induced increase in subsidence is less apparent at this well.

Late Tertiary Uplift and Subsidence

The backstrip curve of well W5, which penetrated Tertiary sequences, indicates an increase in subsidence during Mid-Late Tertiary at ~ 25 – 15 Ma. We attribute this increase in subsidence to formation of a second foreland basin in

Fig. 6.7 Comparison of the backstrip at well W6 to the predictions of a uniform extension model with crust and mantle extension, β , in the range 1.04–1.23. The calculated is based on an initial rift of 260 Ma with rift duration of 15 Myr and second of period rifting starting at 180 with duration of stretching of 30 Ma. The best fit between the early part of the tectonic subsidence curve and the calculated curve is for $\beta = 1.17$ for the initial rifting and $\beta = 1.10$ for the final rifting



response of the collision of the Arabian and Eurasian plates and culmination of Musandam Peninsula.

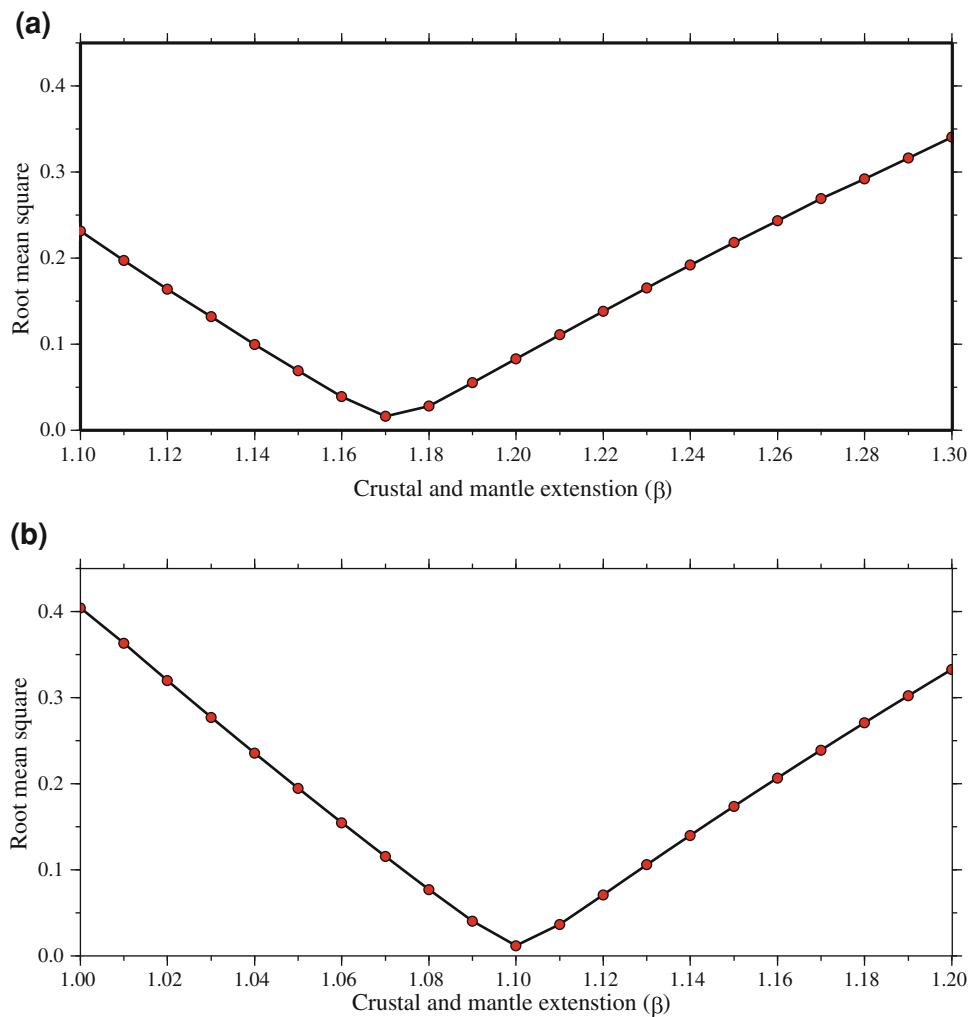
The main features in the backstrip curve at well W6 are repeated at wells W4 and W5 (Fig. 6.6). This reassures us that we have corrected the stratigraphic record at each well for local effects and that backstripping does indeed isolate the main features of the regional tectonic subsidence and uplift. However, the subsidence rate during the second phase of rifting is higher in wells W4 and W5. The increase in subsidence could be related to a repeat Jurassic sequence for well W4 since it penetrated the Oman mountains thrust front. In addition, wells W4 and W5 only penetrated post-rift sequence up to Late Jurassic. Therefore, overall tectonic subsidence is higher due to the compaction effect. Moreover, some of the differences in tectonic subsidence between wells are probably related to secondary mechanisms such as flexure, dynamic topography or highly variable stretching resulting locally more stretching in the east close to wells W4 and W5 during the second phase of Tethyan rifting.

We compare in Fig. 6.7 the tectonic subsidence and uplift at well W6 to predictions of a uniform extension model (McKenzie 1978) with different values of the amount

of crust and mantle stretching, β . We use here a modified form of the McKenzie model (Cochran, 1981), which incorporates the effects of a finite duration of rifting. We assumed two rifting phases. For well W6, the initial rifting started at ~ 260 Ma and ~ 245 Ma appears to mark the onset of the exponential post-rift thermal subsidence, giving an estimate for the duration of stretching of 260–245 Ma, i.e., 15 Ma. In addition an initial crustal thickness, T_c , of 31.2 km was assumed. The second rifting phase started at 180 Ma with a rifting duration of 30 Ma. Furthermore, we moved the observed curves vertically until a satisfactory fit with the modelled curves was achieved. This takes into account the fact that well W6, penetrate the syn-rift Khuff and Unayza Formations as well as post syn-rift sediments.

The calculated tectonic subsidence curves for each rift phase in Fig. 6.7 consist of two parts, the initial syn-rift subsidence and the exponential post-rift thermal subsidence. The best fit for the initial rifting is $\beta \sim 1.2$, which implies a thinning of the crust from 31.2 km before rifting to 27.5 km after. We, therefore, assumed an initial crustal thickness of 27.5 km for the second rifting. This resulted a best-fit of $\beta = 1.1$ for the second rifting. Hence, Fig. 6.7 shows that it is possible to explain the tectonic subsidence and uplift at

Fig. 6.8 Sensitivity analysis showing the root mean square (*RMS*) difference between observed and calculated tectonic subsidence based on predictions of uniform extension model at well W6. **a** The figure shows that for the initial rifting phase the best fitting values of crust and mantle extension, β , is 1.17. **b** For the second period of rifting the figure illustrates that the best fit model to the tectonic subsidence curve β , is 1.10



well W6 with a uniform stretching model in which the amount of initial crustal and mantle extension, β , is 1.2 and the amount of second stretching, β , is 1.1. This parameter-pair explains the backstrip data well as can be seen from the sensitivity analysis in Fig. 6.8. However, there are discrepancies, which we attribute to uncertainties in paleobathymetry, sea level, and stratigraphic ages.

Discussion

The Tethyan margin evolution can be summarized by periods of strong stretching punctuated by periods of slower subsidence or uplift and thermal subsidence. The backstripped subsidence and uplift history suggest at least two rifting phases. The first rift phase started during Late Permian (260 Ma) with a stretching value, β , of 1.2, followed by period of uplift and erosion. This was followed by a second rifting pulse from Early Jurassic to Late Cretaceous (180–90 Ma) with a β of 1.1. There is possibility earlier rifting phase starting Late Carboniferous–Early

Permian, but the well W6 does not penetrate the syn-rift of this rifting episode. These subsidence phases agree with the previous tectonic context. For example, there is general agreement that major rifting also took place in Late Permian (Glennie et al. 1974; Bechennec et al. 1990) and in Late Triassic–Early Jurassic time (Glennie et al. 1974; Searle et al. 1980; Robertson 1986; Bechennec et al. 1990). As a result Robertson and Searle (1990) have proposed a multi-stage rift model in Oman (1) Late Carboniferous–Early Permian initial ‘non-volcanic’ rifting dominated by block-faulting as suggested by Blendinger et al., (1990) (2) Late Permian rifting with volcanism (3) Late Triassic–Early Jurassic volcanism recording final continental break-up.

Moreover, anomalous subsidence involving pulses of rapid subsidence separated by periods of relative tectonic quiescence were observed on the southern and northern Neo-Tethyan margin (e.g., Ellouz et al. 2003; Hanne et al. 2003; Le Nindre et al. 2003; Patriat et al. 2003).

The amount of crustal and mantle extension means a depth-to-Moho of ~ 35.0 km (24.0 km + sediment fill) beneath the UAE foreland. This is consistent to predicted

depth-to-Moho of Ali and Watts (2009) which showed that this depth can explain the observed gravity anomaly.

Ali and Watts (2009) explained the tectonic subsidence and uplift of wells in the UAE foreland basin with a depth-dependent extension model in which the amount of crustal extension, γ , is 1.3 and the amount of mantle extension, β , is 2.5, whereas we have assumed in this paper a uniform extension model with $\gamma = \beta = 1.1$ and 1.2. A possible explanation of such a large difference of thinning is that stretching was spatially variable resulting in more crust and, particularly, mantle stretching to the east where the backstripped wells of Ali and Watts (2009) were located. This is reasonable as a uniform extension model with small amounts of crust and mantle thinning would be expected for the relatively cool, unstretched Arabian plate interior to the west while a depth dependant model with a small increase in crustal thinning and a large amount of mantle thinning might apply for its relatively hot, stretched rifted margin to the east. However, the wells backstripped by Ali and Watts (2009) were relatively shallow and so they did not penetrate the syn-rift and all the post-rift sediments. Therefore, the sediment loading effect, which includes compaction, may have been underestimated and hence the tectonic subsidence overestimated. Another potential difficulty is that some of the differences might be related to secondary mechanisms such as flexure, in-plane compression, dynamic topography and long wavelength contributions to the subsidence of the subduction of the Arabian plate which may have affected, for example, the tectonic subsidence and uplift at the wells in the west more than the wells in the east.

It is clear from the observed and calculated curves in Figs. 6.6 and 6.7 that the uniform extension models are not able to explain all the features of the backstrip curves. In particular, the models cannot account for the excess subsidence which begins at ~ 80 – 85 Ma and reaches a maximum value of ~ 1 km at Early Tertiary times. The tectonic subsidence after ~ 80 Ma is too large to be explained by a thermal contraction model. The initiation of the excess subsidence corresponds in time to the emplacement of the Semail Ophiolite and its associated thrusts. We, therefore, attribute the excess subsidence to orogenic loading associated with flexure of the underlying rifted margin. Ali and Watts (2009) suggested by using gravity and flexure modelling that the excess subsidence after 80 Ma is can be explained by a simple model in which both surface (i.e. topographic) and sub-surface (i.e. ophiolitic) loads were emplaced on a lithosphere with an effective elastic thickness, T_e , of ~ 20 – 25 km.

Furthermore, the increase in subsidence at ~ 25 – 15 Ma that is seen in well W5 correspond in time the collision of Arabia with Central Iran along the Zagros Suture started in the Late Oligocene with indentation of the Musandam peninsula and initiation of the Hagab thrust (Searle 1988a, b;

Searle et al. 1983). We, therefore, attribute the excess subsidence to the development of the second foreland basin (Pabdeh basin) by flexural loading of an underlying Aruma foreland basin and rifted continental margin. Accordingly both regional seismic interpretation and tectonic subsidence curves confirm that at least two phases of thrusting occur in the northern Oman mountains and foreland, one Late Cretaceous and one post-Eocene-Oligocene.

Conclusions

Seismic reflection profiles and deep exploratory well data have provided the key subsurface information needed to better understand the tectonic subsidence and uplift history of the rifted margin and overlying foreland basins. In summary this study has found that:

1. Seismic stratigraphy of regional seismic profiles show that the UAE sedimentary basin can be divided into three main sequences: (1) a lower rifted margin sequence, (2) an intermediate Aruma foreland basin sequence, and (3) an upper Pabdeh foreland basin sequence. The rifted margin sequence comprises at least 4 km of syn-rift and post-rift sediment. The Aruma foreland basin comprises at least 4 km of sediment, whereas the Pabdeh foreland basin comprises 3 km. This yields a total sediment thickness of at least 11 km in the foredeep basins of the UAE.
2. Backstripping of biostratigraphic data from three deep exploration wells suggest two phases of rifting on the Arabian margin in the UAE interrupted by period of uplift. The initial rifting initiated on Late Permian (260 Ma) whereas the final rifting started on Early Jurassic (180 Ma). The tectonic subsidence phases are attributed to thermal contraction following heating and thinning of the crust at the time of rifting. The initial rifting phase is interpreted to be related to the initial opening and final of Tethyan Ocean, whereas the Early Jurassic rifting is attributed to final continental break-up of Gondwana respectively.
3. The tectonic subsidence and uplift history at the wells can be explained by a model in which the margin developed by uniform depth extension with an initial age of rifting of 260 Ma and a stretching factor, β , of 1.2 and final rifting of 180 of β , 1.1.
4. The backstrip curves suggest that transition from an extensional rifted margin to a compressional foreland basin occurred during the Late Cretaceous (at ~ 90 Ma). This corresponds to the timing of the Semail Ophiolite loading and foreland basin flexure. Moreover, the backstrip curves indicate an increase in tectonic subsidence during Late Tertiary. This was attributed to the regional compressional during Late Oligocene–Miocene time was related to collision in the Zagros area.

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References

- Al-Husseini MI, Matthews RK (2010) Calibrating mid-permian to early triassic khuff sequences with orbital clocks. *Geo Arabia (Manama)* 15:171–206
- Ali MY, Sirat M, Small J (2008) Geophysical investigation of Al Jaww Plain, Eastern Abu Dhabi: implications for structure and evolution of the frontal fold belts of the Oman mountains. *Geo Arabia* 13: 91–118
- Ali MY, Sirat M, Small J (2009) Integrated gravity and seismic investigation over the Jabal Hafit structure: implications for basement configuration of the frontal fold-and-thrust belt of the Northern Oman mountains. *J Pet Geol* 32:21–37
- Ali MY, Watts AB (2009) Subsidence history, gravity anomalies and flexure of the United Arab Emirates (UAE) foreland basin. *Geo Arabia* 14:17–44
- Alsharhan AS, Kendall CGSC (1986) Precambrian to jurassic rocks of Arabian Gulf and adjacent areas; their facies, depositional setting, and hydrocarbon habitat. *AAPG Bulletin* 70:977–1002
- Alsharhan AS, Nairn AEM (1994) The late Permian carbonates (Khuff Formation) in the western Arabian Gulf; its hydrocarbon parameters and paleogeographical aspects. *Carbonates Evaporites* 9:132–142
- Alsharhan AS, Nairn AEM (1995) Tertiary of the Arabian Gulf: sedimentology and hydrocarbon potential. *Palaeogeogr Palaeoclimatol Palaeoecol* 114:369–384
- Beaumont C (1981) Foreland basins. *Geophys J Roy Astron Soc* 65:291–329
- Bechennec F, Le Metour J, Rabu D, Bourdillon-de-Grissac C, de Wever P, Beurrier M, Villey M (1990) The Hawasina Nappes; stratigraphy, palaeogeography and structural evolution of a fragment of the South-Tethyan passive continental margin. *Geol Soc Spec Pub* 49:213–223
- Blendinger W, Van Vliet A, Clarke MWH (1990) Updoming, rifting and continental margin development during the late Palaeozoic in northern Oman. *Geol Soc Spec Pub* 49:27–37
- Boote DRD, Mou D, Waite RI, Robertson AHF, Searle MP, Ries AC (1990) Structural evolution of the Suneinah Foreland, central Oman Mountains. *Geol Soc Spec Pub* 49:397–418
- Buck WR, Lavier LL, Poliakov ANB (1999) How to make a rift wide. *Philos Trans R Soc Math Phys Eng Sci* 357:671–693
- Cochran JR (1981) Simple models of diffuse extension and the pre-seafloor spreading development of the continental margin of the northeastern Gulf of Aden. *Oceanol Acta* 4(supplement):155–165
- Cooper DJW (1990) Sedimentary evolution and palaeogeographical reconstruction of the Mesozoic continental rise in Oman; evidence from the Hamrat Duru group. *Geol Soc Spec Pub* 49:161–187
- Corfield RI, Watts AB, Searle MP (2005) Subsidence history of the north Indian continental margin Zaskar-Ladakh Himalaya, NW India. *J Geol Soc* 162:135–146
- De Wever P, Bourdillon-de Grissac C, Bechennec F (1988) Permian age from radiolarites of the Hawasina nappes, Oman Mountains. *Geology* 16:912–914
- DeCelles PG, Giles KA (1996) Foreland basin systems. *Basin Res* 8:105–123
- Dunne LA, Manoogian PR, Pierini DF, Robertson AHF, Searle MP, Ries AC (1990) Structural style and domains of the northern Oman Mountains (Oman and United Arab Emirates). *Geol Soc Spec Pub* 49:375–386
- Ellouz N, Patriat M, Gaulier J-M, Bouatmani R, Sabounji S (2003) From rifting to alpine inversion, mesozoic and cenozoic subsidence history of some moroccan basins. *Sediment Geol* 156:185–212
- Flemings PB, Jordan TE (1989) A synthetic stratigraphic model of foreland basin development. *J Geophys Res* 94:3851–3866
- Glennie KW, Boeuf MG, Clarke MWH, Moody-Stuart M, Pilaar WFH, Reinhardt BM (1974) The geology of the Oman Mountains. *Verhandelingen van het Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap*, p 31
- Glennie KW, Boeuf MGA, Clarke MWH, Moody-Stuart M, Pilaar WFH, Reinhardt BM (1973) Late cretaceous nappes in Oman Mountains and their geologic evolution. *Am Assoc Pet Geol Bull* 57:5–27
- Hanne D, White N, Lonergan L (2003) Subsidence analyses from the Betic Cordillera, Southeast Spain. *Basin Res* 15:1–21
- Haq BU, Al-Qahtani AM (2005) Phanerozoic cycles of sea-level change on the Arabian Platform. *Geo Arabia (Manama)* 10: 127–160
- Haq BU, Hardenbol J, Vail PR (1988) Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. *Spec Pub Soc Econ Paleontol Mineral* 42:72–108
- Jordan TE (1981) Thrust loads and foreland basin evolution, Cretaceous, Western United States. *AAPG Bull* 65:2506–2520
- Karner GD, Watts AB (1983) Gravity anomalies and flexure of the lithosphere at mountain ranges. *J Geophys Res* 88:10449–10477
- Konert G, Afifi AM, Al Hajri SIA, Droste HJ (2001) Paleozoic stratigraphy and hydrocarbon habitat of the Arabian plate. *Geo Arabia (Manama)* 6:407–442
- Lavier LL, Manatschal G (2006) A mechanism to thin the continental lithosphere at magma-poor margins. *Nature (London)* 440:324–328
- Le Nindre Y-M, Vaslet D, Le Metour J, Bertrand J, Halawani M (2003) Subsidence modelling of the Arabian platform from Permian to paleogene outcrops. *Sed Geol* 156:263–285
- Lin AT, Watts AB (2002) Origin of the West Taiwan basin by orogenic loading and flexure of a rifted continental margin. *J Geophys Res*, vol 107
- Lippard SJ, Shelton AW, Gass IG (1986) The ophiolite of northern Oman. *Memoirs of the Geological Society of London*, vol 11
- Maurer F, Martini R, Rettori R, Hillgartner H, Cirilli S (2009) The geology of Khuff outcrop analogues in the Musandam Peninsula, United Arab Emirates and Oman. *Geo Arabia (Manama)* 14: 125–158
- McKenzie D (1978) Some remarks on the development of sedimentary basins. *Earth Planet Sci Lett* 40:25–32
- Michaelis PL, Pauken RJ (1990) Seismic interpretation of the structure and stratigraphy of the Strait of Hormuz. *Geol Soc Spec Pub* 49:387–395
- Miller KG, Kominz MA, Browning JV, Wright JD, Mountain GS, Katz ME, Sugarman PJ, Cramer BS, Christie-Blick N, Pekar SF (2005) The Phanerozoic record of global sea-level change. *Science* 310:1293–1298
- Mitchum RM Jr, Vail PR, Sangree JB (1977) Seismic stratigraphy and global changes of sea level; Part 6, Stratigraphic interpretation of seismic reflection patterns in depositional sequences. *Mem Am Assoc Pet Geol* 26:117–133
- Muttoni G, Gaetani M, Kent DV, Sciunnach D, Angiolini L, Berra F, Garzanti E, Mattei M, Zanchi A (2009) Opening of the neo-Tethys Ocean and the Pangea B to Pangea A transformation during the permian. *Geo Arabia (Manama)* 14:17–48
- Nolan SC, Skelton PW, Clissold BP, Smewing JD (1990) Maastrichtian to early tertiary stratigraphy and palaeogeography of the central and northern Oman Mountains. *Geol Soc Spec Pub* 49:495–519
- Patriat M, Ellouz N, Dey Z, Gaulier J-M, Ben Kilani H (2003) The hammamet, gabes and chotts basins (Tunisia); a review of the subsidence history. *Sed Geol* 156:241–262

- Patton TL, O'Connor SJ (1988) Cretaceous flexural history of northern Oman Mountain foredeep, United Arab Emirates. *AAPG Bull* 72:797–809
- Price RA (1971) Gravitational sliding and the foreland thrust and fold belt of the North American Cordillera: discussion. *Geol Soc Am Bull* 82:1133–1138
- Rabu D (1993) Stratigraphy and structure of the Oman Mountains, Documents—B.R.G.M., pp. 221–262
- Ricateau R, Riche PH (1980) Geology of the Musandam Peninsula (Sultanate of Oman) and its surroundings. *J Pet Geol* 3:139–152
- Robertson A (1987a) The transition from a passive margin to an Upper Cretaceous foreland basin related to ophiolite emplacement in the Oman Mountains. *Geol Soc Am Bull* 99:633–653
- Robertson AHF (1986) Geochemical evidence for the origin of Late Triassic melange units in the Oman Mountains as a small ocean basin formed by continental rifting. *Earth Planet Sci Lett* 77:318–332
- Robertson AHF (1987b) Upper cretaceous muti formation; transition of a mesozoic carbonate platform to a foreland basin in the Oman Mountains. *Sedimentology* 34:1123–1142
- Robertson AHF, Blome CD, Cooper DJW, Kemp AES, Searle MP (1990) Evolution of the Arabian continental margin in the Dibba Zone, northern Oman Mountains. *Geol Soc Spec Pub* 49:251–284
- Robertson AHF, Searle MP (1990) The northern Oman Tethyan continental margin; stratigraphy, structure, concepts and controversies. *Geol Soc Spec Pub* 49:3–25
- Ruban DA, Al-Husseini MI, Iwasaki Y (2007) Review of Middle East Paleozoic plate tectonics. *Geo Arabia* 12:35–55
- Sahagian D, Jones M (1993) Quantified Middle Jurassic to Paleocene eustatic variations based on Russian platform stratigraphy: stage level resolution. *Geol Soc Am Bull* 105:1109–1118
- Searle MP (1988a) Structure of the Musandam culmination (Sultanate of Oman and United Arab Emirates) and the straits of hormuz syntaxis. *J Geol Soc* 145:831–845
- Searle MP (1988b) Thrust tectonics of the dibba zone and the structural evolution of the Arabian continental margin along the Musandam Mountains (Oman and United Arab Emirates). *J Geol Soc Lon* 145:43–53
- Searle MP (2007) Structural geometry, style and timing of deformation in the Hawasina window, Al Jabal al Akhdar and Saih Hatat culminations, Oman mountains. *Geo Arabia* 12:99–130
- Searle MP, Ali MY (2009) Structural and tectonic evolution of the Jabal Sumeini-Al Ain-Buraimi region, northern Oman and Eastern United Arab Emirates. *Geo Arabia (Manama)* 14:115–142
- Searle MP, Graham GM (1982) “Oman exotics”—oceanic carbonate build-ups associated with the early stages of continental rifting. *Geology* 10:43–49
- Searle MP, James NP, Calon TJ, Smewing JD (1983) Sedimentological and structural evolution of the Arabian continental margin in the Musandam Mountains and Dibba Zone, United Arab Emirates. *Geol Soc Am Bull* 94:1381–1400
- Searle MP, Lippard SJ, Smewing JD, Rex DC (1980) Volcanic rocks beneath the Semail Ophiolite nappe in the northern Oman Mountains and their significance in the Mesozoic evolution of Tethys. *J Geol Soc* 137:589–604
- Searle MP, Warren CJ, Waters DJ, Parrish RR (2004) Structural evolution, metamorphism and restoration of the Arabian continental margin, Saih Hatat region, Oman Mountains. *J Struct Geol* 26:451–473
- Sharland PR, Archer R, Casey DM, Davies RB, Hall SH, Heward AP, Horbury AD, Simmons MD (2001) *Geo Arabia Special Publication*, p 2
- Sinclair HD, Coakley BJ, Allen PA, Watts AB (1991) Simulation of foreland basin stratigraphy using a diffusion model of mountain belt uplift and erosion; an example from the Central Alps, Switzerland. *Tectonics* 10:599–620
- Skelton PW, Nolan SC, Scott RW (1990) The Maastrichtian transgression onto the northwestern flank of the Proto-Oman Mountains; sequences of rudist-bearing beach to open shelf facies. *Geol Soc Spec Pub* 49:521–547
- Steckler MS, Watts AB (1978) Subsidence of the Atlantic-type continental margin off New York. *Earth Planet Sci Lett* 41:1–13
- Styles MT, Ellison RA, Arkley SLB, Crowley Q, Farrant A, Goodenough KM, Mckervey JA, Pharaoh TC, Philips ER, Schofield D, Thomas RJ (2006) The geology and geophysics of the United Arab Emirates, pp 1–351. Ministry of Energy, United Arab Emirates, Keyworth, British Geological Survey
- Warburton J, Burnhill TJ, Graham RH, Isaac KP, Robertson AHF, Searle MP, Ries AC (1990) The evolution of the Oman Mountains foreland basin. *Geol Soc Spec Pub* 49:419–427
- Watts AB, Ryan WBF (1976) Flexure of the lithosphere and continental margin basins. *Tectonophysics* 36:25–44
- Watts AB, Steckler MS (1979) Subsidence and eustasy at the continental margin of eastern North America, Maurice Ewing Series, pp 218–234
- Watts KF (1990) Mesozoic carbonate slope facies marking the Arabian platform margin in Oman; depositional history, morphology and palaeogeography. *Geol Soc Spec Pub* 49:139–159
- Watts KF, Garrison RE (1986) Sumeini Group, Oman; evolution of a Mesozoic carbonate slope on a South Tethyan continental margin. *Sediment Geol* 48:107–168
- Ziegler MA (2001) Late Permian to Holocene paleofacies evolution of the Arabian Plate and its hydrocarbon occurrences. *Geo Arabia (Manama)* 6:445–504