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Key Points:
- A major rifting event occurred at 174 Ma and loading of the Semail ophiolite thrust sheet resulted in rapid foreland subsidence at 83 Ma
- An accelerated subsidence during the late Oligocene-Miocene (24-18 Ma) is attributed to the collision of Central Iran and Arabian plates
- West-verging thrusts in the northern region caused repetition of the Permo-Cenozoic section and pop-up structure is observed in the south

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Abstract
The subsurface and surface structural geometries of the United Arab Emirates (UAE) fold-and-thrust belt (FTB) and foreland basins are interpreted from seismic, well data, and surface geology. Twelve horizons ranging in age from Miocene to Lower Jurassic were interpreted and mapped. Additionally, we outlined subsurface extent of Sumeini and Hawasina allochthonous nappes. The tectonic subsidence curves suggest that the final major passive margin rifting event occurred in the early Aalenian and lasted till Oxfordian. Loading of the Semail ophiolite thrust sheet and accompanying allochthonous thrust sheets resulted in uplift at ca. 95 Ma and rapid subsidence at ca. 83 Ma, indicating the transition of the Arabian margin from a rifted passive margin to a foreland basin. The region witnessed an accelerated subsidence during the late Oligocene-Miocene, attributed to the initial collision of the Central Iran and Arabian plates. The Permian-Jurassic NW-SE oriented rift faults were reactivated as thrust faults during the Late Cretaceous ophiolite obduction and late Oligocene-Miocene continental collision. Two different tectonic regimes are identified in the FTB. The northern regime is characterized by major inversion of the rift faults with up to 3,700 m throw, whereas the southern regime has a major pop-up structure with possible basement origin. Four major west-verging and east-dipping thrusts, which cross the northern area, form fault-propagation folds and dissect the entire stratigraphy. Moreover, the Hawasina décollement, together with the inverted basement structures formed the Jabal Hafit anticline as a backthrust structure.

1. Introduction
The formation of rifted continental margins is linked to continental breakup and generation of new ocean basins. At the time of rifting, the continental rift region is characterized by thinned continental lithosphere and high heat flow, which cause a subsidence that is filled with syn-rift deposits (Buck et al., 1999; Lavier & Manatschal, 2006; McKenzie, 1978). After the cessation of the rifting, the thinned and heated margin begins to cool and the postrift deposits accumulate. However, the mechanical and thermal evolution of the rifted margin is greatly affected by formation of foreland basins because of the emplacement of orogenic loads. Foreland basins form in consequence of lithospheric flexure in front of advancing folded and thrustsed allochthons. These basins are commonly wedge-shaped and their sedimentary fill is derived from the advancing allochthonous rock masses (DeCelles & Giles, 1996; Jordan, 1995). Typically, a major advancing thrust front separates the orogenic belt from the foreland basin and a forebulge detaches it from the cratonic interior (Beaumont, 1981; DeCelles & Giles, 1996; Karner & Watts, 1983; Price, 1971). It is evident that the peripheral bulge may exhibit migration across the foreland basin system, either away from the fold-and-thrust belt (FTB) or toward it, in addition to acting as a localized sediment source in some cases. The forebulge may be subjected to erosion or preserved, based on presence or absence of extreme sediment influx from the FTB (or allochthonous masses). In case of extreme sediment influx from the FTB, these sediments may prograde beyond the foredeep into the forebulge, or even beyond it into the backbulge. On the other hand, sediment starvation from orogenic mass would result in exposure and erosion of the forebulge (DeCelles & Busby, 2012). Foreland basins usually have a characteristic stratigraphic architecture, including clastic clinoform wedges with onlapping and offlapping patterns. These patterns are controlled by the migration rates of the FTB, the sediment influx rates and the basement flexural response (Flemings & Jordan, 1989; Jordan, 1981; Sinclair et al., 1991).

The United Arab Emirates (UAE) has a thick sedimentary cover consisting of a foreland basin sequence, which overlies a rifted continental margin section. This sedimentary cover varies in thickness from around 8 km in the western UAE to about 18 km in the foreland basin (Geng et al., 2022). The rifted margin sequence consists mainly of shelf carbonates that was deposited in the Late Permian to Late Cretaceous. These sequences include Wasia,
Thamama, Araej, and Sila Groups (Figures 1 and 2; Glennie et al., 1973, 1974; Ruban et al., 2007; Searle, 1988b). The lower part of the foreland sequence consists of a deep-marine mudstone (Juwaiza and Fiqa Formations). This section was deposited in the late Coniacian-Campanian at the time of emplacement of the Semail ophiolite and the flexural loading of the allochthonous sheets on the underlying Arabian platform (Ali & Watts, 2009; Ali et al., 2008; Boote et al., 1990; Glennie et al., 1974; Patton & O’connor, 1988; Robertson, 1987a, 1987b; Warburton et al., 1990). However, the upper part of the foreland sequence consists predominantly of shale, marl, and limestone. This sequence was deposited as a result of the Oligocene-Miocene uplift and thrust-culmination of the Musandam part of the shelf carbonate sequence (Searle, 1988a).

The region has a complex geological history and hence a great tectonic significance. Several studies investigated stratigraphy and structures of the FTB and foreland basin of the UAE (e.g., Callot et al., 2010; Dunne et al., 1990; Jardin et al., 2013; Naville et al., 2013; Robertson, 1987a; Searle, 1988b, 2007; Searle & Ali, 2009; Styles et al., 2006; Tarapoanca et al., 2013). Several structural studies have outlined the geometry and evolution of the Late Cretaceous ophiolite obduction episode (e.g., Cooper et al., 2014; Dunne et al., 1990; Searle, 1988b, 2007; Searle et al., 1983, 2014). In the UAE, subsurface mapping of the region has been studied by Ali et al. (2008, 2009), Searle and Ali (2009), and Cooper et al. (2014) who interpreted the Sumeini and Hawasina thrust sheets on few seismic sections. Yet there are no maps of the extension of these thrust sheets within the FTB. Furthermore, Ali et al. (2013) used seismic reflection data integrated with backstripping technique on exploration wells in an attempt to identify the tectonic uplift and subsidence history of the UAE’s passive margin and foreland basin. Moreover, within the FTB and foreland basin of the UAE-Oman Mountains, several structural studies were conducted using either seismic reflection profiles or surface outcrops. These studies include Suneinah foreland basin (Boote et al., 1990), northern Oman Mountains (Dunne et al., 1990), Faiyah range (Noweir et al., 1998), Jabal Mundassa and Jabal Malaqet (Abdelghany, 2003; Noweir & Eloutefi, 1997), Jabal Rawdah (Noweir & Abdeen, 2000), Jabal Hafit (Noweir, 2000; Sirat et al., 2007; Warrak, 1996), Jabal Huwyyayah and Jabal Auha (Noweir & Alsharhan, 2000), and Jabal Sumeini (Searle et al., 1990). Woodward (1994) defined an array of NNW-trending thrusts and folds in the study area using shallow seismic reflection profiles. Additionally, several investigations attempted to determine the timing and structural style of the Jabal Hafit anticline (Figure 1). Warrak (1987), Warrak (1996), Zaineldeen and Fowler (2014), and Zaineldeen (2011) stated that folding of Jabal Hafit was initiated synchronous with sedimentation during the middle Eocene and lasted till late Miocene. This interpretation is based on pinching out and unconformities within Eocene-Oligocene sequences, which were resulted from tectonic uplifting. In contrast, Boote et al. (1990), Noweir (2000), and Searle and Ali (2009) asserted that fold development happened after the middle Miocene. This conclusion is supported by the exposure of folded lower Miocene section along the eastern limb of Jabal Hafit anticline. Hansman and Ring (2018), on the other hand, suggested that the Jabal Hafit growth took place from the late Oligocene to the early-middle Miocene.

Western Geco acquired four regional deep seismic profiles (D1–D4; Figure 1) in the northern UAE for the Ministry of Energy to determine crustal structures in the region (Callot et al., 2010; Jardin et al., 2013; Naville et al., 2013; Tarapoanca et al., 2013). Additionally, British Geological Survey and Fugro conducted regional geological mapping, and aerogravity and aeromagnetic surveys, respectively (Styles et al., 2006). Callot et al. (2010) integrated structural and geophysical modeling, as well as thermal and fluid flow modeling, to constrain the structural architecture of D1 and D4 transects that cross the foreland and adjacent foothills in the northern Oman-UAE Mountains. Jardin et al. (2013) focused on advanced seismic processing and depth migration of the deep seismic sections, whereas Tarapoanca et al. (2013) applied coupled kinematic-thermal-petroleum modeling along D1 and D4 profiles. Moreover, Naville et al. (2013) used the same four deep seismic profiles (D1–D4) to constrain the thickness of the Semail ophiolite. They observed a west-dipping basal Semail thrust west of the Masafi window, which they attributed to a late-stage refolding of the Semail and Hawasina-Sumeini thrust sheets during the Neogene duplexing of the underlying Arabian margin.

In spite of these previous studies, the subsurface geological setting of the FTB of the UAE-Oman Mountains remains poorly known because previous interpretations were based on limited and dispersed seismic reflection profiles and hence it was difficult to image the internal structural geometries at different stratigraphic levels and map their distribution. Major geological unanswered questions in the FTB include internal structures of this belt and its relation to the UAE-Oman Mountains, distribution of the different sedimentary sequences and extent of allochthonous sheets. In this study, we present the results that address these questions by integrating seismic reflection interpretation and basin analysis techniques with conceptual modeling for the evolution of the FTB.
supported by surface geology. We reveal a major spreading event during early Aalenian (ca. 174 Ma) and a Late Cretaceous block faulting of earlier extensional faults. The Arabian rifted margin transitioned to a foreland basin at around 95 Ma. The late Oligocene-early Miocene collision of the Central Iran and Arabian plates in the northern part of the UAE-Oman Mountain belt resulted in an accelerated subsidence and erosion of the Upper Cretaceous-Cenozoic sequences in the FTB.

2. Geologic Setting

The UAE was located within an equatorial setting during the early Mesozoic as part of a great carbonate platform of the Neo-Tethys Ocean's southern rifted continental margin. The mid-Permian witnessed early stages of rifting and first establishment of a wide passive continental margin, as observed in the Musandam Peninsula by the Bih Formation (mid-Permian syn-rift deposits) and in the Saiq Formation in Oman. In the Dibba Zone, the Jabal Qamar exotic represents a drowned guyot built on Arabian continental rocks that rifted away from the margin to
become incorporated in the thrust sheets (Béchennec et al., 1990; Robertson et al., 1990; Searle, 1988a; Searle et al., 1983). Later rift stages recorded along the shelf carbonates and in the deep ocean basin (Hawasina complex) occurred in the Late Triassic–Early Jurassic (Robertson et al., 1990; Searle et al., 1983). As the case in many rifted margins, the early rift stage exhibited dominance of continental rifting and block faulting with localized intraplate alkali basaltic volcanism. The subsequent stages of rifting witnessed growth along major bounding faults and localized volcanic intrusions. Additionally, the development of half-graben structures and tilted fault blocks were also prominent through this stage and led to continental breakup (Béchennec et al., 1990; Glennie et al., 1974; Robertson & Searle, 1990; Robertson et al., 1990; Searle et al., 1983). The Permian to Triassic Haybi volcanics outcrop in the Dibba zone and are probably related to passive margin rifting (Glennie et al., 1974; Searle et al., 1980, 2014). By the mid-Cretaceous, the region became part of a mature southern margin of the Neo-Tethys Ocean (Ali & Watts, 2009). The margin sequence (including Wasia, Thamama, Sila, and Araej Groups) is dominated by shelf carbonate deposits and restricted clastics and evaporites (Figure 2).

A stack of thrust sheet complexes outcrops in the northern Oman and UAE Mountains representing the Late Cretaceous Tethyan oceanic crust and mantle that were emplaced over the Arabian carbonate platform. These thrust sheets are represented by the Semail ophiolitic complex, which represents Cenomanian upper mantle and oceanic crust with a thickness of up to 8–15 km, the Haybi thrust sheet consisting of oceanic seamounts and alkaline volcanics of Upper Permian to Cenomanian age, the Hawasina thrust complex consisting of oceanic distal to proximal sedimentary rocks, and the Sumeini thrust sheet comprising proximal carbonate slope sediments (Glennie et al., 1973; Lippard et al., 1986; Searle & Ali, 2009). The Sumeini, Hawasina, and Haybi complexes each contain time-equivalent stratigraphic units formed across the Permo-Mesozoic passive margin of Arabia. The Semail ophiolite thrusting was initiated at depths of about 39–45 km in a northeast dipping intraoceanic subduction zone (Riouxf et al., 2016; Searle & Cox, 1999, 2002). Ophiolite emplacement starting at 95 Ma resulted in loading of the foreland starting in the Turonian, over the Arabian margin causing the margin to flex downward resulting in the Aruma foreland basin and a flexural forebulge. These obducted sheets were deformed, unlike the underlying Mesozoic carbonate margin, which were unaffected by deformation other than insignificant normal faulting linked to the forebulge (Boote et al., 1990; Warburton et al., 1990). Nevertheless, the westward migration of the forebulge, in the front of the propagating thrust sheets, resulted in a regional uplift that removed part of shelf carbonate deposits and led to the Wasia-Aruma break (Glennie et al., 1973). This break divides the top of the shelf margin sequence (Wasia Group) from the overlying foreland basin sequence (Aruma Group). During the late Coniacian-Campanian, the foreland basin was filled with deep-marine mudstones of the Juwaiza and Fqi Formations. This succession reaches a thickness of around 4,300 m in the west of the northern Oman Mountains (Ali et al., 2008; Boote et al., 1990; Patton & O’connor, 1988; Robertson, 1987a, 1987b; Warburton et al., 1990). This succession is covered by conglomerate and shallow-marine limestone of the upper Maastrichtian Simsima and Qahlah Formations (Glennie et al., 1974; Nolan et al., 1990; Shelton, 1984). Two unconformities below and above the Maastrichtian Simsima Formation indicate minor deformations and uplift in the northern Oman Mountains (Mann & Hanna, 1990; Nolan et al., 1990). The northeastern Arabian continental margin remained stable throughout the Paleocene-Oligocene depositing a transgressive sequence consisting of the highly fossiliferous Umm Er Radhuma, Rus, Dammam, and Asmari Formations (Glennie et al., 1974; Searle, 2019; Searle & Ali, 2009).

Collision between the Central Iran and Arabian plates in the late Oligocene-early Miocene caused closing of the Neo-Tethys Ocean and culmination of the Musandam Peninsula (Searle et al., 1983, 2014). This event resulted in large-scale thrusting that emplaced the allochthonous Permi-an-Cenomanian shelf carbonates of the Musandam peninsula over the autochthonous shelf carbonates of the foreland (Ali et al., 2018; Searle, 1988a, 2007). The collision caused major west-verging folds above the Hagab thrust along the western flank of the northern Oman Mountains, reactivation of Mesozoic faults within the FTB, and accompanying flexure of the Pabdeh foreland basin (Boote et al., 1990; Dunne et al., 1990; Kusky et al., 2005; Regard et al., 2005; Ricateau & Riché, 1980; Searle, 1988a, 1988b; Searle et al., 1983, 1990).

3. Materials and Methods

For this study, we used surface geology, a dense grid of 2D seismic reflection profiles comprising 109 profiles from three different surveys and 10 exploration wells (Figure 1). The first seismic survey comprises 92 seismic profiles that were acquired and processed by AMOCO from 1981 to 1983. These profiles have a total length of...
Figure 2. Summarized stratigraphic column of the fold-and-thrust belt (FTB) and foreland basin of the UAE-Oman Mountains (modified after Ali et al. (2013), Alsharhan (1989), and Hu et al. (2016)).
The longest line has a length of about 54 km and the shortest has 11.5-km length. This data set has a poor to good quality, as a result of mainly complex geology of the region. Thirty-four (with a length of about 760 km) of AMOCO seismic profiles were reprocessed in 2007. These profiles have fair to good quality. The second set of seismic survey comprises four seismic profiles from the SCEPTRE survey that was also acquired and processed from 1981 to 1983. These profiles have a total length of 247 km with fair to good quality, as they are located away from the FTB. The third set comprises 13 seismic profiles from AL AIN seismic survey that was acquired and processed from 1990 to 1993. The profiles have a total length of about 400 km with good quality. Generally, the quality of the seismic data is better in the western parts and decreases toward the east, reflecting the geological complexity on the seismic quality. The well data sets include formation tops, lithostratigraphy, biostratigraphy, and conventional well logs (gamma-ray, caliper, deep resistivity, sonic, density, neutron).

The available wells are KB-1, KB-2, MG-1, MG-2, BS-1, QB-1, MD-1, KM-1, L1-A, and BA-1 (Table 1 and Figure 1). We have also used the Biyatih-1 (B1) well, which is located north of the study area (Figure 1). The well logs (e.g., sonic and gamma-ray) were utilized to determine major lithological units and for the well-to-well correlation. Additionally, the biostratigraphic data were used for confirming the age of each formation. The youngest strata comprise recent-Quaternary deposits whereas the oldest penetrated formation in the study area is the Middle Triassic Gulailah Formation as encountered by KB-1 well.

The seismic interpretation procedure included well-to-seismic tie (Figure 3) followed by fault and horizon picking. The definition of seismic horizons was based on the visible reflection characters such as reflection strength, frequency, amplitude, spatial geometry, and continuity (Khan & Abdelmaksoud, 2020). Twelve horizons were picked on the seismic sections, namely (from youngest to oldest), Gachsaran, Miocene Salt, Asmari, Hasa, Simsima, Upper Fiqa (U. Fiqa), Lower Fiqa (L. Fiqa), Juwaiza, Wasia, Thamama, Sila-Araej, and Hamlah. Moreover, two allochthonous thrust sheets (Sumeini and Hawasina) were mapped. Additionally, lithostratigraphic and biostratigraphic data from wells were used for age control and aid geological interpretations of the horizons. The interpreted horizons and faults were used to generate two-way travel time (TWT) structural contour maps for all interpreted horizons, which were then used for calculating the time thickness of the different stratigraphic units. Nevertheless, the TWT maps were not converted to depth due to the lack of velocity information in this geologically complex region. However, time-depth relationships of the studied wells were used to determine estimates of the depths and thicknesses of the sequences.

| Well  | TD (m) | Formation TD | Available data                                                                 |
|-------|--------|--------------|--------------------------------------------------------------------------------|
| KB-1  | 4,722  | Gulailah Formation tops, lithostratigraphy, biostratigraphy, and well logs (caliper, sonic, gamma-ray, density, neutron, deep, and shallow resistivity) |
| KB-2  | 2,112  | Shuaiba Formation tops, biostratigraphy, and well logs (caliper, sonic, gamma-ray, density, neutron, deep, and shallow resistivity) |
| MG-1  | 1,736  | Lower Fiqa Formation tops, biostratigraphy, and well logs (caliper, sonic, gamma-ray, density, neutron, deep, and shallow resistivity) |
| MG-2  | 1,249  | Juwaiza Formation tops, biostratigraphy, and well logs (caliper, sonic, gamma-ray, density, neutron, and deep resistivity) |
| BS-1  | 4,578  | Upper Fiqa Formation tops, lithostratigraphy, biostratigraphy, and well logs (caliper, sonic, gamma-ray, density, neutron, deep, and shallow resistivity) |
| QB-1  | 2,825  | Lower Fiqa Formation tops, lithostratigraphy, biostratigraphy, and well logs (caliper, sonic, gamma-ray, neutron, and deep resistivity) |
| MD-1  | 3,481  | Lower Fiqa Formation tops, lithostratigraphy, biostratigraphy, and well logs (sonic and gamma-ray) |
| KM-1  | 3,048  | Umm Er Radhuma Formation tops, lithostratigraphy, biostratigraphy, and well logs (caliper, sonic, gamma-ray, density, neutron, and deep resistivity) |
| L1-A  | 4,840  | Asab Formation tops, lithostratigraphy, biostratigraphy, and well logs (sonic) |
| BA-1  | 5,029  | Diyab Formation tops, lithostratigraphy, biostratigraphy, and well logs (sonic, gamma-ray, and neutron) |
The Fars horizons (Gachsaran and Miocene Salt) were tied with KM-1, BA-1, and L1-A wells and are present as strong seismic events, except near the frontal parts of the major thrusts. Whereas Asmari and Hasa tops were tied with wells KM-1, BA-1, BS-1, MD-1, and L1-A. Moreover, a part of the Hasa sequence was tied with QB-1 well. Interpretations of the Fars and Hasa Groups on the FTB were based on the seismic patterns and the relation with the highly controlled top Aruma Group. The Top Simsima Formation was tied with wells BA-1, BS-1, MD-1, L1-A, and KB-2. The Upper Fiqa (U. Fiqa), Lower Fiqa (L. Fiqa), and Juwaiza horizons were tied with wells KB-1, KB-2, MG-1, MG-2, QB-1, and MD-1. However, the deeper units have less control, e.g., Wasia was tied with BA-1 and L1-A wells in the foreland, whereas on the FTB it is tied from KB-1 well, where it is mostly eroded. The Thamama and Sila-Araej tops were tied with wells BA-1, L1-A, KB-1, and KB-2, whereas Hamlah was tied only with KB-1 well (Figure 1).

The Hawasina nappe was tied with QB-1 well in the middle of the study area, and the thrust sheet was traced on the rest of the area by its seismic character, which looks like imbricated sheets with different geometry than the underlying and overlying sequences. This interpretation is supported by outcrops of Hawasina in the east of the study area. The Sumeini thrust was not penetrated by any of the available wells, however, mapping of Sumeini

| Fm tops          | TWT (ms) | Depth (m) | Velocity (m/s) | Density (kg/m³) | RC | Seismic section 1QS-N16 | SS | Seismic section 1QS-N16 |
|------------------|----------|-----------|----------------|-----------------|----|------------------------|----|------------------------|
| U. Fiqa          | 440      | 500       | 1000           | 700             | 0.70|                        |    |                        |
| Juwaiza          | 662      | 1000      | 1000           | 700             | 0.70|                        |    |                        |
| L. Fiqa          | 914      | 1500      | 1000           | 700             | 0.70|                        |    |                        |
| Mauddud          | 12913    | 2000      | 1000           | 700             | 0.70|                        |    |                        |
| Shuaiba          | 13032    | 2500      | 1000           | 700             | 0.70|                        |    |                        |
| Habshan          | 14152    | 3000      | 1000           | 700             | 0.70|                        |    |                        |
| Arab             | 16152    | 3000      | 1000           | 700             | 0.70|                        |    |                        |
| Diyab Araej      | 17703    | 3500      | 1000           | 700             | 0.70|                        |    |                        |
| Izhara           | 19833    | 4000      | 1000           | 700             | 0.70|                        |    |                        |
| Hamlah           | 21462    | 4500      | 1000           | 700             | 0.70|                        |    |                        |
| Gulallah         | 23102    | 5000      | 1000           | 700             | 0.70|                        |    |                        |
| TD               | 24703    | 5500      | 1000           | 700             | 0.70|                        |    |                        |

Figure 3. Well-to-seismic tie of KB-1 well and seismic profile 1QS-N16. Density and sonic logs were used to generate the synthetic seismogram. Fm, TWT, RC, SS, and TD stand for formation, two-way travel time, reflectivity coefficients, synthetic seismogram, and total depth, respectively.
The backstrip curves of the wells located in the FTB (KB-1, KB-2, MG-1, QB-1, and MD-1) and the wells in the Pabdeh foreland basin (BA-1, L1-A, BS-1, and KM-1) are shown in Figures 4a and 4b, respectively. The backstrip curves were calculated assuming an Airy model of isostasy, and water and mantle densities of 1,030 and 3,330 kg/m$^3$, respectively. A compaction correction was determined using porosities derived from neutron porosity and sonic logs, and a grain density of 2,670 kg/m$^3$. The paleowater depth was predicted from the biostratigraphic data, and the effect of sea-level change was corrected using the global sea-level curve (Watts & Steckler, 1979).

The backstrip curves suggest that only KB-1 well (Figure 4a), which penetrated Gulaiilah Formation, displays a rift event during the Middle to Late Jurassic with a rift duration of about 14 My (from around 174 to 160 Ma). The tectonic subsidence rate for this period was about 20 m/My. This rift event was followed by a postrift subsidence that lasted till about 95 Ma with slower subsidence rates. There is a noticeable uplift and unconformity event in KB-1 and KB-2 wells that occurred around 95-85 Ma. Wells KB-1, KB-2, BA-1, and L1-A indicate that this event was followed by a period of significant subsidence at ca. 83 Ma with a tectonic subsidence rate of about 18 m/My (Figure 4). The tectonic curves record a second accelerated subsidence that started about 24–25 Ma. This rapid subsidence slowed down at about 18 Ma and continued till the present day. The tectonic subsidence rates resulted from this event range from a maximum of 66–115 m/My at KM-1 well to about 17–20 m/My at BA-1 and L1-A wells. Moreover, the wells (KB-1, KB-1, QB-1, MG-1, and MD-1) located in the FTB display a major unconformity, which eroded most of the Cenozoic and parts of the Upper Cretaceous sediments.

**4.2. Well Stratigraphy**

Figure 5 correlates wells KB-1, MG-1, QB-1, BS-1, KM-1, and BA-1. Wells KB-1, MG-1, and QB-1 lie in the FTB, whereas BS-1, KM-1, and BA-1 wells occur in the Pabdeh foredeep and forebulge areas. The two sets of wells are separated by a major thrust fault with a throw of about 3,500 m, which we named as the Khusub thrust. Wells KB-1, MG-1, and QB-1 show clear effect of uplift and later erosion of the uplifted units, where the Cambrian Upper Fija Formation occurs at depths of 50–500 m and is covered by the upper Miocene Barzaman Forma-
On the contrary, wells BS-1, KM-1, and BA-1 exhibit much greater subsidence during the Oligocene-Miocene because of the loading of thrust sheets at the eastern parts of the study area. Wells KB-1 and BA-1 are the only deep wells that penetrate the Lower Cretaceous, Jurassic, and Triassic succession. Therefore, we have not correlated formations below the Lower Fiqa Formation.

The wells on the FTB are characterized by remarkable thicknesses of the Fiqa and Juwaiza Formations. Moreover, only QB-1 well penetrated the allochthonous red to brown Hawasina shales. Additionally, wells QB-1 and MG-1 intersected 426 and 925 m of Juwaiza conglomerates, respectively. This indicates the proximity of allochthonous nappes (mainly Sumeini and Hawasina) where Juwaiza conglomerates were derived. Besides, the KB-1 well penetrated much less thickness (220 m) of Juwaiza conglomerates as it is located further west. Interestingly, increased amount of coarse clastics in the Upper Fiqa Formation (1,028 m) of QB-1 well may suggest forced regression resulting from a sea level drop or elevated sediment influx from the allochthonous nappes of the UAE-Oman Mountains. Furthermore, the Simsima Formation is present in QB-1 well, unlike wells KB-1 and MG-1, indicating more uplift at the locations of the two later wells.

The wells located on the Pabdeh foredeep, BS-1, KM-1, and BA-1, are characterized by 2,500–3,500-m thickness of Cenozoic deposits, indicating a substantial subsidence and accommodation space that was available during the sedimentation of these units. Moreover, the thickness of the Miocene Salt and Asmari Formation (925 and 875 m, respectively) seems to be exaggerated in BS-1 well as the well is located just to the west of the Khusub thrust (Figure 5). Furthermore, Fiqa facies in these wells are much finer, unlike the FTB wells, which may suggest deepening of the basin.

Figure 5. Well-to-well correlation of MG-1, KB-1, and QB-1 wells on the fold-and-thrust belt (FTB) and BS-1, KM-1, and BA-1 wells in the foredeep and forebulge regions. The light blue color in MG-1 well represents the GR (gamma-ray) values for MG-2 well, as GR values of MG-1 are only available for the upper 200 m. TVD, LITH, V, and TD stand for true vertical depth, lithology, velocity, and total depth, respectively. Insert map shows location of the wells.
4.3. Seismic Stratigraphy and Structural Analysis

The interpretation of the seismic sections revealed presence of major thrust faults and several backthrusts dissecting the entire sequences including the Mesozoic carbonate platform section. The main thrust fault with a remarkable displacement is the Khusub thrust at the area of KB-1 and KB-2 wells. The throw of the Khusub thrust reaches up to 2,000 ms (∼3,700 m) at the northern part of the study area (Figure 6). The thrust forms the

Figure 6. (a) An uninterpreted seismic profile and (b) interpreted seismic profile in the northern part of the study area (for location of the seismic profile see Figure 1). 1 represents Sila-Areaaj Groups, 2 = Thamama, 3 = Wasia, 4 = Lower Fiqa, 5 = Juwaiza, 6 = Upper Fiqa, 7 = Simsimia, 8 = Hasa, 9 = Asmari, 10 = Miocene Salt, 11 = Gachsaran, 12 = Barzaman and Recent deposits, and 13 = Sumeini thrust sheet.
fault-propagation fold of the Khusub fold (Figure 6). On the contrary, the Bid Salma thrust, which is located to the west of the Khusub thrust, has a throw of about 300 ms (~550 m). Additionally, low angle thrusts occur at the base and within the Sumeini nappe, indicating significant lateral transport. The basal thrust (Mughayrah thrust) of the Sumeini nappe extends upward forming the fault-propagation fold of the Mughayrah fold with a throw of up to 500 ms (~900 m). Moreover, another fault-propagation fold, similar to Khusub fold, is present in the north-eastern edge of the region, just below the interpreted Sumeini thrust sheet (Figure 7). The thrust has a throw of about 1,000 ms (~1,800 m) and we name it as Al-Hiyar thrust.

To the south, at Jabal Hafit anticline and Al Ain area, the dominant structural setting is totally different from that of the northern part. This area is characterized by inverted faults and pop-up structure, which remarkably cut across the carbonate platform sequence and terminate in the Lower Fiqa sequence (Figure 8). These faults seem to have deep basement origin. The post-Lower Fiqa sequences are dominated by the Jabal Hafit anticline and the Tarabat backthrust, which at MD-1 well has a throw of about 500 ms (~900 m) and causes repetition of the Cenozoic and Upper Cretaceous units. Moreover, low angle thrusts occur at the base and within the Hawasina nappe, indicating significant lateral transport (Figure 8).

The Sumeini nappe exhibits deformed and undulated reflectors, which seem to intersect and intrude the Coniacian-Santonian Lower Fiqa Formation (Figure 9a). Additionally, the Campanian Upper Fiqa and Juwaiza Formations downlap on the nappe, whereas the Simsima Formation overlies these downlapping units (Figure 9a). The terminations of the Upper Fiqa and Juwaiza Formations were principally onlapping during deposition, but

![Figure 7.](image-url)
now and after the late Oligocene-Miocene compressional event, the terminations seem as downlapping features. The Hawasina nappe has chaotic low amplitude seismic reflections (Figure 9b). Moreover, the Juwaiza Formation, which was derived from the weathering and erosion of the allochthons, exhibit chaotic high-amplitude pattern (Figure 9b). In addition, onlapping terminations are identified within the Miocene sequence (Figure 9c).
Figure 9.
Furthermore, the Lower to mid-Cretaceous Thamama-Wasia Groups are affected by normal block faults, which dissect the entire groups and terminate within the Aruma Group (Figure 10). The TWT structural and time thickness maps of all interpreted horizons are shown in Figures 11 and 12, respectively. The structural maps show that the Upper Cretaceous-Cenozoic sequences are dissected by a set of NNW-SSE striking thrusts and backthrusts, which form a series of folds with axes parallel to the thrusts. Both Gachsaran and Miocene Salt are absent over the FTB, whereas in the same area, the Asmari Formation is almost eroded except in synclinal areas. The Gachsaran Formation outcrops along the eastern limb of the Jabal Hafit anticline (Figure 1). However, the top Gachsaran reaches up to 400 ms TWT (∼700 m) and generally increases toward west (Figure 11a). Similarly, the top Miocene Salt reaches up to 1,200 ms TWT (∼2,240 m) and 100 ms TWT (∼190 m) in the west and east, respectively (Figure 11b). The top Asmari Formation increases in depth toward west and reaches up to 1,600 ms TWT (∼2,980 m). The Asmari Formation outcrops along the northeastern and northwestern flanks of the Jabal Hafit anticline (Figures 1 and 11c). However, the Hasa Group and Simsima Formation are present across the entire region, except at the crests of some anticlinal folds (Figures 11d and 11e). The top of Hasa Group ranges from 100 to 2,200 ms TWT (190–4,100 m) in the eastern and western areas, respectively (Figure 11d). Likewise, the top of Simsima Formation deepen toward west and range from 100 to 3,000 ms TWT (190–5,600 m; Figure 11e).

The Upper Fiqa unit is present across the entire area (Figure 11f). However, the top Upper Fiqa reaches its maximum depth at the western parts of the region with about 3,300 ms TWT (6,150 m). The Juwaiza Formation

Figure 10. Uninterpreted (a and c) and interpreted (b and d) seismic sections highlighting the Late Cretaceous normal block faulting of the Mesozoic carbonate platform. The cyan colored line represents the Wasia-Aruma break, whereas the blue one is the top of Fiqa Formation. 1, 2, 3, and 4 represent Rus to Simsima, Upper and Lower Fiqa, Wasia-Thamama, and Sila to Gulailah, respectively. For location of the profiles refer to Figure 1.

Furthermore, the Lower to mid-Cretaceous Thamama-Wasia Groups are affected by normal block faults, which dissect the entire groups and terminate within the Aruma Group (Figure 10).

The TWT structural and time thickness maps of all interpreted horizons are shown in Figures 11 and 12, respectively. The structural maps show that the Upper Cretaceous-Cenozoic sequences are dissected by a set of NNW-SSE striking thrusts and backthrusts, which form a series of folds with axes parallel to the thrusts. Both Gachsaran and Miocene Salt are absent over the FTB, whereas in the same area, the Asmari Formation is almost eroded except in synclinal areas. The Gachsaran Formation outcrops along the eastern limb of the Jabal Hafit anticline (Figure 1). However, the top Gachsaran reaches up to 400 ms TWT (∼700 m) and generally increases toward west (Figure 11a). Similarly, the top Miocene Salt reaches up to 1,200 ms TWT (∼2,240 m) and 100 ms TWT (∼190 m) in the west and east, respectively (Figure 11b). The top Asmari Formation increases in depth toward west and reaches up to 1,600 ms TWT (∼2,980 m). The Asmari Formation outcrops along the northeastern and northwestern flanks of the Jabal Hafit anticline (Figures 1 and 11c). However, the Hasa Group and Simsima Formation are present across the entire region, except at the crests of some anticlinal folds (Figures 11d and 11e). The top of Hasa Group ranges from 100 to 2,200 ms TWT (190–4,100 m) in the eastern and western areas, respectively (Figure 11d). Likewise, the top of Simsima Formation deepen toward west and range from 100 to 3,000 ms TWT (190–5,600 m; Figure 11e).

The Upper Fiqa unit is present across the entire area (Figure 11f). However, the top Upper Fiqa reaches its maximum depth at the western parts of the region with about 3,300 ms TWT (6,150 m). The Juwaiza Formation
Figure 11. Time structural maps of the interpreted horizons (Gachsaran to Hamlah). BST, Bid Salma thrust; HPU, Hafit pop-up; HT, Al-Hiyar thrust; KBT, Khusub thrust; MGT, Mughayra thrust; TT, Tarabat backthrust. TWT stands for two-way travel time.
Figure 11. (Continued)
Figure 11. (Continued)
Figure 12. Time thickness maps of the interpreted horizons (Gachsaran to Sila-Araej). BST, Bid Salma thrust; HPU, Hafit pop-up; HT, Al-Hiyar thrust; KBT, Khusub thrust; MGT, Mughayra thrust; TT, Tarabat backthrust. TWT stands for two-way travel time.
Figure 12. (Continued)
Figure 12. (Continued)
is present mainly over the FTB (Figure 11g). Its top is shallow above the hanging wall of the Khusub thrust, reaching up to 100 ms TWT (190 m), whereas it reaches up to 3,350 ms TWT (6,250 m) along the footwall of the Khusub thrust (Figure 11g). Similarly, the Lower Fiqqa unit is present over the FTB, and extends further west than Juwaiza Formation (Figure 11b). The top Lower Fiqqa ranges from 550 ms TWT (1,028 m) in the hanging wall of the Khusub thrust to about 3,550 ms TWT (6,600 m) along the footwall (Figure 11h).

The Ruwaydha, Tuwayil, and Mishrif Formations are absent over the FTB as confirmed by KB-1 well, so the Wasia Group has much less thickness over the FTB (Figures 3 and 11i). The top of Wasia ranges from 2,200 ms TWT (4,100 m) below the Jabal Hafit anticline and up to 3,500 ms TWT (6,500 m) in the central and northern parts, whereas in the FTB its top ranges from 1,200 to 3,700 ms TWT (2,240–6,900 m; Figure 11l). Furthermore, Thamama, Sila-Araej, and Hamlah units are all present across the entire area (Figures 11j–11l). These units, together with top of Wasia Group, exhibit similar geometry with a distinguishable thrust propagation fold in the northern area where the tops are shallow. On the footwall of the Khusub thrust, the formations deepen in the northern and central parts of the region (Figures 11k–11l). The top of Thamama range from 1,300 to 3,850 ms TWT (2,420–7,180 m). The top of Sila-Araej lies at about 1,600–4,300 ms TWT (2,990–8,020 m), while the Hamlah range from 1,800 to 4,700 ms TWT (3,350–8,750 m).

The Gachsaran Formation is about 150–1,000 ms (~250–1,700 m) thick, whereas the Miocene Salt is 150–850 ms (~250–1,400 m) thick (Figures 12a and 12b). The thickness of Gachsaran Formation significantly increases toward west, whereas the maximum thickness of Miocene Salt occurs in front of the Khusub thrust (Figures 12a and 12b). The Asmari and Hasa units exhibit, generally, the same thickness distribution, with 150–900 ms (~250–1,500 m) and 150–1,200 ms (~250–2,240 m) thicknesses, respectively (Figures 12c and 12d).

The Simsima Formation has mostly a uniform thickness with a range of 90–360 ms (~160–600 m; Figure 12e). The Upper Fiqqa unit has a thickness range of 100–1,000 ms (~180–1,800 m) with greatest thickness in the west of Jabal Hafit anticline (Figure 12f). The Juwaiza Formation has a thickness range of 50–800 ms (~90–1,400 m) and it is absent in the eastern part of Al Jaww Plain where it is truncated against the Hawasina nappe (Figures 8b and 12g). Whereas the Lower Fiqqa unit ranges in thickness from 150 to 1,600 ms (~280–2,900 m), with its maximum thickness located in the FTB region (i.e., Aruma foreland basin), west of MG-1 and MG-2 wells (Figure 12h). Wasia Group ranges in thickness from about 60 to up to 360 ms (~110–600 m), with no significant variation in thickness distribution except that it is absent in the FTB region (Figure 12i). Moreover, the Thamama Group ranges in thickness from 160 to about 700 ms (~300–1,300 m), respectively (Figure 12j). The Sila-Araej Groups have a combined thickness that range from 200 to 600 ms (~350–1,100 m; Figure 12k).

The structural and time thickness maps of Sumeini and Hawasina nappes illustrate that the Sumeini nappe is present only at the extreme northeastern part of the study area just to the east of MG-1 and MG-2 wells along the border between UAE and Oman (Figures 13a and 13c). However, the Hawasina nappe is present to the south of Sumeini nappe, as confirmed by QB-1 well, so the Hawasina nappe is present to the south of Sumeini nappe, as confirmed by QB-1 well, and throughout the central and southern parts of the study area (Figures 13b and 13d). These nappes exhibit an obvious increase in thickness toward the east. The top Sumeini and top Hawasina complexes range from 200 to 2,250 ms TWT (350–4,200 m) and 550–2,200 ms TWT (1,000–4,000 m), respectively. The time thickness maps of the nappes show that the Sumeini nappe is 150–800 ms (~250–1,400 m) thick, whereas Hawasina is 300–1,800 ms (~500–3,300 m) thick.

5. Discussions

5.1. Tectonic Subsidence and Uplift History

Backstripping of nine exploratory wells located in the FTB (KB-1, KB-2, MG-1, QB-1, and MD-1) and Pabdeh foreland basin (BA-1, LI-A, BS-1, and KM-1) suggest a major rift event during the Aalenian to Oxfordian (174-160 Ma), which corresponds to the final continental breakup and the opening of the Neo-Tethys Ocean. The tectonic subsidence between 160 and 95 Ma is ascribed to cooling and contraction of the margin after rifting. Rousseau et al. (2005) suggested a subaerial exposure episode affected the Arabian platform edge in eastern Oman after the Early Jurassic (?early Pliensbachian), and sedimentation resumed as a mixed siliciclastic-carbonate system during the Toarcian. A terrigenous system remained until the late Bajocian, after which carbonate sedimentation dominated over the platform margin throughout the Bathonian-early Callovian (Rousseau et al., 2005). Moreover, the backstrip curves indicate that the rifted margin transitioned to a compressional foreland basin
at around 95 Ma, which is coincident with the formation of the Semail ophiolite and the beginning of thrust emplacement from NE to SW. The emplacement of Semail ophiolite and its loading onto the Arabian margin caused an accelerated subsidence and development of the Aruma foreland basin. Furthermore, the backstrip curves indicate greater tectonic subsidence at around 83 Ma in wells located in the FTB (e.g., KB-1, KB-2, KB-5, and KB-6).
MG-1, QB-1, and MD-1 wells) than the wells in the Pabdeh foreland basin (e.g., BA-1, LJ-A, BS-1, and KM-1 wells). This result is not unexpected because wells in the FTB (i.e., Aruma foreland basin) are located nearer to the ophiolite load than wells in the Pabdeh foreland basin. Furthermore, the backstrip curves record a second accelerated subsidence that started about 24–25 Ma. Moreover, the backstrip curves at wells KB-1 and MD-1 (Figure 4a) are interesting because they contain repeated sequences since they penetrated the Khusub thrust and Tarabat backthrust, respectively. Moreover, the wells (KB-1, KB-2, QB-1, MG-1, and MD-1) located in the FTB display a major unconformity, which eroded most of the Cenozoic sediments, and partially the Cretaceous sequences in the northern part. The excess subsidence that occurred at 24–25 Ma in the Pabdeh foreland basin, and the uplift and erosion event in the FTB are correlated with the collision of the Arabian plate with the Central Iran plate during the late Oligocene-Miocene (Ali et al., 2018; Searle, 1988a; Searle & Ali, 2009).

5.2. Structural and Stratigraphic Style of the FTB

The structural style of FTB of the UAE-Oman Mountains is poorly understood, mainly because these structures are unexposed. However, the interpretation of the 2D seismic profiles integrated with exploratory well data and geological outcrops allowed the imaging of the subsurface sedimentary structures in the FTB of the UAE-Oman Mountains. Two different tectonic regimes are recognized. The northern portion, starting from Abu Dhabi-Dubai border to the north of Al Ain city, is dominated mainly by large-scale thrusting, and associated folds, that dissect the entire stratigraphy and backthrusts that cut through the Thamama-Wasia sequences (Figure 6). In contrast, the southern part of the study area is characterized by the presence of inverted faults in the Mesozoic sequences and backthrusting in the Upper Cretaceous-Cenozoic succession (Figure 8). The basement high and pop-up structure beneath Jabal Hafit may have prevented the Khusub thrust of the northern regime from extending farther south, creating a transitional zone just to the north of Jabal Hafit.

We have interpreted four major west-verging and east-dipping thrust faults, named as Bid Salma, Khusub, Al-Hiyar, and Mughayra thrusts, dissecting the northern part of the study area (Figures 6, 7, 11, and 12). The Khusub thrust extends further to the central part of the study area (Figures 6, 7, 11, and 12). Ali et al. (2013), Cooper et al. (2014), and Searle and Ali (2009) interpreted the Khusub thrust on limited seismic sections. The Khusub thrust resulted in uplift of up to 2,000 ms TWT (~3,700 m) juxtaposing the Triassic formations and the Upper Cretaceous Aruma sequences. The fault dissect the entire Cenozoic and Upper Permian-Mesozoic shelf carbonate sequences and shows listric pattern that flattens into a basal detachment. These major thrusts (Bid Salma, Khusub, Al-Hiyar, and Mughayra) are contemporaneous with the Hagab thrust, which is an Oligocene-Miocene west-verging and east-dipping thrust that cut up-section from basement to Oligocene on the western flank of Musandam Peninsula (Ali et al., 2018; Searle, 1988a; Searle et al., 2014).

Regional gravity and magnetic data (obtained from Ali et al. (2014, 2017), respectively) and their tilt derivatives are used to delineate the structural features in the study area (Figure 14). The tilt derivative is a useful technique for identifying linear edge structures, such as faults and contacts (Blakely & Simpson, 1986; Cordell, 1979). The zero tilt angle contour tracks structural edges and the positive component of the derivative is associated with the positive density or susceptibility contrast side of the contact (Fairhead et al., 2011; Verduzco et al., 2004). The gravity and magnetic maps (Figure 14) illustrate that the thrust sheets interpreted from seismic reflection profiles are coincident with obvious gravity and/or magnetic features and lineaments.

The significant thickness variation of the Lower Fiqa Formation between the hanging and footwall of the major thrust faults (Figures 6 and 12h) suggests that the northern parts of the region may had an earlier extensional origin. The thrust faults may have started as normal faults throughout the accumulation of the Lower Fiqa Formation and hence allowed great thickness to be deposited on the hanging wall and less on the footwall. Later on, possibly during Oligocene-Miocene, the Lower Fiqa Formation was inverted because of the collision between Central Iran and Arabian plates. To the south of the study area, in the Suneinah foreland about 30 km south of Jabal Hafit, inversion at the leading edge of the advancing nappes resulted in doubling of thickness of the Lower Fiqa shale unit (Boote et al., 1990).

The Sumeini nappe is mapped in the northern part of the study area, and correlated with surface exposure at Jabal Sumeini. Ali et al. (2008), Ali and Watts (2009), Searle and Ali (2009), and Cooper et al. (2014) interpreted the Sumeini thrust sheet on a seismic profile crossing this northern area. Moreover, Dunne et al. (1990) were first to map the Sumeini/Hawasina thrust to the north of the study area by utilizing interpretation of seismic profiles, potential field, and well data. Furthermore, Callot et al. (2010, 2017) Jardin et al. (2013), Naville et al. (2013),
Tarapoaanc (2013) defined the western limit of the Hawasina allochthon on the deep seismic profiles (D1–D4) to the north of the study area. Figure 15 shows stratigraphy penetrated by the Biyath-1 well, which is located north of the study area (Figure 1). The well penetrated 976 m of undifferentiated Hawasina and Sumeini allochthons, which are thrusted within the Aruma sequence. However, for the first time, we mapped the subsurface and
The lateral distribution of the Sumeini nappe in the southern FTB of the UAE-Oman Mountains. The seismic data (Figures 6 and 9a) suggest duplex structures and imbricate thrust systems, which thickened the Sumeini nappes.

The Hawasina thrust was previously interpreted in the northern portion of Al Jaww Plain on a seismic section (Ali et al., 2008, 2009; Cooper et al., 2014; Searle & Ali, 2009). Nevertheless, we have mapped the lateral and subsurface extent of the Hawasina nappe for the first time in the FTB of the UAE-Oman Mountains. The previous interpretations assumed that the Hawasina nappe is only present in the northern part of Al Jaww Plain. However, we have found the Hawasina nappe in the entire Al Jaww Plain and north-central parts of the study area (Figure 13). This interpretation is supported by well QB-1, which penetrated the allochthon (Figure 5). Furthermore, the seismic attributes (Figure 9b) and the correlation with the surface outcrops of Hawasina along the adjacent front of the UAE-Oman Mountains support this interpretation. To the south, the Hawasina allochthon was traced from outcrops to the subsurface of the Suneinah foreland basin (Boote et al., 1990) where it terminates between the Lower and Upper Fiqa Formations. Furthermore, we interpreted multiple imbricated thrusts, which thickened the Hawasina allochthon (Figures 8 and 9b).

The structural style of the southern part, including the Jabal Hafit and Al Jaww Plain is dominated by inverted structures, backthrusting, and folding. The Cenozoic section, Upper Fiqa, and Juwaiza Formations are greatly affected by the Jabal Hafit backthrust. However, the Lower Fiqa Formation is not dissected by the backthrust as it lies below the Hawasina basal thrust, which is possibly a décollement or basal detachment. In Al Jaww Plain, the time structural maps of the Upper Cretaceous-Cenozoic sequences (Figures 11a–11f) illustrate the presence of two NNW-SSE trending synclines and an anticline. This series of fault-controlled folds are subparallel to the

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**Figure 15.** Stratigraphy penetrated by the Biyatih-1 well to the north of the study area (see Figure 1 for location). The well encountered 976 m of undifferentiated Hawasina and Sumeini allochthons, thrusted within the Aruma Group. The red symbol represents a thrust fault.
Jabal Hafit anticline (Ali et al., 2008, 2009; Woodward, 1994). Beneath the Jabal Hafit anticline an inverted pop-up structure is observed at the base of the Aruma foreland basin succession (Figure 8). This pop-up structure is enclosed by listric reverse faults, which penetrate the passive margin sequence. Ali et al. (2008, 2009) suggested that these faults merge at depth and are possibly linked with inversion of deeper structures.

The inverted basement faults and the Hawasina basal detachment possibly formed the Jabal Hafit anticline as a backthrust structure (Figure 16b). The pop-up structure probably acted as an obstacle in the front of the Hawasina thrust sheet, allowing the Upper Cretaceous-Cenozoic sequences to be backthrust and repeated along the Tarbat backthrust. Hansman and Ring (2018) described the Jabal Hafit structure as a trishear fault-propagation fold, caused by a westward propagated footwall wedge that forced the anticline to go up and over the footwall. They suggested that the horizontal shortening ceased in the early-middle Miocene.

Glennie et al. (1973, 1974) suggested that the basal detachment of the Semail ophiolite and other associated allochthons occur above the Mesozoic carbonate platform. In contrast, Bernoulli and Weisert (1987) and Hanna (1990) suggested that the detachment is rather located deeper in the pre-Permian basement as it is the case in the Sahi Hatat and Jabal Akhdar domes in central Oman Mountains. Moreover, along the western edge of the Musandam Peninsula, the Mesozoic carbonate platform sequences are inverted (Searle, 1988a, 1988b; Searle et al., 1983, 2014). However, this study indicates that the Hawasina and Sumeini detachments occur above the platform sequences, although the platform faults were reactivated as thrust faults in the FTB (Figures 16a and 16b). Similarly, Dunne et al. (1990) inferred extensive thrusts within the platform sequences from seismic data throughout the FTB of the northern UAE. Robertson and Searle (1990) considered that some of these inverted platform faults are of Late Cretaceous age, because they are erodionly truncated and overlain by Cenozoic succession. Nevertheless, most of these faults have been reactivated during Miocene because they dissect the entire Cenozoic sequences (Figures 6 and 7). Therefore, the Oligocene-Miocene compression resulted in inversion and folding and hence leading to late-stage “leap-frog” geometries (Dunne et al., 1990; Searle, 1985).

However, we noticed Late Cretaceous block faults that have not been inverted (Figure 10). The faults extend upward to dissect the Thamama and Wasia Groups and are terminated in the Lower Fiqa Formation. The displacements along these faults, at the level of the Wasia-Aruma break, range from about 50 to 200 ms (~100–350 m). These block faults were possibly originated from the earlier rifting faults that were reactivated in the Late Cretaceous because of the lithospheric flexure caused by ophiolite loading.

5.3. Tectono-Stratigraphic Reconstruction

We constructed two tectono-stratigraphic reconstruction models crossing northern and southern Pabdeh foreland and FTB of the study area (Figure 16). The models were extended from the study area to the UAE-Oman Mountains in the east. The thicknesses of allochthonous bodies were estimated from surface outcrops, subsurface models obtained from the present study and the subsurface cross-section of Ali et al. (2020). We have also taken into account the 2D forward kinematic models of Callot et al. (2017) and Tarapoanca et al. (2013), which were based on deep seismic profiles in the northern UAE. The models of the present study are constructed to demonstrate the tectono-stratigraphic evolution of the FTB of the UAE-Oman Mountains and its relation to regional tectonics.

5.3.1. Late Permian-Late Jurassic

The UAE and surrounding region were affected by a major rift phase in the Late Permian, which is related to the opening of the Neo-Tethys Ocean. The NE-SW opening of the Neo-Tethys happened from the Late Carboniferous to late Early Permian times starting east of Australia and then progressed toward the east Mediterranean region (Stampflili & Borel, 2002). In the Late Triassic-Early Jurassic, further NE-SW rift event was recorded in the region, this time caused by the final continental breakup (Béchennec et al., 1990; Glennie et al., 1974; Robertson, 1986; Robertson & Searle, 1990; Searle et al., 1980). The wells used in the present study did not penetrate the Late Permian sequence. However, Ali et al. (2013) suggested the rift was initiated at 260 Ma, based on backstripping of deep exploration wells located in western UAE, in agreement
Figure 16. (a) Simplified tectono-stratigraphic models across the northern Pabdeh foreland, fold-and-thrust belt (FTB), and UAE-Oman Mountains. The northern area is characterized by major thrusting of the earlier normal faults and Sumeini nappe. For location of the models refer to Figure 1. (b) Simplified tectono-stratigraphic models across the southern Pabdeh foreland, fold-and-thrust belt (FTB), and UAE-Oman Mountains. A major pop-up structure or basement uplift, occur below Jabal Hafit anticline, and imbrications of Hawasina nappe are present in the southern area. For location of the models refer to Figure 1.
Figure 16. (Continued)
with stratigraphic evidence for initiation of the mid-Permian shelf sequence (Glennie et al., 1973). The later rift was initiated in Early Jurassic (Ali et al., 2013) corresponding to a regional unconformity exposed in the shelf carbonates. The tectonic subsidence curve of KB-1 well suggests that the later rift was initiated in the early Aalenian (ca. 174 Ma) and lasted until the Oxfordian (ca. 160 Ma; Figure 4a).

5.3.2. Albian-Cenomanian to Turonian

A northeast dipping intraoceanic subduction zone was initiated between around 103 and 95 Ma within the Neo-Tethys Ocean (Agard et al., 2016; Guilmette et al., 2018; Pearce et al., 1981; Rioux et al., 2016). The Semail ophiolite formed above this subduction zone and was separated from the Arabian continental margin by a sequence of time-equivalent oceanic rocks spanning distal (Haybi, Hawasina complexes) to proximal (Hamrat Duru Group, Sumeini Group). The Semail ophiolite was obducted onto the northeastern margin of the Arabian plate, along with the allochthonous thrust sheets beneath (Coleman, 1981; Glennie et al., 1973, 1974; Searle, 2007). The initial oceanic subduction of Tethyan oceanic crust below the Semail ophiolite occurred at about 96-95 Ma from U-Pb zircon dating of metamorphic sole amphibolites accreted along the base of ophiolite (Rioux et al., 2016) and the ensuing continental margin subduction reached its peak high-pressure metamorphism at about 81-77 Ma (Garber et al., 2021; Warren et al., 2003). The obduction of the Semail ophiolite resulted in south-westward thrusting of the accreted slope (Sumeini complex) and deep-marine Hawasina thrust sheets over the Arabian margin (Callot et al., 2017; Tarapoanca et al., 2013). The backstripped curves of wells KB-1 and KB-2 suggest a noticeable uplift and unconformity event at around 95-85 Ma. This event eroded the Turonian-Cenomanian deposits of the Arabian margin, along with the allochthonous thrust sheets beneath (Coleman, 1981; Glennie et al., 1973, 1974; Searle, 2007). This regional unconformity also eroded the older shelf carbonate sequences and formed the Wasia-Aruma break (Glennie et al., 1974; Robertson, 1987a; Searle et al., 1983). O’Connor and Patton (1986) and Robertson (1987a, 1987b) attributed plate margin uplift and erosion event to the formation of a flexural forebulge due to the Tethyan subduction zone and southwestwards migration of the Semail ophiolite and associated allochthons that eventually collided with the Arabian margin.

5.3.3. Coniacian-Campanian

The advancing ophiolite thrust sheets and associated allochthons loaded the margin and caused development of the Aruma foreland basin and deposition of the Lower Fiqa Formation possibly during the Coniacian-Santonian (Figures 16a and 16b). The flexural bulge and advancement of the Semail ophiolite resulted in reactivation of older extensional faults with normal displacements (Figure 10). Hence, the earlier rift related normal faults were extended upward to cut through the lower to mid-Cretaceous passive margin carbonates and terminate below the Fiqa Formation (Figures 10, 16a, and 16b). Late Cretaceous block faulting has been reported in the surrounding areas. For example, Boote et al. (1990) observed in the Suneinah foreland basin that the Mesozoic carbonate sequence is dissected by normal faults representing rift faults that were reactivated as block faulting contemporaneous with the accumulation of the Lower Fiqa Formation in the Late Cretaceous. Additionally, the Fahud-Natih horst in central Oman apparently formed prior the Wasia-Aruma break as it shows a fast growth during Santonian (Loosveld et al., 1996; Tschopp, 1967).

The Lower Fiqa Formation is laterally equivalent to the deep water shales and pelagic limestone of the Sayja Member of Muti Formation in central Oman (Robertson, 1987b). The backstrip curves of the exploration wells (e.g., KB-1, KB-2, QB-1) suggest a rapid tectonic subsidence was initiated at ca. 83 Ma, indicating the transition of the Arabian platform from a rifted passive margin to a foreland basin (Figure 4). This subsidence created accommodation space for the Upper Fiqa Formation in the foredeep parts of the Aruma foreland, and Juwaiza Formation in the front of the developing thrust sheets as a product of the weathering and erosion of these sheets. The Lower Fiqa Formation reaches a thickness of about 1,000 m at KB-1 well, which may indicate the present-day FTB was part of the Aruma foredeep during Campanian.

5.3.4. Maastrichtian

The backstrip curves suggest that the tectonic subsidence slowed down during the Maastrichtian (Figure 4), indicating the cessation of ophiolite emplacement and returning of the stable conditions. This is in agreement with the regional geology that shows shallow water rudist-bearing limestones of the Maastrichtian Simsima Formation unconformably overlying all underlying thrust sheets across the UAE-Oman Mountains. The Simsima Formation was deposited over most of the region after Late Cretaceous-Oman Mountains had ceased (Figures 16a and 16b), with less thickness to the east, over the FTB, and relatively greater thickness to the west. This is supported by the surface outcrops along the western flank of the mountains, where Simsima Formation is only represented by about 80 m
sequence, partly due to postdepositional erosional event (Alsharhan & Nairn, 2003). However, the studied wells record a thickness of about 250 m over the FTB (e.g., wells QB-1 and KB-2), and up to 330–600 m in the foredeep of the Pabdeh foreland basin (e.g., wells BA-1 and BS-1).

### 5.3.5. Paleocene-Early Oligocene

Stable sedimentary conditions continued until the early Oligocene with deposition of the Umm Er Radhuma, Rus, and Damman Formations (Figures 16a and 16b). In general, these formations are thick (~2,000 m, collectively) in the Pabdeh foreland basin, but either thin (~270 m, collectively) or absent in the FTB. This is probably due to a postdeposition uplift event that eroded the formations in the FTB.

Loosveld et al. (1996) suggested the tectonic quiescence commenced at the beginning of the Paleocene and continued until the convergence of the Makran subduction zone in the Oligocene, resulting in the start of the Jabal Al Akhdar uplift. Furthermore, apatite fission track data suggest that Cenozoic compression in the central Oman Mountains began in the late Oligocene, as evidenced by the uplift of the Jabal Al Akhdar between 30 and 25 Ma (Mount et al., 1998). However, recent low-temperature fission track studies (Grobe et al., 2018, 2019; Hansman et al., 2017) suggest that the Jabal Akhdar dome grew from the late Eocene to the Oligocene. However, fission track ages only give a point on the cooling path so cannot be definitively used to explain timing of uplift. An uplift with the size of Jabal Al Akhdar may well have being growing for 10–20 My. Nonetheless, the three main shelf carbonate culminations in the Oman Mountains (Musandam, Jabal Al Akhdar, and Saith Hatat) exhibit different structural geometries, degrees of thrusting and internal folding, and timing of culmination and uplift (Searle, 2019). The timings and strikes of the thrust and folds observed in the study area correlated well with those documented in the Musandam culmination (Ali et al., 2018; Ricateau & Riché, 1980; Searle, 1988a; Searle et al., 2014).

### 5.3.6. Oligocene-Recent

The backstrip curves, mainly from wells located in the Pabdeh foreland basin (Figure 4, BA-1, L1-A, and KM-1 wells), show an accelerated tectonic subsidence from the late Oligocene to early Miocene (24–25 Ma). The subsidence rates are greater than those resulted from the ophiolite emplacement and exhibit increasing toward the FTB (Figure 4). This subsidence is attributed to the regional compression of the collision of the Central Iran and Arabian plates across the Zagros Suture in the late Oligocene-Miocene. This tectonic event refolded the Hawasina allochthon's basal detachment, resulting in intense imbrications and a complex triangular zone in the northern UAE (Callot et al., 2017; Tarapoanca et al., 2013). Furthermore, the reactivation of Late Cretaceous tectonic structures during the late Oligocene-Miocene was kinematically linked to the stacking of tectonic slices of the Arabian platform as a result of a large-scale out-of-sequence contraction (Callot et al., 2017; Tarapoanca et al., 2013). This event also resulted in thrust repetition of the Permian-Mesozoic shelf carbonates and pre-Permian basement onto the foreland in the Musandam—UAE area (Searle et al., 2014) and formation of a second, Pabdeh, foreland basin (Ali & Watts, 2009; Ali et al., 2013). There is an obvious spatial link between the Late Cretaceous ophiolite obduction tectonics of the UAE-Oman Mountains and the Cenozoic Zagros FTB of SW Iran through the Musandam peninsula. The thrusts and folds of Musandam are not laterally continuous across to Zagros, but plunge to the north below the Strait of Hormuz and toward the SSW into the foreland basin of the UAE-Oman (Searle, 1988a). The Pabdeh foredeep is situated to the west of the Musandam shelf carbonate culmination, which was an area of forebulge during the Turonian, indicating a further westward migration of the peripheral bulge. However, the amount of shortening accommodated by the duplexes in the Mesozoic platform beneath the Musandam Peninsula decreases toward the south (Callot et al., 2017; Tarapoanca et al., 2013). This is attributed to a major paleogeographic promontory of the shelf in Musandam, whereas to the south of the Dibba zone was a major re-entrant (Searle, 1988a). Boote et al. (1990) proposed that the Musandam Peninsula acted as a rigid indenter of the Arabian plate, focusing compression and transmitting it back into the northern Oman-UAE Mountains. Moreover, the N-S to NNW-SSE alignment of the mid-Cenozoic thrusts (e.g., Hagab, Khusub, Al-Hiyar, Mughayra, and Bid Salma thrusts) can best be explained by a combination of the curvature of the orogenic belt and the location of the Strait of Hormuz syntaxis, a 90° bend in the orogenic strike (Searle, 1988a). The Musandam peninsula marks the boundary between continental crust under the Arabian Gulf to the west from oceanic crust in the Gulf of Oman to the east. This Musandam promontory has resulted in west-vergent thrusts along a lateral ramp system oriented almost parallel to plate convergence vector. On the other hand, Leever et al. (2011) have shown that thrusting can almost be parallel to the plate tectonics vector as a result of strain partitioning, with increasing fault dips as the convergence angle increases. However, it remains uncertain whether the thrust faults were originally NW-SE
striking, as it is the case in the southern and central Oman Mountains, and then eventually rotated clockwise into a N-S trend, or whether the original trend was N-S. Taking into consideration the regional NE-SW shortening direction, the N-S striking thrusts would have behaved as oblique ramps, and they should be characterized by dextral transpressional kinematics (Carminati et al., 2020). Nevertheless, there are no field observations for these kinematics and consequently, Carminati et al. (2020) suggested a passive rotation of thrust faults.

The strike of compressional structures varies from NW-SE in the southern and central portions of the UAE-Oman Mountains to approximately N-S in the northern portion, with the presence of a minor undulation across the Dibba Zone (NE-SW compressional structures; Carminati et al., 2020; Dunne et al., 1990). Crustal shortening by thrust stacking is transferred from the NE-SW Dibba zone to the N-S Musandam and across the Strait of Hormuz to the NW-SE Zagros trend by a series of thrust transfer zones along branch lines at different structural levels (Searle, 1988a). The presence of a basic transfer mechanism was implied by Dahlstrom (1970), enabling adjacent, roughly contemporaneous structural features to take over the shortening functions of those that die out. The transfer zones exhibit progressive thicker-skinned tectonics from UAE-Oman Mountains to Irani Zagros. The zones become younger from UAE-Oman to Iran and their timing correlates with collision of the Arabian plate with the Central Iran plate and the ensuing crustal-scale folding and thrusting of the Zagros orogeny (Searle, 1988a). The Musandam peninsula separates the continent-continent collision in the Zagros from the continent-ocean collision of the UAE-Oman Mountains. The Strait of Hormuz and the western part of the Gulf of Oman are consequently unique and complex regions of plate segmentation associated with early stages of the continent-continent collision (Searle, 1988a).

The seismic profiles suggest that the lower Miocene reflectors onlap folded upper Oligocene deposits, suggesting that the folding event started prior to the deposition of the lower Miocene deposits (Figure 8c). The compressional event continued through the Miocene until the present day, folding the Miocene to Recent deposits (Figure 8c). Moreover, the major thrusts (e.g., Bid Salma, Khusub, Al-Hiyar, and Mughayra) continue upward into the Fars and Pabdeh Groups, and hence indicate a possible post-Oligocene-Miocene thrust motion that may have continued to the present day (Ali et al., 2013). On the FTB, this compressional event resulted in the erosion of the Upper Cretaceous and Cenozoic sequences (Figures 16a and 16b). This event is contemporaneous with the culmination of the Musandam Peninsula along the main Hagab thrust (Ali et al., 2018; Ricateau & Riché, 1980; Searle, 1988a; Searle et al., 2014). Other authors (e.g., Boote et al., 1990; Kusky et al., 2005; Regard et al., 2005) reached the same conclusion by linking Cenozoic compressional deformation in the northern Oman-UAE Mountains and the Musandam Peninsula to the Zagros collision. In the Musandam Peninsula, the shortening postdates the middle Eocene and predates the deposition of upper Miocene strata (Searle, 1985; Searle et al., 1983). Whereas, along the western flank of Musandam, the Hagab thrust and associated thrust faults are covered by the flat-lying marls and clays of the Miocene Barzaman Formation (Michaelis & Pauken, 1990; Searle, 1988b, 2007; Searle et al., 1983). Oligocene-Miocene rethrusting of the Late Cretaceous thrust sheets dies out toward the south with minor offsets observed in Jabal Sumeini (Searle, 2019; Searle & Ali, 2009; Searle et al., 1990).

The stress regime seems to change within the Arabian plate from transpressional to the north in the UAE-Oman Mountains, to strike-slip in the Gulf of Aden region to the south. This could indicate a decrease of the compressional intensity away from the Zagros collision. Nevertheless, the E-W to NE-SW directions of compression recorded in the Arabian plate are not parallel to the convergence vector between the Arabian and Eurasian plates, which is mainly N-S (Regard et al., 2005; Vernant et al., 2004). The origin of the E-W to NE-SW compression is not entirely clear. Some authors have suggested an oblique collision of Arabia with the Indian plate as a possible cause (Filbrandt et al., 2006) of east-west compressive stress, but this is not supported by the lack of Late Cretaceous—Paleocene deformation along the south coast of Oman. The deformation recorded in the Miocene-Pliocene sequences at the southern flank of the Oman Mountains indicates a rotation of the compression trend from ENE-WSW to almost N-S toward the north (Fournier et al., 2004, 2006).

6. Conclusions

Tectonic subsidence curves suggest that the final major passive margin rifting event following mid-Permian continental breakup occurred in the early Aalenian (ca. 174 Ma) and lasted till Oxfordian (ca. 160). Rapid subsidence was initiated at ca. 83 Ma, because of ophiolite obduction and loading indicating the transition of the Arabian platform from a rifted passive margin to a foreland basin. Further accelerated subsidence which occurred
at 24–25 Ma is attributed to the collision between the Central Iran and Arabian plates along the Zagros Suture in Iran and in the Musandam region during the late Oligocene-Miocene, and formation of the Pabdeh foreland basin to the west of the Musandam Peninsula. This event resulted in the erosion of the Upper Cretaceous and Cenozoic sequences in the FTB and westward migration of the Late Cretaceous forebulge. The Pabdeh basin dies out to the south and thickens toward the Zagros ranges to the NW. Thus, the Musandam region and UAE show a classic example of early continentalcollision tectonics between Late Cretaceous ophiolite obduction thrust sheets in Oman to the SE and the late Cenozoic continental collision along the Zagros mountains to the NW.

The northern area is characterized by four major west-verging and east-dipping thrusts, named as the Khusub, Bid Salma, Al-Hiyar, and Mughayra thrusts, causing repetition of the Permian to middle Cenozoic sequences. The Sumeini nappe is mapped in the northern part of the study area, west of Jabal Sumeini, with a thickness range of ~250–1,400 m. The Khusub thrust has up to 3,700 m throw and forms a fault-propagation fold. The fault dissects the entire sequences including the carbonate platform section. The southern area has a major pop-up structure or basement uplift, below the Jabal Hafit anticline, and several imbrications of Hawasina thrust sheets. The pop-up structure is indicated from the inverted faults that terminate in the Aruma sequence. The Hawasina décollement, together with the inverted structure possibly formed the Jabal Hafit anticline as a backthrust structure. The Hawasina thrust sheets are recognized in the central and southern parts with a thickness range of ~500–3,300 m. The basal thrust detachment of the allochthons is suggested to be above the platform, with the presence of platform faults that were reactivated as thrust faults. Moreover, Late Cretaceous block faulting of the earlier extensional faults is observed, possibly due to flexure that resulted from the ophiolite loading.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Restrictions apply to the availability of the data.

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