The sedimentary record of ophiolite obduction in North Oman

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Abstract

The Semail Ophiolite in the Oman Mountains is the world's largest and best-exposed thrust sheet of oceanic crust and upper mantle. Ophiolite obduction was associated with development of a flexural foreland basin in front of the thrust sheets. Published models disagree on the kinematics of the obduction process, the formation and migration of any paired flexural forebulge and foredeep, and the character of the foredeep fill. It is unclear how far the classical foreland basin model, derived from continent–continent collision and retroarc settings, applies to ophiolite obduction.

This thesis assesses the entire Late Cretaceous sedimentary record of ophiolite obduction and, in particular detail, the syntectonic Cenomanian to Campanian section through the first integrated analysis of the relevant outcrop, seismic, and well data. The results demonstrate important departures from the classical model. No significant sediment was shed from the orogenic belt into the foredeep, because the obducting oceanic plate remained subaqueous. The sediment-starved foredeep remained underfilled for some 20 Myr. It was eventually filled with hemipelagic carbonates, minor prograding carbonate platforms and, locally, siliciclastic mud sourced from hinterland uplifts. Deformation of the foreland before and during obduction was strongly controlled by pre-existing NE–SW basement terranes and lineaments perpendicular to the obduction front, combined with NW–SE regional compression related to interaction with the Indian plate. Uplift and erosion were influenced more by these factors than by a migrating forebulge.

The study fundamentally re-interprets and re-defines the syn tectonic, Turonian to Santonian, Muti Formation, the transgressive unit reflecting subduction of the continental plate beneath the ophiolite. This unit erroneously included underlying deformed platform

margin deposits and an overlying tectonic mélange incorporating elements of overthrust units.

Because Oman has experienced limited deformation since obduction, it offers an exceptional analogue for foreland basin development associated with ophiolites now incorporated into mountain belts.

I hereby declare that the work described in this thesis is my own, except where otherwise stated.

Hendrik Johan Droste

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I am grateful to Bruce Levell, Mike Searle and Frans van Buchem for encouraging me and offering the opportunity to pursue this DPhil, and to Stuart Robinson for making it possible at the University of Oxford. After completing my Master's, I received a job offer from Shell Research at a time when career opportunities for geologists were limited, which led me to "postpone" doctoral studies. However, the idea never left my mind, and this DPhil has allowed me to finally fulfil that long-held dream.

This study draws upon many years of personal research and discussions with fellow geoscientists on the subsurface and outcrop geology of Oman. It extends the legacy of geologists whose work over the past century laid much of the groundwork for modern understanding. While advances in geological science since that time have been substantial, their precise and detailed observations remain a vital resource for further studies. I am grateful to Bruce Levell, Mike Searle, Mia Van Steenwinkel, and the late Janos Urai for sharing their time with me in the field. Their feedback and stimulating discussions greatly helped me gain confidence in my work.

I would like to thank Mike Searle for sharing his extensive knowledge of the Oman Mountains, ophiolites, and mountain-building processes. When I started this project, most of these topics were relatively new to me, but I now feel much more confident—and no longer intimidated—when reading papers on tectonic models, metamorphic petrology, or temperature–pressure plots. His insights have been a great help to me placing my work in a broader geological context.

I am especially grateful to Bruce Levell for his very helpful and friendly guidance and support throughout this work. Despite his busy schedule, including his role as editor of the

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I am deeply grateful to my wife Mia, and my daughters, Elise and Hester, for all their patience, support, and encouragement throughout this study, which helped me to bring it to a successful end.

I dedicate this thesis to my beloved parents, both of whom passed away during my DPhil study. Their hard work and sacrifice made it possible for me to pursue university studies, an opportunity they themselves had wished for but were denied. They took great pride and joy in my decision to embark on this journey, and I remain deeply grateful to them for their love, support, and inspiration.

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1 Introduction

1.1 Problem statement

The Oman Mountains are well-known for a large intact thrust sheet of Late Cretaceous oceanic crust and upper mantle (Semail Ophiolite) emplaced from NE to SW onto the previously passive continental margin of Arabia (Figure 1-1). This ophiolite obduction, starting in the Cenomanian and ending in the Early Maastrichtian, was associated with significant reconfiguration (steepening and back-stepping) of the contemporaneous carbonate platform edge and the formation of a flexural foreland basin (Aruma Basin) in front of the thrust sheets. The top of the subducted continental margin, beneath the nappe pile, now exposed in the Oman Mountains, shows an apparently missing section, of approximately 1.5 km from mid Cretaceous down to Triassic, attributed to truncation. The pre-obduction unconformity and the sedimentary infill of the foreland basin are the main focus of this thesis. However, to understand the sedimentary record associated with the obduction process, it is also necessary to consider the inherited structural framework and basement trends that have influenced both sedimentation patterns and the obduction process itself.

Published models agree that in the process of thrust emplacement a "classical" foreland basin / forebulge system developed (Béchennec et al., 1995; Boote et al., 1990; Breton et al., 2004; Glennie et al., 1974; Patton and O'Connor, 1988; Robertson, 1987b; Warburton et al., 1990). However, there is disagreement on the nature of the basin and forebulge. They are regarded either as part of a migrating wave of flexural subsidence

(basin) and uplift (forebulge) that preceded the advance of the thrust stack or as static and non-migratory features related purely to the end-state. There is also disagreement in literature as to the location of the proposed bulge. Furthermore, the ophiolite obduction process is not necessarily the same as the crustal thickening and loading processes associated with typical continent-to-continent collisions or retro-arc settings from which classical foreland basin models are derived.

This study sets out to critically examine field and subsurface evidence of the obduction process, as recorded by coeval sediments, and to elucidate their relationship with inherited structures and trends. This thesis draws on a comprehensive review of the available literature on the eastern Arabian Plate, four winter seasons of geological fieldwork in the Oman Mountains and foothills, and detailed subsurface mapping using well and seismic data in the foreland basin area. Integrating subsurface and outcrop observations was central to the study and enabled a unified understanding of North Oman's geology. The insights from this study will serve a multitude of wider applications: (1) There are no modern examples of active ophiolite obduction but Oman, because of the limited tectonic deformation after the obduction event, can serve as a good analogue for the emplacement of other ophiolite complexes now incorporated into mountain belts. 2) The study also addresses along-strike continuity issues between Oman and the UAE. (3) It provides a unified understanding of North Oman geology, which has long been a challenge because of poorly integrated and inconsistent naming and interpretations between subsurface and outcrop. (4) This stratigraphic study complements existing studies from the perspectives of the structural geology of the thrust stack

(Cooper et al., 2014; Mount et al., 1998; Searle, 2007), metamorphic and geochronological studies on the metamorphic sole of the ophiolite (Rioux et al., 2021; Searle et al., 2022), as well as the structural deformation of the autochthon (Grobe et al., 2018; Grobe et al., 2019). It is the first comprehensive review of the syn-obduction

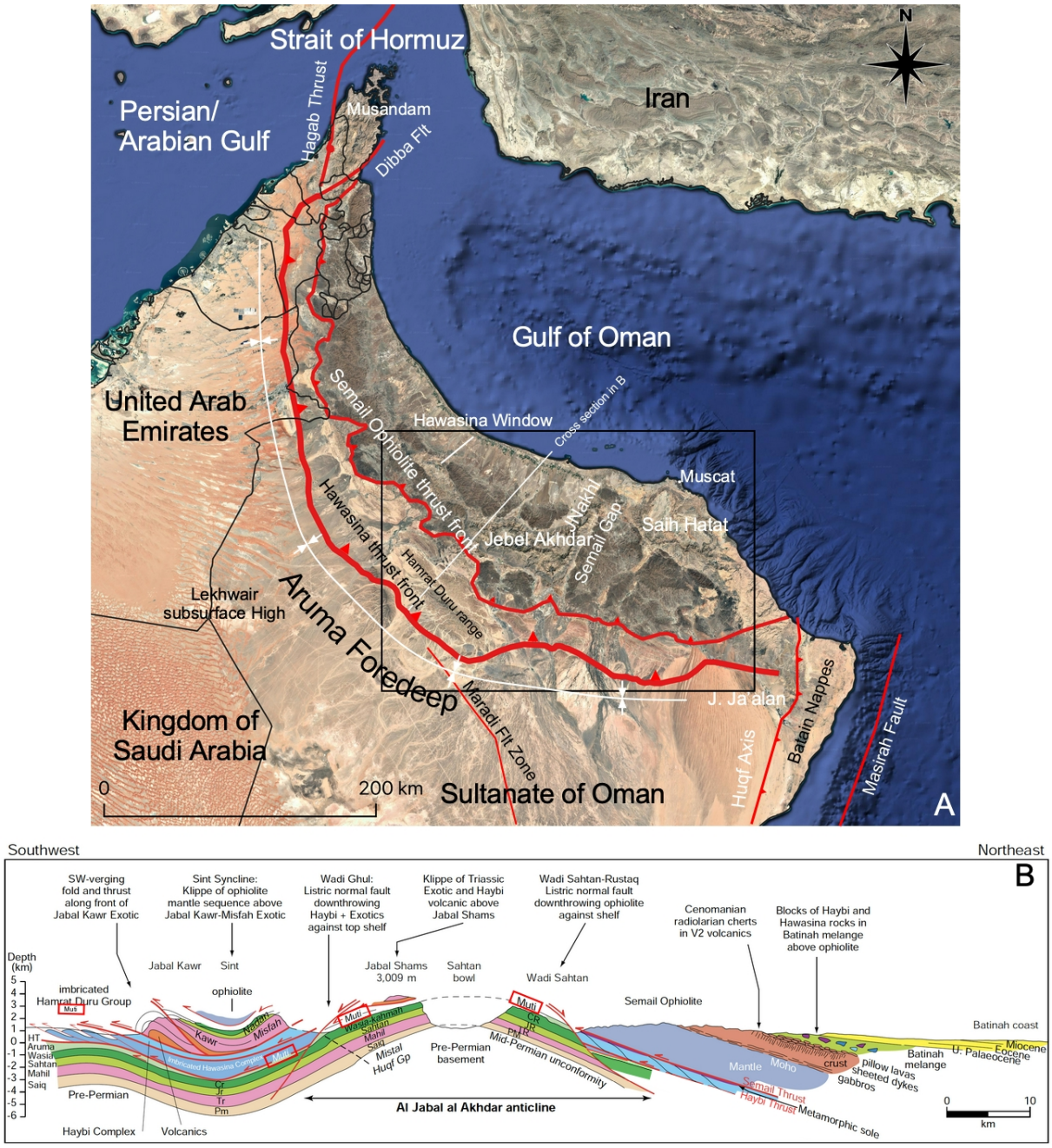


Figure 1-1 Google Earth satellite map of northern Oman with the outline of the obduction complex. Inset: outline of geological map in Figure 1-5. B: NE-SW geological cross section through the central part of Jebel Akhdar showing the thrust complex and the autochthonous carbonate platform separated by the synorogenic Muti Fm. (red boxes). Location of cross section is indicated on map. Modified from Searle (2007).

sediments since the pioneering work of Robertson (1987a; 1987b) and the BRGM (Bureau de Recherches Géologiques et Minières) geological mapping project (Rabu et al., 1993).

1.2 Present day plate tectonic setting

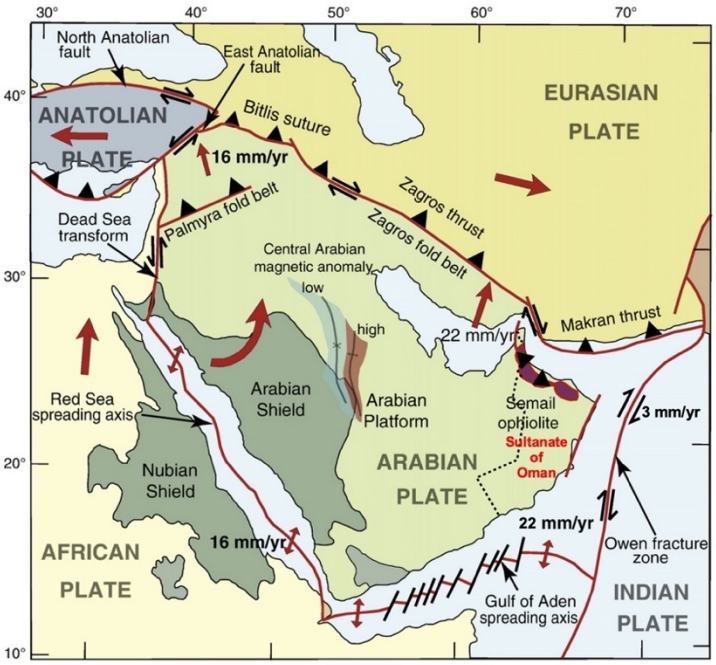


Figure 1-2 Simplified map showing the plate boundaries of the Arabian Plate with approximate plate convergence vectors. The Sultanate of Oman is located on the eastern plate margin. Modified from Stern and Johnson (2010).

The Sultanate of Oman is located on the easternmost part of the Arabian Plate (Figure 1-2), which rifted away from the African Plate in the south during the late Eocene to early Oligocene with the opening of the Gulf of Aden at 35 Ma (Leroy et al., 2013) and the Red Sea at 25 Ma (Ghebreab, 1998).

North of Oman the plate margin is formed by an active subduction zone overlain by the Makran accretionary wedge which extends from southeastern Iran into the Gulf of Oman, some 100 km north of the Oman coast, and the continental Zagros collision zone further west in Iran. The Makran subduction zone is thought to have started shortly after 120

Ma during the late Early Cretaceous and the sedimentary prism accreted during the Cenozoic (Burg, 2018; Kopp et al., 2000). The Zagros fold and thrust belt formed during the Arabia-Eurasia collision. Estimates for the timing range from Late Cretaceous to Pliocene. Plate reconstructions suggest a ca 27 Ma (Oligocene) initial collision age (McQuarrie and van Hinsbergen, 2013). However, recent provenance studies indicate that, in places, the collision possibly started before the Eocene (Sun et al., 2023). GPS measurements show that at present Arabia is converging towards Eurasia with a velocity of 22 mm/yr (Masson et al., 2007; Sella et al., 2002).

East of Oman the Arabian plate boundary is formed by the Owen fracture zone, a strike slip boundary located on the east-facing escarpment of the NNE trending Owen ridge in the Indian Ocean, some 250 km from the Oman coast (Fournier et al., 2008; Fournier et al., 2011). Both the Indian and Arabian plate are moving northward relative to the Eurasian plate, but Arabia is moving slightly faster resulting in a dextral motion of some 3 mm/yr (DeMets et al., 2010). Movement along the Owen fracture zone started at approximately 2.4 Ma, during the Pliocene (Rodriguez et al., 2019).

The transform boundary between Africa/Arabia and India formed around 90 Ma in the Late Cretaceous (Turonian) when the India-Seychelles plate separated from Madagascar and moved northward towards Eurasia along strike-slip margins (Rodriguez et al., 2016). This plate boundary is thought to have been originally located further west closer to the Oman coast (Mountain and Prell, 1990; Royer et al., 2002) but jumped to the vicinity of the Owen Ridge and changed to a dextral motion during the late Eocene-Oligocene (Rodriguez et al., 2019). However, the exact location of the original boundary is not clear (Royer et al., 2002).

The change to dextral motion may be related to the Zagros and Himalaya collision (Rodriguez et al., 2016).

In the south the plate boundary is formed by the mid-oceanic Sheba spreading ridge which separates Arabia from the northeastern African Plate. Rifting started 34 – 33 Myr ago in the latest Eocene to early Oligocene (Leroy et al., 2013; Leroy et al., 2010). The spreading ridge became active at 19.7 Ma during the Oligocene and the spreading rate is 22 mm/yr south of the Dhofar area in South Oman (Fournier et al., 2010). Escarpments of up to 1800 m high along the Dhofar coastline and the up to 450 m high cliffs of the Al Halaaniyaat Islands define the northern rift shoulder. The conjugate margin of this oblique rift is formed by the northern coast of Somalia and the island of Socotra (Yemen) (Leroy et al., 2013).

1.3 Tectonostratigraphy

An overview of the tectonostratigraphy of Oman is shown in Figure 1-3. A detailed description of the lithostratigraphy in the subsurface is provided by Forbes et al. (2010), and of the tectonic history by Droste (2014). The geological record extends deep into the Neoproterozoic and the oldest sedimentary rocks encountered to date were deposited 870 – 810 Myr ago (Bauer et al., 2025). The sedimentary record shows a wide variety of sediments ranging from glacial siliciclastics to tropical carbonates and records the movement of the Arabian Plate through different climate belts. The sedimentary record is interrupted by several major hiatuses which are related to major plate tectonic events. The missing sections in Oman cover a much wider age interval than the interior parts of the Arabian Plate and reflect Oman's position close to the plate margin. The main tectonic events are: (1) the Pan-

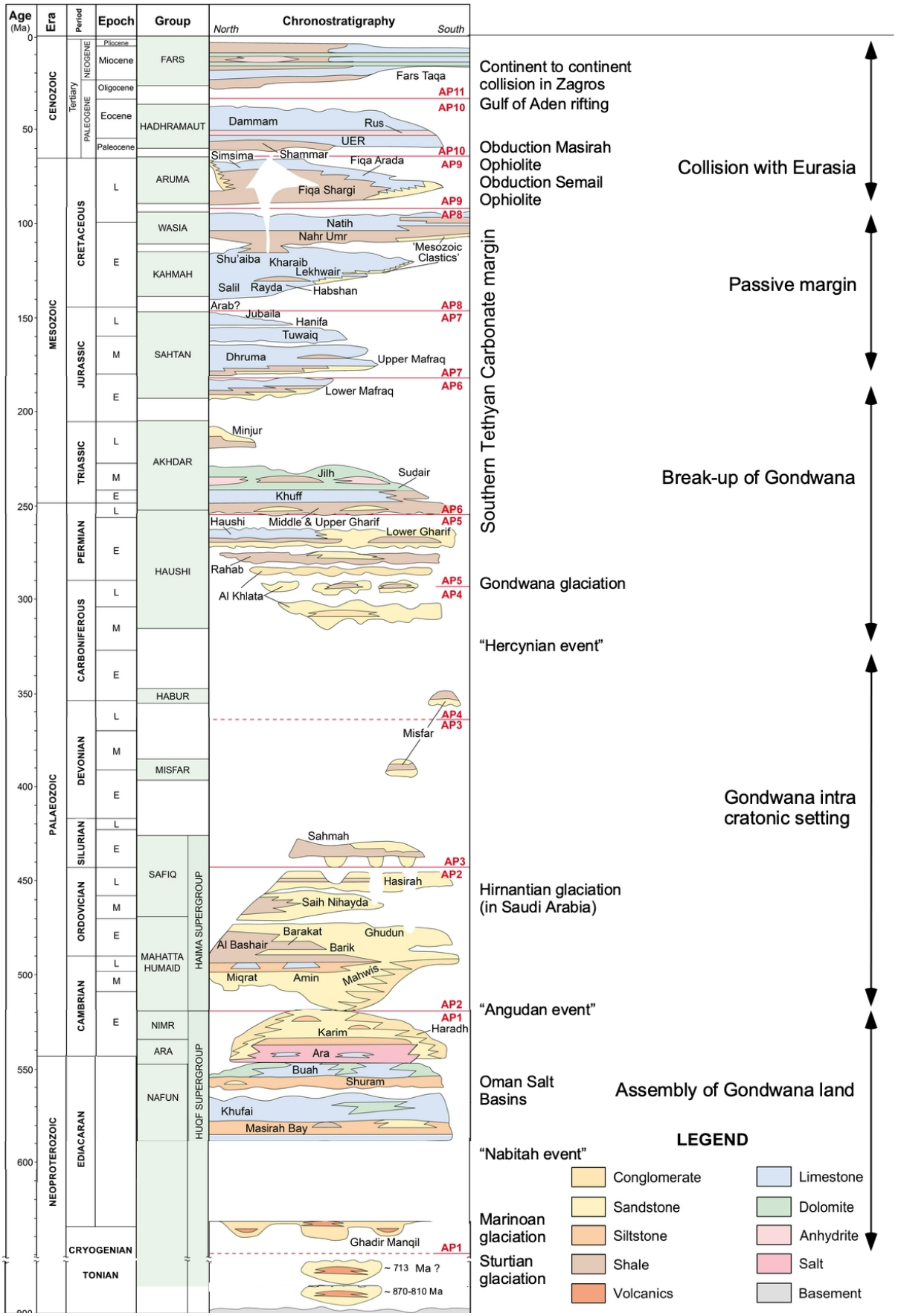


Figure 1-3 Chronostratigraphic chart with subsurface lithostratigraphic units and main tectonic events in Oman modified from Droste (2014). AP labels refer to major regional unconformities on the Arabian Plate described by Sharland et al. (2001). Plate reconstructions of the mid-Carboniferous, middle Permian and Early Cretaceous are shown in Figure 1-4.

Neoproterozoic – earliest Cambrian, (2) a poorly understood mid Carboniferous gentle deformation associated with major uplifts, (3) Permian to Jurassic extension leading to the break-up of Gondwana, (4) Late Cretaceous ophiolite obduction in North Oman and (5) Neogene compression linked to the Zagros orogeny. During the younger tectonic events, basement terrane boundaries often formed zones of more intense deformation and basement-rooted faults were re-activated by transtension or transpression (Bell, 2004).

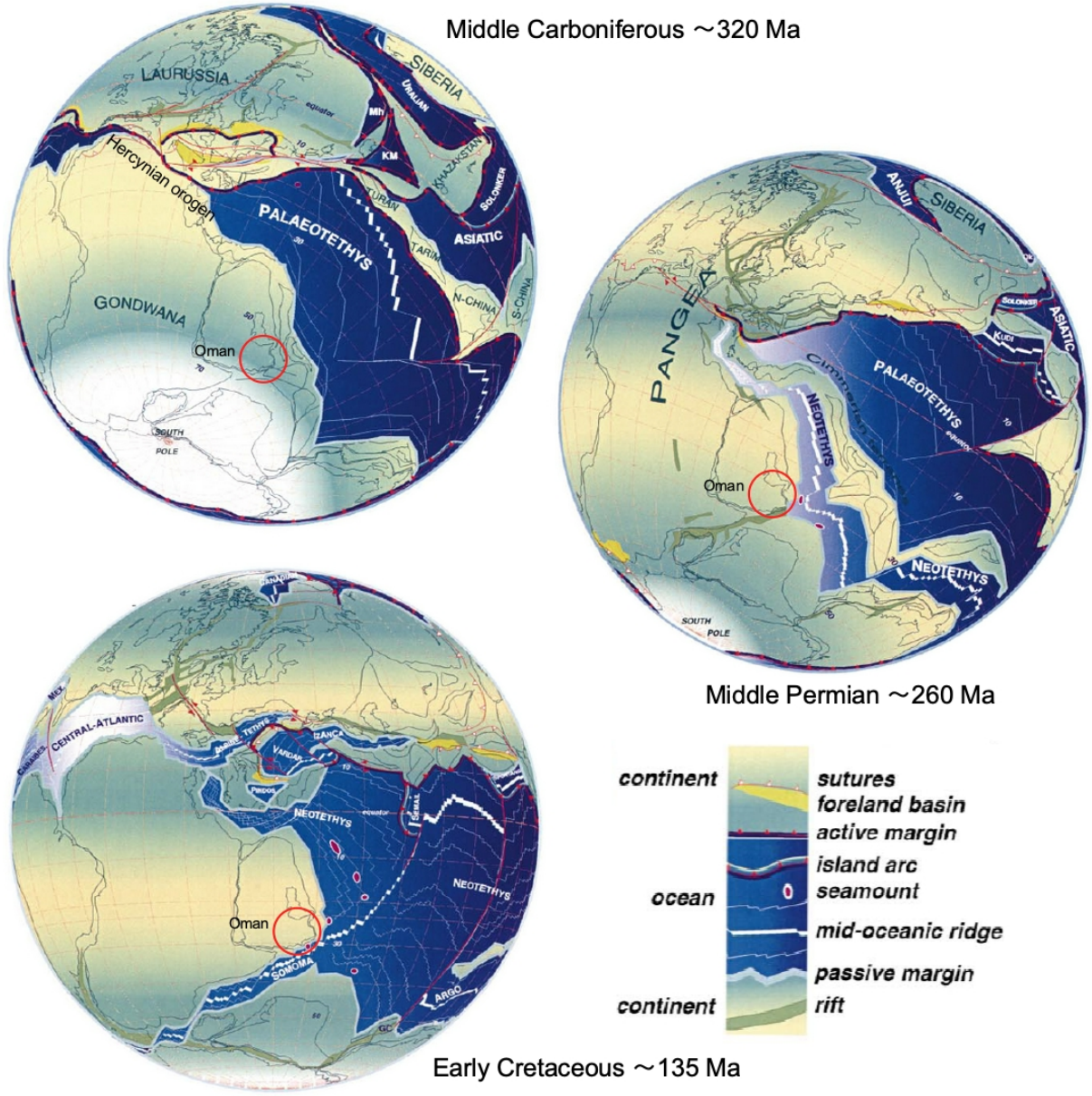


Figure 1-4 Plate tectonic reconstructions for the middle Carboniferous (Bashkirian), middle Permian (late Wordian) and Early Cretaceous (Valanginian) showing the location of Oman during the break-up of Gondwana. Modified from Stampfli and Borel (2002).

1.4 Geological features and regions mentioned in the thesis

This section provides an overview of the main geological features and regions in Oman that are mentioned in the thesis and hence play a role in the described geological evolution. An up-to-date overview of the geology of the Oman Mountains is provided in Searle (2019) and Scharf et al. (2021), a description of the main outcrop localities in North Oman in Hoffmann et al. (2016). Major data sources on the surface geology of Oman are a detailed study by Glennie et al. (1974) and the maps and explanatory notes of the geological mapping project by the BRGM and the Institute of Mineralogy and Petrography/Geological Sciences in Berne for the Ministry of Petroleum and Minerals of Oman summarised in Rabu et al. (1993)

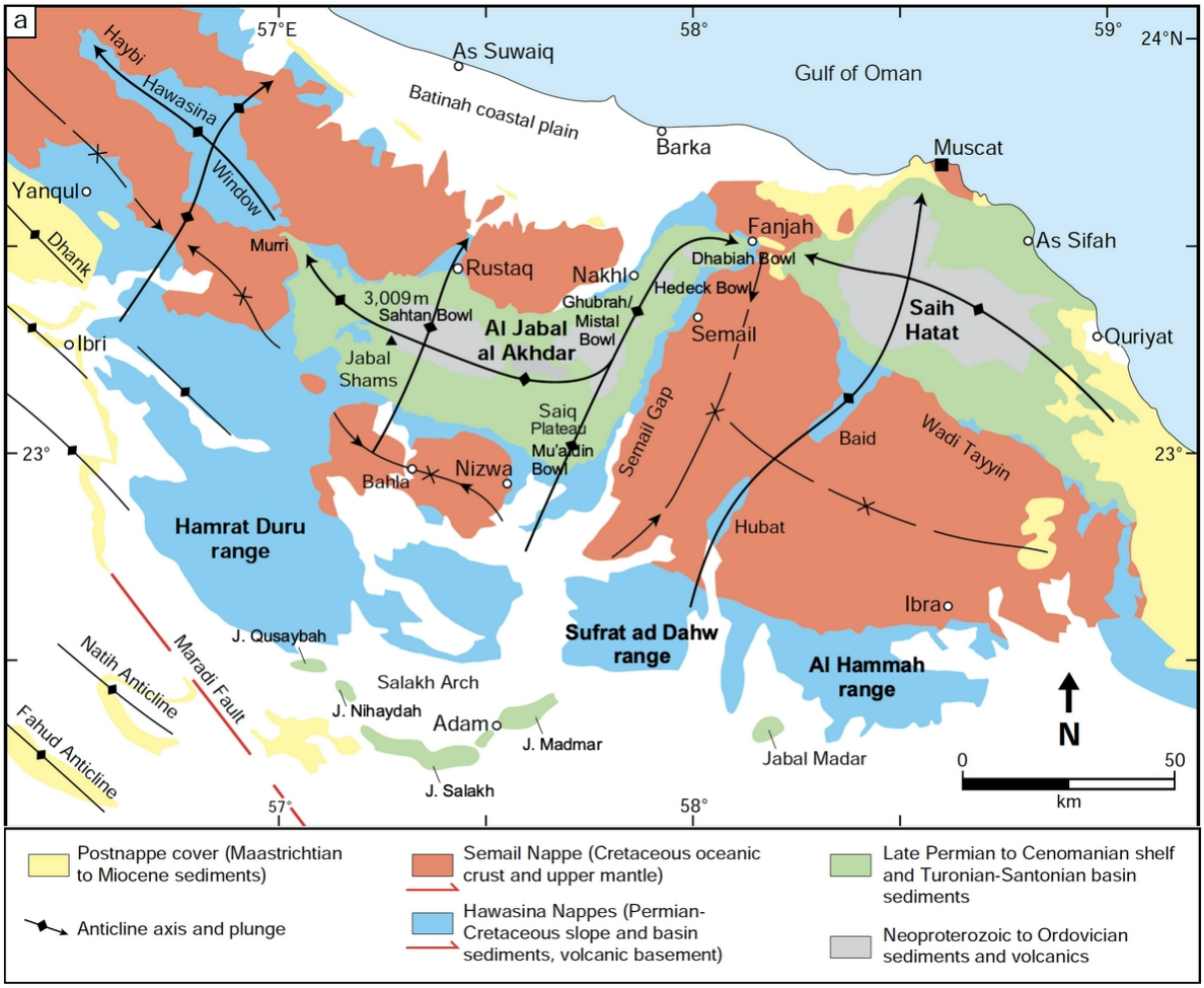


Figure 1-5 Simplified geological map of the central and eastern Oman Mountains with main structural features. For location see inset in Figure 1-1. Modified from Searle (2007).

and Le Métour et al. (1995b). Outlines of the subsurface geology and the stratigraphic nomenclature can be found in Droste (2014) and Forbes et al. (2010) respectively.

1.4.1 Semail Ophiolite

The Semail Ophiolite consists of oceanic crust and the upper part of sub-oceanic mantle which have been emplaced on the Arabian margin during the Late Cretaceous. It extends almost 500 km along the northern coastline of Oman, and the maximum width of the preserved ophiolite belt is some 120 km. The Semail ophiolite is wedge-shaped tapering towards the SW. Though the aggregate maximum thicknesses of all preserved units is estimated at least 16 km (Lippard et al., 1986), gravity data of the ophiolite blocks shows a maximum structural thickness of 7.5 km and an average thickness of some 5 km (Shelton, 1990). An overview of the formation of the Semail ophiolite and its obduction onto the Arabian Plate margin is provided in Lippard et al. (1986), Searle et al. (2022) and Najafi et al. (2026). Rioux et al. (2021) provide a detailed overview of geochronological data for the Semail ophiolite.

Dated plagiogranites intruded into the ophiolite crustal sequence show that the oceanic crust was formed in ~1 Myr between 96.1 and 95.2 Ma (middle Cenomanian (Rioux et al., 2021; Searle et al., 2022)). It is thought to have formed along a NE-dipping intra-oceanic subduction zone (Figure 1-6) probably associated with slab rollback (Najafi et al., 2026). Studies of the age of metamorphism of the metamorphic sole of the ophiolite (the protolith of which includes the Haybi complex basalts and sediments of the subducting plate), suggest that the initiation of this subduction zone started shortly before, or synchronously with, the ophiolite formation at c. 97-96 Ma (middle Cenomanian, Rioux et al. (2021), Searle et al. (2025). Much earlier ages, even before c. 104 Ma (late Albian) have been suggested in

literature (Guilmette et al., 2018). However these ages have been shown not to be accurate (Garber et al., 2025; Rioux et al., 2023).

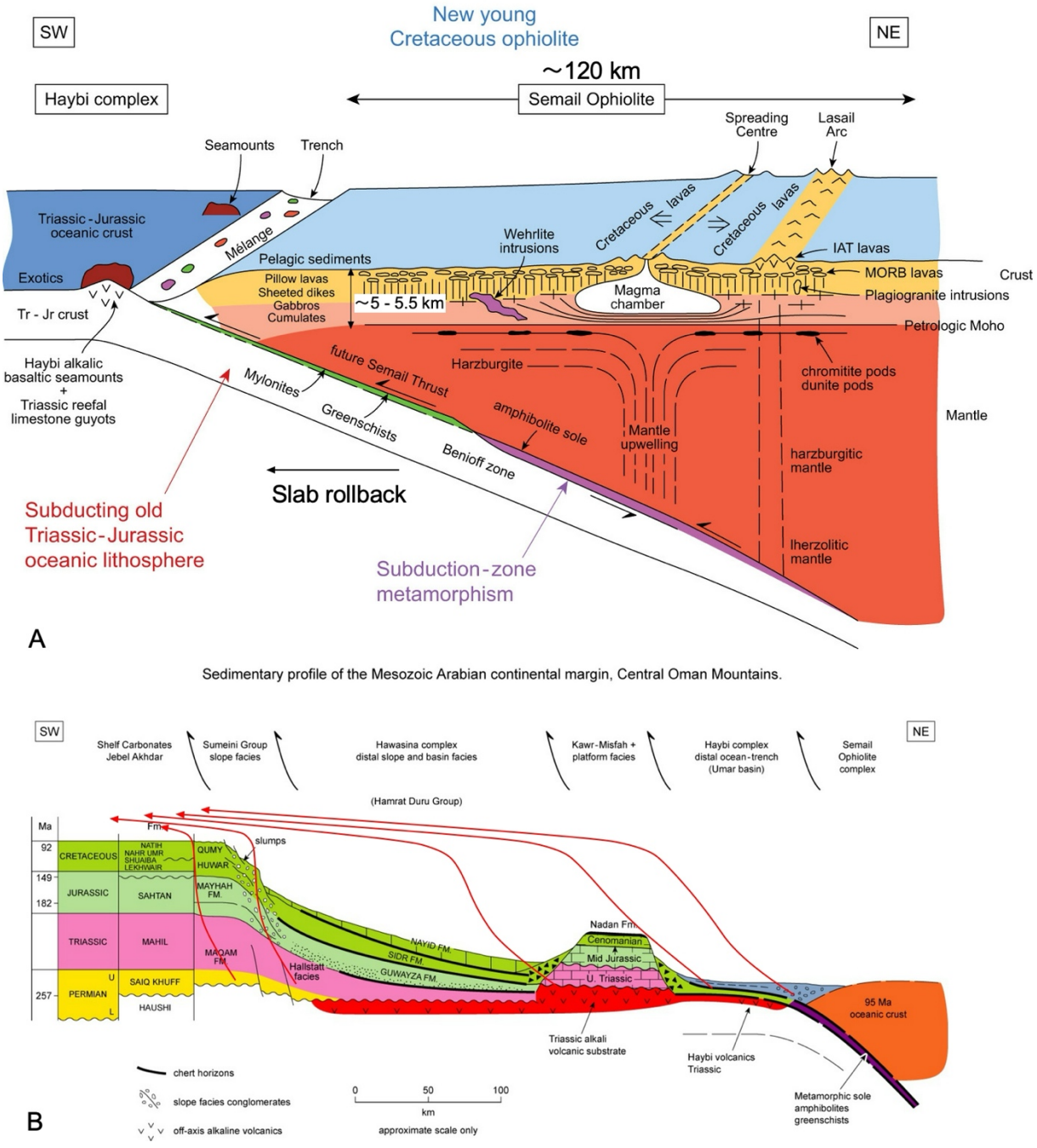


Figure 1-6 A: Supra-subduction zone model for the Semail ophiolite. The reconstruction shows the situation immediately prior to emplacement at 95.5 Ma (middle – late Cenomanian boundary). Figure modified from Searle and Cox (1999) and Searle (2014), thicknesses ophiolite crust from Nicolas et al. (1996). B: Schematic palinspastic reconstruction of the Cenomanian continental margin before thrusting and obduction. The main thrusts are indicated by red arrows. Modified from Searle (2007).

After its formation, the ophiolite together with basinal and slope sediments as well as isolated off-margin carbonate build-ups were emplaced as an imbricated thrust complex onto the Mesozoic carbonate platform margin (Figure 1-6B). An overview of the stratigraphical and structural nomenclature of the nappes is provided by Robertson and Searle (1990).

Estimates of the width of the Hawasina basin separating the Semail ophiolite from the Arabian platform, based on balanced and restored cross sections, range from 235 to 475 km (see Najafi et al. (2026), and references therein). The most recent study, by Najafi et al. (2026) indicates a minimum basin width of 235 km.

The initial emplacement of the ophiolite is thought to have occurred through subduction of the transitional zone of the continental margin. Najafi et al. (2026) estimate obduction rates based on restored nappe widths and best estimates of timings. According to their results, obduction over the Umar subbasin and the Oman exotics (Kawr Misfah platform in Figure 1-6B) occurred between 95.2 and 90 Ma (late Cenomanian to latest Turonian). This was followed by obduction of the Hawasina and Semail units onto the continental slope between 90 and 85 Ma (latest Turonian to early Santonian). Convergence rates during these stages are estimated at ~22 mm/yr. Final emplacement of the nappe complex onto the shelf carbonate platform occurred between 85 and 80 Ma (middle Santonian to early Campanian), accompanied by a reduced convergence rate of ~16 mm/yr.

1.4.2 Oman Mountains

The Oman (or Al Hajar) Mountains are located along the northern coastline of Oman between the Straits of Hormuz in the north to just west of Ras al Hadd in the southeast

(Glennie et al., 1973; Glennie et al., 1974). The mountain range is approximately 600 km long and extends some 30 to 130 km towards the interior of Oman (Figure 1-1).

The northern end is formed by the Musandam peninsula, which is separated by the Straits of Hormuz from the Zagros Mountains in Iran. The highest peaks in this area are just over 2 km and, as this part of the mountain chain is now strongly subsiding, the coastline is characterised by large fjords. The peninsula is bounded to the west by the Hagab thrust, a major west-vergent thrust that caused significant uplift of Permian to Cretaceous platform carbonates during the Neogene (Searle et al., 2014). To the south the carbonates of the Musandam High are separated by the Dibba zone from the Oman Mountains and the Semail ophiolite exposures. The Dibba zone is structurally very complex with numerous Late Cretaceous thrust sheets. It forms a NE-SW trending topographic depression bounded to the north by the Dibba Fault, a large Neogene normal fault down-throwing to the ESE. The Dibba zone is interpreted as an oblique-rifted passive margin segment and probably was the location of the carbonate platform margins during the Triassic to middle Cretaceous (Robertson et al., 1990).

The central and eastern part of the Oman Mountain range has a recumbent S-shape and consists of the Jebel Akhdar and Saih Hatat culminations with an offset formed by the NNE-SSE trending Jebel Nakhl (Figure 1-5). East of Jebel Nakhl is the Semail gap, a depression which is the main N-S access route between the coast and the interior of Oman. The Semail gap has been interpreted a lateral-ramp associated with thrusting of pre-Permian basement and folding of the Jebel Akhdar and Nakhl anticlines probably during ophiolite obduction in the Late Cretaceous (Searle, 2007). At the west margin of Jebel Akhdar/Jebel Nakhl is the Semail gap fault, a large down-to-the-east normal fault with offsets up to 3-4 km active

during the Neogene uplift of the Jebels. The highest peak is Jebel Shams with an elevation of 3009 m located in the Jebel Akhdar dome.

The mountain range is now flanked by remnants of the Upper Cretaceous ophiolite complex. During the Late Cretaceous, oceanic crust (Semail ophiolite nappe), isolated carbonate platforms and deep-water-to-slope sediments (Hawasina nappes) from the Neo-Tethys ocean were emplaced onto the Arabian continental margin (Glennie et al., 1973; Glennie et al., 1974; Searle, 2007). Zircon and Apatite Fission Track (ZRT & AFT) studies show the uplift of mountain range was ongoing at least by 40 Ma (mid-Eocene) and almost certainly started prior to this (Hansman et al., 2017). Erosion during this uplift and doming removed the obduction complex over the highs exposing the underlying autochthonous sequence in several tectonic windows. This is where most of the outcrop work for the current study was done. Where erosion reached more easily erodible clastic-dominated units below the Permian to Cretaceous carbonates, deep depressions ("Bowls") formed in the core of the mountain range. In the culmination that forms the Hawasina window, NW of Jebel Akhdar, erosion only reached the allochthonous sequence below the Semail thrust and the Mesozoic carbonate platform is not exposed. Saih Hatat is a similar dome, exposing autochtonous rocks in its core, but the northern part of the Saih Hatat culmination is strongly deformed by ductile shear zones formed during the Late Cretaceous exhumation of continental crust which brought eclogites that formed at depths of around 100 km in a NE dipping subduction zone back to the surface along the coast near As Sifah (Searle et al., 2004).

1.4.3 Frontal ranges

The Hamrat ad Duru, Sufrat ad Dawh and Al Hammah frontal ranges are located south of the Semail Ophiolite thrust front (Figure 1-5) and consist of imbricated thrust sheets of Jurassic to Lower Cretaceous deep water, continental rise deposits of the allochthonous Hamrat Duru Group and Wahrah Fm. of the Hawasina nappe complex (Cooper, 1988; Cooper, 1990; Cooper, 1986; Glennie et al., 1974). These arcuate features on the geological map appear at first glance to be simply frontal ranges along the major mountain-front thrust. Closer study reveals a more complex explanation.

The present-day elevation of these ranges is low, at maximum a few hundred metres above the surrounding alluvial plains. However, gravity, seismic and well data indicate the presence of major domal structures bounded by both north and south dipping fault systems in the autochthonous Mesozoic carbonates below these ranges.

Some of these highs show reverse faulting with throws of at least 1.5 km. Analysis of sonic transit times of Albian and Cenomanian shales in a well drilled on the hanging wall of one structure suggests that at least 900 m, perhaps 1800 m, of the nappes and overburden have been removed. Shale velocity trends in other structures below the nappes also suggest uplifts in the range of 1-1.5 km. Deep burial is also suggested by the maturity of organic material in the Hawasina nappes which is much higher in this well than would be expected from present day burial depths. These data indicate that uplift occurred after emplacement of the thrust sheets. The erosion removed both the Cenozoic cover and the upper part of this frontal thrust complex which was therefore much thicker than the currently preserved remnants. The late deformation resulted in gentle folding and localized faulting of the overlying Hamrat Duru imbricated thrust stack and unconformably overlying Palaeogene

carbonates. The timing of uplift is Late Miocene or younger as indicated by deformation of Palaeogene limestones around the Hamrat ad Duru range and tilting of Miocene strata in the adjacent subsurface (Warburton 1990).

1.4.4 Salakh Arch

The Salakh Arch is a chain of six doubly plunging anticlines some 50 – 70 km south of Jebel Akhdar at the Hawasina thrust front (Figure 1-5). It exposes mid-Cretaceous carbonates and shales of the Natih and Nahr Umr Fms. Deformation of Pliocene deposits, the displacement of Cenozoic seismic reflections, thrusting of the Mesozoic carbonates over Miocene conglomerates, and the absence of Cretaceous platform carbonate clasts in Pre-Miocene deposits all imply that most uplift (some 2 km) and erosion occurred during the Neogene (Al-Kindi, 2020; Béchennec et al., 1992c; Filbrandt et al., 2006; Hanna and Smewing, 1996). Outcrop and subsurface studies by (Al-Kindi, 2020) suggest the main factors controlling the position and shape of the uplifts in the Salakh Arch are pre-existing basement faults and the related thickness changes in overburden (Al Kindy 2020). Reverse faults that bound the uplifts may represent NW-SE trending Late Cretaceous normal faults which were re-activated as reverse and transtensional faults during Neogene NE-SW compression.

1.4.5 Jebel Madar

Jebel Madar is an isolated mountain, some 8 km across and about 500 m of relief, located in the alluvial plain some 10 km south of the Al Hammah Frontal Range (Figure 1-5). The Jebel has flanks dipping up to 38° and seismic data show it is underlain by a salt dome (Claringbould et al., 2013; Mount et al., 1998). Some small outcrops of Hawasina nappes just south of the Jebel indicate that it was originally below the thrust complex. The Jebel exposes

scattered syn-obduction Muti Fm. outcrops along the flanks, and the mid-Cretaceous Natih to Triassic Mahil Fms. in the core.

1.4.6 Maradi Fault

The Maradi Fault zone (MFZ) is a system of NNW-SSE trending normal and reverse faults forming elongated horsts and grabens (Filbrandt et al., 2006; Loosveld et al., 1996). It is a major structural feature which extends from the Cretaceous thrust front north of the Natih Field for some 160 km to the Qarn Alam area in central Oman and lines up with the Haushi Nafun Fault in the Huqf area (Figure 1-1). Poor seismic data do not allow mapping below the Semail and Hawasina nappes, but the MFZ seems to line up with major Neogene thrusts along the western flank of the Oman Mountains in northwest Oman and the United Arab Emirates. Most of the fault zone is mapped with subsurface data. In the northwest it crops out as a series of low ridges and deformed wadi gravels indicating that the fault has been active as recently as the Plio- Pleistocene (Hanna and Nolan, 1989). In the subsurface, the fault zone is up to 10 km wide and has maximum vertical displacements in the order of 750 m but locally possibly 2000 m (Filbrandt et al., 2006). The fault zone cuts through the entire Mesozoic down to the Lower Palaeozoic where it becomes difficult to trace on seismic (Filbrandt et al., 2006). The MFZ is thought to have originated in the Neoproterozoic during the Pan-African orogeny (Stuart-Smith et al., 2007) but there is little firm evidence for activity before the Late Cretaceous (Al-Kindi and Richard, 2014; Filbrandt et al., 2006; Stuart-Smith et al., 2007). Major sinistral transtensional deformation with normal faulting occurred in the Late Cretaceous with lateral movement of some 10 km and transpressional dextral deformation during the Neogene up to the Plio- and Pleistocene (Filbrandt et al., 2006; Loosveld et al., 1996).

1.4.7 Huqf Axis

The Huqf Axis is a NNE-SSW trending basement high along the eastern coast of Oman, extending from Jebel Ja'alan in the north to Mirbat in the South (Figure 1-1, Loosveld et al., 1996). The core of this high is formed by the East Oman Metamorphic Belt, a micro-continent that was accreted to the Arabian Plate during the Neoproterozoic Pan-African Orogeny (Stuart-Smith et al., 2007; see Chapter 2). The boundaries of this persistently uplifted basement terrane have been reactivated numerous times during later tectonic events, as shown by numerous truncations and onlap surfaces and reduced thicknesses of overlying stratigraphic sequences compared to the salt basins of interior Oman.

1.4.8 Lekhwair High

The Lekhwair High is a Late Cretaceous NNE-SSW trending, north-plunging subsurface arch located in northwest Oman at the triple border junction with the UAE and Saudi Arabia (Figure 1-1). The arch is some 100 km wide and some 200 km long and is underlain by a major gravity high (Ali et al., 2014b; Stewart, 2016). At the crest of the high more than 1000 m of mid-Cretaceous carbonates and Late Cretaceous shales have been eroded before deposition of Palaeogene carbonates (Filbrandt et al., 2006). During the Early to mid-Cretaceous it was however not a major positive area, part of the high was even covered by mid-Cretaceous intra-shelf basins (Droste, 2014). Despite its NNE-SSW orientation the Late Cretaceous uplift is considered by some to be related to the development of a peripheral bulge in response to the emplacement of the Semail and Hawasina nappes (Boote and Mou, 2003; Boote et al., 1990). The structure was inactive during the Palaeogene but it was tilted 0.5 – 1° to the NNE in the Miocene at the same time as the late uplift of the Oman Mountains (Boote and Mou, 2003; Filbrandt et al., 2006).

1.4.9 Masirah Transform Fault and Batain nappes

The Masirah Transform Fault (MTF) forms the eastern margin of the Arabian continent and runs parallel to the eastern coastline of Oman (Figure 1-1). The MTF became active around 90 Ma, when the African Plate started to move northwards relative to the Greater India Plate (Rodriguez et al., 2020) and was active during the Late Cretaceous and Palaeogene. The Masirah Ophiolite Complex and the Batain nappes were emplaced along this transform fault from SE to NW onto the continental margin of Oman during latest Maastrichtian and/or early Paleocene (Immenhauser et al., 1998; Peters et al., 2001; Schreurs and Immenhauser, 1999). The nappes consist of Permian to Late Cretaceous allochthonous sedimentary and volcanic rocks and are exposed on the Batain. The latter extends for some 135 km in a NE-SW direction along the coast from Ras al Hadd in the north to Ras Jibsch in the south and some 30 km inland from the coastline. The foredeep to the ophiolite nappe complex is formed by the subsurface Masirah Trough, a 20 km wide north-south trending basin located between the thrust belt in the east and the uplifted Huqf axis in the west. The basin was formed by down-bending and faulting of the margin during the emplacement of the nappe complex (Loosveld et al., 1996). It shows extensive faulting related to strike slip deformation along the margin.

1.5 Data analysis and list of abbreviations and conventions

This thesis is based on an extensive review of the available literature on the eastern Arabian Plate, four winter field seasons in the Oman Mountains and foothills, and subsurface mapping using well and seismic data. Integration of subsurface and outcrop data formed a

key component of this study and enabled a unified understanding of the geology of northern Oman.

The literature review focussed on:

- The regional plate history from the Neoproterozoic to the mid-Cretaceous, to determine the location and potential influence of pre-existing structures on deformation patterns in the foreland basin during emplacement of the obduction complex. This review draws on published literature from the eastern Arabian Plate as well as previous own work carried out in the region.
- Foreland basin systems and the different models proposed for the development of the Late Cretaceous foreland basin in northern Oman.
- Compilation of published stratigraphic data on synorogenic sediments, including original data from the less accessible explanatory notes accompanying the BRGM mapping sheets.
- Possible analogues of the structural and stratigraphic features observed in the Oman subsurface and outcrops.

The outcrop study was conducted over four field seasons (November 2020 to March 2024), comprising approximately 20 weeks of fieldwork and around 130 localities in the Oman Mountains. The work focused on characterising and mapping the Base Aruma Unconformity, analysing the syn-obduction Muti Formation and its facies variations, and assessing its relationship to inherited pre-obduction structural trends. The Muti Formation—the transgressive unit associated with subduction of the continental plate—required fundamental reinterpretation and remapping.

A total of 178 surface samples were collected, from which 106 thin sections were prepared for biostratigraphic and petrographic analysis. Many samples were strongly recrystallised due to tectonic overprint, limiting their stratigraphic use. Outcrop descriptions, sample data, and coordinates are provided in Appendix 1; maps showing sample and thin-section locations are presented in Appendices 2 and 3.

The subsurface dataset comprises approximately 20 vintage seismic sections across the foredeep. As the foredeep succession lies above intervals of primary interest to the petroleum industry, detailed interpretations were not made or published, and the foredeep sequence was reinterpreted for this study. Stratigraphic interpretation was carried out in Canvas X Draw using TWT sections. Except for regional line SL-19, the seismic data have not been depth converted; however, calibration with well data and approximate calculations using interval velocities from nearby wells were used to estimate foredeep thicknesses. The seismic data were also used to construct regional geological cross-sections. The locations of seismic lines and cross-sections are shown in Appendix 4.

Data from approximately 1,100 wells across the foreland basin were used to construct regional subcrop isochore maps, regional geological cross sections and stratigraphic correlations of the Mesozoic platform and the foredeep fill, and palaeogeographic maps. Stratigraphic picks were checked and updated where necessary, and wells affected by fault cut-out were excluded from isochore mapping. Data were compiled in Excel and mapped using QGIS, with final figures prepared in Canvas X Draw. The well data are confidential and are not included in the thesis, the well distribution is shown in Appendix 4.

The isochore maps were constructed to visualise, in combination with the stratigraphic subcrop maps below the major unconformities, regional patterns of uplift and subsidence

during the Phanerozoic. These were used to assess the potential influence of Neoproterozoic basement trends on foreland basin development.

Isochore maps should be interpreted with caution, as thickness variations reflect not only erosion and subsidence, but also lateral facies variations and facies-related differential compaction (e.g. platform to intra-platform basin transitions), variable maximum burial depth, and the presence or absence of hydrocarbons. Hydrocarbons inhibits chemical compaction in carbonate reservoirs, as this process requires pore water (Feazel and Schatzinger, 1985). These effects may introduce significant local variability (see example in Figure 1-7) and noise into regional maps. Structural inversion features, such as salt domes, may also produce anomalies. Correction of isochore maps for burial history and hydrocarbon emplacement is beyond the scope of this study, as it would require detailed constraints on erosion, burial depth, and timing of hydrocarbon charge, which are not available.

Isochore maps were generated by gridding well data; however, the dataset is unevenly distributed, with clustering on structural highs and limited control in intervening areas. Data from structural highs may not be representative of adjacent lows with different burial histories. More accurate interpolation would require detailed seismic mapping and depth conversion. Consequently, the maps should be used primarily to assess regional-scale trends in conjunction with subcrop data.

A simple inverse distance weighted (IDW) interpolation was applied in QGIS, whereby sample points are weighted such that their influence decreases with distance from each grid node. QGIS uses a power-law weighting algorithm, with the default being 2 (i.e., an inverse square law). This is an exact interpolation meaning that the gridded surface passes through all the observed data points. Alternative gridding methods, which fit an elastic plate surface through the data, produced unrealistic isochore values outside the range of the dataset, including negative thicknesses.

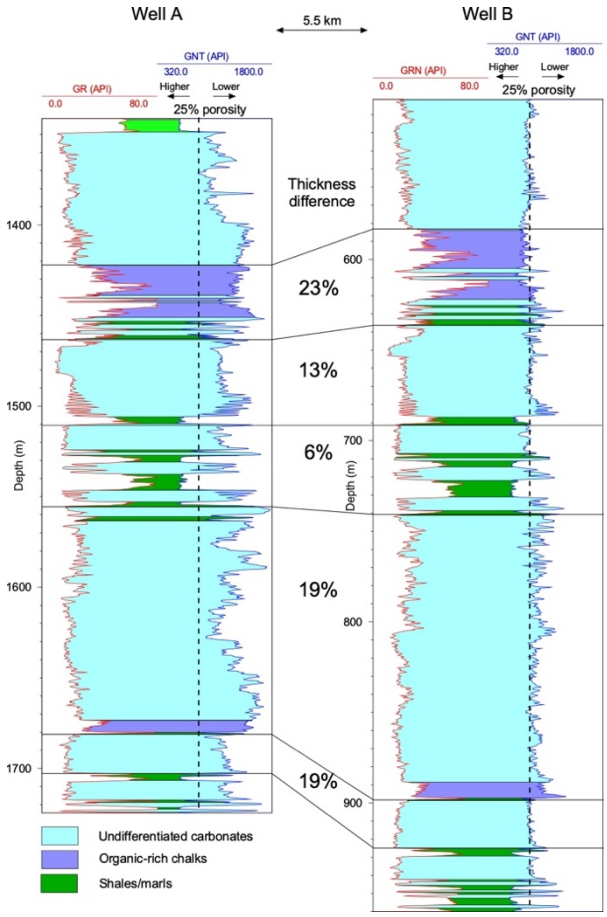


Figure 1-7 Lateral thickness variations in the Natih Formation in the Fahud area are attributed to differential compaction. The two wells, located a few kilometres apart, display the same stratigraphy and facies succession but are separated by a major fault. Well A is situated on the hanging wall, which was inverted during the Neogene, and experienced a maximum burial depth approximately 1000 m greater than at present. Well B is located on the footwall, experienced less burial, and was charged with hydrocarbons. The greater burial depth and absence of hydrocarbons in Well A resulted in enhanced chemical compaction, as reflected by reduced thicknesses and significantly lower porosities (as indicated by the GNT log).

A grid size of 500 × 500 m and a distance coefficient of 4 provided the most consistent results for this dataset. Lower distance coefficients resulted in overly smoothed, trendless maps due to excessive averaging in undersampled areas. Larger coefficients resulted in blocky patterns as the value of the nearest well starts to dominate (see examples in Appendix 5).

Abbreviations used in this study:

EAT	Eastern Arabian Terrane
BAU	Base Aruma Unconformity
BRGM	Bureau de Recherches Géologiques et Minières
EOMB	East Oman Metamorphic Belt
FT	Fahud Terrane
LMA	Limestone marls alternation (LMA)
MTF	Masirah Transform Fault
MFZ	Maradi Fault Zone
PDO	Petroleum Development Oman
SOSB	South Oman Salt Basin
TWT	two-way-travel time, vertical scale on seismic panels
WDF	Western Deformation Front

The geological time scale of Gradstein et al. (2020) is used throughout, unless otherwise indicated. The reference coordinate system used in the thesis is WGS84.

1.6 Previous work

Understanding of the syn-obduction stratigraphy (the Muti Formation) is a complex problem that has remained unsolved because of the difficulties disentangling the underlying platform collapse sediments of the autochthon from genuine syn-obduction sediments (that are also associated with platform retreat and drowning), and from overlying tectonic mélanges associated with emplacement of thrust sheets over soft platform margin slope sediments. The different models presented in the literature and *critical uncertainties* extracted from them are described below.

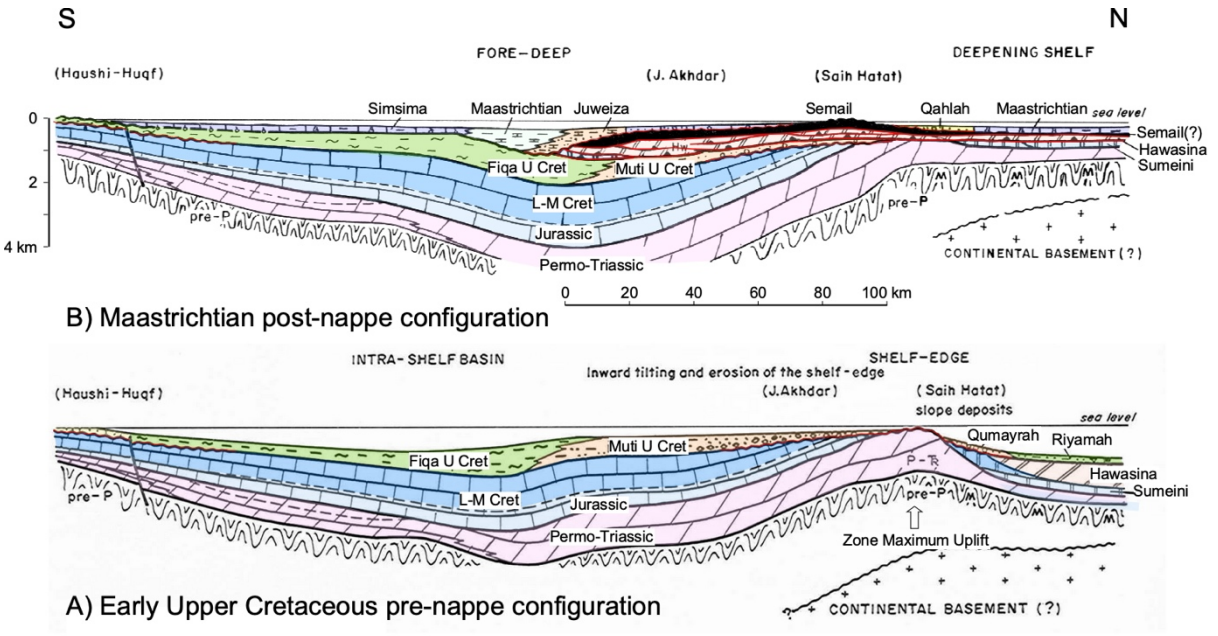


Figure 1-8 The Glennie model. Relationship between Late Cretaceous sedimentation and nappe emplacement on the Oman continental shelf pre- (A) and post-(B) nappe emplacement proposed by Glennie et al. (1974). A key element is a pre-emplacement uplift along the shelf edge to explain the missing section in this area. Sediments eroded from this uplift are deposited as Muti Fm. in an intra-shelf basin that formed landward of the uplift and as Qumayrah and Riyamah facies on the sea-ward side. During emplacement of the nappes this intra-shelf basin developed into a foredeep. The scales indicated are approximate and from the original figure, note the suggested thickness of the Hawasina and Semail nappes is considerably underestimated, e.g. only the crustal part of the Semail is already estimated as 5 – 5.5 km thick (Nicolas et al., 1996), and a much thicker allochthonous sequence than shown here has to cross the uplift. Modified from Glennie et al. (1974).

1.6.1 Outcrop studies Oman

Glennie et al. (1974), Robertson (1987a) and the mapping and studies by the BRGM geologists (Béchennec et al., 1995; Le Métour, 1988; Rabu, 1988; Rabu et al., 1993) argued for significant erosion of the Triassic to middle Cretaceous carbonate platform margins of the Arabian continental margin. They interpreted this to be related to a tectonic doming during the Turonian – Coniacian of some 1.5 km connected in some way to the emplacement of the nappes. This uplifted margin was considered to be the source of the carbonate megabreccias and olistostromes of the Muti Fm. deposited in an "Aruma foredeep" landward of the uplifted margin (Figure 1-8). Most of the mapped truncation occurs over a relatively narrow zone of some 30 km along the northern edge of Jebel Akhdar and Saih Hatat and much of

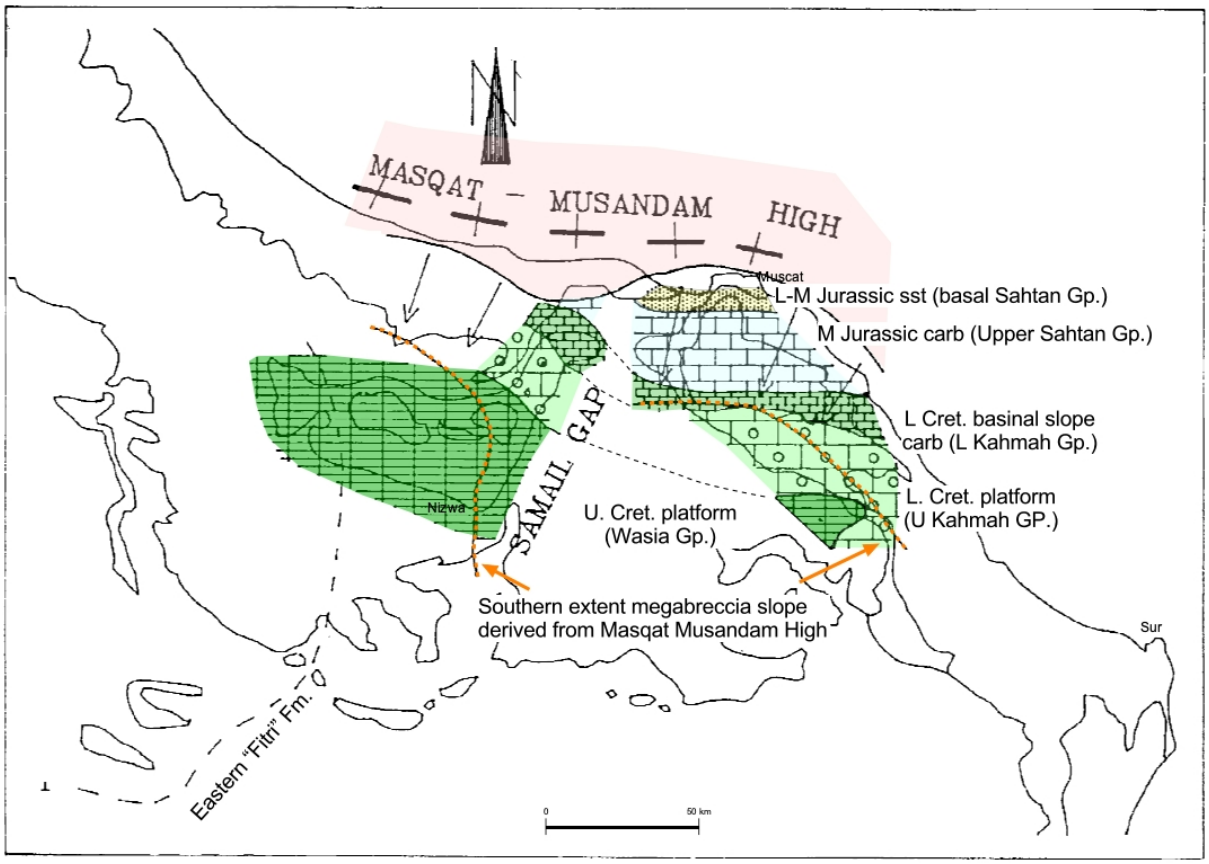


Figure 1-9 Subcrop map of the base Aruma unconformity and the inferred location of the Muscat-Musandam High according to BRGM geologists. Megabreccias assigned to the Muti Formation are thought to have been derived from the southern margin of this high. Modified from Rabu et al. (1990).

this area is covered by Muti sediments, predominantly mass flow deposits. To explain this puzzling distribution of sediments over the axis of the truncated zone BRGM geologists postulated that the main uplift was in fact located still further to the NE along an offshore high ("Muscat – Musandam High") from where the Muti mass flows were derived (Figure 1-9). Particular note was taken of carbonate clasts from the Permian, which has not been found to subcrop the base Muti unconformity in the outcrops. Subsequently released seismic data conclusively demonstrates that there is no such offshore high (Levell et al., 2021).

A further, more basic problem became evident early in this study. The BRGM stratigraphic and mapping interpretation of the Muti needed a comprehensive re-assessment as it includes a wide range of units which are unrelated to one another and are difficult to fit into one coherent model. In part this is an inevitable by-product of the use of aerial photographs and satellite imagery for mapping whereby similar colour units in roughly the same tectonostratigraphic position, between the autochthon and the thrust stack, have been assigned to the Muti Fm. This is especially so in the Saih Hatat area, where a thick sequence of undated prograding slope deposits overlying deeply eroded Jurassic and Triassic platform deposits was included into the Muti. Elsewhere tectonic units at the base of the thrust stack have also been assigned to the Muti. A major part of this study was therefore a re-examination of all mapped Muti Fm outcrops, with perhaps just one third passing the test of belonging to the Muti Formation as now understood. For space reasons all this detailed mapping and logging work is presented in the Appendix and is abstracted into the thesis only where required.

The most detailed stratigraphic and sedimentological study of the syntectonic sediments in the Oman Mountains and presentation of the arguments for flexural

deformation of the continental margin is that of Robertson (1987a; 1987b; 1988). He used a very broad definition of the Muti Fm. which essentially includes all sediments, both in the autochthonous and the allochthonous units, that were deposited during the deformation period ranging in age from ?late Cenomanian to late Campanian. Five members were defined based on interpretations of their restored palaeogeographic position. These include carbonate platform, slope and abyssal plain deposits as well as redeposited sediments and olistostromes interpreted as trench deposits. The latter is derived both from collapsing seamounts entering the trench and from the orogenic wedge and Arabian passive margin. The slope and base-of slope deposits show evidence of platform margin collapse. The only autochthonous interval (Sayja Mbr.) directly overlies the base Aruma unconformity (BAU) and contains two units (Robertson, 1987b). The basal unit is c. 75 m thick and consists of concretionary and argillaceous limestones with some ferruginous and phosphatic deposits, and bioclastic packstones with iron formations. These deepen upward into a hemi-pelagic marlstone facies. The upper unit is up to 750 m thick and contains a wide range of lithologies: non calcareous shale, turbiditic quartzose siltstones and sandstones, calciturbidites, lithoclastic debris-flows, monomict debrite beds with clasts from the underlying Natih carbonates, and detached blocks of platform carbonates.

The model proposed by Robertson (1987b) was an attempt to reconcile the observations with classical foreland basin development (Figure 1-10). It starts with the formation of a flexural bulge during the Turonian-Coniacian along the platform margin causing exposure and deep erosion and mass wasting on the oceanward side. During gradual

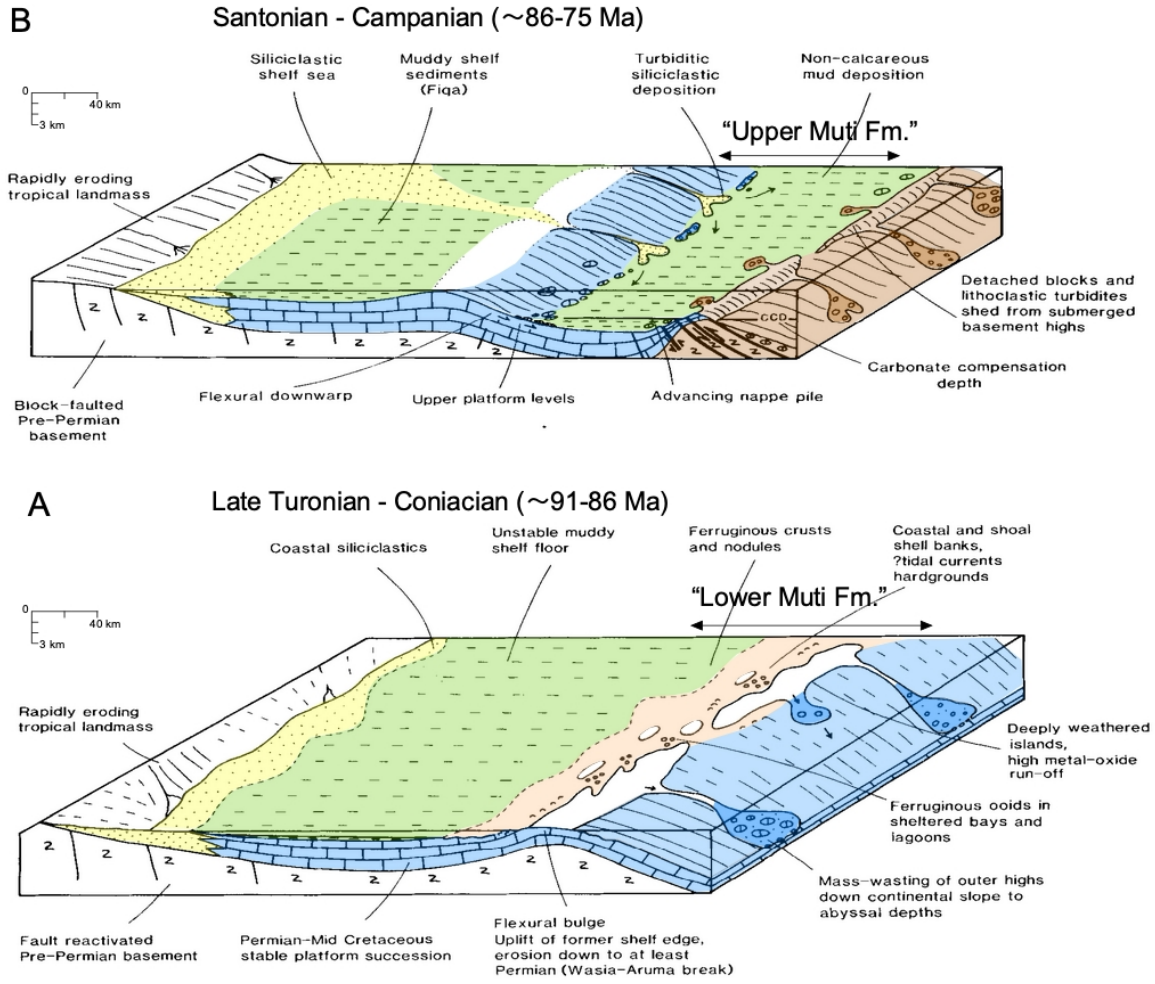


Figure 1-10 The Robertson model. Schematic palaeogeography for the syntectonic deposition of the Muti formation proposed by (Robertson, 1987b). A: Development of a migrating flexural bulge during the Turonian- Coniacian along the platform margin caused exposure and deep erosion and mass wasting on the oceanward side. During gradual submergence the high was covered by marginal high energy sediments of the "Lower Muti" (Lower Sayja Mbr.) . B: Emplacement of the nappes during the Santonian to Campanian caused flexural downwarp of the platform and development of a landward migrating foredeep. The deep-water "Upper Muti" (Upper Sayja Mbr.) sediment fill of the foredeep contains slump sheets and debris flows from the exterior side of the downwarp and siliciclastic sediments from the hinterland. Note that no evidence is presented for the landward migration of facies belts in either A or B. Note also that the vertical scale shown is not appropriate to the Muti Formation itself, which is much thinner than shown (maximum a few hundred metres, and often less than 100m). Modified from (Robertson, 1987b).

submergence this high was covered by marginal high-energy sediments of the “Lower Muti”. Emplacement of the nappes during the Santonian to Campanian caused flexural downwarping of the platform and development of a landward migrating foredeep. The deep-water “Upper Muti” sediment fill of the foredeep contains slump sheets and debris flows from the landward carbonate margin as well as siliciclastic sediments from the hinterland. Limestone blocks and debris flows are interpreted to have been sourced from submarine mass wasting along the collapsing platform margin. This model, often used in subsequent studies, is confusing in that it seems to suggest that the Lower Muti was deposited in the back bulge basin, which, in the case of a migrating forebulge would *predate* forebulge erosion. Also, erosion from the already collapsed margin seaward of the forebulge seems unlikely. The forebulge has an unlikely amplitude (1.5km). The forebulge usually is a subtle topographic feature with an amplitude of typically 2.5 to 4% of the basin subsidence (Crampton and Allen, 1995). The reason that this erosional area has been included into the model is that this is the only area which could source clasts as old as Permian to the interpreted mass flow deposits.

As will be shown in section 5.2, inspection of the outcrops described in Robertson (1987) indicates that the interval assigned to the “Upper Muti” shows strong tectonic deformation. The wide range of lithologies, large blocks and megabreccias in this interval represent a tectonised mélange with a mixing of Muti sediments, including mass flows, with imbricated and deformed components derived from the overlying thrust sheets. This observation has major consequences for the tectonic model and is explored further in section 5.4.

1.6.2 Subsurface UAE

Patton and O'Connor (1988) and O'Connor and Patton (1986) presented a tectonic and stratigraphic model for the middle to Late Cretaceous in the northern foredeep located in the UAE based on isopach maps and facies data (Figure 1-11). They report a similar pattern of

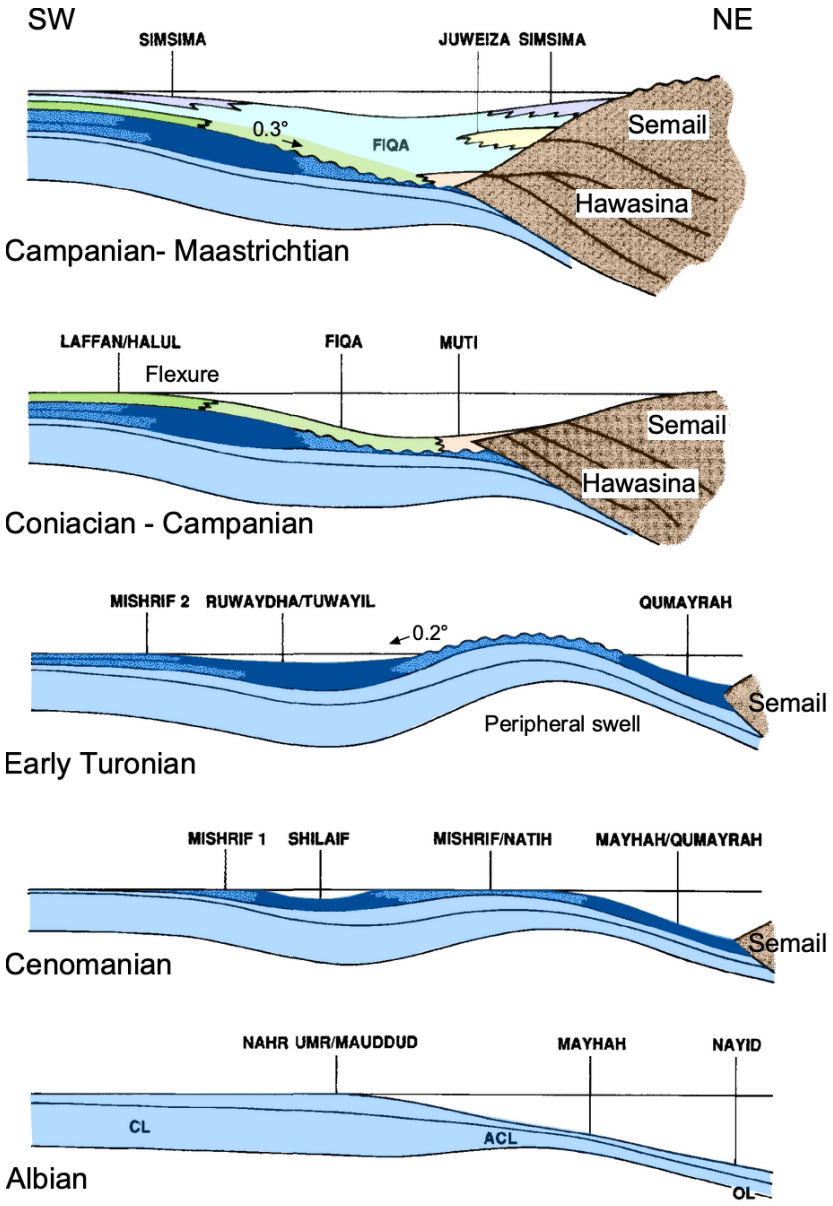


Figure 1-11 Flexural evolution of the northern Oman Mountains foreland in the UAE by Patton and O'Connor (1988). A major peripheral swell developed during the Turonian base Aruma unconformity (between the blue and green rock units). The Shilaif intra-platform basin may have developed as a back-bulge basin. The swell collapsed during the Santonian and a flexure developed further west forming the western margin of the foredeep. Note that in these sections the foredeep is static - the fill post-dates and onlaps the thrust stack. ACL= attenuated continental lithosphere, CL = older continental lithosphere, OL = oceanic lithosphere. Figure modified from adapted original Patton and O'Connor (1988) in Burchette (1993).

forebulge development to Robertson's model for Oman. As the continental lithosphere entered the subduction zone, a westward migrating peripheral swell with regional upwarping developed during the Cenomanian and reached maximum uplift in Turonian time. The NW-SE trending swell axis is parallel to the Oman Mountains front and estimated to be some 150 km wide, and 244 m high. During the Santonian, the swell moved faster than the advancing load causing a sudden jump of the location of the swell some 200 km to the west. It is thought that this is related to a widening of the down-flexed area as the allochthonous terranes started to load thicker, more rigid, continental lithosphere, possibly in combination with the presence of zones of weakness and heterogeneities in the basement. The authors mention there is no strong evidence for lateral migration between the two positions of the bulge. They noted that the initial uplift may have already occurred in the Cenomanian during deposition of the upper part of the pre-Aruma carbonate platform, thereby forcing westward progradation of carbonate wedges into an intra-platform ('back bulge') basin (Shilaif Basin) west of the main carbonate platform margin. They also suggest the latest Albian to Cenomanian development of this intra-platform basin may be a far-field effect related to the onset of convergence. The model will be discussed in more detail in Chapter 4

Large-scale regional stratigraphic studies by Franco et al. (2021; 2018) suggest widespread buckling and uplift extending hundreds of kilometres from the margin uplift, together with growth of Cambrian salt diapirs and influx of siliciclastic sediments from the southwest. They indicate that the western margin of the Cenomanian intra-platform basin was controlled by a reactivated basement ridge.

Abdelmaksoud et al. (2022) described the structural geometries in the fold-and-thrust belt and foreland basin system of eastern UAE, using integrated seismic, well and

outcrop data. Tectonic subsidence curves indicate the 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. The amount of uplift and any evidence of forebulge migration are not indicated. The downgoing plate shows fault activity during the Coniacian to Campanian with normal displacement (interpreted as re-activated earlier rift faults) which has been related to flexural extension of the down-going plate.

Late Cretaceous intra-platform basins are also present in the Oman subsurface and outcrop studies hint at possible tectonic influences in the younger part (late Cenomanian to early Turonian) of the platform sequence (van Buchem et al., 2002). Comparing the stratigraphic architecture of the upper part of the mid- Cretaceous platform (Albian and younger) in Oman with that below the UAE part of the foredeep will help to further understand the flexural deformation along the margin. This has been done in this thesis by mapping of the subcrop and regional truncation patterns below the Base-Aruma Unconformity in the Oman subsurface.

The UAE dataset presented by Abdelmaksoud et al. (2022) is located landward of the orogenic wedge and there is less information on the Muti Fm. below the thrust complex than there is in the Oman outcrops.

1.6.3 Subsurface studies Oman

Two groups have published on the foredeep evolution based on subsurface data in Oman. Boote et al. (1990) present a regional overview of the structural and stratigraphic development of the foredeep area located in NW Oman and UAE (Suneinah foredeep) based on subsurface seismic and well data (Figure 1-12). Warburton et al. (1990) and Warburton et al. (1986) present a sequence stratigraphic interpretation of the foreland basin infill based on

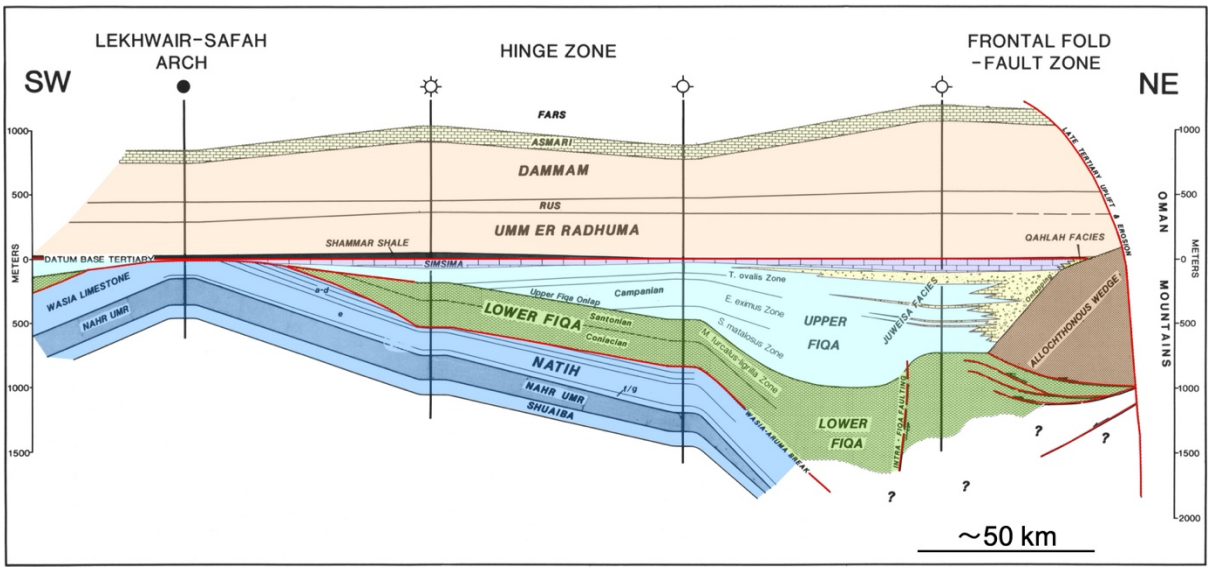


Figure 1-12 The Boote model. Well correlation in Suneinah foredeep from Boote et al. (1990). Note the horizontal scale reflects the distance between the wells and the section is not projected along a straight line perpendicular to the structures. The distance between the Lekhwair High and the thrust front is only about 100 km. Location XS-13 in Appendix 4. Modified from Boote et al. (1990).

outcrop, well and seismic data within and south of the Hamrat Ad Duru Range (Figure 1-13). The seismic lines used in these studies cover just the frontal parts of the thrust complex.

Boote et al. (1990) suggested that the top of the mid-Cretaceous platform (Natih Fm.) shows a progressive truncation towards the NE below the BAU. This was interpreted to be related to uplift in the Turonian associated with the development of a flexural bulge at the margin of the platform 100 km further north (in the mountains), where outcrops show the erosion cuts down much deeper into the platform carbonates (as described above). This was followed by down-warping and deposition of deep-water shales of the Lower Fiqa Fm. during the Coniacian and Santonian in water depths as great as 300 – 500 m. These sediments are age-equivalent to the outcrops of Muti Fm. in the Oman Mountains. Seismic data shows that during this time the down-bending platform was also affected by block faulting. During the

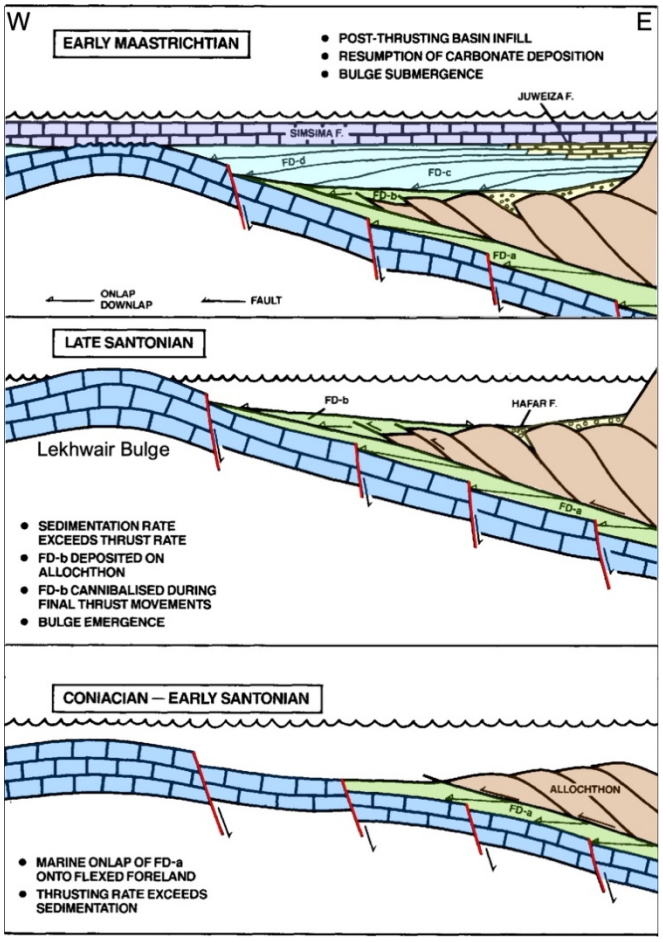


Figure 1-13 The Warburton model. Foreland basin fill and seismic sequences in NW Oman proposed by Warburton et al. (1990). The final emplacement of the nappes was during the Santonian. Note the southward prograding geometries shown in the upper figure are probably seismic artifacts, see Figure 5-24. Modified from Warburton et al. (1990).

early Campanian the allochthon was emplaced over, and partly incorporated into, the Lower Fiqa shales. The thrust emplacement is thought to have been very rapid as the ages of the Lower Fiqa shales in the subsurface and the Muti Fm. in the outcrops further north, below the thrusts, are both in the same Coniacian - Santonian range. In the west, the uplifted and eroded Lekhwair High was interpreted as a peripheral bulge related to down-bending of the foreland basin by the allochthonous wedge. The authors see no evidence for migration of this bulge and suggest that this may be related to the rapid emplacement of the nappes. During the Campanian to Maastrichtian the foredeep was filled by marls and chalks of the Upper Fiqa, which onlap both the Lekhwair High and the thrust complex. These marls interfinger with nappe-derived detrital clastics (Juweiza Fm.) just in front of, or above, the thrust complex. Only by the early Maastrichtian (5-7 Myr after mid-Campanian thrust emplacement) was the foredeep largely filled and shallow-water limestones (Simsima Fm.)

were deposited. These limestones also transgressed and overstepped the exposed and eroded thrust complex and possibly the Lekhwair High. The transgression is interpreted to have continued into the Palaeogene, interrupted only by a minor base Palaeogene unconformity.

Warburton et al. (1990) and Warburton et al. (1986) present a detailed sequence stratigraphic interpretation of the foreland basin infill based on the interpretation of onlap and downlap geometries on seismic lines calibrated with unpublished oil company biostratigraphic interpretations. Erosional or truncation surfaces associated with sequence boundaries are not clearly imaged on the seismic. The nose of the frontal wedge shows southward downlapping geometries into the foredeep but is itself affected by thrusting. This suggests that the frontal parts of the thrust sheets consist of debris shed from the thrust stack that itself became deformed and incorporated into the thrust complex as the thrusts propagated into the foredeep basin. This syntectonic interval is early to late Santonian in age. The base of the interval is coincident with the basal décollement of the allochthon, suggesting that the final nappe emplacement is in the Santonian in the study area. The overlying clinoform sequence shows pronounced downlap suggesting northward progradation into the foredeep. The height of the clinoforms suggests water depths in the order of 1000 m in the foredeep. The clinoforms consists of hemipelagic mudstones of late Santonian to early Campanian age and is part of the Upper Fiqa Fm.

Warburton et al. (1990) suggest the Lekhwair High represents a static peripheral bulge that formed at the BAU, at the same time as the erosion of fault blocks on the tilted carbonate platform in the foredeep and was progressively onlapped during the Late Cretaceous by hemipelagic sediments. They see no evidence of forebulge migration; if the

forebulge had migrated, the stratigraphic hiatus at the BAU in the foredeep would have been much longer, comparable to that observed on the Lekhwair High. Also, the simple geometry on the Lekhwair High of continuous and rapid onlap of the base Fiqa does not support a migrating bulge. The 1.5 km erosional truncation along the platform margin in Jebel Akhdar and Saih Hatat is thought to be possibly related to an earlier flexure ahead of the advancing allochthon as suggested by Patton and O'Connor (1988).

Modern 3D Seismic studies in the Lekhwair and surrounding areas highlight the presence of seismic artifacts in the datasets: interbed multiples generated in the strong sub-horizontal, parallel reflectors upper Cenozoic succession overprint much weaker reflections in the foredeep succession (Butler and Al Shukaili, 2023; Cullen, 1979; Feddersen, 2025; Hozayen et al., 2008; Melville et al., 2004). Some of the onlapping features onto the Lekhwair High as well as the southward prograding geometries from the orogenic wedge reported by Boote et al. (1990) and Warburton et al. (1990) are questionable, especially as these studies are based on vintage 2-D data only. These features and the implication of alternative interpretations will be discussed in section 4.5 and 5.2.6. Also, there is uncertainty in the age assignments as there are few well data to calibrate the seismic lines and most of the biostratigraphic information has been extrapolated lithostratigraphically from distant wells.

A better understanding of the Lekhwair High, based on subcrop patterns, shows a more a circular, rather than a linear feature (section 4.5). It is necessary to consider if this feature is related in any way to Late Cretaceous flexural deformation or is simply a re-activation of an older structural feature.

Regional subsurface studies in North Oman southwest of the foredeep show that flexural uplift is not well expressed south of the thrust front and the area was in an

extensional regime during the Late Cretaceous due to down-bending of the plate (Al-Kindi and Richard, 2014; Filbrandt et al., 2006; Loosveld et al., 1996). The extension was accommodated by a regularly spaced set of northwest-southeast trending normal faults (Figure 1-14). Simultaneous with this northeast-southwest extension a component of sinistral transpression is recognised along the eastern margin of Oman attributed by these authors to the northward movement on the Indian Plate. This resulted in a NW-SE oriented maximum horizontal stress regime adding a strike slip component to the normal faults, re-activation of older faults and some minor inversion structures. However localised uplift, in places more than 1000 m, has been observed. Emplacement of the Masirah ophiolite and a mélange of Permian to Cretaceous sediments and volcanic rocks (Batain nappes) along the eastern coastline of Oman from ESE to the WNW occurred during the late Maastrichtian/early Paleocene at ca 65 Ma (Immenhauser et al., 1998; Peters, 2000). The NW-SE oriented stress regime started in the late Santonian and may have lasted into the early Palaeogene. It is also thought to have affected the northern edge of the Arabian Plate.

Subsurface studies therefore indicate that the Late Cretaceous deformation in North Oman is not only controlled by the Semail ophiolite obduction. The NW-SE oriented compression could also have affected the development and infill of the foreland basin system. Mapping the truncation patterns below the BAU, the Late Cretaceous uplift and lateral variations in the shape and infill of the foredeep are required to determine its effect (see section 4).

Studies of the basement of Oman (Bell, 2004; Stuart-Smith et al., 2007) showed the presence of a collage of NE-trending basement terranes accompanied by major regional N-S trending fracture and fault zones formed during accretion of the Gondwana continent during

the Pan-African Orogeny (c. 850–520 Ma). The basement lineaments have been subjected to both transtensional and transpressional deformation during younger tectonic events and influenced both infra-Cambrian and Phanerozoic basin evolution and sedimentation.

Basement re-activation likely also occurred during the obduction. It is not known how much the obduction was influenced by pre-existing geological lineaments, for example the platform shape of the passive margin and /or transform faults. In this thesis we therefore



Figure 1-14 Surface illumination of near top Kharaib TWT map from a merged 3D seismic dataset in North Oman showing faulting patterns in the mid-Cretaceous carbonates. The faults were active during the Late Cretaceous. The Lekhwair and Makarem Highs show a pervasive fishnet pattern of conjugate faults. In the salt basins there is salt diapir reactivation, reactivation of faults and formation of NW-SE trending transpressional syn-depositional faults, especially in the foredeep area. The fault patterns suggest NE-SW extension These faults were reactivated during the Neogene NE-SW compression. Seismic line is shown in Figure 1-15. Modified from Filbrandt et al. (2006).

examine which basement features affected uplift and subsidence patterns in pre-obduction times and how they may have controlled the three-dimensional geometry of the continental margin.

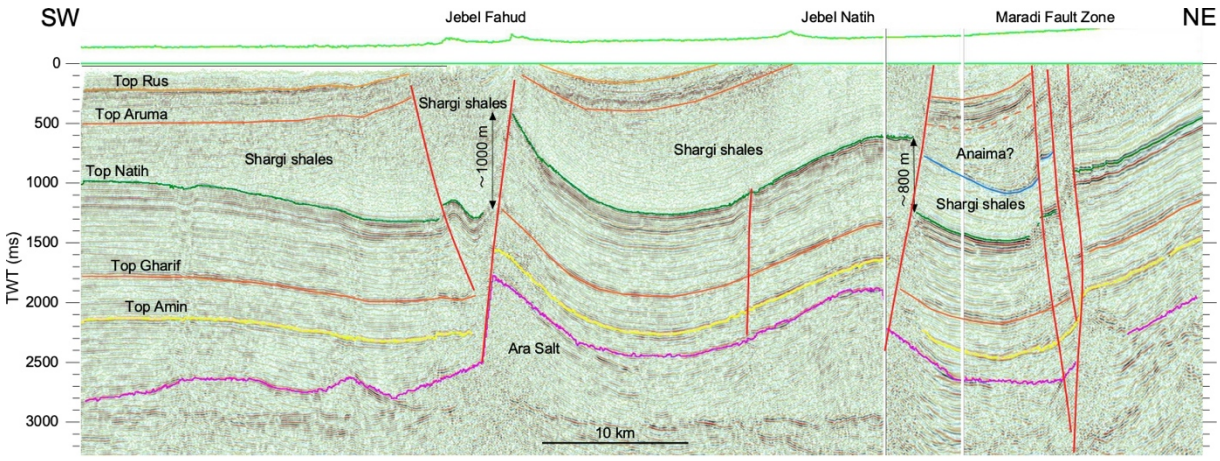


Figure 1-15 Regional seismic showing Neogene inversion structures in the northern Fahud Salt Basin. The Fahud Fault started as a Late Cretaceous growth fault with a displacement of more than 1 km, the Natih Fault is thought to have been only active during the Neogene (Terken, 1999), the Maradi Fault zone is probably linked to a Neoproterozoic basement lineament (Filbrandt et al., 2006) For location: see Figure 1-14, SL-10 in Appendix 4.

1.7 Key questions to resolve – Thesis Outline

The uncertainties and questions that arose from the above have been investigated in this study and are outlined in the thesis as follows:

Chapter 2: Pre-Mid Cretaceous Structures and Trends.

- Which basement features were affecting uplift and subsidence patterns in pre-obduction times?

Chapter 3: The Pre-Obduction Mid-Late Cretaceous Platform and Margin

- Are there any signs on the platform of the onset of obduction?
- Is there any uplift along the platform prior to the obduction?
- Where was the platform margin located through time?

Chapter 4: The Base Aruma Unconformity – Forebulge erosion or not?

- Mapping the truncation patterns below the BAU, the Late Cretaceous uplift.
- Was there a forebulge or not?
- Did the NW-SE oriented compression affect the development and infill of the foreland basin system?

Chapter 5: Initial fill of the foredeep – the Muti Formation

- A comprehensive re-assessment of the Muti Formation. This has involved a large amount of detailed field geological mapping and sedimentary logging, which are summarised in Appendix 1. Of particular importance in this work were stratigraphic age determinations, facies analysis and the provenance of clasts in mass flow deposits and mélanges. This work resulted in substantial changes to the published geological maps, which are also summarised in Appendix 1. Only the details relevant for the arguments are presented here.

- Do the debrites and a variety of slumps and slides represent the slope facies at the platform margin, or are they related to the syn-obduction sequence? And how to distinguish either of these two from mélanges created by the thrusting and imbrication of semi-coherent thrust units over incompetent autochthonous slope deposits? It is necessary to disentangle and interpret the genesis of debrites.

Chapter 6: Infill of the foredeep

- What is the nature of the sediments filling the foredeep and what is their provenance?
- Is there evidence for a forebulge controlling depositional patterns?

- What are the lateral variations in the shape and infill of the foredeep.
- Is the sequence affected by any tectonic events that may be linked to the obduction or to re-activation of basement structures?
- Is there evidence for major uplift and erosion of the orogen during foredeep fill?

Chapter 7: Foreland basin evolution, to what extent does this fit with classical models from orogenic belts on continental crust?

- Chronostratigraphic (Wheeler) diagram
- Palaeogeographic reconstructions and restored cross sections showing correlation sedimentary fill to obduction stages
- Discussion of filled and underfilled foredeep basins
- Foreland basin model for Oman Ophiolite obduction

Chapter 8: Summary and conclusions

2 Structural inheritance? Pre mid Cretaceous geological history of the northeastern Arabian continental margin

2.1 Introduction

In this chapter the history of the Arabian plate up to the onset of obduction in the Cenomanian is assessed. This part of the thesis is based on an extensive review of published data supplemented with own work including analysis of up to 1100 wells used to construct the isopach and subcrop maps for the different tectonostratigraphic units.

The purposes of this chapter are to:

1. Describe and present the supporting evidence for structures in the Arabian plate that influenced the obduction process, by extrapolating from areas less affected by the obduction itself (i.e. further south and west).
2. Highlight those geological provinces whose histories suggest the likelihood of differences in geomechanical responses to thrust emplacement, fault reactivation, and crustal-scale loads during the obduction process.
3. Establish the geometry and stratigraphy of the passive margin sequence and specifically what its shape and structure were at the onset of obduction. This will help to assess its influence on thrust emplacement in space and time in the subsequent chapters.
4. Present the evidence for the earliest detectable onset of obduction-related events from the perspective of the stratigraphic development of the Arabian plate for

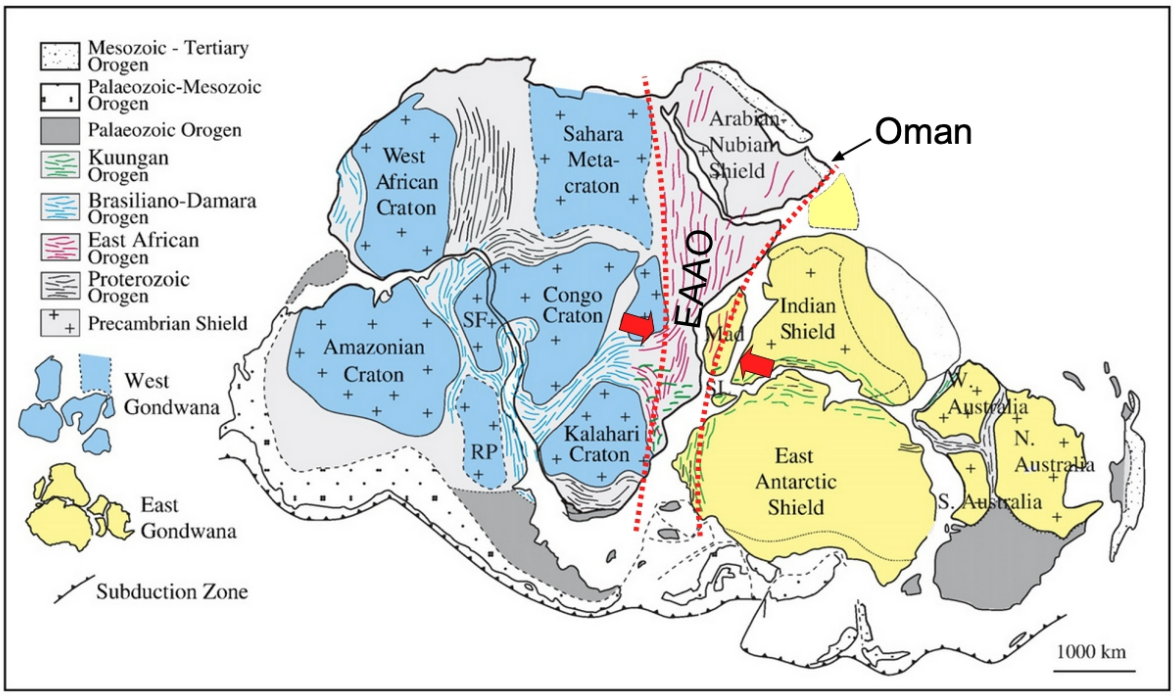


Figure 2-1 Location of the East African Antarctic Orogeny (EAAO) within the Gondwana supercontinent. Oman is located within the deformed belt just west of the Eastern Gondwana Continent. Modified from Meert and Lieberman (2008) and Stern and Johnson (2010).

comparison with the radiometric dating of the ophiolite, its metamorphic sole and associated subduction-related metamorphism.

2.2 Pan-African orogeny and the Angudan unconformity (~870 – 520 Ma)

2.2.1 Overview of basement trends in Arabia and Oman

The basement of the Arabian plate was formed in the collisional zone between the East and West Gondwana continents about 800 to 520 Myr ago during the Neoproterozoic, leading to formation of the Gondwana supercontinent (Figure 2-1). This tectonic period is known as the Pan-African orogeny (Stoeser and Camp, 1985), East Africa Antarctic Orogen (EAAO) (Stern and Johnson, 2010), or East African Orogeny (Allen, 2007). In Arabia, it encompasses several separate tectonic events with collision and amalgamation of several intra-oceanic island arcs, some microcontinents and associated foreland basins (Al-Husseini, 2000; Allen, 2007; Stern and Johnson, 2010).

The basement structure in Oman has been described by Stuart-Smith et al. (2007) in several in-house studies for Petroleum Development Oman (PDO) using seismic, gravity and magnetic data calibrated with a limited number of petrographic and radiometric analysis from wells and outcrops. These studies have been presented at conferences but have not been published. Three main basement areas were recognised (Stuart-Smith et al., 2007): A complex of NE trending accreted basement terrane belts in the eastern part of Oman, the Fahud Terrane (FT) in the northwest and the East Arabian Terrane (EAT) in the west (Figure 2-2 and Figure 2-3A). The terrane belts in eastern Oman consists of westward accreted terranes which include an accretionary wedge, ophiolitic belt and a magmatic arc. These underlie the later South Oman and Ghaba salt basins (Figure 2-3B). They are bounded to the

east by the East Oman Metamorphic Belt (EOMB) which is partly exposed in the basement

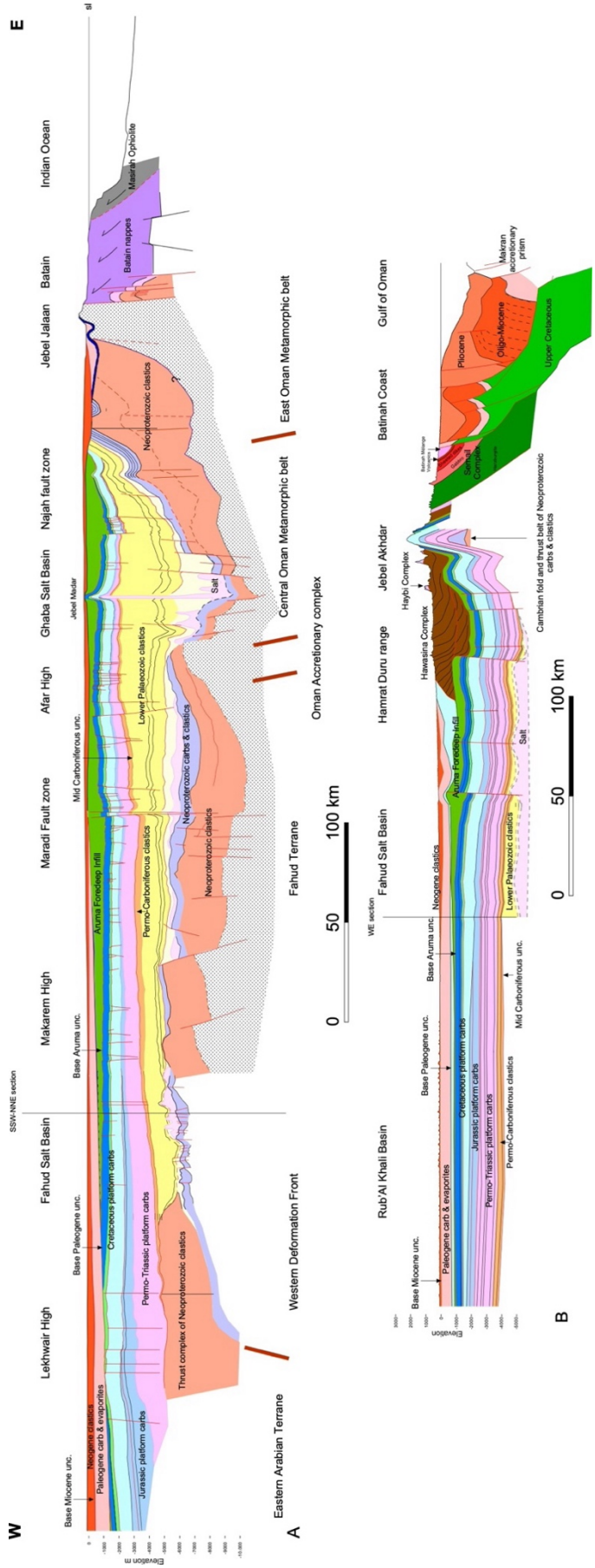


Figure 2-2 Regional geological cross sections through North Oman showing the main tectonostratigraphic units. Repeated reactivation of N-S trending basement structures throughout the Phanerozoic caused major lateral variations in tectonic uplift, subsidence and basin inversion. Both cross sections are based on own work using regional seismic data calibrated with well penetrations. In cross section B the Hamrat Duru section is based Cooper (1986) and Warburton et al. (1990), the Batinah coast and offshore is modified from Levell et al. (2021). Location of the sections is shown in Figure 2-3 and as XS-1 and XS-2 in Appendix 4.

outcrops in Qalhat, Jebel Ja'alan, Al Jobah (Huqf area), Mirbat and the Al Halaaniyaat Islands. These represent the margin of a much older microcontinent with a siliciclastic sedimentary protolith of > 1300 Ma (Mesoproterozoic) that was accreted and metamorphosed in a volcanic arc some 890 – 830 Myr ago (Alessio et al., 2018; Allen, 2007; Mercolli et al., 2006). The Fahud and East Arabian terranes are interpreted as micro-continents (Stuart-Smith et al.,

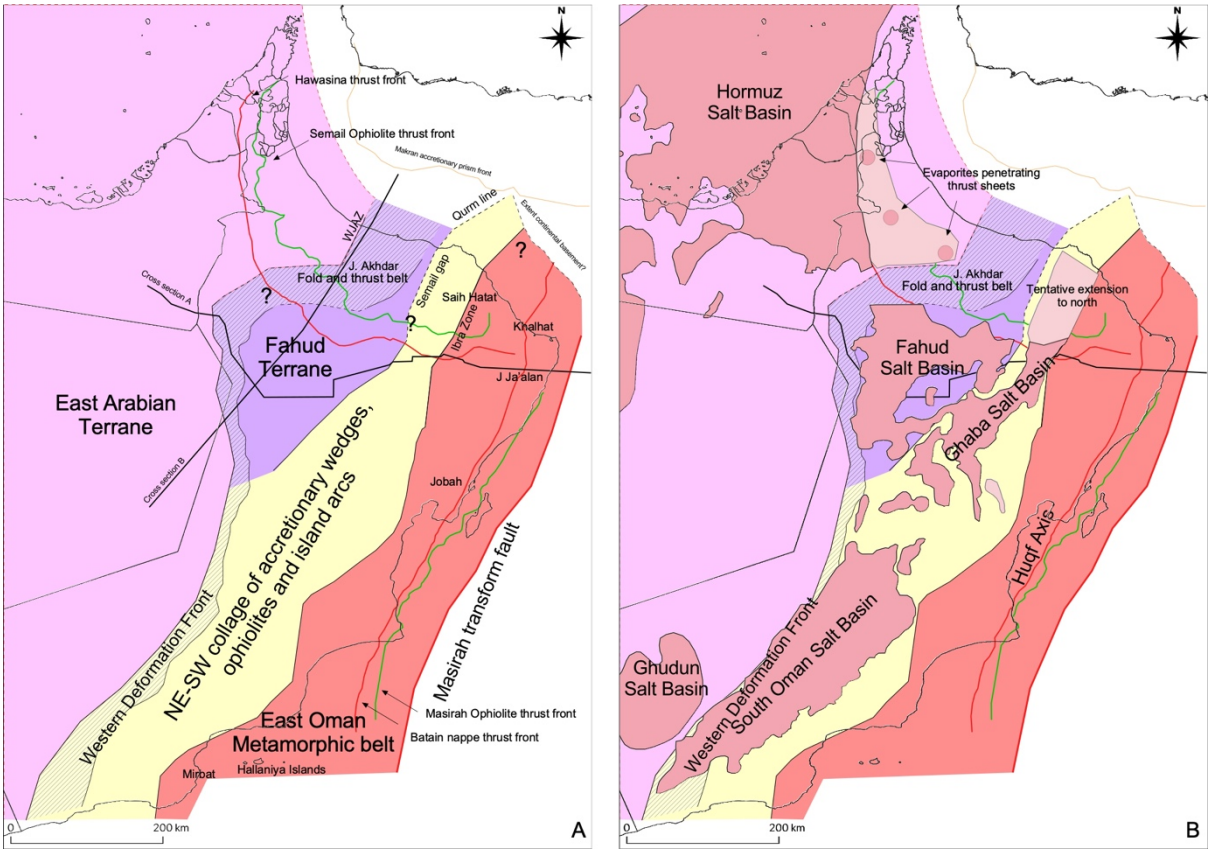


Figure 2-3 Neoproterozoic basement and salt basins in Oman. A: Basement terranes in Oman and the location of the Late Cretaceous (Semail) and Maastrichtian (Masirah) ophiolite obduction complexes. The basement trends are perpendicular to the Late Cretaceous thrust front. The Masirah transform fault became active around 90 Ma, when the African Plate (including Oman) started to move northwards relative to the Greater India Plate (Rodriguez et al., 2020) and was active during the Late Cretaceous. Khalhat, J. Ja'alan, Jobah, Mirbat and Al Halaaniyaat Islands are localities with igneous basement outcrops. The Western Jebel Akhdar Zone (WJAZ), Semail Gap trend and the Ibra Zone line are delineated by lower-crustal shear-wave velocity trends as interpreted by Weidle et al. (2023). Map has been further based on Bauer et al. (2025); Cozzi et al. (2012); Gómez-Pérez and Morton (2025); Gómez-Pérez et al. (2024); Stuart-Smith et al. (2007). B: Location of the latest Neoproterozoic – earliest Cambrian salt basins plotted over basement terranes. The deep South Oman and Ghaba Salt basins overly the more mobile easily deformable belt with ophiolite and accretionary wedges. Salt outlines have been compiled and modified from Al-Kindi (2020); Edgell (1991); Forbes et al. (2010); Geng et al. (2022); Stewart (2016). Cross section A and B are shown in Figure 2-2.

2007). All the above terranes were assembled into the Oman microcontinent by ～730 Ma (Stuart-Smith et al., 2007). Later, at about 600 Ma, the Oman microcontinent collided and amalgamated with western Arabia (Nabitah orogeny, see Droste (2014). Additional accretion of the Arabian plate occurred further eastward of Oman with the collision of West and East (greater India) Gondwana, which was completed about ～510 Ma (Malagasy orogeny, see Droste (2014). However, there is still discussion on the sequence of collision events. Recently it has been proposed that, based on detrital zircon chronology, the final suture between eastern and western Gondwana is located along the eastern margin of the East Arabian Terrane (Gómez-Pérez and Morton, 2025; Gómez-Pérez et al., 2024).

During this assembly, major regional N-S trending fracture/fault zones formed that cut through the accreted terranes. These terrane boundaries and basement faults were reactivated and controlled the basin distribution and deposition during the Neoproterozoic (Allen, 2007; Bell, 2004). The siliciclastic and carbonate sediments of the Huqf Supergroup were deposited in basins that developed during these different orogenic events.

During re-activation of basement lineaments in the final stages of the Pan-African orogeny at about 565 Ma, the NE-oriented, intra-continental salt basins were formed on the Arabian Plate (Al-Husseini, 2000; Koopman et al., 2007; Van den Berg et al., 2008). These late Neoproterozoic basins in Oman are represented by the South Oman, Ghaba, Fahud, and Ghudun Salt Basins (Blood, 2001; Loosveld et al., 1996). The main salt basins are the South Oman and Ghaba salt basins which overlie the accreted terrane complex, and which experienced greater subsidence than the more stable Fahud and Eastern Arabia continental terranes. These basins are up to 100 km in width and 300 km in length and their initial infill consisted of the carbonate evaporite system of the Ara Formation which can be up to 2 km in

thickness (Mattes and Conway Morris, 1990). The Ara was deposited around the Ediacaran-Cambrian boundary over a period of less than 10 Myr (Bowring et al., 2007).

The Pan-African orogeny ended with a major reactivation of basement terrane boundaries and faults leading to thrusting and inversion (Stuart-Smith et al., 2007). This has been interpreted as resulting from a transpressional tectonic stress regime, which marks the final amalgamation of Gondwana in the early Cambrian between ~540 and 520 Ma (Koopman et al., 2007; Richard et al., 2019). The deformation along these boundaries varies and is partitioned by the reactivated NS-trending basement faults. During this period, the "Western Deformation Front" (WDF) was formed (Loosveld et al., 1996). This is a zone of major east-verging compressional deformation at the boundary of the westernmost two accreted basement terranes and the East Arabian Terrane (EAT) along the western margin of the South Oman Salt Basin. This deformation extended to the north along the EAT boundary towards the Lekhwair High and even further into the Jebel Akhdar.

The end of the WDF deformation is marked by the early Cambrian Angudan unconformity which is a peneplained surface that marks the start of a passive infill and onlap of the remnant topography. The WDF tectonic movements terminated the deposition of the carbonate-evaporite systems which were replaced by syntectonic alluvial fan, lacustrine, and playa-lake clastics of the Nimr Group. Layered Ara salt in the Fahud Salt basin may also be part of the onlapping succession on the WDF (P. Spaak pers. comm. 2016, see also seismic line in Fig. 4c of Gómez-Pérez et al. (2024)).

2.2.2 Basement structure along the northern plate margin

Apart from Jebel Ja'alan, which is in the East Oman metamorphic belt, there are no autochthonous crystalline basement outcrops in the Oman Mountains and there are no deep

seismic reflection data that allow a calibration with the structures observed south of the mountains. However, shear wave velocities interpreted from ambient noise seismic tomography and receiver function analysis show several NNE striking boundaries in the lower crust below the Oman Mountains (Weidle et al., 2022; Weidle et al., 2023) . These align with basement terrane trends recognised further south. Their Western Jebel Akhdar Zone aligns with eastern EAT boundary, the Semail Gap Fault with the eastern limit of the FT and the Ibra Zone with the western boundary of the EOMB. This suggests that the collage of accreted terranes between the FT and EOMB with the overlying Ghaba Salt basin extends northwards below the Semail gap and Saih Hatat (Figure 2-3 B).

Other arguments for the extrapolation of the basement trends into the Oman Mountains below the obduction complex (Figure 2-3) are based on the following:

1) The presence of deformed Neoproterozoic sediment exposed in the Jebel Akhdar window which have been correlated with the WDF along the eastern margin of the EAT.

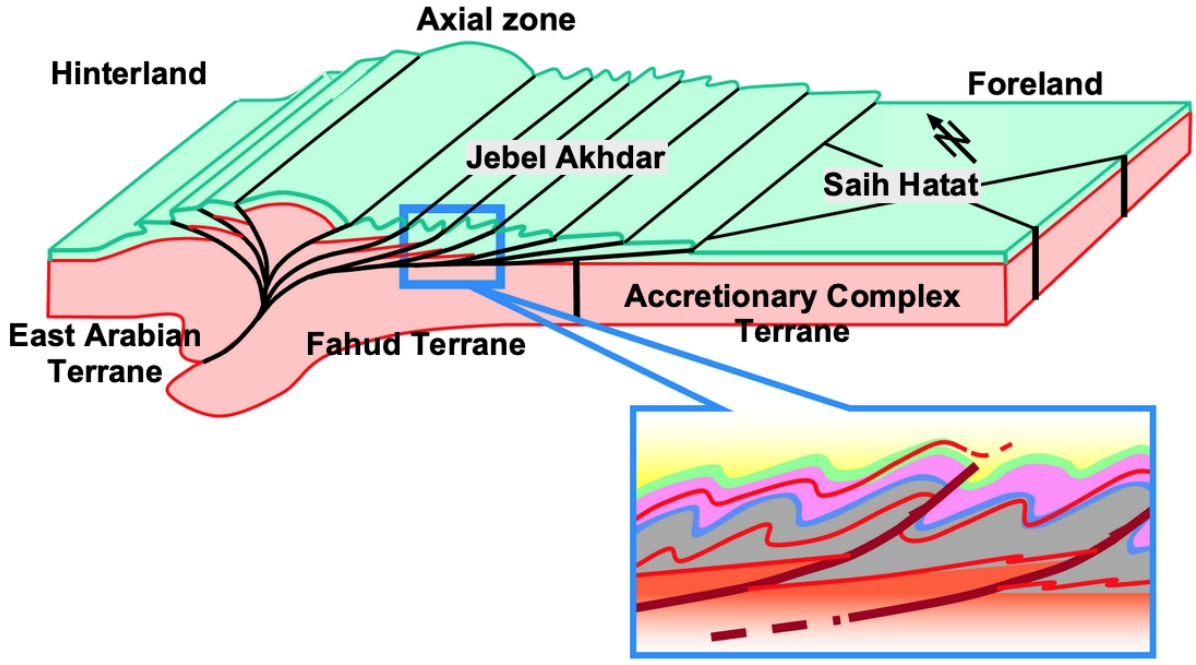


Figure 2-4 Schematic structural model showing the location of Jebel Akhdar and Saih Hatat areas in the early Cambrian orogenic belt in northern Oman which may be linked to the WDF. Modified from Breton (2005) and Gómez-Pérez and Morton (2025).

The Neo-Proterozoic to earliest Cambrian Huqf Supergroup sequence exposed in the Jebel Akhdar tectonic window has been strongly deformed with tight folds with wavelength and amplitude of 3 to 5 km and low angle thrusts accommodating some 50-70% shortening (Béchennec et al., 1992a; Beurrier et al., 1986; Breton, 2005; Mann and Hanna, 1990). The attitudes of the limbs, axial planes and axes of the folds document a NW-SE regional compression with a shear component verging top to the SE. Breton (2005) suggests that the deformation occurred under a light load, indicated by the brittle character of the deformation and absence of associated regional cleavage, and involved stacking of thrusted slabs in the basement. It is suggested that the Jebel Akhdar area is underlain by a fold and thrust belt located in the external part of a collision zone, striking NE-SW and located to the NW (Figure 2-4). This deformation is truncated by the Pre-Permian unconformity and can be related to the latest Pan-African deformation event (Béchennec et al., 1992a; Breton, 2005) and not to the mid-Carboniferous unconformity as suggested previously (Al-Husseini, 2004; Mann and Hanna, 1990; Michard, 1982). This can also be demonstrated on subsurface seismic and well data, which show deformed Neoproterozoic sediments unconformably overlain by undeformed Lower Palaeozoic Haima Group sediments (Droste, 2014; Loosveld et al., 1996).

The pre-Permian deformation is much less intense in the eastern Jebel Akhdar tectonic windows (Mistal, Hedeck and Dhabiah windows (Béchennec et al., 1992a; Rabu et al., 1986)) and is absent still further east in Saih Hatat, where no major pre-Permian and pre-Ordovician deformation can be observed (Breton, 2005; Le Métour et al., 1986b) and where the pre-Permian stratigraphic succession is entirely different (thick Tonian and thick Ordovician with no Cryogenian to Cambrian). With respect to the vergence of pre-Permian folds in Jebel Akhdar the Saih Hatat is in an exterior position to the orogen and may have

been the location of a foreland basin (either now eroded or represented by the Cambro Ordovician Amdeh Fm. (Breton, 2005; Gómez-Pérez and Morton, 2025). From the BRGM geological map the presently exposed width of the Jebel Akhdar deformed zone is at least 50 km (Béchennec et al., 1992a). The deformation may be related to inversion of a pre-existing extensional basin in a transpressional setting along a reactivated basement lineament NW of the Jebel Akhdar area. Similar basement-controlled inversion features have been reported from the Late Cretaceous to Cenozoic in the Andes (Amilibia et al., 2008), the Late Palaeozoic Anadarko Basin in Oklahoma (Kolawole et al., 2020) and the Late Cretaceous to Paleocene Laramide deformation in Wyoming (Speece et al., 1994). This lineament may be an extension of the EAT / FT boundary and the deformed sequence in Jebel Akhdar could thus be a continuation along strike of the WDF.

2) The presence of Carboniferous, Al Khlata Fm., glaciogenic sediments in Wadi Daiqa in the Saih Hatat overlying thick Palaeozoic clastics suggests a similar stratigraphy as in the Ghaba Salt basin in the south, indicating that this basin may have extended further north below the Late Cretaceous thrust sheets in the Saih Hatat area (Heward and Penney (2014), Figure 2-5A). Carbonate megabreccias and shales at the top of the Neoproterozoic Hijam Fm. dolomite below Palaeozoic Amdeh Fm. clastics in the western Saih Hatat window mentioned by Gomez-Perez et al. (2024a); Gomez-Perez et al. (2024b) could represent a dissolution remnant of a carbonate-evaporite basin but this needs further investigation.

3) Palinspastic reconstructions of the intense Late Cretaceous folds in the Upper Permian carbonate platform suggest that this platform extended at least some 90 km to the ENE of Saih Hatat (Chauvet et al., 2009). No such extension is known from the Jebel Akhdar segment suggesting a major NE-SW promontory north of Saih Hatat.

4) Eclogites embedded in impure marble-schists (likely metamorphosed Permian lavas and limestones) at As Sifah at the NE margin of Saih Hatat have been exhumed from depths of 80-90 km (Agard et al., 2010), suggesting that the leading edge of the Arabian Plate extended some 120 km to the NE (assuming a dip of 40° for the subducting plate). This part of the plate may have formed a promontory in the continental margin north of the Saih Hatat dome and east of the Qurm line, an offshore structural boundary that broadly lines up with the onshore Semail gap between Jebel Akhdar and Saih Hatat and the eastern FT boundary further south (Levell et al., 2021; Ninkabou et al., 2021).

5) Ara Fm. evaporites that pierce the thrust sheets in the Oman Mountains (Figure 2-3 B). Gypsum bearing diapirs penetrate the Hamrat Duru thrust sheet In the Hawasina window (Ali et al., 2014a; Csontos et al., 2010) and salt intrusions occur in the Sumeini thrust sheet in Jebel Qumayrah (Cooper et al., 2013; Cooper et al., 2012). A further unpublished location occurs in the Jebel Sumeini Mountain front (Ali et al., 2014a). These indicate a northward extension of a salt basin under the thrust complex. As these localities are located north of the deformed Neoproterozoic sequence in Jebel Akhdar, they are located on the EAT and probably form part of the Hormuz Salt Basin, which is considered an Ara equivalent west of the Oman salt basins (Immerz et al., 2000) and has been recognised in Saudi Arabia, UAE, the Arabian Gulf and below the Zagros Mountains (Ali et al., 2014a; Edgell, 1991; Geng et al., 2022; Husseini and Husseini, 1990; Kent, 1979; Stern and Johnson, 2010; Stewart, 2016; Stewart, 2018).

2.2.3 SUMMARY: Potential significance of Pan-African accreted terranes and the Angudan unconformity for the obduction process

All the NNE-SSW trending basement lineaments related to the Pan-African orogeny are nearly perpendicular to the Late Cretaceous SW verging obduction complex. This implies that along strike of the obduction front major changes in basement composition of the subducting slab were present over distances of several tens to some 100 km, especially along the eastern section (Saih Hatat, the "Afar" area to the SW of Saih Hatat and the Huqf axis). Evidence has been presented for extrapolation of the basement trends into the Oman Mountains below the obduction complex.

Furthermore, the local extension of salt basins below the subduction complex may have also affected the platform shape and the deformation of the continental and carbonate platform margins during the Permian to Cretaceous passive margin phase, the deformation during Late Cretaceous subduction/obduction and the plan-form shape of the thrust slices.

2.3 Lower Palaeozoic basins of the Haima Supergroup (~520 – 420 Ma)

2.3.1 Overview of basin trends

Post-orogenic continental and marine clastic sediments of the Haima Supergroup fill in and onlap the topography formed in the final stages of the Pan-African orogeny and locally can contain sediments more than 6 km thick (Droste, 1997; Droste, 2014; Millson et al., 2008). By Early Ordovician times the whole topography was covered and deposition occurred in an intra-cratonic basin where thickness was controlled by variation of subsidence across basement lineaments and above unstable salt (Droste, 1997), as detailed below.

The Haima basins follow the NE-SW trending basement lineaments that also controlled the Salt Basins (Figure 2-5A). Following the initial onlap onto the Angudan

topography the main sediment input for Late Cambrian and Early Ordovician braid delta systems in North Oman was from the south. More distal open marine facies were developed towards the north (Droste, 1997; Millson et al., 2008). The main depocentre was in the Ghaba Salt Basin. Major (800+ m) superimposed canyon incisions with a deep-water infill occur in the upper part of the Haima Supergroup (Middle-Upper Ordovician – Lower Silurian Safiq Group (Al-Najwani, 2009; Al-Najwani, 2011; Forbes et al., 2010; Ghafri et al., 2022). Their outlines were determined by seismic and biostratigraphic data from wells. These canyons start in central Oman and coalesce towards the north into a single channel along the western margin of the Ghaba Salt Basin (Figure 2-5 A). No data are available on this channel below the thrust front, but it trends towards the Semail gap area. These canyons may have been initiated as incised valley systems during relative sea level falls in the Late and possibly Middle Ordovician and developed into submarine canyon systems following a sea level rise along an unstable shelf affected by salt movement (Forbes et al., 2010). The Upper Ordovician infill predates the latest Ordovician Hirnantian and the incisions are not related to the Hirnantian glaciation as suggested previously (e.g. Droste (1997). They may be related to a mid-Ordovician failed intra-continental rift event, an early stage in the break-up between Africa/Arabia and India, which has been suggested on the basis of the alkaline petrology of Ordovician basaltic intrusions in the Huqf outcrop area (Loosveld et al., 1996; Oterdoom et al., 1999). The incisions and facies trends in the sequence suggest a marginal and open marine setting towards the north.

The Saih Hatat region contains the northernmost occurrence of Lower Palaeozoic clastics in eastern Oman: equivalent to the subsurface Haima Supergroup of Central Oman. These deposits belong to the Amdeh Formation which mainly consists of quartzites and is some 3400 m thick (Heward et al., 2018a; Heward et al., 2023; Heward et al., 2018b;

Lovelock et al., 1981; Moss et al., 2025). Ordovician Amdeh siliciclastics are also thought to have been metamorphosed into highly deformed quartz mica schists now exhumed in the As Sifah area on the NE margin of Saih Hatat (Searle et al., 2004).

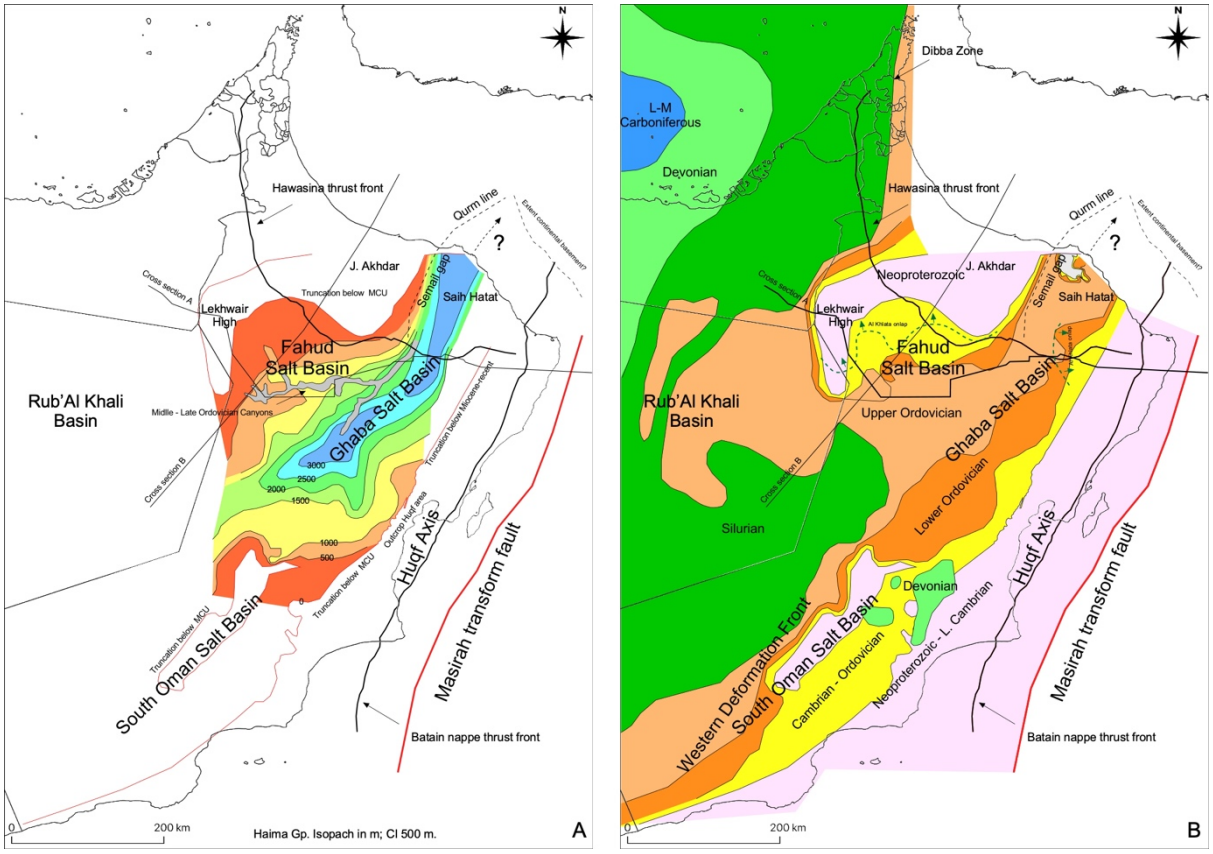


Figure 2-5 Maps showing Palaeozoic basin outline and truncation below the mid-Carboniferous unconformity. A: Isopach map for the Lower Palaeozoic Haima Supergroup. Map is based on well data and only shows overall trends. Seismic data suggest that in the salt basins locally much thicker sections occur. The thickness in Saih Hatat outcrops in the north is similar and on trend with the Ghaba Salt Basin suggesting a continuation of this basin to the north. This is also indicated by the trend of submarine canyon system mapped on seismic data in the upper part of the sequence shown in Ghafri et al. (2022), which has been plotted in grey on the map. The Haima Supergroup. is also present in the SOSB but thicknesses are highly variable due the syn- and post depositional salt movement. B: Subcrop of mid-Carboniferous unconformity. The map clearly shows significant uplift along and to the east of the WDF Neoproterozoic deformation belt in north Oman. In the salt basins salt diapirism caused uplift and erosion. The isolated occurrences of Devonian in the NW part of the SOSB occur in salt depressions. In the west, the Rub 'Al Khali Basin, some NNE-SSW trending highs are related to reactivation of basement faults. The map is based on well and outcrop data, well penetrations in the west and northwest are sparse and the outlines here are poorly controlled. The cross sections are shown in Figure 2-2. Compiled and updated from Bell and Spaak (2011); Faqira et al. (2009); Konert et al. (2001a); Konert et al. (1999); Konert et al. (2001b); Svendsen (2004).

West of Saih Hatat in Jebel Akhdar the Lower Palaeozoic clastics are absent and the Permian Saiq Formation directly overlies deformed carbonates and clastics of the Upper Neoproterozoic Huqf Supergroup. As sea levels were very high during the Ordovician it is likely that this area was also submerged but that deposits were eroded before the deposition of the Permian carbonates (Heward et al., 2018a). The Jebel Akhdar area may have been an intra-basinal high which was only covered during the highest sea level periods and had a reduced thickness of Amdeh/Haima sediments. The thick Amdeh sequence in the Saih Hatat area is thought to onlap the Jebel Akhdar High (Gomez-Perez et al., 2024a; Gomez-Perez et al., 2024b).

Further to the northwest in the Dibba zone, UAE, some rafts of the Ordovician Rann Formation occur within a tectonic mélange (Fortey et al., 2011). These shallow marine deposits are thought to have formed on a siliciclastic shelf, later becoming detached fault blocks along a Triassic fault scarp. These sediments were estimated to originally be some 100 m thick (Fortey et al., 2011). During ophiolite obduction they were included as rafts in the allochthonous Haybi Complex (Robertson et al., 1990). The occurrence of these clastics suggests another Early Palaeozoic depocentre northwest of the Jebel Akhdar High, possibly an extension of the Hormuz salt basin.

2.3.2 SUMMARY: Potential significance of the Lower Palaeozoic for the obduction process

The distribution and thickness variations of the Lower Palaeozoic deposits highlight areas of subsidence variation caused by tectonic reactivation across Pan-African basement lineaments and above unstable salt. This helps confirm the positions of the main basement trends.

2.4 The mid-Carboniferous unconformity and the Haushi basin (~315 – 269 Ma)

2.4.1 Overview

The Lower Palaeozoic and Neoproterozoic sediments and basement are separated by a major stratigraphic hiatus from overlying mid Carboniferous and younger sequences. In central parts of the Rub 'Al Khali Basin in Saudi Arabia, where the stratigraphy is more complete, palynological dating indicates that the hiatus is in the middle Carboniferous and covers approximately the Namurian-early Westphalian (Serpukhovian – Bashkirian), a time gap of some 15 Myr (Al-Husseini, 2004). This suggests that the minimum age for the mid-Carboniferous unconformity is ~ 315 Ma.

The subcrop map for Oman (Figure 2-5) suggests that the main uplift at this time was along a NE-SW trending axis, which stretches for some 750 km along the eastern coast of Oman from the Dhofar Mountains in the south, through the Huqf area towards Jebel Ja'alan in the north. In the easternmost part of this axis this unconformity has itself been eroded by basal Jurassic and younger unconformities. But in the northeastern coastal Batain area a well has penetrated Permian carbonates of the Akhdar Group and some probable Permian clastics overlying Neoproterozoic clastics (Mount et al., 1998), which suggests that most erosion was indeed pre-Permian. Over most of interior Oman the subcrop consists of Ordovician to Silurian continental to marine siliciclastics of the Haima Supergroup (Droste, 1997; Forbes et al., 2010). These Haima sediments are preferentially preserved in the areas underlain by the salt basins. The tectonic tilt of Haima strata below the unconformity along most of the regional highs in the subsurface is less than 1°, forming a gentle monocline dipping to the west (Svendsen, 2004). Patchy occurrences of Devonian along the eastern and northeastern flank of the SOSB occur in mini-basins formed by removal of underlying Ara Salt (Forbes et

al., 2010). Salt tectonics and near surface dissolution also affected the subcrop in the SOSB, thus creating salt-induced highs of Neoproterozoic to early Cambrian deposits (Al-Barwani and McClay, 2008; Heward, 1990).

There was a second region of uplift in north Oman. This ran along a N-S trending axis: in the Lekhwair area, in Jebel Akhdar and at the northern edge of the Saih Hatat. Seismic and well data show that Lower Palaeozoic clastics are progressively truncated towards the Lekhwair and Jebel Akhdar highs from the east, south, and west (Figure 2-5 B) and are onlapped by Carboniferous and Lower Permian clastics of the Haushi Gp. The Neoproterozoic fold and thrust belt subcrops on the highs.

In Saih Hatat the Lower Palaeozoic siliciclastics of the Amdeh Formation form a wide arch with a NNW-SSE trending axis below the Permian Saiq Formation (Le Métour, 1988). The tectonic tilt of the strata with respect to the unconformity is some 10° - 30° (Le Métour, 1988; Le Métour et al., 1986b). The crest of the Saih Hatat arch was eroded during the pre-Permian and, in the north, erosion cut through the Amdeh clastics into the Neoproterozoic. Heward and Penney (2014) documented pre-late Carboniferous fault movement in Amdeh outcrops in Wadi Daiqa (SW of Saih Hatat), which indicates that this deformation may be related to the mid-Carboniferous event.

The amount of uplift and erosion related to the mid-Carboniferous event is difficult to assess in Oman, as the unconformity along the Huqf flank may also overprint older Devonian to Carboniferous unconformities, each of which is potentially associated with significant stratal hiatuses, or erosion (Figure 1-3). Regional cross sections suggest that the total amount of Pre-Permian erosion could be in the order of several km (see Figure 3 in Droste (1997)).

The tectonic model for the mid-Carboniferous unconformity is poorly understood. The uplift in Oman has been associated with uplift of the Neo-Tethys rift shoulder (Stampfli et al., 2001) and also with a triple junction located northeast of Oman (Al-Belushi et al., 1996) preceding the Permian Neo-Tethys rift along the northern and eastern margins of Arabia. This hiatus also correlates with an important regional mid-Carboniferous intra-continental tectonic deformation phase that affected the Lower Palaeozoic of northern Gondwana in North Africa, Arabia and India (Al-Husseini, 2004; Faqira et al., 2009; Konert et al., 2001a; Konert et al., 1999; Konert et al., 2001b). In Saudi Arabia this hiatus is known as the Pre-Unayzah unconformity (Al-Husseini, 2004; McGillivray and Husseini, 1992), named after the overlying Unayzah Formation which is the equivalent of Oman's Haushi Group. Other publications refer to this event as the "Hercynian unconformity" because of the broad age equivalence to the mid-late Carboniferous Hercynian orogeny in Europe (Faqira et al., 2009).

Subcrop maps (Figure 2-5) below the mid-Carboniferous unconformity over Arabia show the presence of NE trending arches some 500 km long and N-trending fault-bounded structures several 100's km in length in central, eastern and northeaster Saudi Arabia and Kuwait (Faqira et al., 2009; Wender et al., 1998). The arches are several 100 km wide and have a vertical amplitude of 1 km. It is suggested that the formation of the arches and basins is related to broad flexuring of the continental crust. The fault-bounded structures are thought to be related to re-activation of pre-existing basement terrane sutures or intra-terrane shear zones trends (Bell, 2004). The deformation has been interpreted as a far-field effect of the collision of Laurasia with Gondwana along the western margin of Africa (Wender et al., 1998), or a southerly directed subduction zone of oceanic crust along the northeastern boundary of Gondwana (Al-Husseini, 2004). In Oman, the Huqf axis is considered another broad NE-

trending late Palaeozoic swell (Al-Husseini, 2004), whereas the Lekhwair High represents a more localised re-activated basement feature.

The Late Palaeozoic deformation ended with the formation of a large intra-cratonic basin covering western Oman, southeastern Saudi Arabia and the UAE. Oman was located along the eastern border of this basin, a semi enclosed basin bounded by the following highs: the Huqf (-Dhofar) arch in the southeast, highs located below the present-day Oman Mountains and the Lekhwair area in the north, and the Hadhramaut arch and the Arabian Shield in the south and southwest. This basin is known as the Eastern Rub 'Al Khali basin and is separated by the uplifted Qatar Arch from the Western Rub 'Al-Khali basin in Central Saudi Arabia (Stewart, 2016).

The initial infill of the basin in Oman consists of glaciogenic clastics (diamictites, fluvial conglomerates and sandstones, and lacustrine deposits) of the Al Khlata Formation (Hughes Clarke, 1988; Levell et al., 1988). The Al Khlata Fm. was deposited in proglacial environments during deglaciation phases. Several erosionally bounded units, each associated with the advance and retreat of ice sheets into pro-glacial lakes, have been recognised (Osterloff et al., 2004b). These are overlain and overstepped by fluvial channel sands, floodplain, lacustrine, and subordinate shallow marine sediments of the Lower to Upper Permian Gharif Formation (Angiolini et al., 2004; Blendinger et al., 1990; Osterloff et al., 2004a). The Gharif deposits are part of a large delta system that prograded from uplands located east of the Huqf High towards the East Rub 'Al Khali basin in south-eastern Saudi Arabia. This delta formed after a major transgression following the melting of the ice sheets of the Permo-Carboniferous glaciation.

The thickness of onlapping Al Khlata sediments varies between 0 and 800 m and is mainly controlled by syn-depositional subsidence related to Ara salt doming and dissolution (Levell et al., 1988; Osterloff et al., 2004b). The overlying Gharif Formation is remarkably uniform in thickness, ~230 metres in Central Oman (Forbes et al., 2010) and thins onto regional highs. Assuming a regional thickness of the Al Khlata sediments of some 200 m, the initial depositional topography of the regional highs in the north and east at the base Haushi unconformity was at maximum a few hundred metres. Some of the original post-tectonic topography may have been smoothed by glacial erosion during Al Khlata times. The presence of Al Khlata and Gharif sediments SE of the Saih Hatat area (Heward and Penney, 2014) indicates a northern extension of the Eastern Rub 'Al Khali basin below the Late Cretaceous thrust front.

2.4.2 SUMMARY: Potential significance of the-mid Carboniferous unconformity and Haushi basin for the obduction process

Carboniferous to Permian depositional patterns indicate that the movement of basement features was subdued relative to the Lower Palaeozoic. But such movements are still readily detectable through subcrop, thickness and facies patterns, particularly along the Huqf axis, and the Jebel Akhdar and Lekhwair highs.

2.5 Opening Neo-Tethys- Permo-Triassic epeiric carbonate platforms (~269-210 Ma)

2.5.1 Overview

Palinspastic reconstructions show that the northern part of Gondwana experienced a rifting event causing the breakaway of the Cimmerian continental ribbon terranes to the north and leading to the opening of the Neo-Tethys ocean during the late Carboniferous to late early Permian (Stampfli and Borel, 2002). Detachment of the ribbon terranes started in

the east of Australia and progressively moved westward towards the Eastern Mediterranean. At the same time a rifting phase started between Africa-Arabia and India to the east of Oman placing Oman at a triple junction (Al-Belushi et al., 1996; Chauvet et al., 2009). One branch extended southward to the East African / Madagascar region but was aborted in the Permian. It experienced renewed rifting during the Late Triassic but the basin only opened during the Jurassic (Hauser et al., 2002; Stampfli et al., 1991).

Opening of the Neo-Tethys ocean north of Oman is thought to have started at～ 269 Ma (in the early late Permian: early Guadalupian, Wordian, (Blendinger, 1988; Blendinger et al., 1990)). This is indicated by the presence of Permian deep-water sediments on pillow lava basalts and volcaniclastics in some of the allochthonous units exposed in the Oman mountains. Following the opening of the Neo-Tethys, a nearly 2 km thick epeiric carbonate platform was deposited over most of Oman during the Permian and Triassic. It consists of shallow water carbonates and evaporites intercalated with some fine-grained alluvial to coastal plain siliciclastics derived from the south. Depositional sequences can be correlated over 100's of km. Thickness changes and evaporite distribution suggest that the main depocentre is located in the Eastern Rub 'Al Khali Basin west of Oman (Aigner et al., 1990).

In interior Oman syn-depositional unconformities in the Permian Gharif Fm. siliciclastics suggest uplift along the northern and eastern margin and the Lekhwair High (Angiolini et al., 2004; Blendinger et al., 1990; Osterloff et al., 2004a). This corresponds with an increased influx of coarse siliciclastics in the Upper Gharif (Osterloff et al., 2004a) with incised valley systems (Angiolini et al., 2004; Crumeyrolle et al., 1997). The Permian clastics are conformably overlain by Permian shallow water carbonates of the Khuff Fm. (Akhdar Gp.), deposited during a widespread transgression. This led to the establishment of the

epeiric carbonate platform that covered most of the Arabian Plate until middle Cretaceous times. The onset of carbonate deposition represents the start of the drift phase of the Neo Tethys opening (Droste, 2014).

In the Oman Mountains and the Lekhwair High areas, the ocean opening was associated with a major marine transgression over exposed Neoproterozoic and Palaeozoic strata. Deposition starts with a fluvial to restricted marine basal conglomerate and siliciclastic interval of up to 25 m thick, locally with volcanic intercalations and coaly shales (Le Métour, 1988; Le Métour et al., 1995a; Rabu et al., 1986; Rabu et al., 1993). These are overlain by shallow marine carbonates of the Saiq (Oman Mountains) / Khuff Fms. (subsurface). In Jebel Akhdar the sequence onlaps a palaeo-relief of up to some 100 m (Bendias et al., 2013) and lateral thickness changes in the overlying units suggest differential syn-depositional subsidence (Walz et al., 2013).

In the Saih Hatat area, syn-depositional N-S trending horst and graben structures have been recognised and the basal Permian sequence shows considerable lateral thickness and facies changes (Chauvet et al., 2009; Le Métour, 1988; Rabu et al., 1993). It consists of clastic and carbonate sediments, clastic mélanges and conglomerates, pillow basalts and volcaniclastics, conglomeratic breccias with limestone fragments and, on uplifted blocks, condensed carbonates (Figure 2-6 A). Palinspastic reconstructions by Chauvet et al. (2009) show the grabens formed during early Permian extensional rift tectonics on the Arabian platform (Figure 2-6 B). Some of these faults are indicated on the Permo-Triassic isochore map in Figure 2-7 A. They suggest that the rifting in the Saih Hatat area occurred over a short period: < 5 Myr during the Murghabian. The geochemical composition of the volcanics in Saih Hatat and other similar age volcanics in the Hawasina nappes indicates an intraplate

setting. They have been related to a mantle plume and continental lithospheric thinning (Lapierre et al., 2004; Maury et al., 2003). The same plume was the source of contemporaneous volcanics that form the Panjal traps in northwestern India and is linked to the opening of the Neo-Tethys and separation of Arabia and India. The E-W to ENE-WSW extension suggested by the reconstructions would indicate that the Saih Hatat area was indeed located close to a triple junction formed by the intersection of the Neo-Tethys and the Arabia India rifts (Chauvet et al., 2009).

Apart from the NE corner of Saih Hatat, typical rift-related features such as large-scale uplift, extensive volcanism, rotated fault blocks or half grabens with an infill of siliciclastics or evaporites are missing along the northern Arabian Plate margin (Bell and Spaak, 2011). Blendinger et al. (1990) suggest this could indicate the Oman margin was located on the little deformed side of an asymmetrical “simple shear” rift. Bell and Spaak (2011) speculate that a “soft” separation of the Cimmerian terranes was made possible by reactivation of older weaknesses in the crust. Another possibility is oblique opening of the Neo-Tethys along a broadly east-west transform margin as suggested by Ricou (1994). This would also be in line with the ENE-WSW to E-W extension documented in Saih Hatat by Chauvet et al. (2009).

There are no autochthonous exposures of platform margin facies, but Permo-Triassic platform margin facies can be seen in the allochthonous Sumeini Group. Watts and Garrison (1986) show that the northern platform margin exposed in the Sumeini outcrops developed from an initial distally steepened ramp into a steep escarpment bypass margin. This margin contains coral reefs along the edge and debrite deposits along the base of slope, with boulders and blocks of shallow and deeper water (up to 100 m deep) limestones in the Middle to Late Triassic (Ladinian to Norian). Cessation of reefal debris influx and bypass of

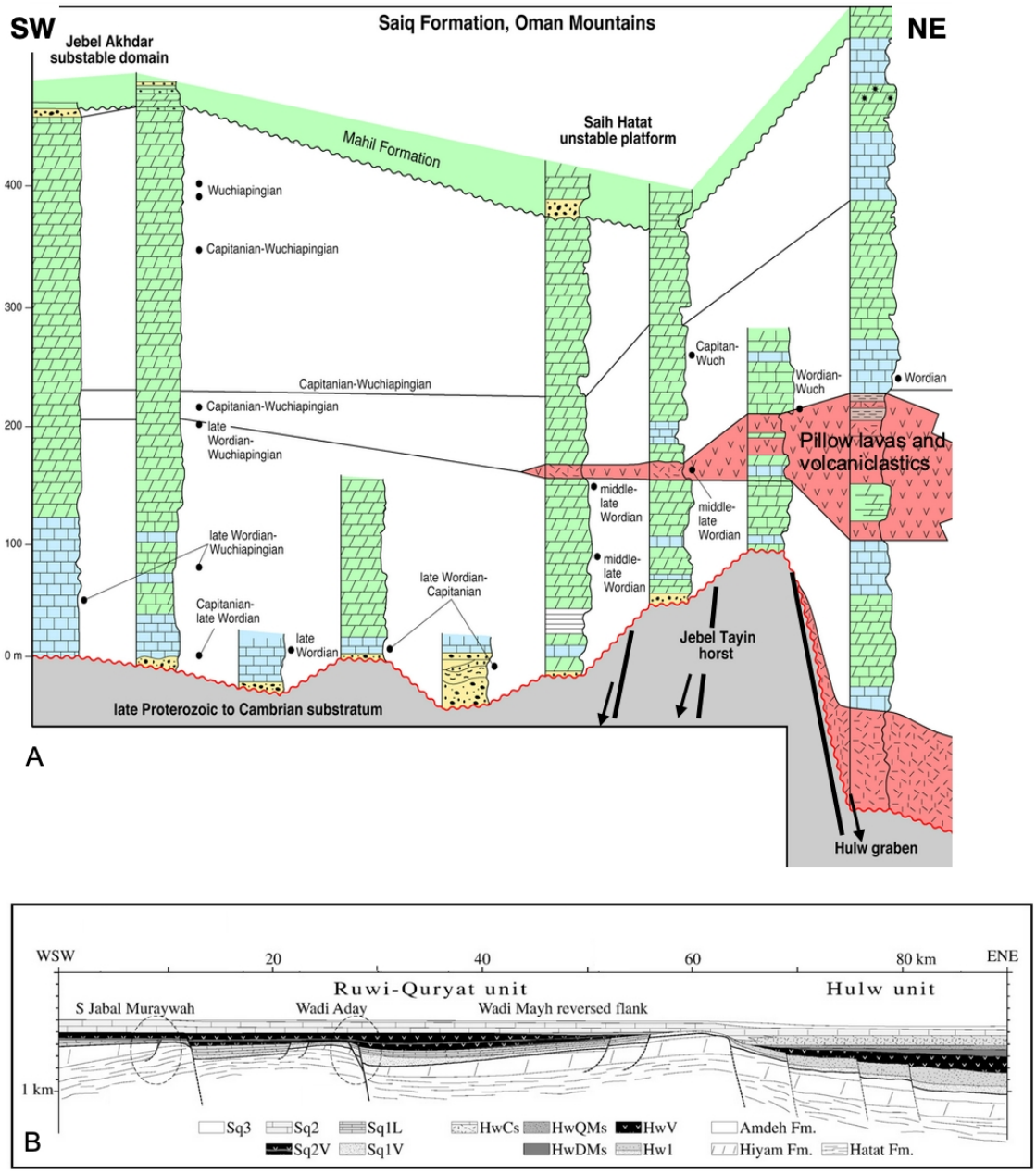


Figure 2-6 Middle to upper Permian Saiq Fm. in Jebel Akhdar and Saih Hatat. A: Outcrop correlations showing lateral thickness and facies variations. Middle Permian basal clastics fill an erosional topography and are overlain by shallow marine carbonates. In Saih Hatat horst and graben structures occur associated with conglomeratic limestone breccias, volcanics and volcaniclastics. Modified from Rabu et al. (1993), courtesy J. Mattner. B: Unfolded and restored section of the Permian platform margin in the northern Saih Hatat area (Chauvet et al., 2009). The palinspastic restoration in this section implies a shortening of 70 km, which is part of the argument for a projection of the carbonate platform to the NE of the present-day coast offshore Saih Hatat (see Figure 2-7).

siliciclastics into the basin suggest emergence of the platform during the Late Triassic. The platform escarpment is thought to have been structurally controlled by down-to-east normal

faulting (Watts, 1990). Uplift and emergence is probably related to the onset of the Late Triassic-Early Jurassic regional uplift discussed in the next section. Whatever the explanation, an important point to note is that the Permian and younger passive margin of northern Oman, excluding Saih Hatat, at least that part that is now represented by the autochthonous successions, was largely unfaulted prior to the Late Cretaceous obduction. The evidence of fault-related subsidence is almost exclusively related to the platform margins preserved in the allochthonous units, which palinspastically were positioned several tens of kilometres north of the current coast.

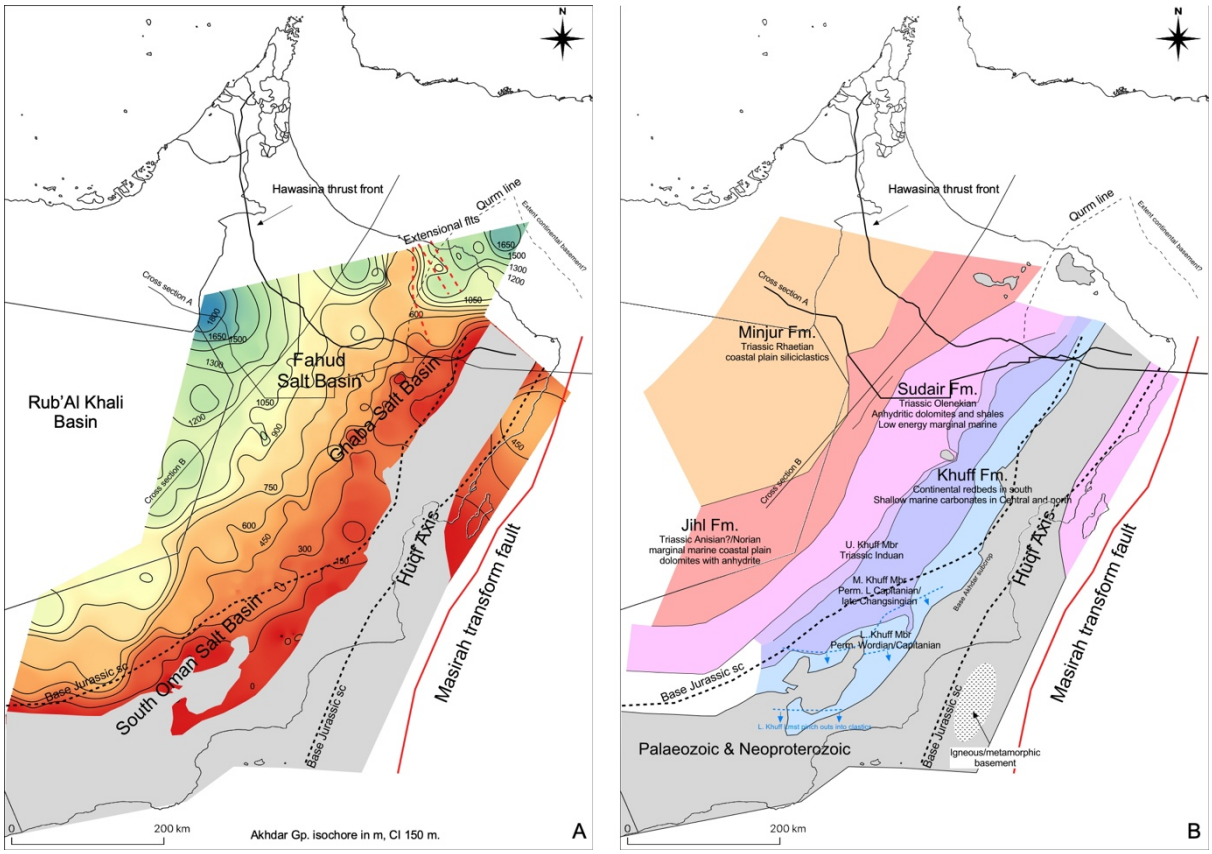


Figure 2-7 Maps showing the isochore (A) and truncation below the base Jurassic unconformity (B) of the Permo-Triassic Akhdar Group. The maps are based on own work using outcrop and well data and only show overall trends. The ages and depositional setting are from Forbes et al. (2010). The thicknesses and faults north of the Saih Hatat area are based on a reconstruction of the margin by Chauvet et al. (2009) (see also Figure 2-6), outcrop data based on BRGM Geological maps, (Coy, 1997; Glennie et al., 1974; Kapp and Llewellyn, 1965).

The Batain nappes in the east also contain Permo-Triassic deep water and slope sediments, associated with Late Triassic volcanics. These nappes however are thought to represent parts of the western margin of the Indian Plate that were emplaced onto Oman along the Masirah transform fault (Hauser et al., 2002).

2.5.2 SUMMARY: Potential significance of the Opening Neo-Tethys and Permo-Triassic epeiric carbonate platforms for the obduction process

The Permian and younger passive margin of northern Oman, at least that part that is now represented by the autochthonous successions, was largely unfaulted prior to the Late Cretaceous obduction. The evidence of fault-related subsidence is almost exclusively related to the platform margins preserved in the allochthonous units, which palinspastically were positioned several tens of kilometres north of the current coast. The boundary between allochthon and autochthon was apparently set up by the sharp boundary between faulted and unfaulted areas, possibly the edge of the “necking domain” (Chenin and Manatschal, 2025).

The Permo Triassic passive margin /shelf margin was not a linear feature but had a distinct promontory offshore the Saih Hatat area, extending perhaps 100 km further to the NE than in the Jebel Akhdar segment

2.6 Base Jurassic unconformity and Sahtan Group

2.6.1 Overview

In Oman a major unconformity separates the Lower Jurassic from underlying deposits with a minimum hiatus of some 13 Myr comprising the Hettangian to Lower Pliensbachian. Some of the uplift already started in the latest Triassic with the deposition of early-syntectonic coastal plain deposits of the Minjur Fm. in northwestern Oman and the Rub’al

Khali Basin in the west (Forbes et al., 2010). Subsurface data show that the underlying strata are progressively truncated from west to east below this unconformity and the main uplift is again along the Huqf axis. Here, the base Akhdar Gp. subcrops and the unconformity cuts into underlying Palaeozoic clastics and Neoproterozoic carbonates and clastics reaching metamorphic-granitic basement along the southern part of the Huqf axis (penetrated by wells in the southeast offshore area). Assuming the Permo-Triassic carbonate platform covered the whole of Oman, the isochores suggest at least 1800 m of erosion in the east along the Huqf axis (Figure 2-7).

In the sub-surface of North Oman, a locally thicker and more complete Akhdar Gp. section occurs in salt withdrawal basins (e.g. Qarn Nihayda, see Al Shuaily (2007)). This suggests active salt tectonics took place during this period. Isolated pods with thicker Akhdar Group sediments are also preserved within narrow salt dissolution synclines along the eastern flank of the South Oman Salt Basin (Heward, 1990; Osterloff et al., 2004a). However, as these underlie Albian Nahr Umr, they could also have formed during the Late Jurassic and/or Aptian tectonic events. The sequence overlying the Permian rift in the Saih Hatat in the NW, seems less affected by uplift and a thick Akhdar section of nearly 2 km is still preserved. The regional tilting toward the NW may have been associated with uplift of rift shoulders along the Huqf axis during an early stage of the opening of the ocean between the African/Arabian and Indian Plate.

Seismic data in northern Oman show an irregular topography at the top Akhdar Gp. and bedrock-incised channels (Al Shuaily, 2007). This topography is overlain by a transgressive sequence of mixed carbonates and clastics of the Lower to Middle Jurassic Mafraq Fm. deposited in alluvial, fluvial, coastal plain and shallow marine to offshore

environments that onlaps the truncated Akhdar Gp. from northwest to southeast (Forbes et al., 2010). In the Oman Mountains the top of the Akhdar Gp. is a karstified surface with karst cavities extending 2 m into underlying dolomites. The karst is covered and filled in by conglomerates and iron-rich, quartz sandstones with root marks, of Pliensbachian age (Bendias and Aigner, 2015; Rabu et al., 1990). In southeastern Oman and the Huqf outcrop area the unconformity is marked by up to 30 m thick deep, red-coloured lateritic/bauxite palaeosols (Dubreuilh et al., 1992), in the subsurface these are also present and known as the “Oman soil”. This may have formed during both the earliest Jurassic and latest Triassic (Forbes et al., 2010).

Following the transgression, a shallow marine epeiric carbonate platform was re-established that covered the whole of Oman during the Middle and early Late Jurassic. Several transgressive-regressive cycles can be recognised which show thickening and progradation to the west and the main depocentre was in the Rub’al Khali Basin.

The Jurassic platform margin is not exposed, but Jurassic slope and deep-water sediments do occur within the nappe complex. Slope deposits in the Sumeini nappes have been described by Watts (1990); Watts and Garrison (1986). These consist of an apron of thin-bedded peri-platform limestones cut by debris-filled gullies with coarse-grained sediment and clasts derived from coeval slope and platform margins as well as clasts reworked from the Triassic. They are interpreted as a gullied bypass slope along a partly exposed Triassic platform margin. The platform margin has a very irregular outline which is structurally controlled. These studies suggest that the margin follows NNW-SSE trending, down to east normal faults formed during the Triassic and Jurassic that affected the

allochthonous rocks currently exposed in the Jebel Sumeini and Wadi Qumayrah windows, and a possible NE-SW trending transform fault in the Dibba zone.

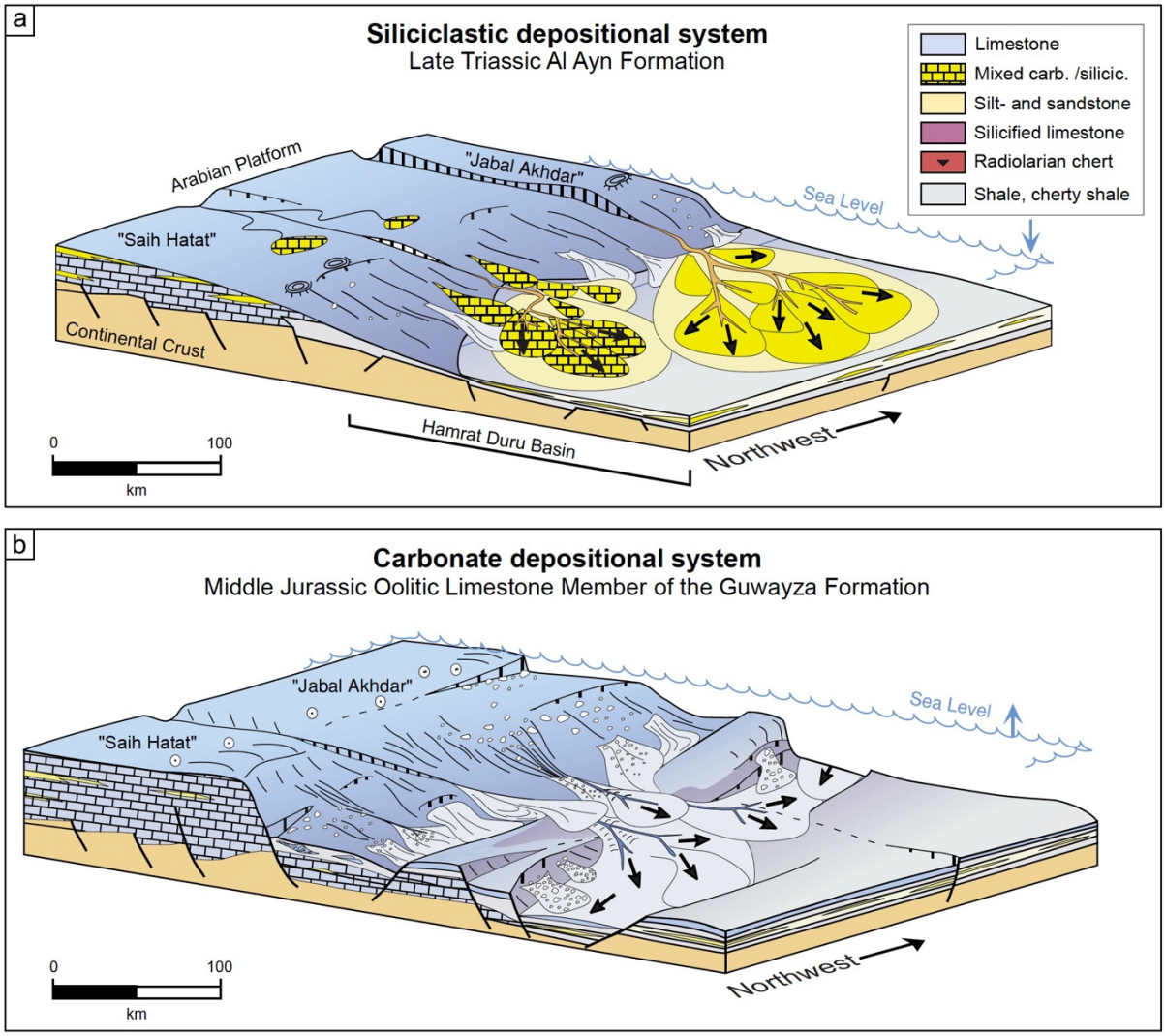


Figure 2-8 Schematic models for the Late Triassic and middle Jurassic Neo-Tethys platform margin in Oman. The margin remained in the same position during this time but was re-activated by faulting leading to the development of escarpments. The arrows indicate flow directions (Blechschmidt et al., 2004).

More basinal depositional sequences exposed in the Hamrat Duru nappes are discussed by Blechschmidt et al. (2004) and shown in Figure 2-8. They show two phases of siliciclastic turbidite influx, indicating that clastics by-passed the carbonate shelf: the first was during the Late Triassic (Rhaetian) and is equivalent to the Minjur Fm. on the platform; the second was during Early to Middle Jurassic (Pliensbachian to early Bajocian) and corresponds

to the shelf clastics in the Mafraq Fm. A major influx of ooid-dominated turbidites during the middle Bajocian to early Callovian suggests that the epeiric platform margin was formed by oolitic shoals rather than reefs. Flute casts and ripples in the submarine fan systems show a northerly transport direction in proximal settings, whereas in distal settings the direction changes to the east or southeast. This indicates a NW-SE trending basin axis especially from the Middle Jurassic to Early Cretaceous. Towards the top of the sequence the Guwayza Fm. contains thick-bedded conglomerate bodies and olistoliths with clasts and metre-sized boulders of Triassic reefal and lagoonal carbonates and bioclastic Lower Jurassic limestones in an oolite matrix. This suggests strong tectonic instability, leading to a collapse of the platform margin during the Middle to Late Jurassic. This will be discussed in the next section.

2.6.2 SUMMARY: Potential significance of the base Jurassic unconformity and the Sahtan Group for the obduction process

The reworking of Triassic platform margin clasts into the Jurassic slope sediments, as well as the superposition of these slope deposits in the Sumeini outcrops, suggests the platform margin remained at the same location during this period. The margin was steep and at times formed an escarpment with sediment bypass. It was most likely structurally controlled by Triassic or ?Permian faults. This aggradational platform morphology variably influenced the subsequent Cretaceous platform margin bathymetry and hence the 3d shape of the top of the autochthon during obduction.

2.7 Late Jurassic unconformity and the Kahmah Group

2.7.1 Overview

The Lower to Middle Jurassic carbonate platform was truncated during the Callovian-Oxfordian by an extensive unconformity that is related to a regional tilting of less than 1°

down to the NW, yet again with uplift along the Huqf axis, (Figure 2-9 A, Droste (2014); Rousseau et al. (2006)). On the Huqf axis the entire Jurassic has been eroded, and the base Cretaceous unconformity cuts down to the Neoproterozoic. The Jurassic re-appears in wells drilled offshore to the east and is in places more than 300 m thick. This observation suggests that the N-S trending normal faults observed on seismic along the eastern margin of the

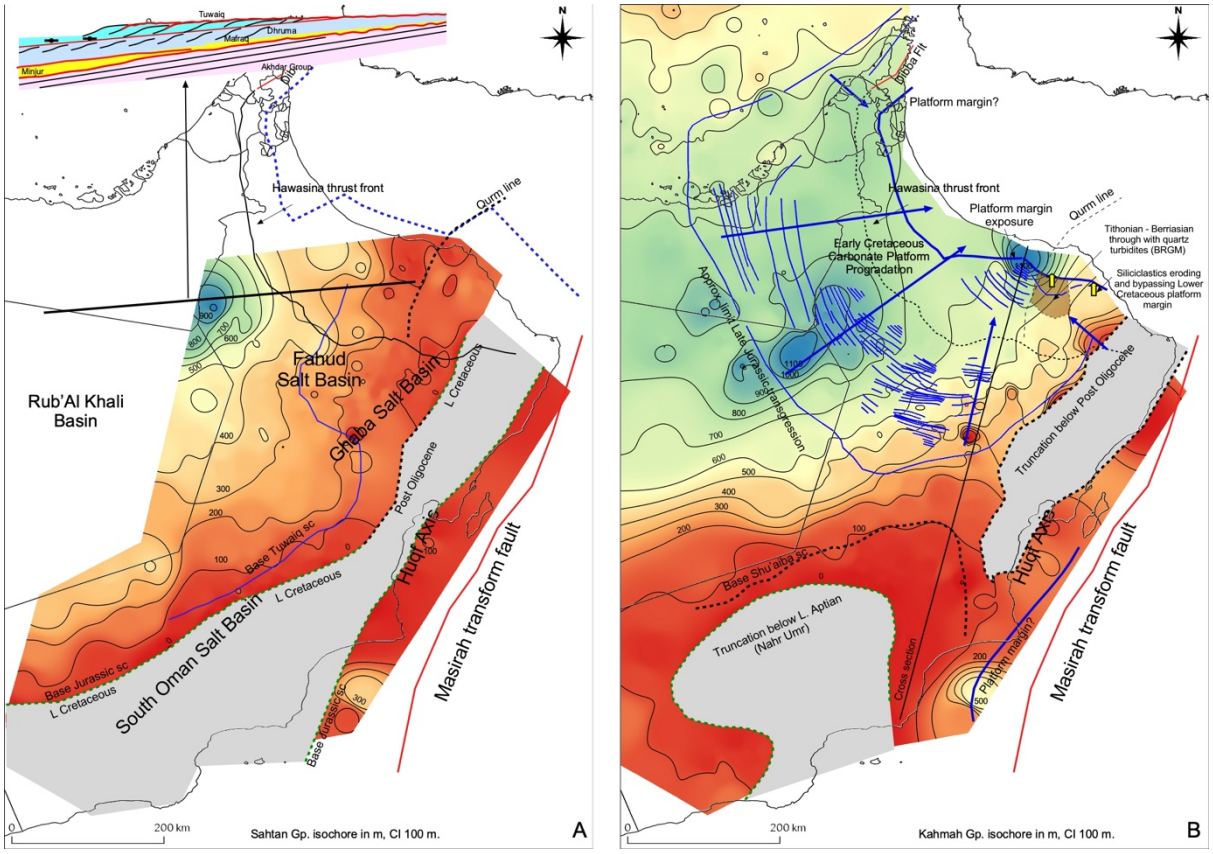


Figure 2-9 Map of Jurassic isochores showing the truncation below the Late Jurassic unconformity. The main uplift is along the Huqf axis in the east. Inset shows a schematic cross section of the Lower Jurassic onlap and truncation towards the Huqf axis. Based on own work using well penetrations. Position of the Jurassic margin modified from Pratt and Smewing (1990); Pratt and Smewing (1993). B: Isochore map of the Lower Cretaceous carbonate platform formed by the Kahmah Group. The prograding platform filled a SW-NE trending depression between the Huqf axis and the Dibba lineament in the north. Blue lines indicate consecutive platform margins mapped from seismic and outcrops. The map is based on own work and consulted publications (Aziz and El-Sattar, 1997; Dujoncqouy, 2011; Dujoncquoy et al., 2018; Haan et al., 1990; Hassan et al., 1975; Landmesser and Saydam, 1996; Razin et al., 2012). Cross section through the platform located in B is shown in Figure 2-2.

Huqf high were active during this time.

An important point related to this unconformity, well-illustrated by Rousseau et al., 2006, is the extremely gradual nature of the tilt over the large area that would subsequently be the site of the ophiolite obduction. It is clear that, as at base Jurassic time, the autochthon was acting as a coherent, slowly rotating slab on the scale of several hundred km without faulting or folding. The only exception to this are anomalies along the Semail line where variation in the amount of truncation across the Semail gap between Jebel Akhdar and Saih Hatat suggests relative uplift of the eastern flank of Jebel Akhdar (Pratt and Smewing, 1990; Rabu, 1988; Rabu et al., 1990; Rousseau et al., 2005).

In contrast to the base Jurassic unconformity there is no clear evidence of karst along this surface in the outcrops. It is marked by a hardground overlain by Upper Jurassic to Lower Cretaceous deep-water sediments. In places some scouring and erosional topography can be seen. Triassic and Jurassic lithoclasts locally occur above the surface in the western Jebel Akhdar, and in thin sections volcaniclastics have been reported in Wadi Mu'aydin (Rabu, 1988; Rabu et al., 1986; Rabu et al., 1990). There are no outcrops in this area where the base Cretaceous overlies the Triassic, but there is a clear and gradually increasing amount of truncation of the Jurassic from west to east. Possibly the Triassic clasts were derived from the uplifted eastern flank of Jebel Akhdar or eastern flank of Saih along the Semail gap. Also, Rabu (1988) mentions that the only place where a clear angular unconformity can be observed in the field between the Lower Jurassic Sahtan Gp. and the Lower Cretaceous is in this area (Wadi Al Qet, south of Al Bir). A subsurface core in the Lekhwair area shows a well-developed karst penetrating some 25 cm into underlying limestones filled by bivalve-rich skeletal packstone containing mudstone extraclasts and glauconite pellets (Rousseau et al., 2006). Lowstand deposits related to this unconformity are the carbonate conglomerates in the upper part of the allochthonous Guwayza Fm. (Hamrat Duru Gp.) mentioned in the

previous section, which contain clasts up to 100 m long (Brookfield et al., 2006; Cooper, 1989). In addition to tectonic tilting, a global scale sea level fall of 40-80 m in the Late Callovian, possibly due to a glacial event (Dromart et al., 2003), may have contributed to the erosion.

On the platform the unconformity is overlain by a major drowning sequence: a condensed horizon with belemnites, casts of ammonites and fish remains, and in places some crinoid grainstones (Haan et al., 1990; Pratt and Smewing, 1990). Deep water conditions were established over large parts of the platform with deposition of the chert-bearing pelagic limestones of the Late Jurassic to Lower Cretaceous Rayda Fm. Water depths on the drowned platform must have been in the order of a few hundred metres (Droste and Van Steenwinkel, 2004).

This drowning event is also recognised in the slope and basinal deposits exposed in the nappes thanks to a regionally correlatable radiolarian chert interval that covers the slope and

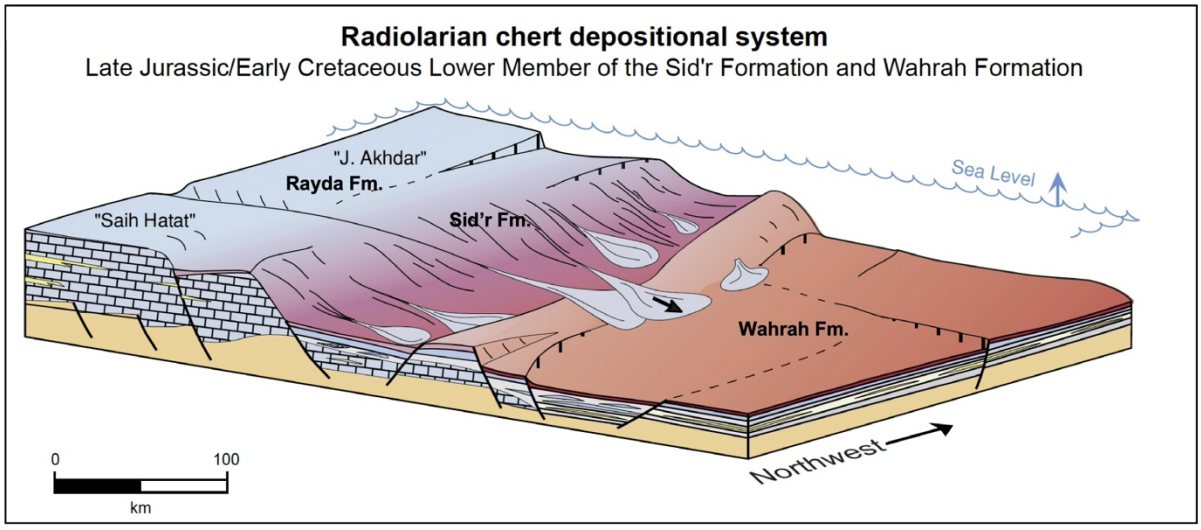


Figure 2-10 Schematic model for the drowned Late Jurassic to Early Cretaceous Neo-Tethys platform margin in Oman. The faulted and collapsed margin was covered by radiolarian cherts and siliceous limestones of the Sid'r Fm., the drowned platform by siliceous limestones of the Rayda Fm. while radiolarian cherts of the Wahrah Fm. dominate in the deep basin. Modified from Blechschmidt et al. (2004).

basinal deposits and is known as the Sid'r Fm. in the Hawasina Complex and the Mayhah B in the Sumeini Group (Figure 2-10).

A regional map with isochore and progradation patterns of the overlying Kahmah carbonates suggests that the Rayda Fm. flooding event was associated with the formation of a more than 500 km wide, NW-SE trending, depression bounded by the Huqf uplift in the SE and an uplift aligning with the Dibba lineament in the NW (Figure 2-9 B). The Huqf axis and the eastern offshore area were not covered by deep water facies and remained a high during most of the lower Cretaceous. These areas were most likely subaerially exposed and acted as the source areas for the siliciclastic turbidites, which have been reported by Le Métour (1988) and Rabu et al. (1993) within the Lower Cretaceous deep water sediments overlying the unconformity in the Saih Hatat area. The Huqf high only became covered by shallow marine carbonates of the Kahmah Gp. during the Barremian and early Aptian.

Little information is available on the northwestern margin of the Late Jurassic depression. Robertson et al. (1990) interpret the Dibba Zone as an oblique-rifted margin segment of the Arabian Peninsula, formed during the opening of Neo- Tethys Ocean. The Musandam area formed a major promontory with an oceanic embayment to the south. Murris (1980) interpreted the Dibba line as an ocean to continent transcurrent fault, bounding the east side of the Musandam promontory. Regional faulting in the UAE does not show clear relationship to the outline of the depression (Johnson et al., 2005). The depression is only apparent from isochore and facies trends and its subsidence is likely related to subtle movement along deeply buried basement structures. Jabir et al. (2023) showed, in a regional subsidence and uplift study in the UAE, the presence of a NE-SW-oriented basin in central UAE, which was interpreted as a Jurassic intracratonic rift influenced

by pre-existing structures. The Oman data suggest the depression is much wider and extends all the way to the Huqf axis in the east.

The Middle to Late Jurassic uplift and drowning event that affected the eastern margin of the plate coincided with the opening of the Indian Ocean and the initiation of a transform fault margin located in the Arabian Sea just east of Oman, which became active during the Late Jurassic (Besse and Courtillot, 1988; Edwards et al., 2000; Mountain and Prell, 1990). Subsidence of the platform top west of the uplifted margin of the Huqf axis, resulted in a deep basin that was connected to the open ocean towards the north. This seems similar to a post-break-up rim basin formed by a sag behind a rifted margin described by Veevers (1977; 1981). However these basins typically occur 10^3 km inboard of the continental edge and subsidence rates are typically very low (Allen and Allen, 2013). The centre of the basin in Oman is only a few 100 km from the margin while the drowning suggests rapid subsidence.

The Oman/UAE continental margin was the site during the Late Jurassic to Early Cretaceous of north to eastward prograding carbonate platforms of the Kahmah Gp. Building out from central Oman in the south and the eastern UAE in the west over a distance of some 250 – 300 km (Aziz and El-Sattar, 1997; Droste and Van Steenwinkel, 2004; Dujoncqouy, 2011; Dujoncquoy et al., 2018; Haan et al., 1990; Hassan et al., 1975; Landmesser and Saydam, 1996; Le Métour et al., 1995b; Razin et al., 2012). The progradation lasted more than 15 Myr but stopped during the Barremian-Aptian, after which platform growth was aggradational and an epeiric carbonate platform was re-established (Figure 2-11, Droste and Van Steenwinkel (2004)). The change in stacking pattern can be seen all over the eastern Arabian plate and probably is related to an increased rate of eustatic sea level rise documented during the middle Cretaceous (see Haq (2014)). The onset of the aggradational phase is

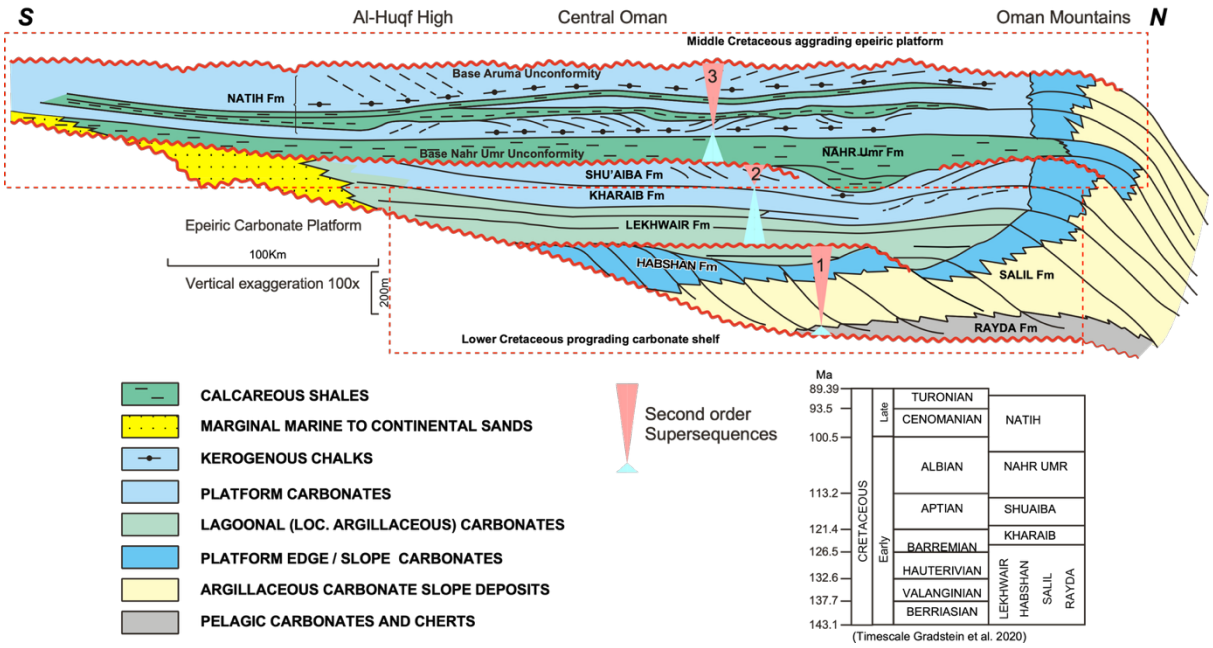


Figure 2-11 Geological cross section through the Lower to middle Cretaceous carbonate platform in Oman. Following a major flooding in Late Jurassic, the platform started as a strongly prograding carbonate shelf which developed into an aggrading epeiric platform during the middle Cretaceous. Location of section shown in Figure 2-9 B and as XS-3 in Appendix 4. Modified and updated from Droste and Van Steenwinkel (2004) and Droste (2014).

associated with the development of the Bab intra-platform basin during the Aptian (Droste, 2010b; van Buchem et al., 2010). This basin was some 70 m deep and surrounded by shallow water carbonate platforms of the Shu'aiba Fm. The initial fill of the basin consists of pelagic organic-rich chalks. This was followed by prograding wedges of fine siliciclastics and carbonates (Bab Mbr.) during a Late Aptian lowstand that exposed the Shu'aiba platform.

The Lower Cretaceous platform along the northern Huqf axis and the Saih Hatat area is complex and less well known, outcrops are difficult to access, and the sediments are strongly deformed. The only descriptions of this interval that are available are a thesis (Le Métour, 1988), and the BRGM geological mapping (Le Métour et al., 1992b; Le Métour et al., 1986b; Rabu et al., 1993). These show a very different Lower Cretaceous sequence compared to both the Jebel Akhdar outcrops and the Oman subsurface data. Siliciclastic turbidite

deposits are intercalated in the Upper Jurassic to Lower Cretaceous deep-water carbonates until Valanginian times.

During the early stages of the basin fill, Le Métour (1988) and Rabu et al. (1993) infer the presence of a N-S trending turbiditic trough over the western part of Saih Hatat and the nose of Jebel Nakhl area that is controlled by broadly N-S running faults roughly following the Semail trend. This inference is based on the occurrence of yellowish turbiditic siltstones and calc-silicate schists with quartz-bearing limestones on top of a bedded Jurassic limestone interval over a distance of some 5 km in the Jebel Abyad area (Villey et al., 1986). Towards the east (central Saih Hatat) these turbidites overlie pelagic limestones with chert of the Rayda Fm. which are missing in the Abyad section. The turbidites have been interpreted as a lateral equivalent of the pelagic limestones, though interfingering of the two facies has not been observed. Wells in NE Oman south of Saih Hatat also lack the typical Rayda pelagic limestones and cherts, which may indicate an overall shallower water setting closer to the Huqf axis. However, as this area has been affected by strong shearing during Late Cretaceous exhumation and uplift, cut out of the deeper water, thin-bedded units along detachment surfaces cannot be excluded. Another possibility is that the bedded deep-water sequence in the Abyad section, which is atypical for the Jurassic, is in fact part of the younger (Early Cretaceous) Kahmah sequence. The contact seems to be transitional while the deeper contact of the bedded Jurassic with the underlying Lower Jurassic shallow water limestones is very abrupt, but this suggestion needs further study.

Further infill of the basin consists of Valanginian to Barremian slope deposits with carbonate conglomeratic breccias and lithoclastic and silty to muddy limestones followed by Barremian to Lower Aptian subtidal shelf carbonates. The coarse-grained slope deposits

suggest an unstable carbonate platform margin that showed very little progradation. Lower Cretaceous platform margin trends seen in the subsurface further south than the Saih Hatat outcrops show that westward progradation from the Huqf axis could have been less than 50 km. Siliciclastic influx has been encountered throughout the sequence and a southern source of these clastics from the Huqf axis has been suggested in the BRGM work. However, well data and the outcrop in Jebel Madar do not show silts or sandstones in the Lower Cretaceous platform. The siliciclastic source area is more likely located along the northern part of the Huqf axis. This implies exposure of the Huqf axis to the southwest of Saih Hatat, at least at times in the Early Cretaceous. There is no record of an Aptian to Albian platform margin facies in the Saih Hatat area. We will return to the Albian history of these areas in the next chapter.

2.7.2 SUMMARY: Potential significance of the Late Jurassic unconformity and the Kahmah Group for the obduction process

The map view outline of the Kahmah platform margin (Figure 2-9 B) is the main expression of basement heterogeneity and may have influenced the formation of individual nappes (e.g. Sumeini Group) and nappe emplacement. As will be discussed later, the landward shift of the early-mid Cretaceous (Kahmah Gp.) margin position relative to the Jurassic escarpment created a stepped profile at the composite margin that affected the geometry of the frontal thrust. Both the Huqf Axis and Dibba Lineament influenced sedimentation during the Early Cretaceous and indicate along-strike mechanical heterogeneity on the downgoing plate. However, the overall deformation between these lineaments was a gentle depression, comparable to the uniform westward tilting experienced by the Jurassic Sahtan Group.

The Huqf high is shown to be a source of siliciclastic material, albeit limited, and indeed the sole source of siliciclastics.

2.8 Conclusions

1) Re-activation of NE-SW trending basement terranes and faults during tectonic deformation is clearly evident from the stratigraphic record. These elongated basement terranes are perpendicular to the obduction front and can be expected to have behaved mechanically differently from each other during flexural loading.
2) There is abundant evidence of a first order difference in geological history between the Jebel Akhdar and Saih Hatat areas that affected deposition from Neoproterozoic to mid-Cretaceous, originating most likely in pan-African events
3) Despite 1 & 2 above, there is strong evidence that prior to obduction the Permian to mid- Cretaceous passive margin section of the autochthon behaved as a single block with significant (km scale) tilting down to the west and multiple uplift events along the Huqf axis in the east.
4) Sedimentological evidence for positions of carbonate platform margins suggests that these broadly stacked over time at a position within what are now the allochthonous thrust sheets. They probably stacked along normal faults from which these thrust sheets are now detached (apart from some footwall cut-offs in the Qumayrah and Sumeini windows (Cooper et al., 2014)).
5) The pre-obduction margin was offset in plan view probably along NE-SW lineaments associated with terrane boundaries, leading to the promontories and embayments indicated in reconstructions of the Permo Triassic and the Jurassic, and Cretaceous shelf edge. The latter is based on the position of the Sumeini slope deposits (Cooper,

1988; Searle et al., 1990; Watts, 1990). Speculatively, these offsets might well have been related to transforms in the oceanic crust.

6) The evidence for syn-depositional faulting during the Permian and middle Jurassic rifting events is scarce and largely found near the Semail line or in the NE Saih Hatat area.

3 The pre-obduction mid – Late Cretaceous carbonate platform and margin – initial stage of subduction

3.1 Introduction

The objective of this chapter is to present a detailed overview of the palaeogeographic and subsidence/uplift history of the epeiric platform immediately prior to ophiolite obduction and to examine if there were changes at the onset of subduction.

An issue of particular concern is determining the position of the platform margin through time. This is of importance for two main reasons. The first reason is that movement of the margin may track subsidence caused by thrust loading. The second reason is that it is necessary to disentangle and interpret the genesis of debrites encountered near the margin. Do the debrites and a variety of slumps and slides represent the slope facies at the platform margin, or are they sourced from the syn-obduction sequence? And how to distinguish both these two sedimentary mélanges from tectonic mélanges created by the thrusting and imbrication of semi-coherent thrust units over incompetent slope deposits of the autochthon? Only by understanding the genetics of these packages can the Muti Fm. sensu stricto (i.e. the syn-orogenic deposits) be defined and hence the sedimentation during plate obduction be better understood.

Addressing these problems has involved a large amount of detailed field geological mapping and sedimentary logging, which are summarised in the Appendix 1. Of particular importance in this work were stratigraphic age determinations, facies analysis and the provenance of clasts in mass flow deposits and mélanges. This work has resulted in a substantial number of changes to published geological maps, which are also summarised in Appendix 1. Only the observational details relevant for the broader arguments are presented here in the main text.

A location map of the field exposures, the wadi names and key well locations is shown in Figure 3-10 and 11.

3.2 The Platform

At the onset of subduction (see 1.4.1) the passive margin was the site of an extensive mixed carbonate and siliciclastic epeiric platform system (Bromhead et al., 2022; van Buchem et al., 2011). The sediments of this system belong to the Wasia Group and are Albian to Early Turonian in age (Figure 3-1). The Wasia Group consists of two main units:

- A laterally extensive transgressive unit of shallow-marine, calcareous shales at the base; the Nahr Umr Fm. These grade into lime mudstones towards the north and become sandier to the south, especially where they onlap pre-Cretaceous clastics.
- A carbonate-dominated sequence, the Natih Fm., with mainly mud-supported and some grain-supported limestones with local rudist development, alternating with calcareous shales. It contains two organic-rich chalk levels with source rock potential deposited in intra-platform basins (Hughes Clarke, 1988; van Buchem et al. 1996, 2002). In the UAE the equivalent unit is the Salabikh Fm. which consist of carbonate

margins prograding into an intra-platform basin with pelagic carbonate deposition (Burchette, 1993).

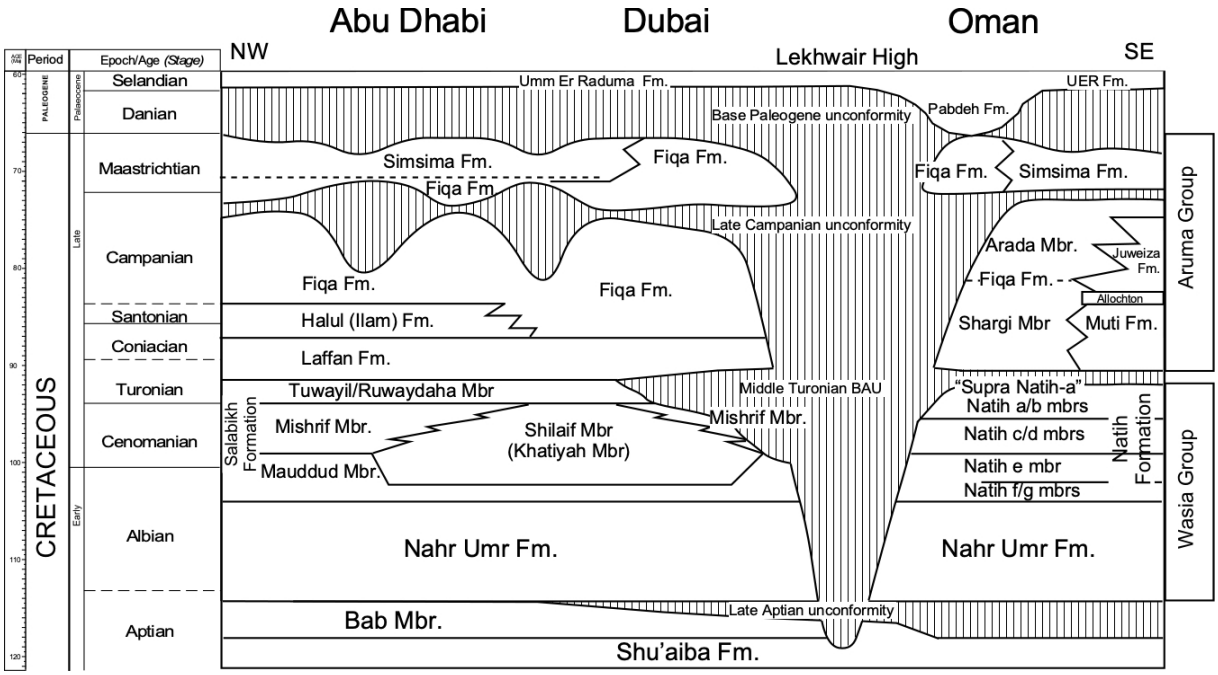


Figure 3-1 Simplified chronostratigraphic and lithostratigraphic framework for the mid and Late Cretaceous in Oman and the UAE. Modified after Burchette and Britton (1985). Not to scale.

Tectonic deformation during the middle Turonian, late Campanian and early Paleocene caused major erosion and incision of the Wasia Gp. over re-activated basement structures and salt diapirs.

3.2.1 The Nahr Umr Formation – latest Aptian to late Albian

The Nahr Umr Fm. is a widespread siliciclastic unit that covers most of the Arabian epeiric platform during the latest Aptian to late Albian (Davies et al., 2002; Murris, 1980). The Nahr Umr consists of fossiliferous marls with orbitolinids, fine terrigenous clastics, silty marls, rare sandstone lenses and palaeosols (Dubreuilh et al., 1992; Platel et al., 1992). It overlies a major late Aptian unconformity at c. 118 Ma, associated with subaerial exposure and incision of the underlying Shu'aiba carbonate platform (van Buchem et al., 2010; van Buchem et al., 2011). Outcrop and subsurface studies in Oman also suggest that the Nahr Umr Fm. has a

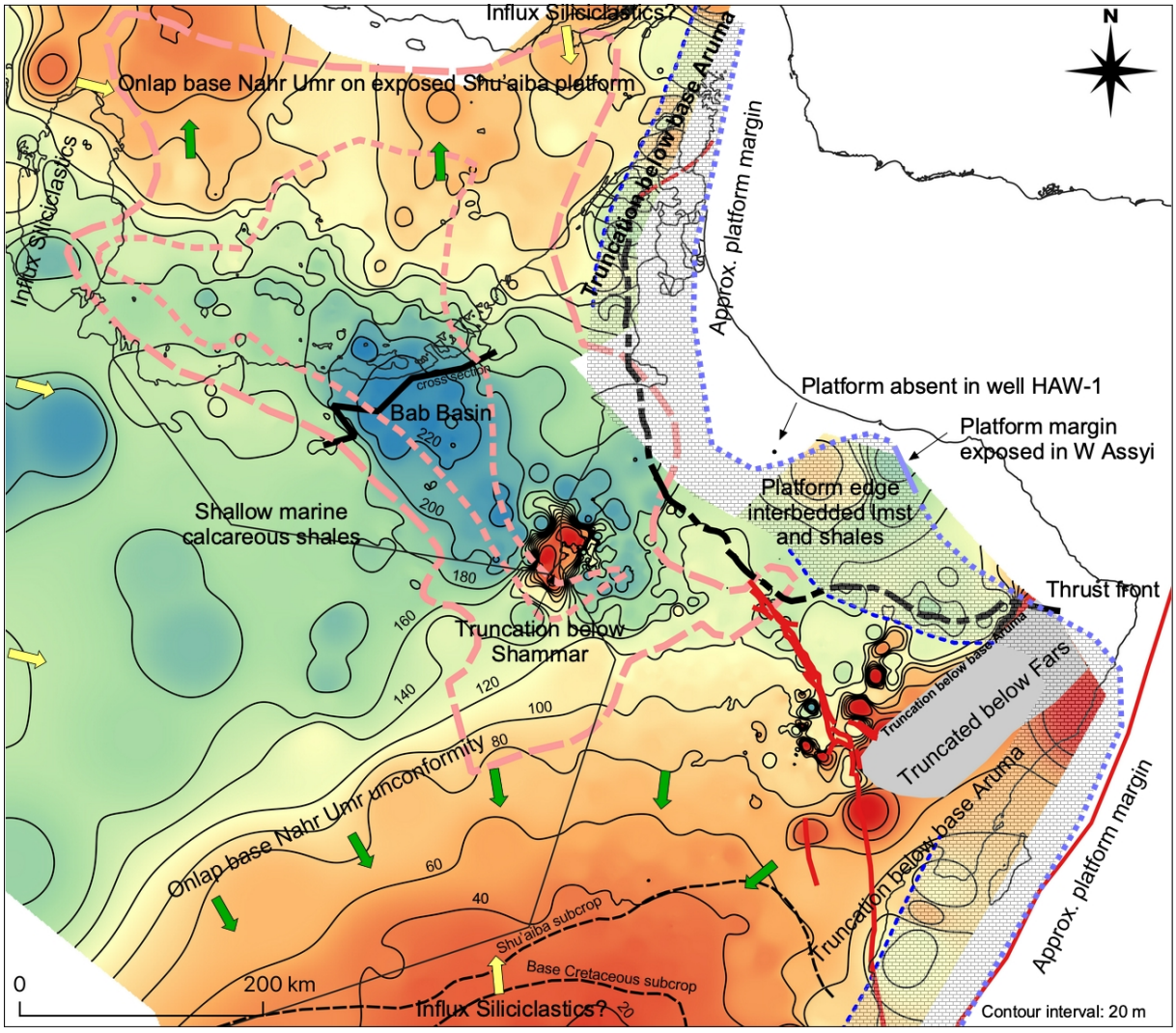


Figure 3-2 Isochore and facies patterns of the Nahr Umr Formation in eastern Arabia. Based on own work: systematic re-interpretation and re-correlation of some 1100 wells from the following consulted publications: Droste (2010b), Vahrenkamp et al. (2015b) , Alsharhan (1991), Piryaei et al. (2011), Mansouri-Daneshvar et al. (2015), Hohman et al. (2005) and Murris (1973; 1980). Pink dashed lines indicate the overall outline (thick) and central part (thin) of the underlying Aptian Bab intra-platform basin. The thin blue dashed lines mark the onset of increasing limestone beds within the shales. Cross section is shown in Figure 3-3. The thickness trends are based on inverse distance gridding of wells. Note that the well distribution is very uneven, and values have a high uncertainty. There is no indication that the "Saih Hatat promontory" still exists in the Albian. This suggests a major (c. 100 km) back-step of the margin from the Triassic/Lower Jurassic to the Albian in this area.

late Aptian to late Albian age (Forbes et al., 2010; Hughes Clarke, 1988; Immenhauser et al., 1999b; Scott, 1990; Witt and Gökdag, 1978). The top Nahr Umr Fm. is within the late Albian; the Albian-Cenomanian boundary is located within the lower Natih Fm. The base of the Nahr Umr is in the late Aptian within the Bab intra-shelf Basin (van Buchem et al., 2010) but

youngs to the southeast to the mid – late Albian due to onlap onto the Huqf axis (Witt and Gökdag, 1978). A late Aptian age for the base is inferred by Immenhauser et al. (1999b) in the Oman Mountains, however studies by BRGM geologists suggest mid and late Albian ages (Béchennec et al., 1992a; Le Métour et al., 1995b; Rabu, 1988). The younger age indicates an onlap from the intra-shelf basin towards the platform margin in the east, which makes sense regionally.

The isochore and facies trends for the Nahr Umr interval are shown in Figure 3-2.

The Nahr Umr clastics are thought to have been mainly sourced from the Arabian Shield in the west (Murris, 1980) through eastward prograding floodplain and delta deposits located west of Qatar (Alsharhan, 1994; Davies et al., 2002). East of Qatar deposition is dominated by marine, probably pro-delta shales (Davies et al., 2002). However, in South Oman Lower Palaeozoic and Lower Cretaceous clastics subcrop the base Nahr Umr unconformity (Forbes et al., 2010) and may also have sourced siliciclastic sediments to the north during the lowstand and initial stage of transgression. Piryaei et al. (2011) mention sandstones in outcrops of Kazdhumi Fm., the Nahr Umr equivalent in Iran, in the Bandar Abbas Area. This highlights the possibility of additional influx of siliciclastics into the remnant Bab basin from the north.

Towards the NE margin of the shelf the Nahr Umr shales are increasingly interbedded with limestones. Outcrops in North Oman show that limestone beds are spaced 10 to a few tens of metres apart. Discontinuity surfaces, developed on top of the limestone beds, show evidence of hardground development, often with indications of subaerial exposure. This are interpreted as due to periods of rapid sea-level drop (Immenhauser et al., 2000; Immenhauser and Matthews, 2004; Immenhauser et al., 1999a). Increasing limestone

intercalations can be seen in the Musandam area, the Jebel Akhdar outcrops and in wells just south of Jebel Akhdar and Saih Hatat, as well as along the on- and offshore area east of the Huqf axis. These proximity indicators have been used to draw a tentative outline of the Albian platform margin (blue dotted line in Figure 3-2).

Part of the margin is exposed in Wadi Assyi along the western flank of Jebel Nakhl and consists of a 200 m thick sequence of slope sediments, a stabilised rim with *Lithocodium* boundstones associated with blocks of coral-rudist patches, and lagoonal deposits of the Hassanat Fm. (Immenhauser et al., 2001; Masse et al., 1997). Using structurally corrected bedding and geopetal-fill measurements Immenhauser et al. (2001) demonstrated an ENE facing margin with a lower slope inclination of some 10°, and a steeper upper slope ranging between 32° and 40° (not corrected for compaction). This margin will be discussed in detail in section 3.3.1.

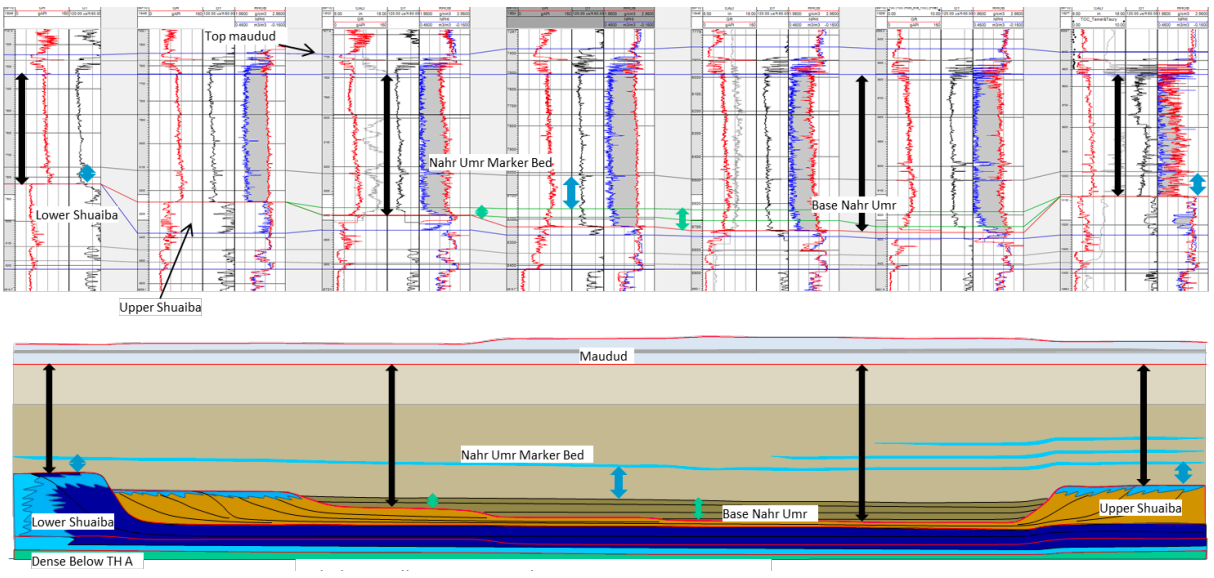


Figure 3-3 SW-NE well correlation through the intra-shelf Bab Basin in the UAE showing the depositional architecture of the Aptian Shu'aiba and Albian Nahr Umr Formations. Location of cross section is shown in Figure 3-2 and as XS-4 in Appendix 4. The Nahr Umr is a transgressive sequence that initially fills in the remnant topography of the intra-shelf basin and subsequently oversteps its margin covering the whole area with a thick sheet of fine-grained clastics. Figure modified from Vahrenkamp et al. (2015b).

The isochore patterns (Figure 3-2 and Figure 3-3) show regional thickness variations related to infill of the topography of the Bab intra-platform basin, as well as to onlap onto uplifted areas located to the north and southeast. Local variations are due to salt diapirism in the Oman Salt Basins and the Arabian Gulf area, and Late Cretaceous basement uplifts in the Lekhwair area and along the northern Huqf axis. The maximum thickness is some 230 m and occurs in the centre of the Bab Basin. The deepest part of the Bab basin (thin dashed pink line in Figure 3-2) in the UAE trends NW-SE but the overall outline of the basin (thick dashed pink line in Figure 3-2) does not show a clear trend and seems to follow the irregular residual margins of the Lower Shuaiba carbonate platforms surrounding and within the basin. Towards the centre of the Rub'al Khali in the southwest there is limited data control, but a few wells show the presence of shale-prone Aptian facies similar to the Bab Basin in the UAE. This could indicate that the main depocentre runs NW-SE and is bounded by more elevated areas in the north and southeast. The NW-SE structural trend in the deep Bab Basin could be a more local feature, Vahrenkamp et al. (2015b) suggests it may be related to differential subsidence along a Neoproterozoic Najd fault system, which regionally shows a similar orientation.

To the southwest of the Bab basin, the Nahr Umr thins to some 30 m and further south to only a few metres. This is because of onlap onto a gentle bulge overlying the South Oman Salt Basin. Along this bulge the Shu'aiba, the rest of the Kahmah Gp. as well as the base Cretaceous unconformity and even the Jurassic, Triassic and Palaeozoic deposits have been progressively truncated. The subcrop patterns suggest a regional uplift and some gentle inversion of the SOSB below the base Nahr Umr unconformity. In the northern Arabian Gulf

between offshore Qatar and coastal Fars the Nahr Umr onlaps towards the north onto a truncated and subaerially exposed Lower Shu'aiba carbonate platform (Murris, 1980; Raven et al., 2010). The southern margin of the intra-shelf basin, located along the UAE/Saudi Arabia border, shows a WSW-ESE trend. At the base the Nahr Umr Fm. is in a condensed, sandy, glauconitic, iron-rich, siliciclastic facies which persisted for most of the early Albian (Raven et al., 2010).

Based on channel incisions on the platforms and the stratigraphic architecture of the infill of the Bab basin, van Buchem et al. (2010) concluded that the exposure of the Shu'aiba platforms was associated with a gradual sea-level fall of at least 40 m, which lasted some 4-5 Myr. This was followed by a rapid rise during the latest Aptian at ca. 114 Ma. The slow fall and rapid rise, the magnitude, and the widespread occurrence of this sea level change strongly suggests that it was related to a glacial eustatic sea level change (van Buchem et al., 2010). Similar incisions observed in the late Aptian across the Tethyan region and other continents are now attributed by most authors to glacio-eustatically driven sea-level fall of approximately 60–70 m (see Ben Chabaane et al. (2025) and references therein). However the inversion of the SOSB and some gentle (less than 10 m) stratigraphic truncation that can be seen over some structures shows that at least locally there is also a tectonic component. Al-Fares et al. (1998) show a change in plate motion on the polar wander path for Kuwait (and Arabia) at c. 110 Ma, related to the opening of the equatorial Atlantic. They suggested that uplift through far-field stresses may have caused erosion and sudden influx of clastics in Arabia. Alternatively, and more locally, a late stage of the convergence between the Indian and the East African-Arabian plate margins during the Hauterivian-Barremian suggested by Gaina et al. (2015) could have re-activated some basement lineaments in southern Oman.

The Nahr Umr Fm. is conformably overlain by carbonates of the Natih Fm. Locally the Nahr Umr has been truncated by Late Cretaceous or younger unconformities. In the Musandam area, the northern Huqf axis and the eastern offshore Masirah Bay the Nahr Umr are affected by erosion below the Turonian BAU. On the Lekhwair High the Nahr Umr has been truncated below the base Umm er Radhuma Fm. unconformity (Eocene) which follows a late Campanian – Maastrichtian erosional event.

3.2.2 The Natih Formation – late Albian to Turonian carbonate platform

The shale-dominated sequence of the Nahr Umr Fm. is overlain by late Albian to Turonian epeiric platform carbonates of the Natih Fm. in Oman and the Mauddud, Shilaif, Mishrif, Tuwayil and Ruwaydha Members of the Salabikh Fm. in the UAE (Figure 3-1). In Oman, the epeiric platform shows a strong depositional cyclicity of shallow and deep marine deposits and repeated influx of fine siliciclastics from the Arabian Shield and the southern Huqf axis. The cyclicity has been used to subdivide the Natih Fm. into 7 members labelled from top to bottom as “a” to “g” (Figure 3-4); Forbes et al. (2010); Hughes Clarke (1988). In Oman, the system consists of two major transgressive-regressive cycles internally composed of higher order sequences (Razin et al., 2017; van Buchem et al., 2002; van Buchem et al., 1996). These are related to major relative sea level rises during the latest Albian (c. 102 Ma) and the middle to late Cenomanian (c. 95 Ma).

In the UAE the sequence consists of deep-water chalks of the intra-platform Shilaif Basin and surrounding platform margin carbonates (Figure 3-4). The main depositional cyclicity is expressed by variation in the organic and argillaceous content of deeper water pelagic chalks and prograding platform margin wedges. The stratigraphic correlation of the basal part between Oman and UAE is straightforward from log response but for the upper

part is still uncertain. This is because of the difference in depositional facies, poor biostratigraphic control and erosional truncation due to Late Cretaceous uplift over the Lekhwair High that separates the two areas. Published correlations are based on $\partial^{13}C$ isotope trends, calibrated with limited biostratigraphic data (Hennhoefer et al., 2019; Vahrenkamp et al., 2015a; Vahrenkamp, 2013; Wohlwend et al., 2016). These work well in deep water

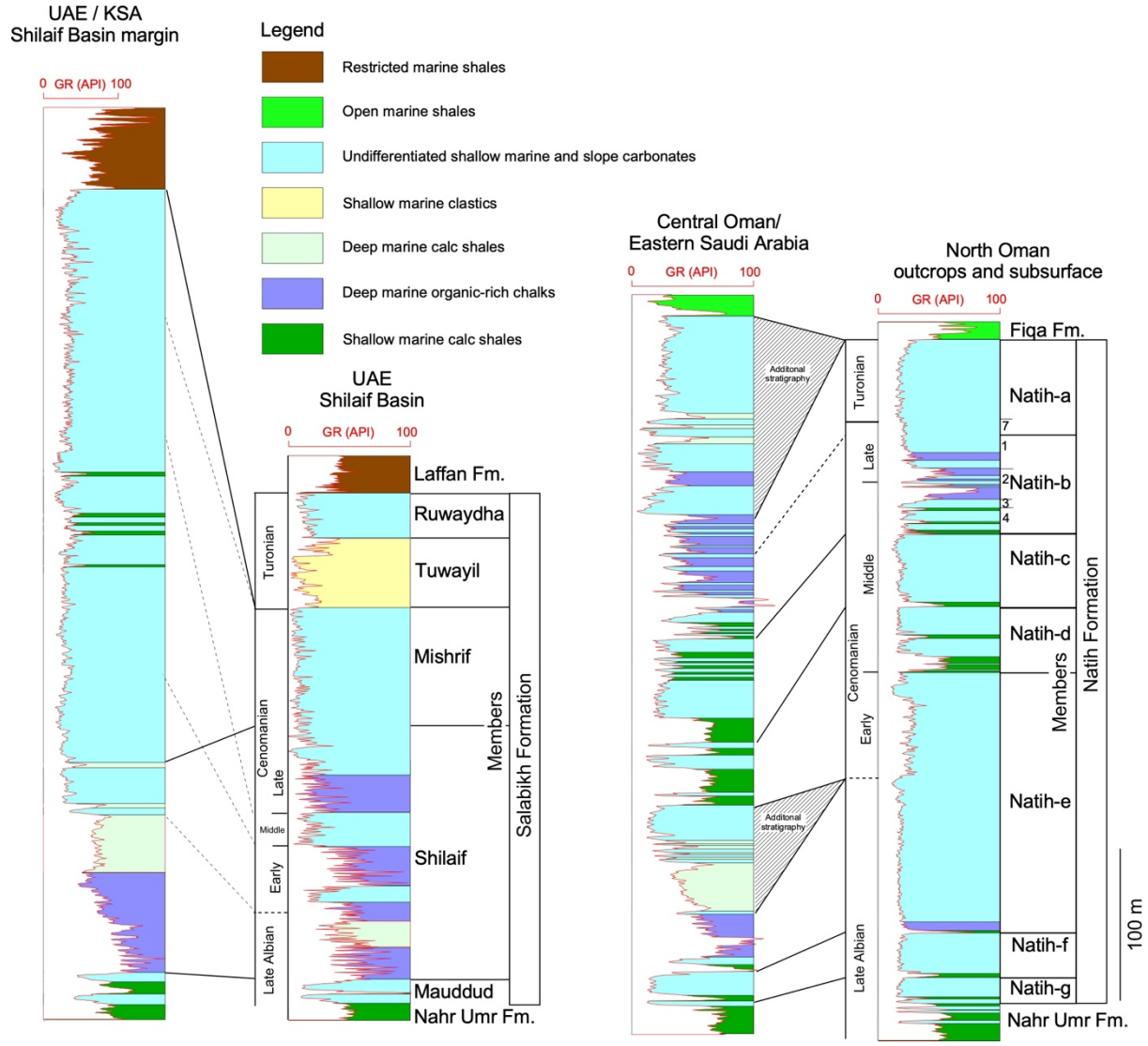


Figure 3-4 Representative well sections of the correlation panels in Figure 3-6 and 3-7 showing the gamma ray log response, lithology and stratigraphy of the Albian to Turonian interval in Oman and the UAE. Stratigraphic ages are approximate and interpreted from Newell and Hennington (1983), Vahrenkamp et al. (2015a), Hennhoefer et al. (2019) and Bromhead et al. (2022) and papers cited therein. Dashed lines between Shilaif basin wells are tentative timelines from basin into the margin. Hatched areas between the Oman wells indicate additional stratigraphy not captured in Natih correlation studies using North Oman outcrop and well data. A major cause of the thickness differences between these wells is differential compaction between intra-shelf carbonate and basinal shale and pelagic limestones.

settings such as the Shilaif Basin, where there is a good chance for preservation of a complete section. However, subsurface well data used in these studies from central Oman

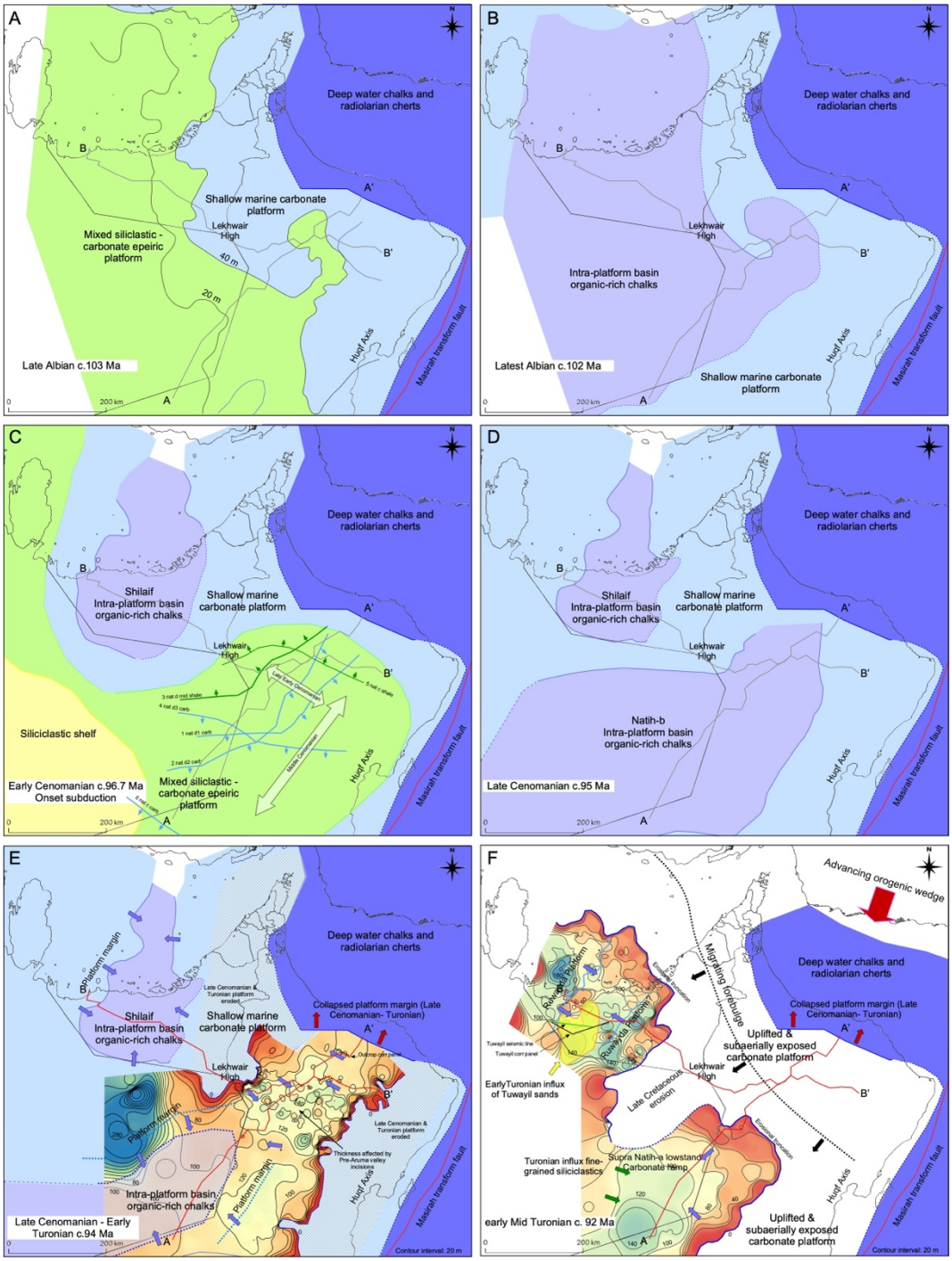
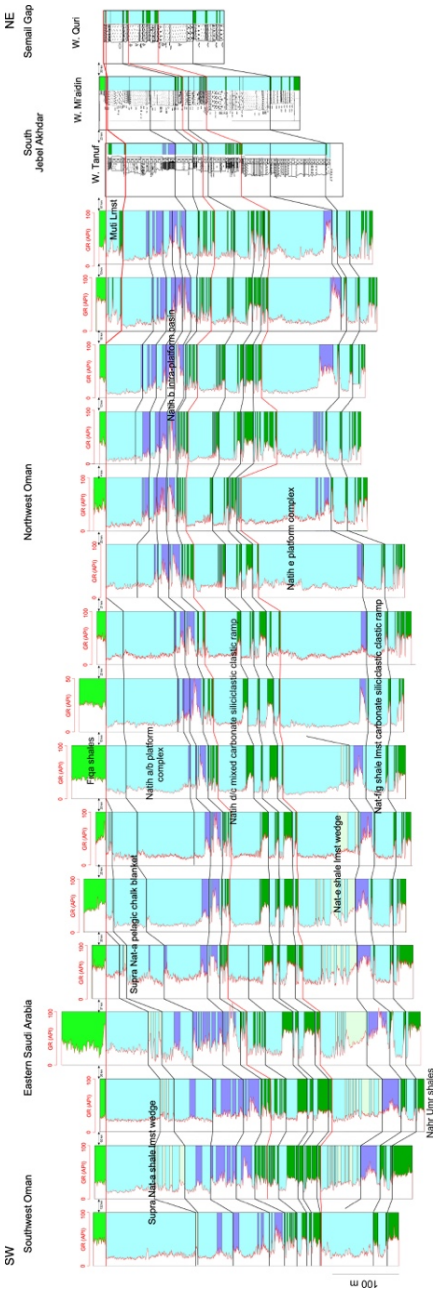


Figure 3-5 Palaeogeographic and isochore maps showing the Albian early-mid Turonian platform evolution along the eastern margin of the Arabian Plate. The isochore of the late Cenomanian and early Turonian depositional wedges are based on well data and their patterns are strongly affected by Late Cretaceous erosion. Updated and reinterpreted from various sources (Droste and Van Steenwinkel, 2004; Franco et al., 2021; Franco et al., 2018; Murris, 1973; Murris, 1980; Newell and Hennington, 1983; Vahrenkamp et al., 2015a; Vahrenkamp et al., 2015b). Note the significant shift of the platform isochore of the Turonian (E to F). (See cross section in Fig 3.6 for illustration of the depocentre shift and ensuing south westward progradation. The white area in F includes an area of uplift and erosion that has the form of a "forebulge". Note that the Natih Fm. mapped here includes only the "back-bulge" sediments. Thin, partially time-equivalent (early-mid Turonian) Muti Fm. sediments are found northeast of the "forebulge". The two long cross sections A-A' and B-B' are shown in Figure 3-6 and 7.

show that the Natih type sections in the Oman foothills and in subsurface wells in North

Oman are themselves incomplete (Figure 3-4). They do not include some prograding wedges in the lower Cenomanian and a nearly 200 m thick, extra, Turonian-aged section at the top



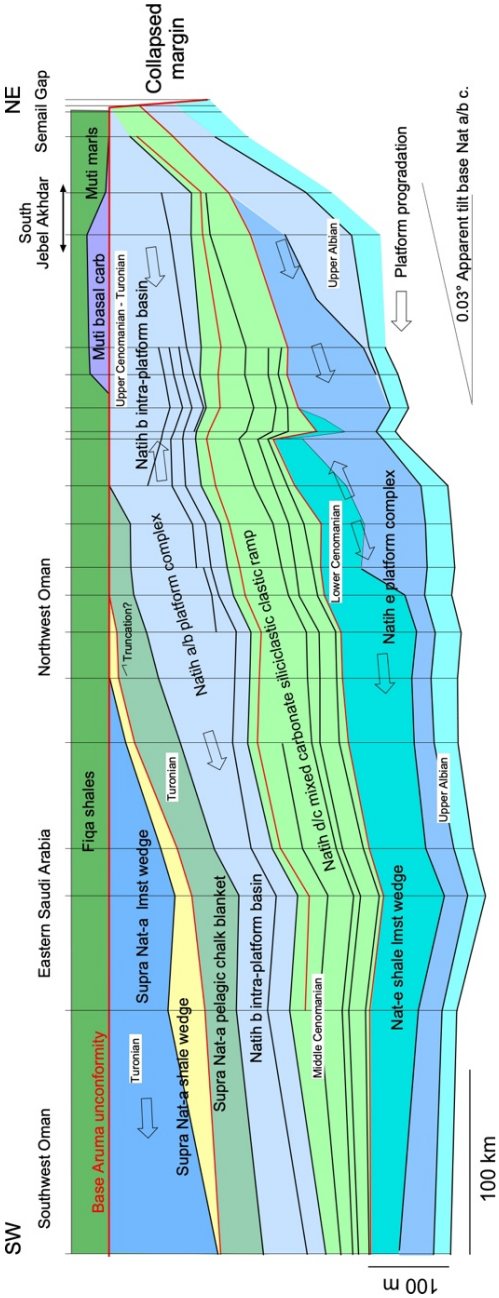


Figure 3-6 Well and outcrop correlation of the Natih Fm in Oman and eastern most Saudi Arabia. For location of cross section see A-A' in Figure 3-5. The epeiric platform margin is to the right and the intra-shelf basin to the left. Upper section is flattened on base Muti marl/Fiqa shale, showing lithology and gamma log response. The lithology legend is shown in Figure 3-4 and as XS-5 in Appendix 4. Lower section is a scaled version flattened on the BAU, showing the platform geometry and ages. The lateral thickness variations in the Natih-e are mostly related to differential compaction of platform vs. basinal deposits. Double arrow below South Jebel Akhdar shows location of section in Figure 3-7. Well data reinterpreted from previous work: Droste and Van Steenwinkel (2004) , Homewood et al. (2008), outcrop sections from Philip et al. (1995) and van Buchem et al. (1996).

Natih seen in the subsurface of Central Oman.

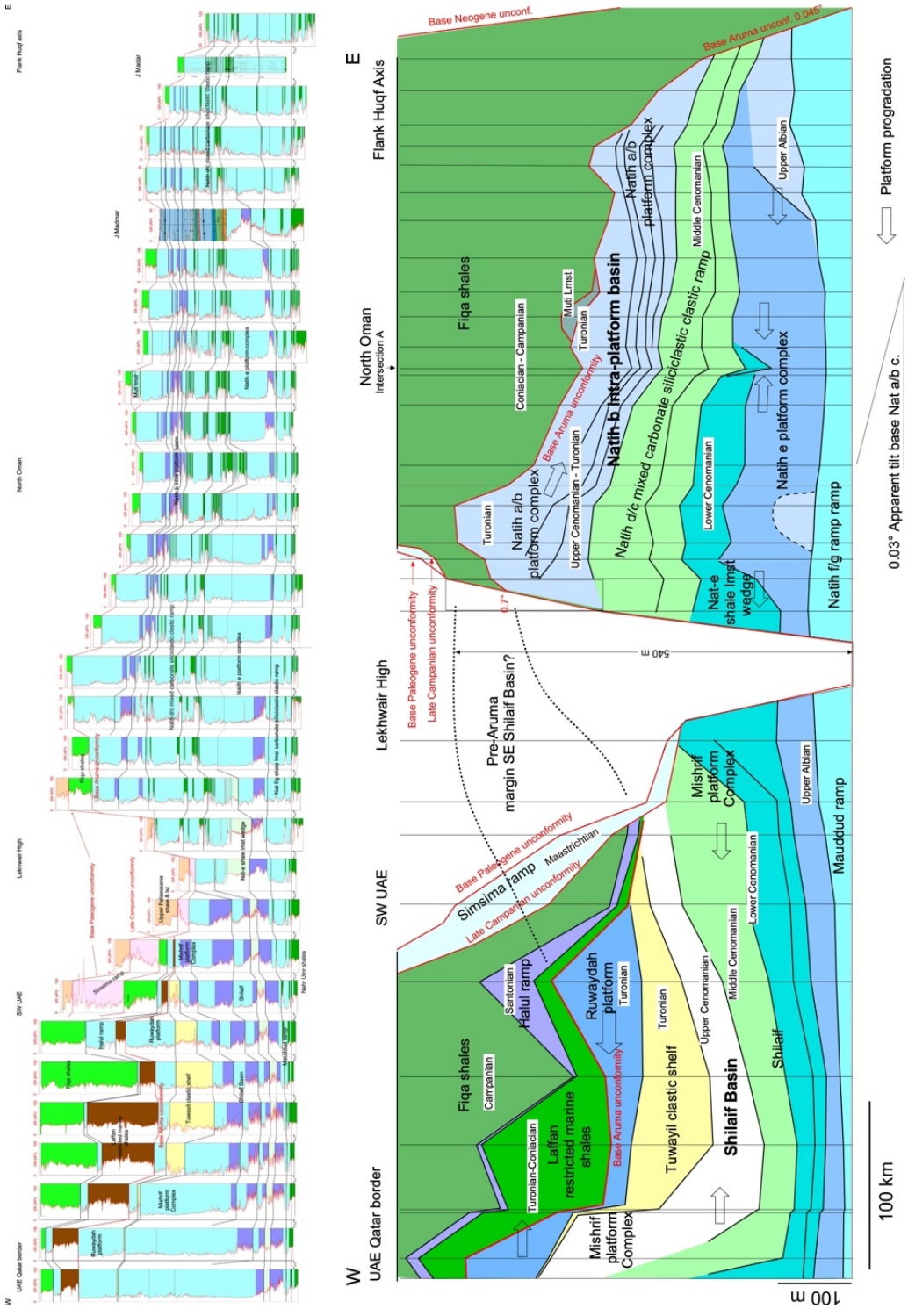


Figure 3-7 Well and outcrop correlation of the Natih Fm in Oman and the UAE flattened on top of Nahr Umr Fm. Location cross section see B-B' in Figure 3-5 and XS-6 in Appendix 4. Upper section: lithology and gamma log response; lithology legend is shown in Figure 3-4. Lower section is a scaled version showing the platform and intra-shelf geometry and ages. Based on well data compiled from various publications (Droste and Van Steenwinkel, 2004; Franco et al., 2021; Franco et al., 2018; Vahrenkamp et al., 2015a) outcrop sections from van Buchem et al. (1996).

The intra-platform basins were formed by differential growth of carbonates during sea level rises (Droste, 2010a; Razin et al., 2010). Seismic geometries and well correlations in Oman suggest these basins were some 60 to 100 m deep (Droste, 2010a; van Buchem et al., 2005) but well correlations in the UAE from Vahrenkamp et al. (2015a) show that the depths there could have exceeded 150 m. The initial fill consists of pelagic, organic-rich chalks indicating periods of high organic productivity (Al Balushi and Macquaker, 2011). Further infill of these basins was by shallow-water derived sediments from prograding carbonate platform margin complexes in both Oman (Droste, 2010a; Droste and Van Steenwinkel, 2004) and the UAE (Al-Zaabi et al., 2010; Burchette, 1993; Burchette and Britton, 1985; Pascoe et al., 1994).

The general palaeogeographic evolution is shown in Figure 3-5 and the stratigraphic architecture is illustrated in regional well and outcrop correlation panels in Figure 3-6 and 3-7.

The transgression during the late Albian (c. 102 Ma) caused a regional drowning of the Nahr Umr clastic shelf and the formation of a huge intra-platform basin of some 400 km (E-W) by 800 km (N-S). The initial flooding is associated with the deposition of shallow marine transgressive Mauddud limestones (Sadooni and Alsharhan, 2003) and the Natih-g, -f and basal e Members in Oman (Figure 3-5 A and Figure 3-6). The interval is relatively thin, some 5 to 10 m within the centre of the basin, but thickens into a shallow water carbonate platform of some 50 – 60 m thick towards the shelf margin in the north and east, and some 50 m over the Qatar High in the west and in southern Iran (Frei, 1984; Vahrenkamp et al., 2015a; van Buchem et al., 2014). In the basin the transgression culminates with the deposition of pelagic, organic-rich chalks (Figure 3-5 B). The flooding event could be related to worldwide sea level rise in the latest Albian and the Oceanic Anoxic Event OAE 1d

(Breistroffer Event, see Gradstein et al. (2020)), a global interval of enhanced organic carbon burial (Jenkyns, 1980).

Following an initial aggrading phase the intra-shelf basin was largely filled by progradation of the rimming carbonate platforms during the early to middle Cenomanian (Droste, 2010a). In Oman the basin was filled, and the interior platform was covered, by a mix of shallow water carbonate and fine siliciclastics (Figure 3-5 C and Figure 3-7). This overall palaeogeography persisted until the middle Cenomanian, after which platform growth was predominantly in an aggradational mode. A major change in the strike of limestone and shale pinch-outs can be seen on the mixed clastic carbonate platform during the middle Cenomanian: changing from NW-SE to NE-SW. This shift suggests an expansion of the carbonate belt towards the south. This may be related to a decrease in accommodation space along the northern margin and/or a reduction in siliciclastic input from the south.

In the UAE offshore, a remnant of the late Albian intra-shelf basin, now only some 150 – 200 km wide, was preserved and is known as the Shilaif Basin (Al-Zaabi et al. (2010); Figure 3-5 C and Figure 3-7). The basin fill consists of deeper-water, dark, organic-rich limestones and light-coloured fine bioclastic limestones of the Shilaif Mbr., bioturbated packstone slope deposits and coarse-grained rudistid shoal deposits of the Mishrif Formation (Burchette, 1993; Burchette and Britton, 1985). Along the western margin seismic shows a belt about 40 km wide with prograding wedges composed of slope deposits, dipping some 3° to the east (Caeiro et al., 2018; Goudket et al., 1992; Wharton, 2015). The thickness of these prograding platform wedges is about 200 m (Burchette, 1993; Goudket et al., 1992). The total thickness of the carbonate platform reaches 550 m in its interior part. The water depths in

the basin were generally less than 100 m but could have been up to 200 m (Burchette et al., 2010).

The platform along the margin of the Shilaif Basin in the eastern UAE is less well defined and generally less than 300 m thick, much thinner than in the west. Here, seismic also shows prograding wedges (Al-Zaabi et al., 2010; Goudket et al., 1992; Neo, 1996; Pascoe et al., 1994), 120 – 150 m thick. Westward tilting of the eastern platform during the middle to late Cenomanian is indicated by progressively more westward prograding, offlapping geometries towards the basin. Pascoe et al. (1994) suggests that long periods of exposure and non-deposition related to this tilting are the main cause for the reduced thickness over the eastern platform, rather than erosion in a single major uplift, as suggested by Patton and O'Connor (1988). However eastward thinning is also clearly related to erosional truncation further east (Neo, 1996), as indicated by erosional cut-out of Mishrif platform margin belt and progressive erosion into the Albian Mauddud Mbr. and Nahr Umr Fm.

3.2.3 The first sign of subduction initiation – middle Cenomanian

At the end of the middle Cenomanian a major change in the platform configuration occurred with the development of a new intra-platform basin, the Nath-b Basin, in Oman (Figure 3-5 D). Pelagic organic-rich chalks were deposited over most of interior Oman while aggradational platform growth occurred along the Lekhwair and Huqf Highs (Figure 3-7). The Natih-b basin axis ran NE-SW and had a width of about 150 km in the north. Limited data-points in the south could indicate a possible widening to c. 350 km. Well and seismic data in the UAE (Vahrenkamp et al., 2015a) suggest that the organic-rich chalk deposition of the Natih-b may correlate with deposition of the uppermost organic-rich chalk in the Shilaif Basin. The preferential carbonate growth on the Lekhwair High is the first time that this high

appears to influence the sedimentation during the Cretaceous. Based on the interpreted age of the Natih-b this occurs around 95 Ma. The Natih b basin configuration changes coincide with the initiation of intra-oceanic subduction c. 96.7 Ma and the formation of the Semail ophiolite (c. 96.1 – 95.2 Ma) at least 235 km north of the continental margin (Cooper, 1988; Najafi et al., 2026; Searle et al., 2022). The changes in regional stresses that caused the initiation of the subduction may therefore have caused some reactivation of basement structures underlying both the Lekhwair area and the Huqf axis.

The infill of the Natih-b basin started in the late Cenomanian and continued into the Turonian by platform progradation from the north, east, and west, which had the effect of limiting pelagic carbonate deposition to the SW just across the border in Saudi Arabia (Figure 3-5 E). Part of the Turonian consists of lowstand deposits within the intra-platform basin, which were deposited while the surrounding platforms were exposed.

The infill of the Natih-b basin in northern Oman has been well documented along an outcrop transect on the southern flank of Jebel Akhdar by Philip et al. (1995), van Buchem et al. (2002), Homewood et al. (2008), and Razin et al. (2021). The 60 km long transect is shown in Figure 3-8. The thickest section is of the Natih a-b interval: some 135 m in Wadi Kahmah. A detailed description of the different facies associations is provided in van Buchem et al. (1996). This section records the onset of uplift of the platform that resulted in the subaerial exposure of the platform along the Wasia/Aruma unconformity. The sequence starts with middle Cenomanian interbedded clays and limestones, which overlie the top Natih-c exposure surface. The limestone beds are often capped by hardgrounds and deposition took place in a low energy restricted lagoon. This well layered unit is laterally continuous and only 10 m thick. The same interval occurs in the subsurface of north Oman where it is known as

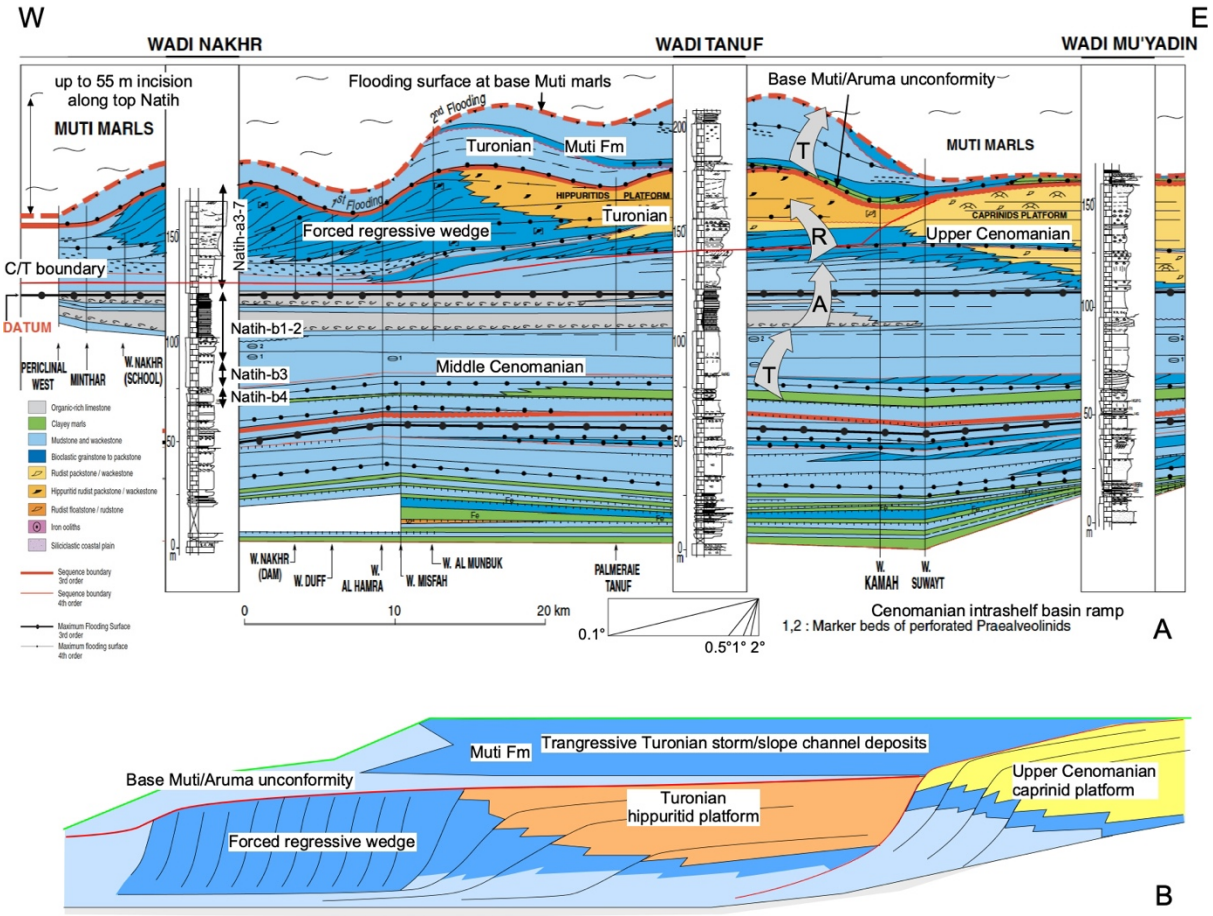


Figure 3-8 A: Regional transect of outcrops of the upper part of the Natih Formation along the southern flank of Jebel Akhdar modified from van Buchem et al. (2002). The section has been flattened along a sequence boundary on the top of the Natih-c. The distance between the western and easternmost logged sections is 60 km. Grey arrows indicate overall stacking trends of depositional cycles: T-transgressive, A-aggrading and R-regressive. B: New - schematic – correlation using the same outcrop data but calibrated with seismic data and flattening on an intra Muti datum. This implies more differential subsidence and steeper dips. Note the difference in the BAU between A and B. Location of section shown in Figure 3-5 E and as XS-7 in Appendix-4.

the Natih-b4 sub-member (see Figure 3-4). This interval is overlain by several metres of more open marine fine-grained carbonates which lack shales and are part of a deepening upward trend during which the platform / basin differentiation occurred. This interval is known as the Natih-b3 sub-member in the subsurface (see Figure 3-4). Deepening continued into fine-grained outer ramp carbonates culminating in an organic-rich intra-shelf basin facies. In the eastern part of the transect the organic-rich facies pinches out into outer ramp carbonates. The depositional slopes from the correlation are less than 0.1° and indicate aggradational

stacking (Razin et al., 2021). This 40 m thick interval corresponds to the Natih-b1 and b2 sub-members in the subsurface (see Figure 3-4).

The upper part of the margin consists of Upper Cenomanian caprinid rudist banks and bioclastic shoals which prograde and downlap above the organic-rich mudstone interval. Well data further south indicate the margin is trending in a N-S direction.

The second phase of infill is early Turonian in age and consists of a wedge formed by a hippuritid rudist platform bordered by a 20 km long belt of high angle (20° dips; van Buchem et al. (2002)) oblique clinoforms, containing coarse-grained tabular cross-bedded rudstones with rudist and gastropod fragments, and oolitic grainstones. This prograding wedge pinches out towards the west into basinal mudstone facies. Quiquerez and Dromart (2006) interpreted this wedge to have formed in a distally steepened ramp with water depths of 20-80 m. The wedge sharply overlies deep water pelagic mudstones suggesting a strong basinward shift in facies. The hippuritid platform is capped by a major exposure surface, the top of the prograding wedge is a burrowed surface and overlain by muddy inner platform carbonates. The progradational unit corresponds to the Natih a3 to a7 sub-members in the subsurface.

The sequence stratigraphic interpretation of the upper part of the outcrop transect section in the east shown in Figure 3-8 by van Buchem et al. (2002) is tentative and the position and stratigraphic relationship of the contact between the Cenomanian and Turonian platform is interpreted differently in papers by the same authors. This may be related to "over-correlation" between sections that are far apart which tends to flatten the stratigraphy. This is indicated by the very low angles of less than 0.1° for the slope deposits in the upper part of the transect shown in Figure 3-8. Clinoforms in the Natih Fm. observed on seismic,

calibrated with well data, indicate that the slopes of progradational depositional wedges range from less than 0.5° for marly slopes to 5° for coarser grained slopes (Droste, 2010a; Droste and Van Steenwinkel, 2004) and in the Shilaif Basin slopes dipping at 3° have been reported (Caeiro et al., 2018; Goudket et al., 1992; Wharton, 2015). These dips are small but have a significant impact on the correlation, as the distance between the sections is relatively large. For example, a platform prograding with a slope of only 1° into a 50 m deep basin would downlap over 2.9 km while with a 2° dip this would be 1.4 km. These distances are much less than the distances between most of the sections in the transect. With the vertical to horizontal scale ratio of Figure 3-8 A, a dip of more than 2° appears close to vertical!

A second reason for correlation issues is the choice to flatten the section on the top of the underlying mixed carbonate/siliciclastic platform, an Upper Cenomanian datum from before the tectonic re-activation and differential subsidence. The Cenomanian and Turonian platforms are then presented as adjacent to each other. However, flattening of the section along the flooding surface at the base of the Muti marls (Figure 3-8 B) would place the Turonian platform in a downdip position with respect to the Cenomanian platform. This datum would also suggest onlap of the basal Muti onto the BAU indicating laterally varying accommodation space between the margin and basin centre and suggesting that the Turonian platform is a lowstand wedge following a relative drop in sea level. This interpretation implies minimal erosion at the BAU, but the preservation of additional Muti stratigraphy above the Turonian platform does fit with evidence of higher subsidence in this part of the basin (discussed further in Chapter 4 South Jebel Akhdar transect).

3.2.4 Platform top and initial drowning

The uppermost unit of the section in Figure 3-8 overlies a major planed-off erosion surface. It consists of a transgressive sequence of coarse-grained carbonate sands with re-deposited shallow water bioclasts, which onlaps the underlying sequence. This was originally interpreted as the uppermost sequence of the Natih Formation of inferred Turonian age, which is tectonically influenced. As will be discussed section 5.2.3, this interval is better assigned to the Muti Fm.

The outcrops along the Southern Jebel Akhdar transect (see Appendix 1) show that both the Turonian and Cenomanian platforms were covered and onlapped by a transgressive sheet of shallow, open-marine storm deposits (Figure 3-8 B). This was followed by a rapid drowning, with a condensed horizon and iron oolite deposits, covered by pelagic marls of the basal Muti Fm. The suggested relative sea level drop of some 25 m in Figure 3-8 B is tentative and could be higher. However, it is within the range of the very low magnitude (c. 30 m) short term (< 3Myr) sea level changes during the Turonian mentioned in a review of Cretaceous sea level changes by Ray et al. (2019). Well data in North Oman show that this lower Turonian wedge is overlain by a regional blanket of up to c. 60 m thick of pelagic chalks ("Supra Natih-a chalk blanket" in Figure 3-6), indicating a major deepening event in the basin during the lower part of the Turonian. This blanket is erosionally (?) truncated towards the north below the BAU (Figure 3-6) and is a younger offlapping wedge than the lowstand wedge in the outcrops shown in Figure 3-8 B.

In West Central Oman the Supra Natih-a chalk layer is overlain by a yet younger shale-limestone cycle, which has not been encountered in outcrops or wells in North Oman (southwest part of section in Figure 3-6; Droste and Van Steenwinkel (2004)). The shale at

the base of this cycle is the first shale influx since the middle Cenomanian ("Supra-Natih-a shale limestone wedge" in Figure 3-6). The well correlation shown in Figure 3-6 A suggests an erosional base in the north. The interval is clearly recognisable from well logs, but very little information is available on the facies and depositional setting. The base is characterised by an up to several 10's m thick interval of calcareous shales, in places with quartz sands, interbedded with marls (yellow in Figure 3-6 B). These grade upward into fossiliferous fine-grained limestones (sky blue in Figure 3-6 B). The maximum thickness of the unit is c. 130 m; it thins and pinches out towards the margins by truncation below the BAU (Figure 3-5 F and 3-6). The erosional base and the re-appearance of fine-grained siliciclastics suggest a second relative drop in sea level.

A similar interval with siliciclastic influx forms the final marine fill of the Shilaif Basin (Figure 3-9). This consists of the Tuwayil and Ruwaydha Members. which onlap and overstep the western basin margin (Al-Zaabi et al., 2010; Azzam, 1995; Azzam and Taher, 1993; Burchette, 1993; Loutfi et al., 1987; Vahrenkamp et al., 2015a). In the centre of the Shilaif Basin the Tuwayil consists of dark pyritic shales, interbedded with thin limestones with abundant planktonic foraminifera. Towards the western margin of the Shilaif basin there is an increase in siliciclastic content (Azzam, 1995). Here the Tuwayil Member is more than 100 m thick and starts with a lower unit of burrowed bioclastic limestones which becomes more argillaceous and marlier towards the basin centre. The upper unit can be more than 18 m thick and consists of shales interbedded with fine-grained sandstones and siltstones with plant debris. The clastics form a wedge-shaped unit thinning to the east. Tidal ripples and cross-bedding, possible hummocky cross-stratification, and bioturbation observed in cores indicate a shallow marine storm-dominated shoreface setting with possibly some tidal

influence. Remnants of shales and sandstones of less than 3 m thick occur on the platform to the west.

The Tuwayil clastics are overlain by limestones of the Ruwaydha Member. In the basin, the Ruwaydha Member has a similar facies to the Shilaif Member and consists of dark-coloured organic-rich very fine to fine-grained wackestones and packstones with pelagic foraminifera and calcispheres (Goudket et al., 1992). These were deposited in a deep water basinal environment. On the western platform the Ruwaydha Member consists of shallow water carbonates deposited in a backstepping platform margin with oolitic grainstone shoals and a low energy platform interior (Al-Zaabi et al., 2010; Azzam and Taher, 1993; Burchette, 1993) . The Ruwaydha Member pinches out toward the eastern part of the Shilaif Basin due to truncation below the base Aruma (BAU) and younger unconformities. In places remnants of a westward-facing platform slope have been recognised (Franco et al., 2021; Franco et al., 2018).

The age of the Ruwaydha Member is early Turonian, based on nannoplankton (Goudket et al., 1992). The ages quoted for the Tuwayil range between late Cenomanian and Turonian. The late Cenomanian ages are inferred from stratigraphic position and correlation with a global sea level fall in the late Cenomanian (Azzam, 1995; Burchette, 1993). Vahrenkamp et al. (2015a) interpreted a lower-middle Turonian age based on biostratigraphic and carbon isotope data. More recently, planktonic foraminifera reported from the southwestern part of the Shilaif basin suggest an age no older than intra-early Turonian (Hughes, 2019; Simmons et al., 2025).

The clear onlap of the Tuwayil Member. onto the platform margin, the presence of soils and rooting on the platform top, and influx of clastics into the intra-platform basin

suggest this is a lowstand deposit. The basal carbonate in the Tuwayil probably represents a

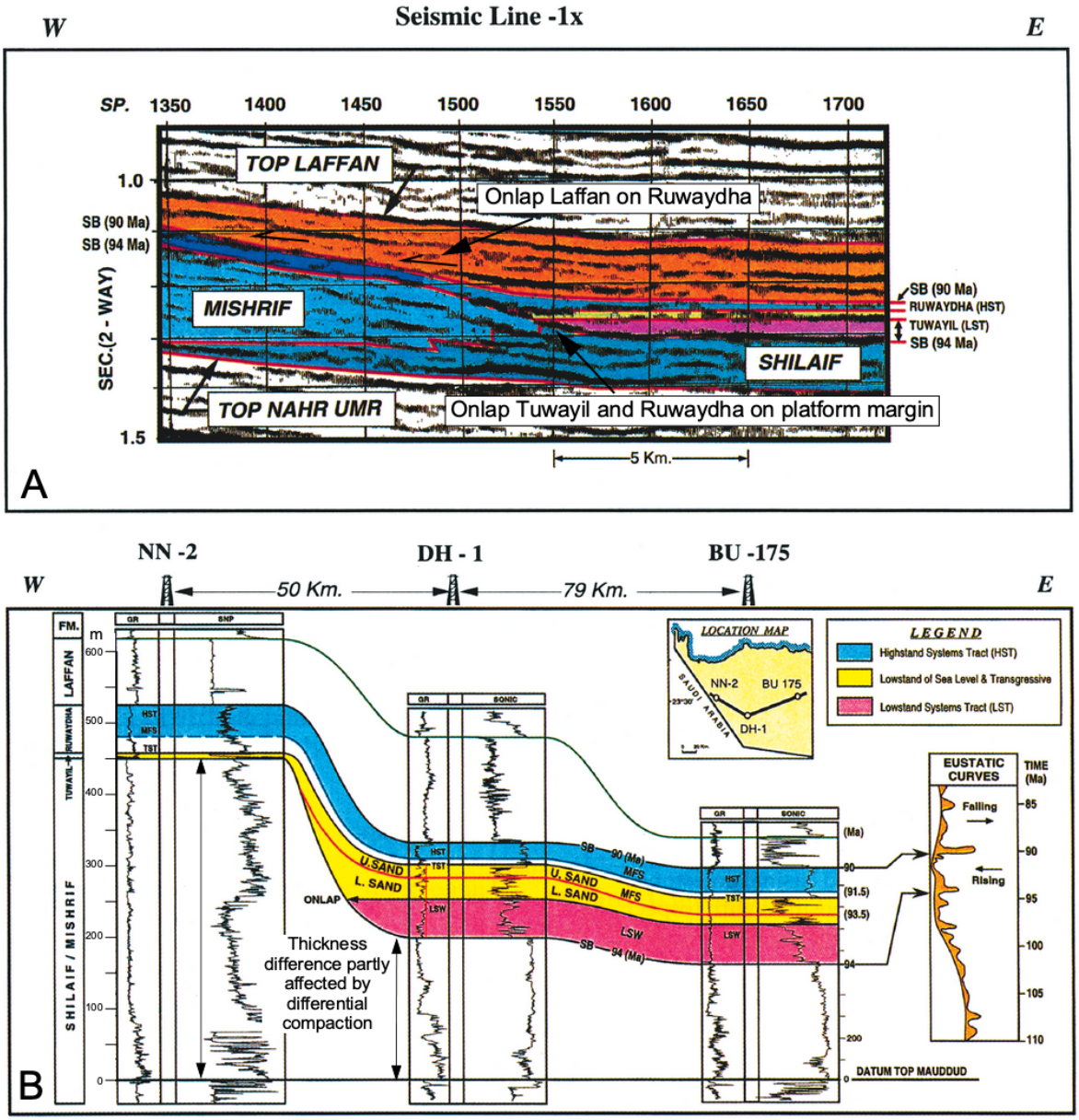


Figure 3-9 Seismic cross section (A) and well correlation (B) showing onlap of the Tuwayil and Ruwaydha Members onto the Cenomanian carbonate platform along the southwestern margin of the Shilaif Basin (for location see Figure 3-5 F and SL-12 and XS-8 in Appendix-4). Age and sea level curve shown in B are from Haq et al. (1987); the 90 Ma fall corresponds to the late Turonian, the 94 Ma to the late Cenomanian. The Tuwayil and Ruwaydha Members represent lowstand and transgressive systems tracts following a relative sea fall at SB-90. The seismic onlap of Laffan shales onto the Ruwaydha suggests an eastward tilting at the SB-90 event, though differential compaction along the platform to basin transition (with more subsidence in the basin) may also have contributed to this. Differential compaction clearly enhanced the apparent platform basin topography, both on the seismic section and the well correlation. The basinal chalks of the Shilaif Member and the fine clastics of the Tuwayil Member were much more affected by compaction than the coarser grained carbonates of the platform. The original topography was much less, as shown on the well correlation. The top of the Tuwayil was probably close to the level of the platform top, which is also suggested by the overlying Ruwaydha showing limited lateral thickness changes. Basin depth at start Tuwayil may have been some 150 m. Figures modified from Azzam (1995).

lowstand wedge with redeposited carbonates (Bromhead et al., 2022), likely of the same age as the Turonian lowstand in Central Oman. Redeposited coarse-grained pebbly carbonates have also been reported along the eastern margin of the Shilaif Basin associated with a clear seismic erosional surface (Shimomura and Yamanaka, 2021; 2022). These have been interpreted as base of slope deposits consisting of debris flows and turbidites and thought to be associated with the early-middle Turonian unconformity (Shimomura and Yamanaka, 2021). Possibly these sediments correspond to the Tuwayil lowstand carbonates in the west. Palaeogeographic maps (Murris, 1980; Ziegler, 2001) show siliciclastic belts rimming the Arabian shield located west and southwest of the Shilaif Basin and sands from these areas may have crossed the exposed carbonate platform via rivers during the lowstand. The Ruwaydha was deposited during the subsequent transgression.

Burchette et al. (2010) note that there appears to be no major erosional unconformity between the Ruwaydha and base Laffan Members in the western part of the Shilaif basin and correlate the base Tuwayil sea-level fall with the BAU on the platform. This would imply that the unconformity is early Turonian and that the Tuwayil and Ruwaydha Members should be included into the Aruma Group, as suggested in Craigie (2015); Hughes (2019). However, truncation in the eastern part of the basin clearly indicates that these formations pre-date the BAU and Bromhead et al. (2022) therefore incorporate this interval in an early to middle Turonian (Tu1) sequence preceding the mid-Turonian unconformity. The magnitude of the sea level drop could not be determined due to lack of data showing the offlap break of the clastic wedge. Thus, the basin fill records several drops in relative sea level during the Turonian, which exposed the shallow water platforms. The magnitude seems to have been in the order of several tens of metres, and it is not clear whether these relative falls are also related to tectonic events.

Well correlations show regional truncation below the BAU towards both the Huqf and Lekhwair axes (Figure 4-1) as well as to the NE (e.g. Figure 3-6). The last suggests an uplift parallel to the obduction direction with the just-described sequences in a back bulge setting and will be discussed in section 4.3.



Figure 3-10 Location of outcrops of the middle Cretaceous platform margin and slope. The sections are shown in Figure 3-12 and Figure 3-14.

3.3 The margin and slope

Outcrops of Albian to Turonian epeiric platform margin and slope deposits are relatively scarce. Remnants occur below the thrust complex along the flanks of Jebel Nakhl, and in Saih Hatat, as well as in the Sumeini Nappes (Figure 3-10). Lower slope and basinal equivalents are exposed in the Hamrat Duru nappes.

3.3.1 The Albian epeiric platform margin

3.3.1.1 Nakhl area

The late Aptian to earliest late Albian high-energy platform margin is exposed in Wadi Assyi (Laasi) near Al Hassanat on the northeastern edge of Jebel Nakhl (Figure 3-10 and Figure 3-11) and consists of a fringing lowstand wedge complex known as the Al Hassanat Fm. (Gréselle and Pittet, 2005; Hillgärtner et al., 2003; Immenhauser et al., 2001; Masse et al., 1997). A reconstruction based on these outcrop studies and fieldwork for this thesis is shown in Figure 3-12. Geopetal fills and slope bedding measurements suggest the platform margin in this area was dipping to the ENE (Immenhauser et al., 2001). The platform margin at this locality is overlain by middle Albian lagoonal deposits and the equivalent margin of these deposits may be located a few km further north but is difficult to access and has not been studied. Poorly exposed slightly younger marls cover the platform margin and planktonic foraminifera indicate an earliest late Albian age for this flooding event (Immenhauser et al., 2001). Following this flooding there was a backstep of the platform margin of some 20 km to the south and the Aptian/Albian margin therefore represents the maximum extent of the mid-Cretaceous platform. For this reason, it is important to reconstruct the platform slope geometry, as this is the slope that confronted the advancing thrust stack in the Coniacian - Santonian. Major lateral changes in thickness in the margin

complex were attributed to syndepositional movements along older faults in the Jurassic basement (Hillgärtner et al., 2003). Slope instability in the lower Aptian is indicated by the occurrence of metre to decametre sized limestone blocks with rudists within the deep water shales in Wadi Al Assyi (Hillgärtner et al., 2003; Masse et al., 1997; Masse et al., 1998). In the above-mentioned studies, the northward tapering wedge-shaped geometries in the Jebel Nakhl area are all interpreted as depositional features. However, during this study it became apparent that the area is affected by detachment surfaces associated with low angle normal

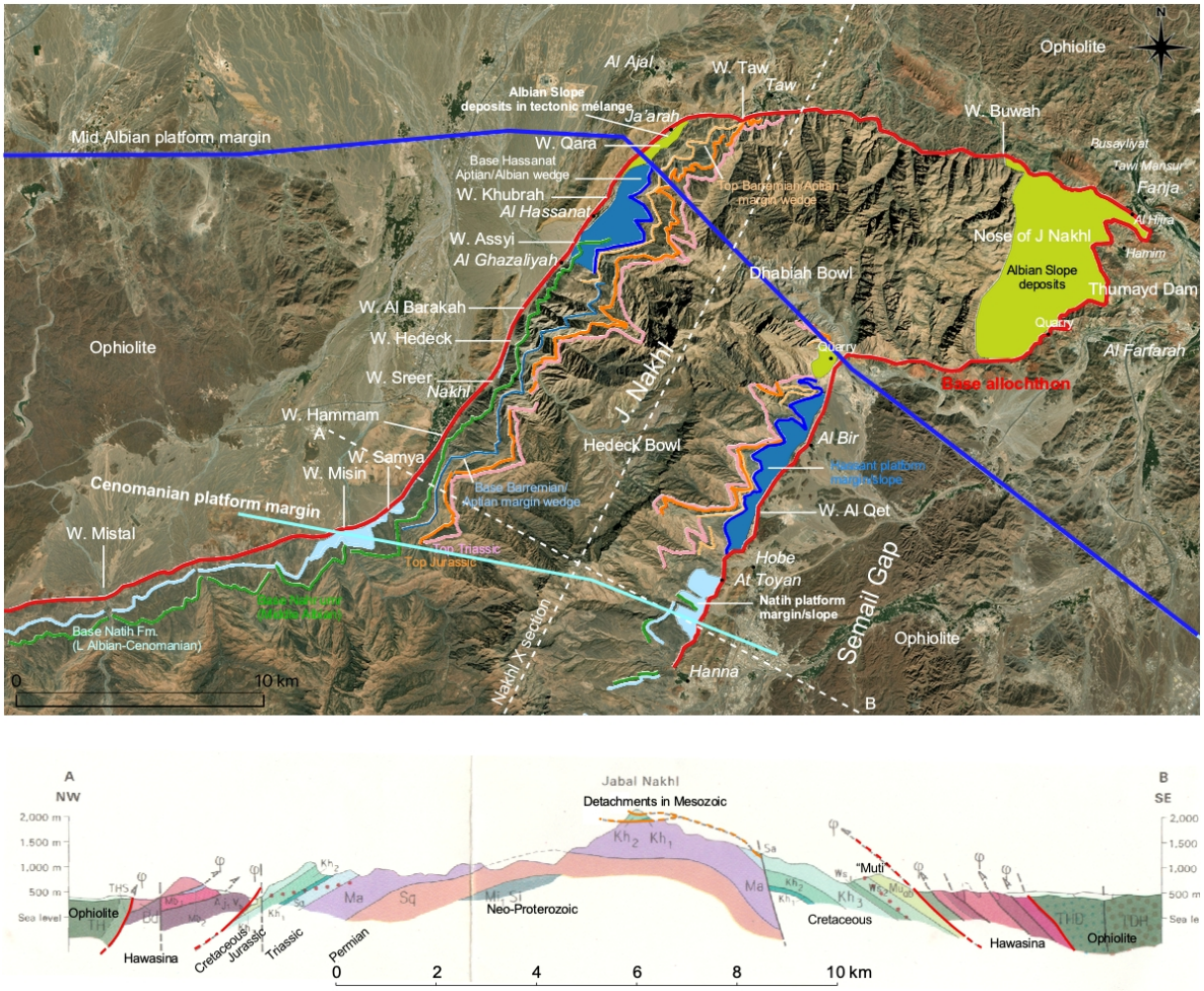


Figure 3-11 Cretaceous platform margin along the Nakhl anticline. Dark blue is the position of the Albian platform margin, green areas to the north are strongly sheared slope deposits. Light Blue is the approximate position of the collapsed and backstepped Cenomanian margin. Below is a cross section through the Jebel Nakhl anticline, (located as A-B on map) modified from the Nakhl 1:100k geological map (Rabu et al., 1986). Major detachment surfaces occur within the Mesozoic sequence along the flanks as well as the top of the structure suggesting a pre-folding origin. The geological interpretation along the NNE-SSW Jebel Nakhl cross section (dotted white line) is shown in Figure 3-12.

faulting during (?)Neogene exhumation that have caused major stratigraphic cut-outs. More detailed structural mapping is required to separate structural and depositional features.

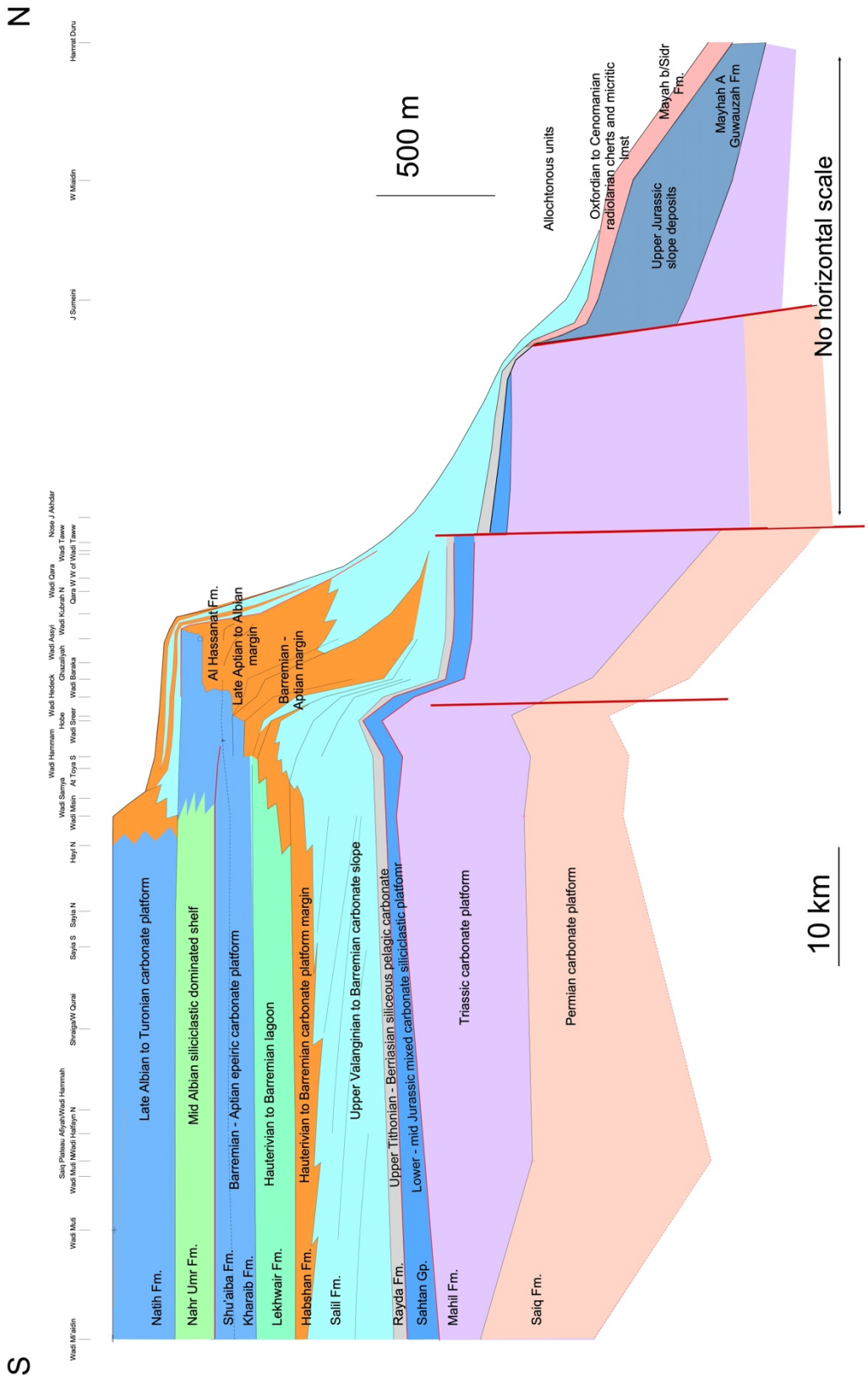


Figure 3-12 Reconstruction of the Mesozoic carbonate platform margin along Jebel Nakhl based on own outcrop study and supplemented with data from BRGM notes, Hillgärtner et al. (2003), Dujoncqouy (2011), Razin and Grélaud (2011) and Watts and Blome (1990). For location see Figure 3-11 and XS-9 in Appendix-4. This reconstruction depicts, quantitatively, the geometry of the composite platform margin immediately prior to the top to the SW emplacement of the thrust stack.

On the eastern dip slope of Jebel Nakhl, in the Semail gap, the Al Hassanat is exposed for 6 km between Hobe and Al Bir. This dip slope consists of steep to vertical dipping very light grey to white weathering limestones. These were originally mapped as Muti "reef" limestone on the geological map by Rabu et al. (1986). Later the interval was assigned to top Kahmah (Béchennec et al., 1992a; Rabu, 1988). The limestones have been strongly sheared and recrystallised and fossils are often not recognisable. However some rudists can be recognised amongst which thin dark shelled rudists which may be *Requienia migliorinii* which according to Skelton and Masse (2000) is most common in the Upper Aptian-Albian limestones in Wadi Al Assyi. As in the Al Hassanat area this limestone wedge pinches out northwards into basinal and lower slope limestones with cherts and calc-silicate schists. These are again exposed north of Al Bir and are strongly deformed showing recumbent isoclinal folding and shearing. The Hassanat margin in this area is directly overlain by whitish Triassic volcanic and radiolarian cherts of the overthrust Haybi or Hawasina Complex. There is no indication for the presence of any Muti sediments or mélange between thrust stack and autochthon.

3.3.1.2 Nose of Jebel Nakhl

Strongly sheared slope facies are exposed on the nose of Jebel Nakhl. These outcrops were originally interpreted as Jurassic by Glennie et al. (1974) but were not further discussed. This interpretation was followed by Pratt and Smewing (1990), who assigned this interval to their Jurassic "Hatat Fm". However, the presence of rudist debris shows conclusively that these deposits are Barremian to Aptian in age. According to Rabu (1988) the lower part of the exposed section consist of 150 m of interbedded limestones and calc-silicate schists. The limestones are strongly re-crystallized and in places consist of monomict

limestone conglomerates. The faunal content suggests that the clasts are derived from a shallow Cretaceous platform, and the beds are interpreted as proximal sediment gravity flows. There is also some influx of fine quartz grains. The upper part of the section is overlain by a 110 m thick interval which contains limestone breccias with a wider variety of limestone clasts derived from both from shallow and deep-water facies. Some of the clasts resemble the distinctive siliceous pelagic limestones of the basal Cretaceous Rayda Fm. The sequence is capped by an interval of shallow water bioclastic carbonates containing late Barremian to Aptian benthic foraminifera. According to Rabu (1988) this interval may be *in situ*, but it is also possible that these are, like the pelagic limestone clasts, reworked and part of a large olistolith. This unit is overlain by 30 m of calc-silicate schists with limestone breccias containing Aptian to Albian age clasts, quartz sandstones and calcareous silts. This unit is assigned by the BRGM to the Muti Fm. (see Nakhl Nose outcrop description in Appendix 1).

Along the flanks of the nose of Jebel Nakhl, below the contact with the allochthonous, locally biscuit-coloured, marls, thin limestone and debrite beds occur, sometimes incorporated into a tectonic mélange below the basal Hawasina thrust. A clast within a thin limestone conglomerate bed in the marls contains orbitolinids and fragments of radiolitid rudists, indicating an Albian to Cenomanian age. These marls have also been mapped as the syntectonic Muti Fm. but are likely part of the lower Cretaceous carbonate platform and correlate with the earliest late Albian flooding event in the Al Hassanat area. The turbiditic character with a siliciclastic influx suggests that these deposits may well be related to similar rocks in the Lower Cretaceous in the Saih Hatat area (see below: Wadi Saal).

3.3.1.3 *Wadi Saal and Nujum*

On the northwestern nose of Saih Hatat, a c. 200 m thick section of slope deposits overlie deep-water carbonate turbidites have been assumed to be Jurassic because they in turn conformably overlie *Lithiotis*-bearing limestones (Le Métour, 1988). The sequence is strongly

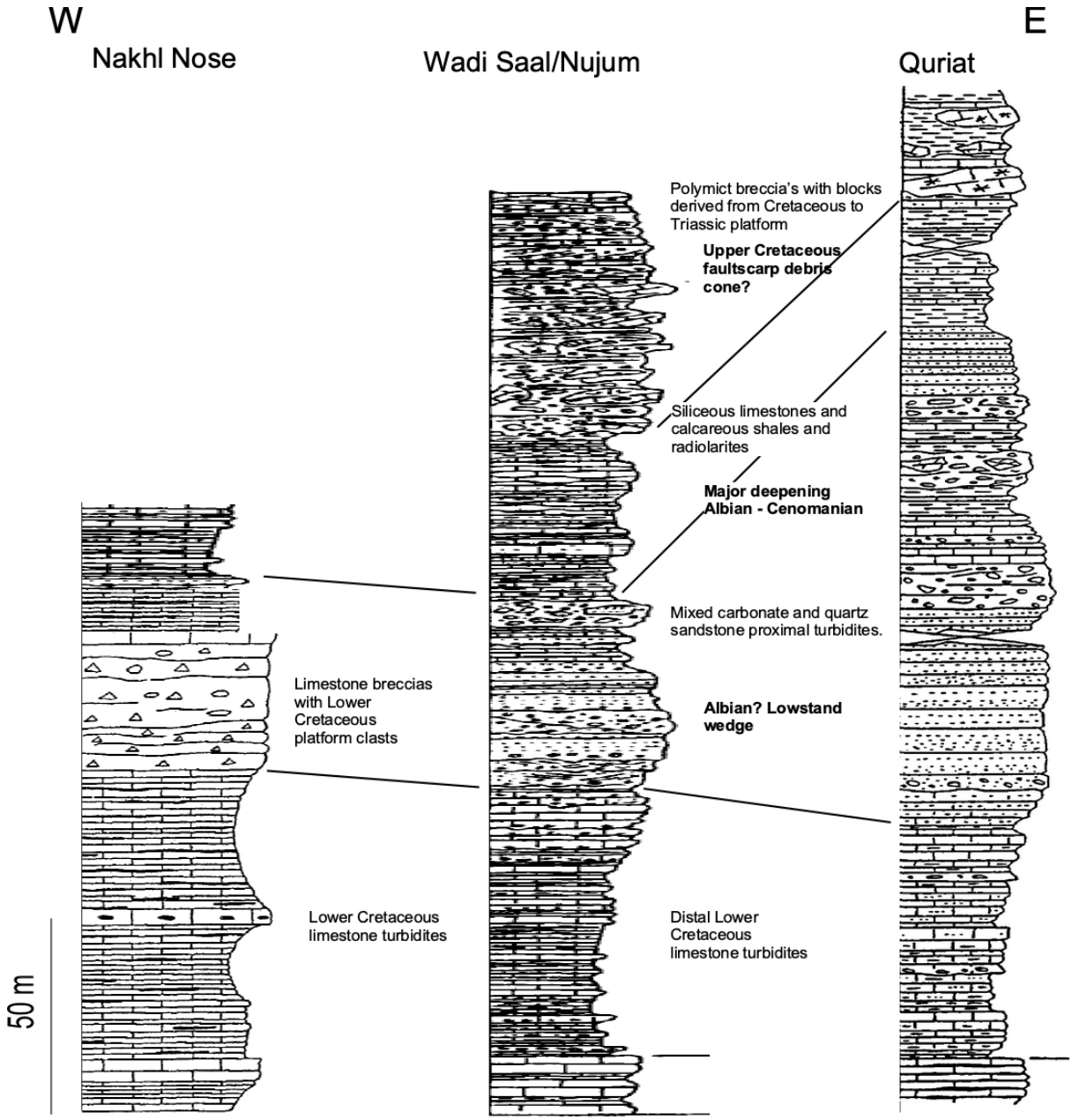


Figure 3-13 NW SE Section through mid to Late Cretaceous slope and basinal sediments north of the Albian platform margin. Deposition of distal carbonate turbidites is interrupted by an influx of platform derived breccias and, in the eastern section, quartz sandstone turbidites of a, probably Albian, lowstand wedge. This is followed by a major deepening with deposition of siliceous limestones and calcareous shales and radiolarites. In the eastern sections these contain polymict megabreccias with Cretaceous, Jurassic and Triassic clasts. For location see Figure 3-10; more detailed descriptions in Appendix 1. Modified and reinterpreted from Rabu (1988) and Le Métour (1988).

recrystallised and sheared. It shows strong lateral thickness changes and pinch-outs, which are due to low-angle normal faults related to exhumation of the Saih Hatat structure

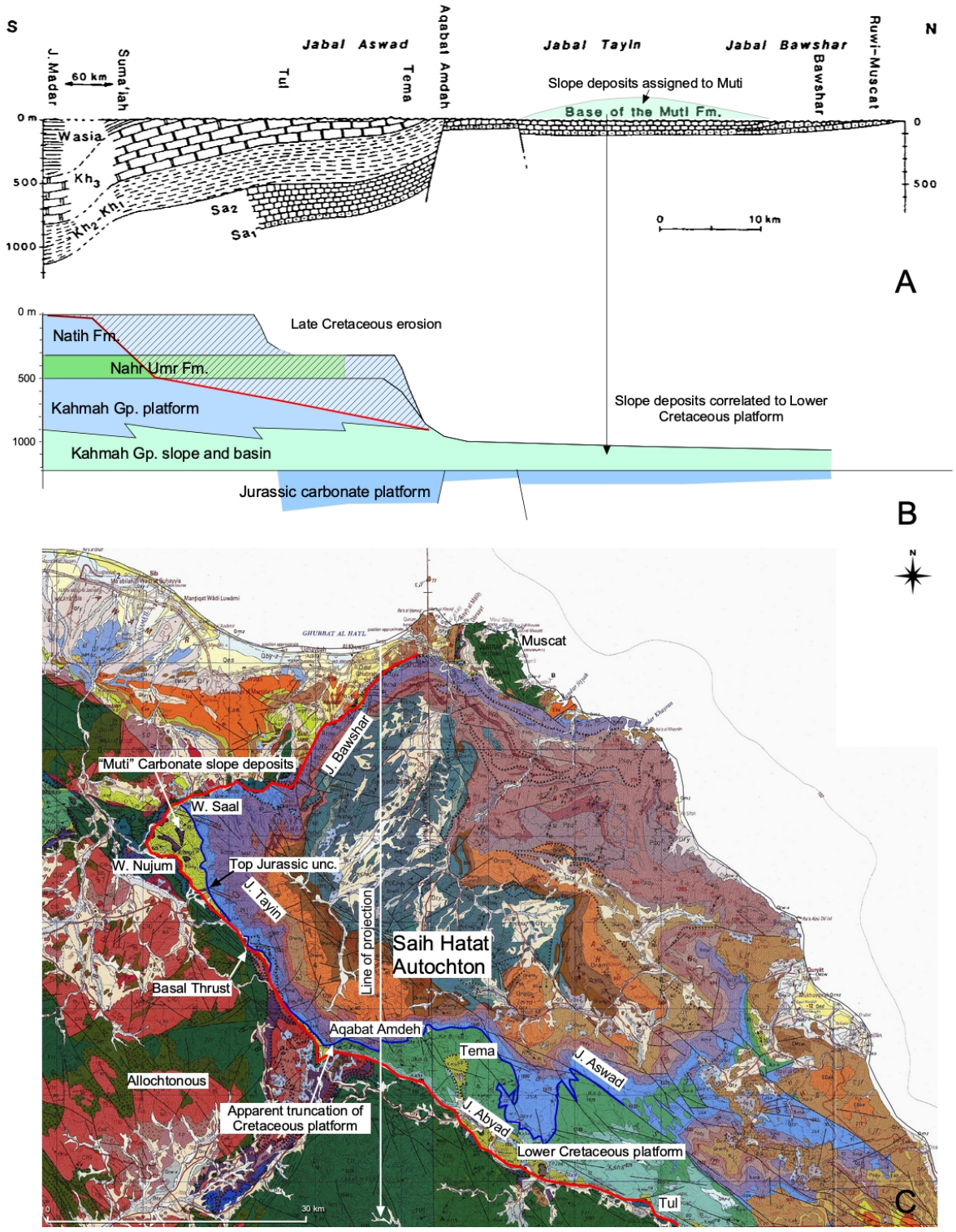


Figure 3-14 Reconstructed section of the Cretaceous in the western Saih Hatat area A: after Le Métour (1988), assuming erosion of Cretaceous by uplift along the margin, B: re-interpreting the slope deposits assigned to the Muti by Le Métour as being Lower Cretaceous and suggesting that the apparent truncation was caused by platform margin collapse. C: location of section on geological map, see also Figure 3-10 and XS-10 in Appendix-4.

(Coffield, 1990). Due to the tectonic overprint, the matrix could not be dated, but the presence of rudists in clasts in the upper part of the sequence suggests a Cretaceous age. The interval has also been assigned to the Muti Fm. by the BRGM geologists (Béchennec et al., 1992a; Rabu, 1988; Villey et al., 1986) based on lithofacies: the occurrence of siliciclastic turbidites and megabreccias in the upper part of the sequence. Glennie et al. (1974) mapped the lower part as Kahmah and the top as Muti but provide no further detail. Coffield (1990) mapped the outcrops as Jurassic. Pratt and Smewing (1990) include the whole sequence into their Jurassic Hatat Fm. However, the presence of rudists shows this is incorrect. More likely it is only the Jurassic deep-water carbonate turbidites at the base of section, which correspond to the Hatat Fm.

A detailed description of several sections in the Saal and Nujum area is provided by Le Métour (1988). It consists of a sequence of distal silty carbonate turbidites that become more proximal upwards, with limestone micro-breccias and conglomerates. This is overlain by an interval up to several tens of m thick of mixed carbonate and siliciclastic proximal turbidites. These are very coarse-grained and contain pebbles of limestones, dolomite and quartzite. The quartz sandstones form lenticular bodies extending for several km, or lenses of variable thickness (0-70m) in channels which are associated with carbonate conglomerate deposits.

The basal part of this sequence forms a prograding carbonate slope with siliciclastic influx and is like the Lower Cretaceous sequence exposed 10 km to the west in the nose of Jebel Nakhl and in Jebel Abyad 30 km to the southwest along the western flank of Saih Hatat. Also, the contact with underlying bedded Jurassic slope deposits is like that in Jebel Abyad. The new palaeontological observations, lithofacies and regional context suggest that this is

the slope of the Lower Cretaceous platform and not a Late Cretaceous sequence overlying truncated Jurassic. The influx of quartz sandstones is much more prominent near the top and the association with reworked clasts from the platform suggests the development of an erosional platform margin with bypass, or axial supply (from the Huqf) of siliciclastics. The channelised turbidites occur in submarine canyons or gullies along the slope (Le Métour, 1988). The age of these is poorly constrained. Reworked benthic foraminifera of Barremian to Albian age occur in the turbidite sequence (Le Métour, 1988). And the Albian to Cenomanian age range for reworked bioclasts in marls overlying the sands in the Nose of Jebel Nakhl point to an Albian to ?Cenomanian age. The siliciclastic turbidite sequence is overlain by a thinner-bedded sequence of siliceous limestones and calcareous shales, thin conglomerates and more distal turbidites with decreasing siliciclastic influx. This changes upward into a background sedimentation of purple clays, siliceous limestone and radiolarites. This deepening may correlate to the late Albian flooding event.

The re-interpretation of the slope deposits in Wadi Saal and Nujum as Lower Cretaceous in this thesis as shown in Figure 3-14 A implies that the amount of erosional truncation below the BAU is significantly less than in the previous models of Glennie and BRGM: it may even be zero. Previous models by BRGM assuming absence of Lower Cretaceous deposits suggested hundreds of metres of erosion along the platform margin down to Jurassic / Triassic levels by a major uplift preceding the emplacement of the nappe complex (Le Métour, 1988). However, the absence of shallow marine Lower Cretaceous carbonates in the north is largely related to a lateral facies change from platform to slope and basinal deposits. Furthermore, the incompetent slope deposits are more strongly deformed and prone to tectonic cut-outs and incorporation into the tectonic mélange along the basal

thrust, leading to further reduction in apparent thickness but by tectonic rather than erosional processes.

The re-interpretation of the Jebel Nakhl nose and Wadi Saal sections as Lower Cretaceous slope and base of slope deposits has speculative implications for other outcrops which unfortunately lack any depositional ages. These are developed further below:

3.3.1.4 Quriat area

A sequence of slope deposits exposed in a small area near Quriat village is like that in the Wadi Saal and Nujum area located 70 km to the NW (Le Métour, 1988; Le Métour et al., 1986b). The whole Quriat sequence was deposited in a basinal to slope setting. Following a major transgression above the mid-Jurassic exposure surface, deposition started in a basinal setting with pelagic carbonates, shallowing upward into a slope setting with slumps and influx of carbonate turbidites. A significant influx of clastics, associated with carbonate debrites in the upper part of the sequence, indicates erosion of a carbonate platform located to the south, and bypass of siliciclastics. A significant deepening near the top is indicated by the disappearance of the sandstones and silty sediments, and the change in background sedimentation to radiolarian cherts and cherty limestones. The association with the megabreccia indicates that this is accompanied by significant erosion of a nearby carbonate platform, probably along a fault scarp. Due to the strong tectonic overprint and metamorphism (to carpholite grade; >7 kbar) no biostratigraphic data for these outcrops are available.

3.3.1.5 Northern edge of Saih Hatat

A mélange of intensely folded, sheared and partially recrystallised metasedimentary rocks is exposed between the autochthon and the ophiolite complex along the northern

edge of Saih Hatat (Le Métour, 1988; Le Métour et al., 1992b; Le Métour et al., 1986b). Because of its tectonic position below the nappes these rocks have been assigned to the Muti Fm. They overlie Lower Jurassic carbonates and siliciclastics and predominantly consist of siltstone and yellow silty carbonates that have been recrystallised into grey-green, yellowish-beige or pinkish schists and calc-silicate schists. Locally, they contain beds and rafts of turbiditic, coarse, quartz sandstones and conglomerates with carbonate and silicious pebbles, lenses, boulders and blocks of recrystallised, possibly reefal, limestone. These are similar lithologies and facies to those in the Wadi Saal and Nujum area, which are now interpreted as Lower Cretaceous. Lenses of greenish metabasic rocks of basaltic lavas, and possible sills or dykes, and rafts of radiolarian cherts in the mélange probably have been tectonically mixed in from the overlying Hawasina thrust sheet. As in the Wadi Saal and Nujum areas, it is suggested that the Jurassic was overlain by Lower Cretaceous slope to basinal deposits, which have here been incorporated into a tectonic mélange. The limestone rafts may be part of megabreccias formed by collapse of the margin before the obduction. In the Ruwi area in Muscat the Muti Fm. is tectonically overlain by a slab of Triassic Mahil dolomite overlain by Sahtan siliciclastics. This contact has been interpreted as a SW-vergent overthrust on the 1:100k Geological map (Le Métour et al., 1986a). However as the slab is folded and closes towards the north, Hanna (1990) interpreted this as a gravity fold at the front of a surge zone from the Saih Hatat culmination. This entire section is the 750m thick “Upper Muti” of Robertson, which drove his migrating foreland basin model (Chapter 1). However, it consists of a mix of likely Lower Cretaceous slope deposits, Muti and a purely tectonic mélange.

3.3.1.6 Sumeini nappes

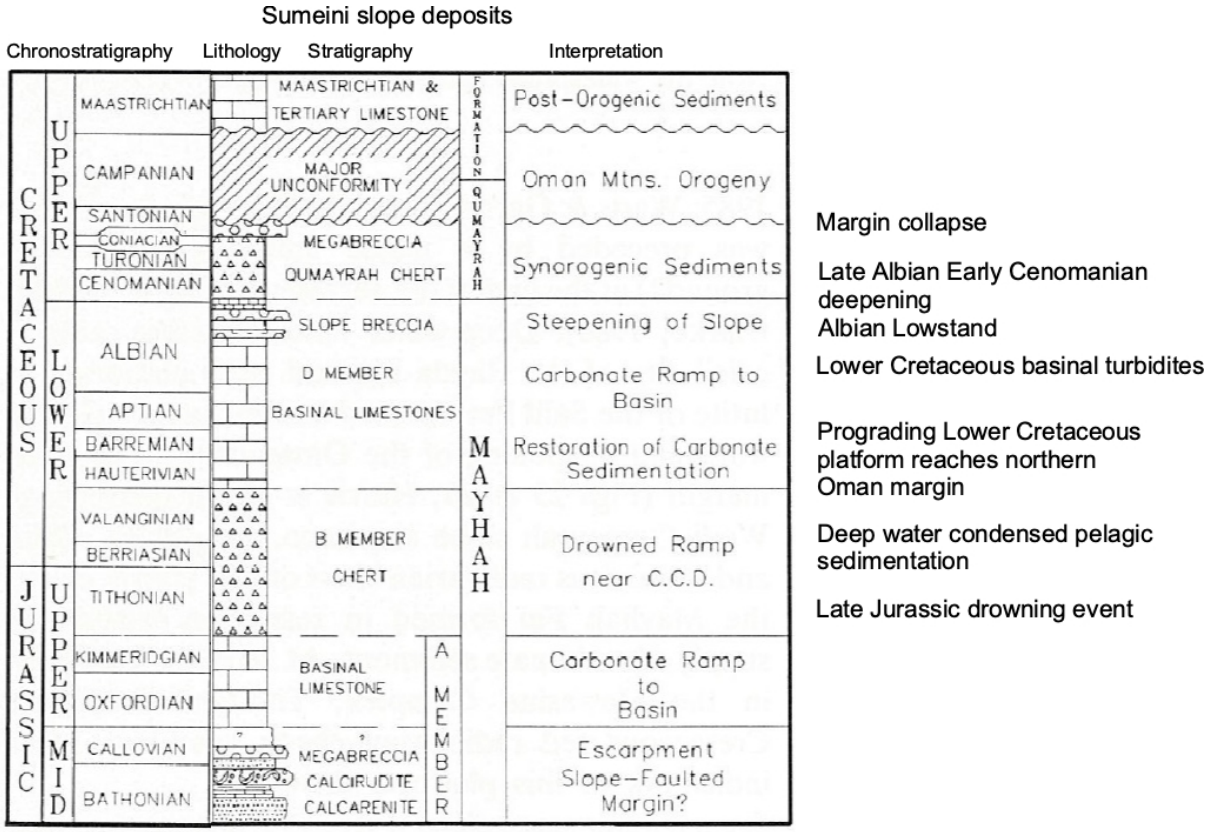


Figure 3-15 Jurassic and Cretaceous litho-stratigraphy and depositional interpretation of the Sumeini nappes, which contain the slope to basinal deposits of the Mesozoic carbonate platform. Modified from (Watts and Blome, 1990).

A further control point on the position of the composite platform edge is provided by the allochthonous Sumeini thrust sheets (Figure 3-15). Basinal deposits exposed in the Sumeini nappes show continued deposition of silicified radiolarian lime mudstones (B-Mbr of the Maynah Fm.) at least into the late Valanginian to Hauterivian (Watts, 1990; Watts and Blome, 1990). These lime mudstones are truncated by mass flow complexes associated with uplift and collapse of the margin during the Cenomanian to Coniacian. The more distal deposits in the Hawasina nappes show that, at this location, deposition of radiolarian cherts and silicified lime- mudstones continued into the Cenomanian (Blechschmidt et al., 2004).

3.3.1.7 Outline of the mid Cretaceous platform margin

A tentative outline of the mid Cretaceous platform margin is shown in Figure 3-10. The only location where the actual margin is exposed in the autochthon is in Jebel Nakhl near Al Ajal. The northernmost limit of the platform edge further east is indicated by outcrops of the Lower Cretaceous slope deposits at the nose of Jebel Nakhl, Wadi Nujum and Wadi Saal on the west flank of Saih Hatat, and in the Quriat area. These have been strongly sheared and may have experienced large horizontal displacements. To the west, an exploration well, Hawasina-1, drilled to the sub-thrust section in the Hawasina window, is significant in that it did not encounter Cretaceous platform carbonates. Instead, above typical Jurassic platform deposits, a Cretaceous open marine sequence with shallow water-derived bioclasts like the slope deposits in the Al Hassanat area was found beneath the Sumeini nappe. This suggests that the Natih and Kahmah platform edge are located between the Muri outcrops (western end of J. Akhdar (Figure 3-10) and the Hawasina well. Unless the margin is very irregular, it is unlikely that the nearby allochthonous Sumeini outcrops, some 15 km northwest of the well, overly the Cretaceous platform. Thus, the edge is most likely located south of the Hawasina window. The outline drawn further to the northwest follows the tentative trends suggested

by Searle et al. (1990) south of the Musandam peninsula, calibrated with geoseismic sections by Dunne et al. (1990).

3.3.2 The Late Albian to Turonian platform margin

3.3.2.1 Jebel Nakhl flanks

Scattered outcrops between the base Hawasina thrust and the top of the middle Albian platform along the flanks of Jebel Nakhl investigated for this thesis and described in Appendix 1, suggest a major flooding event during the late Albian. This resulted in a backstepped late Albian to Cenomanian platform margin some 17 km to the south of the middle Albian margin at Al Hassanat (Figure 3-11 and Figure 3-12).

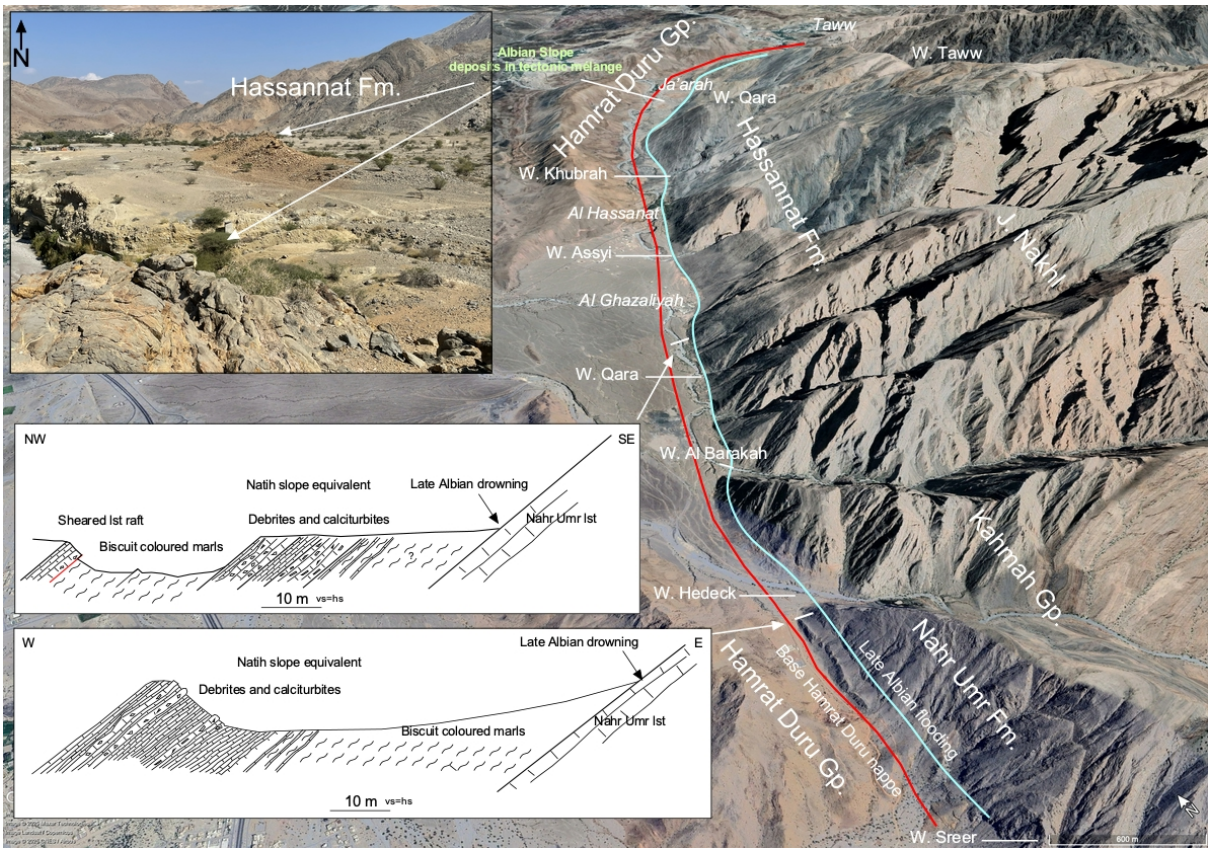


Figure 3-16 Oblique view of Google Earth satellite image along the western flank of Jebel Nakhl, with locations and sections of Albian to Cenomanian slope deposits. The outcrops are located along the foot of the dipslope and, in the north, as rafts within a tectonic mélange.

3.3.2.2 Western flank of Jebel Nakhl

Along the western dip-slope from Al Ja'arah in the NE to Wadi Misin in the SW a basin-to-platform transect can be observed, although it is strongly affected by low angle to bed-parallel down to the north- shearing (Figure 3-16).

In the north, at the entrance of Wadi Qara, the drowning of the Al Hassanat margin is indicated by a 20 m thick interval of pelagic limestones and cherts that overlies coarse-grained slope deposits. The basal contact of this deep-water section is also a detachment surface. Within this pelagic interval Masse et al. (1997) reported some thicker beds with re-sedimented radiolitids (*Eoradiolites*) of late Aptian – Albian age. This interval is overlain by 30 m of well-bedded limestones with thin marl interbeds. The bioclastic limestones are fine-grained, with abundant crinoid ossicles and shallow-water derived bioclasts, muddy carbonate intraclasts, planktonic foraminifera and calcispheres. These rocks are interpreted as distal carbonate turbidites, derived from a platform located further south.

At Al Ja'arah isolated limestone hills with carbonate slope deposits stick out of the alluvial plain, with poorly exposed orange shales between the mid-Cretaceous dipslope and ridges to the west with Hamrat Duru nappes. The shales are tightly to isoclinally folded and sheared and in places the contact with the underlying limestones on the dip-slope is tectonised. They consist of very slightly to non-calcareous, greenish grey, micaceous, in places 'silky' (phyllitised) red-brown shales (claystones), with siltstone beds. Harder (coarser silt) cm – dm thick beds have a wedge-shaped sheared appearance with dm long lenses. Within the shales isolated dm-sized, sometimes folded, blocks and rafts of grey bioclastic limestone layers occur. These limestones are cemented and hard, and contain radiolitid rudist fragments in a mud matrix with fine detrital quartz. The matrix contains small calcispheres and possible planktonic foraminifera. The limestone ridges are encased by red-

brown greenish shales. In most parts the limestones are strongly deformed m-thick beds intercalated with calcareous shales or marls. The beds are undulating and poorly defined, sheared and contain abundant horizontal calcite veins, slickenside surfaces and rusty brown cherty patches. In some less deformed parts, they show a sequence of fine-grained, wavy, thin to medium bedded limestone, containing burrows filled with coarser sediment. These are intercalated with m-scale breccia beds with angular blue grey limestone blocks, bioclastic grainstone and fine-grained limestone clasts. Some debrites pinch out over a few metres and seem channelised. The clasts in the shales and hills in the plain are broken up layers of redeposited shallow water derived sediments from an Albian to Cenomanian carbonate platform. These slope deposits have been reworked into a tectonic mélange and mixed with shales and sandstones from the overlying Hamrat Duru nappes. The collapse of the slope probably occurred following steepening of the slope just before the arrival of the nappes, which is comparable to the formation of the breccias described by Watts and Blome (1990) in the Sumeini Group. The deposits at Al Ja'arah have been mapped as Muti, Fm. Sayja Mbr. (Cooper, 1986).

Southwards along the NW flank of Jebel Nakhl, between Wadi Assyi and Al Ghazaliyah, the Middle Albian platform is overlain by biscuit-to pinkish coloured thin bedded bioturbated marls, interbedded with limestones containing planktonic foraminifera and calcispheres. At the entrance to Wadi Assyi the planktonic foraminifera indicate an earliest Late Albian age (Immenhauser et al., 2001). New outcrops south of Ghazaliyah studied for this thesis, shows that a 20 m thick interval of debrite beds intercalated with several m thick intervals of thin bedded limestones occurs within the marls. The debrite beds can be up to 3 – 4 m thick and show a very irregular top. The clasts consist of irregular-shaped cm-sized shallow-water derived material with radiolitid rudist fragments, and dm long, flat, mud

pebbles. The bedded limestones consist of bioclastic grainstones with shallow water fauna and rudist fragments and contain large tube-like burrows. Higher up in the marl sequence sheared rafts of debrites and bedded limestones occur.

A similar sequence can also be seen yet further south at the entrance of Wadi Hedeck. Here a limestone ridge runs for some 700 m along the foot of the main dip-slope formed by platform carbonates equivalent to the Nahr Umr. The basal part of the section in the ridge is argillaceous with nodular limestones. This unit is overlain by thin planar bedded limestones with intercalations of massive beds up to 50 cm thick. The limestones are interbedded with thin argillaceous streaks. These fine-grained beds consist of peloidal packstone containing calcispheres, simple planktonic forams and fine bioclastic hash. The thicker interbeds of up to some 50 cm thick are debrites with poorly sorted, up to dm-sized limestone clasts, which are difficult to distinguish from the matrix. The clasts are monomict grey limestones, irregular shaped and subrounded. The top of the ridge consists of a very fine-grained limestone, which in thin section shows a peloidal packstone texture with calcispheres, simple planktonic forams and fine bioclastic hash. The presence of the debrites suggests more proximal slope setting compared to those in the north. Masse et al. (1997) assigned an uppermost Albian (or lowermost Cenomanian?) age to cherty limestones with planktonic foraminifera and calcispheres from this ridge.

At Wadi Misin a c. 200 m thick section at the entrance of the wadi was assigned to the Nahr Umr and Kahmah on the BRGM geological map and Natih Fm. by Scott (1990). Fieldwork for this thesis shows that the upper part of the sequence consists of several tens of metre-thick ledges and wedges of dm to m scale bedded limestones containing radiolitid rudists and praealveolinids. Beds are amalgamated; bed boundaries are poorly defined. The

limestones are poorly sorted, coarse bioclastic, rudstones to packstones with large radiolitid rudist fragments and in places contain light grey lime-mud clasts. These packages are separated by a few m thick recessive intervals consisting of thin-bedded (cm to 10 cm) coarse bioclastic limestones and light rusty argillaceous limestones. The beds show pinch and swell structures, ripples, cross-lamination and dm-scale cross-beds dipping to the north. At the base the beds show scouring, and internally they fine upward. The presence of

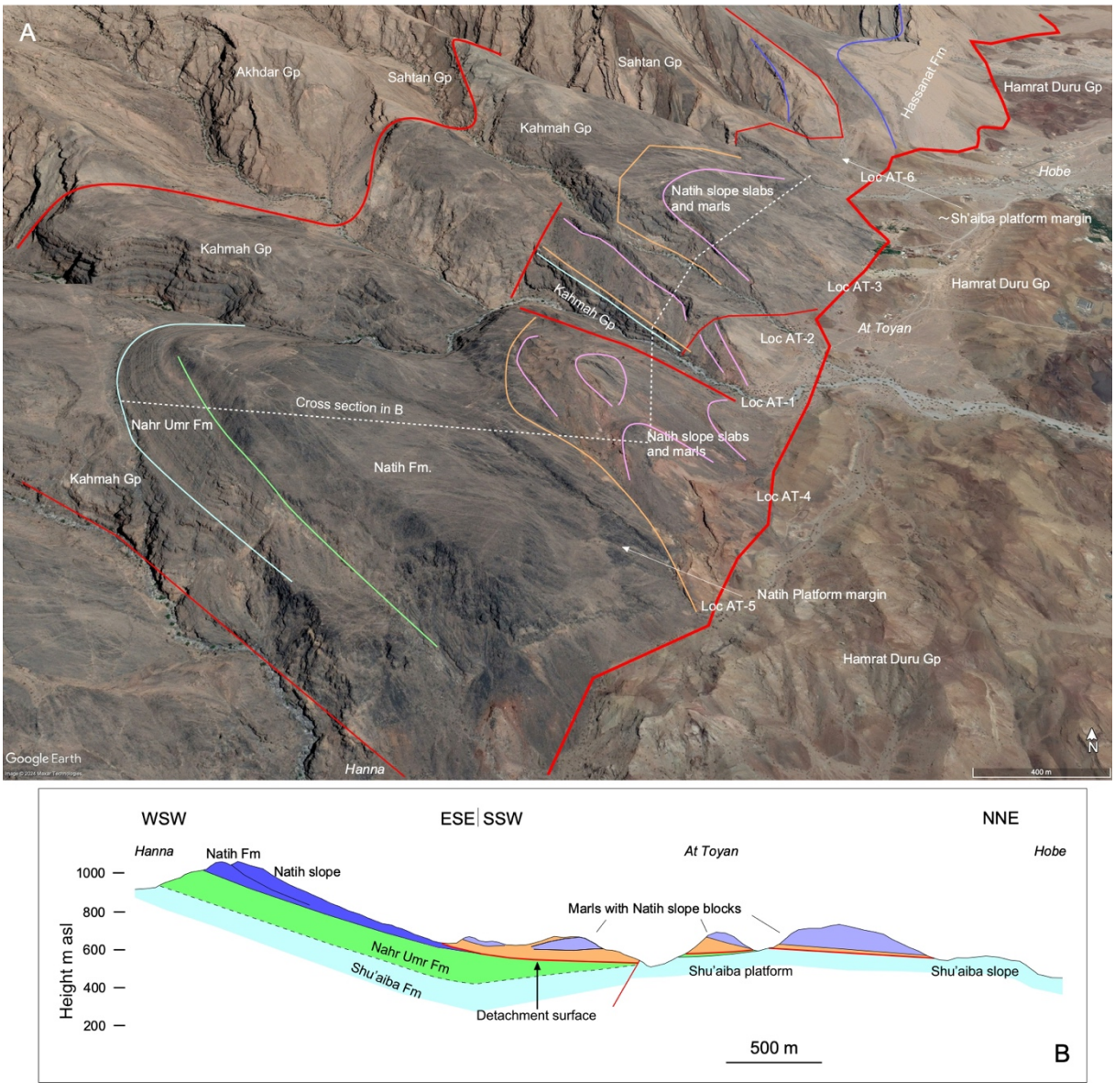


Figure 3-17 Satellite image (Google Earth) of the Hanna to At Toyan area showing the northern collapsed margin of the Natih platform. B: Geological cross section along the dip-slope (see A for location) showing the Muti megabreccia with Natih slope-facies rafts on top of a near horizontal surface (slide plane) truncating the Natih and Nahr Umr Fms.

praealveolinids clearly shows that Cenomanian, Natih equivalent, strata are still present in these wadis, and the geological maps are not correct. Shallow water features like exposure surfaces or major hardground surfaces were not observed. This sequence is interpreted as a proximal slope facies with redeposited Natih platform interior sediments, mixed with some reworked lithoclasts from the slope. This interpretation also explains the erroneous northernmost mapped occurrence of the Natih in this area, some 1500 m west of this outcrop, on the BRGM maps. The change from platform to slope is associated with a significant increase in the occurrence of detachment surfaces along zones of weakness between the platform and slope and within the slope wedges. For example, at Wadi Missin a low angle normal fault can be seen which cuts out a large part of the lowermost Natih slope and upper Nahr Umr deposits.

3.3.2.3 Eastern flank Jebel Nakhl

On the eastern dip-slope of Jebel Nakhl, Natih equivalent slope deposits are exposed along a stretch of 2.8 km north of the Natih platform limit near Hanna (Figure 3-17). The Albian to Cenomanian margin is at least 10 km further south than the Aptian-Albian Al Hassanat margin along the same dipslope near Al Bir (Figure 3-11). The outcrops consist of a chaotic assemblage of metre- to hectometre-sized blocks of slope deposits within biscuit-coloured marls in a calc-silicate schist matrix. These marls and schists overly tectonically truncated Natih and Nahr Umr Fm. sediments.

The marls contain some recrystallised belemnites and are strongly folded and sheared

The blocks contain a variety of slope deposits:

- Debrite beds with cm – dm sized angular to subrounded clasts in a finer argillaceous matrix. In some the matrix is less argillaceous, and the clasts are only faintly visible.

Bioclastic limestones with cm-sized thin-shelled rudists, some with black shell lining, small radiolitid rudists, large radiolitid rudist fragments and oncoids. The facies look very similar to the platform margin facies of the Hassanat Fm., but the radiolitid rudists suggests these are younger and represent the platform margin equivalent of the Albian to Cenomanian Natih Fm.

- Amalgamated fining upward layers of limestone conglomerates to rudstones. The conglomerates contain dm-sized, slightly rounded, limestone clasts which are difficult to distinguish from matrix.
- Marls interbedded with cm to dm thick bioclastic limestone beds and lenses overlain by massive limestones.

The dips of the different blocks vary greatly and some of the blocks align to form discontinuous pseudo-beds. At the foot of the Natih escarpment a 2 m thick debrite layer can be followed over a few 100 m. The abundance of debrites in the slope deposits suggest an erosional margin during the late Albian to Cenomanian. Instability of the margin may be related to faulting and tilting. However it could also be simply related to self-erosion of the platform following oversteepening of the slopes during aggradational growth while keeping up with relative rising sea level (Schlager and Camber, 1986).

The contact of the limestone blocks with the marl matrix is sharp but does not show clear evidence for shearing. The debrites do not contain any clasts from the surrounding marls. This suggests the Natih slope deposits have later been reworked into the marls. They may represent a mass transport complex derived from the platform margin following tilting and faulting, possibly as the margin enters the foredeep. The complex was subsequently deformed by folding and shearing during obduction and exhumation. Low-angle normal

faults along the basal part of the mélange cut-out the top of the Nahr Umr Formation on satellite images and in the wadi at locality AT-1 (Figure 3-17). The slope complex is overlain by a tectonic mélange of platy greenish grey limestones, strongly folded biscuit-coloured laminated argillaceous beds and pillow lavas of the Hawasina Complex.

These transects along the flanks of Jebel Nakhl show lateral facies changes from platform to basin in the Natih Formation and from a shale- to carbonate-dominated margin in the Nahr Umr Formation. This is combined with removal of stratigraphy along low angle normal faults that resulted in an apparent thinning or truncation of these units towards the north. In previous interpretations this apparent truncation has led to the assumption of major uplift of several 100 m and subaerial exposure before emplacement of the nappes (Béchennec et al., 1995; Breton et al., 2004; Glennie et al., 1974; Patton and O'Connor, 1988; Robertson, 1987b; Warburton et al., 1990). However, the present study shows that there is no evidence of subaerial exposure, nor any need to invoke major uplift and erosion. The recognition that the observed thinning is primarily due to the geometry of an aggradational and back-stepping carbonate platform margin, makes the tectonic story much simpler: a simple flexural down-bending in the foredeep in advance of the thrust stack. What is remarkable though is the extent to which the basal thrusts have not removed the slope deposits of the composite carbonate platform but rather climbed over it (or rather the 'autochthonous' slope has passed beneath the thrusts!) with just a modest amount of tectonic incorporation.

3.3.2.4 Jebel Nakhl Nose

Below the basal thrust, scattered outcrops of biscuit-coloured marls interbedded with limestone and thin debrites overlie Lower Cretaceous slope deposits. Rudist fragments in the

debrites suggest a Late Albian-Cenomanian age. Though the marls have been mapped as Muti Fm., they more likely represent the Late Albian flooding event, as seen in the Al Hassanat area.

3.3.2.5 Wadi Saal Nujum

These sections show several metres to tens of metres thick channels containing conglomerates and megabreccias with m-sized blocks cut into deep-water shales and cherts. Deep erosion of the platform occurred. This is indicated by polymict breccias with blocks of Cretaceous rudist limestones, Jurassic oolitic limestones and sandstones, and Triassic dolomites. The clasts are rounded, lack matrix, and suggest proximity to an escarpment. Erosion down to the Triassic implies removal of at least 300 m of Cretaceous and Jurassic. The clasts are of the same facies as the platform interior deposits in the underlying section at this locality. This indicates that this escarpment was along a fault scarp in the interior platform rather than being the platform margin collapse (which is also located much further to the north). The outcrops are located on the footwall and the megabreccia pinches out towards the west. This may indicate a N-S running fault, which would be in line with the pre-existing structural grain in this area (Figure 2-3). On the BRGM geological map larger NW-SE trending normal faults occur along the upper part of the western Saih Hatat flank 10 km to the east. They seem to have already affected the stratigraphy during the mid-Carboniferous event. Alternatively, the breccias could have been derived from inverted platform carbonates along the western flank of Saih Hatat.

The megabreccias postdate the Lower Cretaceous platform but there is no age control on the matrix. Similar megabreccias have been reported from the allochthonous Sumeini nappes, where the matrix indicates an Albian? to Cenomanian age.

3.3.2.6 Sumeini nappes

Albian to Coniacian slope deposits are exposed in scattered isolated outcrops of the Sumeini thrust sheets (Figure 3-15) and their stratigraphy and sedimentology have been described by Watts (1990); Watts and Blome (1990); Watts and Garrison (1986); Cooper et al. (2016) and in the geological mapping documentation by the BRGM (Béchennec et al., 1993a; Béchennec et al., 1992b; Béchennec et al., 1993b; Le Métour et al., 1992a; Le Métour et al., 1991).

The total thickness of the section is up to 500 m. The sequence records a tectonically induced steepening and deepening of the slope, followed by a catastrophic collapse of the platform margin (Watts, 1990). During the Albian the slope deposits were dominated by hemipelagic carbonates associated with gravity flows, slumps and slides. During the late Albian the background sedimentation changed to siliceous mudstones and radiolarian cherts, indicating water depths below the CCD (Watts and Blome, 1990). This could be related to a rise in CCD related to decrease in hemipelagic sediment input. That decrease may be due to exposure of the platform margin and/or further deepening of the slope below the CCD. The margin collapse is evidenced by the influx of megabreccia calcirudite beds which cut deeply into the underlying Permian to Cretaceous slope deposits. The megabreccia intervals can be more than 200 m thick with clasts up to 40 m (Watts, 1990). These clasts consist of slope-derived limestones and cherts, Cretaceous and Jurassic platform-derived clasts, Triassic reefal boundstones and dolomites. The breccias are clast-supported and lack matrix. Their age is poorly constrained by the age of the blocks and some broad ranging ages of radiolarians in chert intervals. Biostratigraphic data in the BRGM studies suggest that major collapse of the

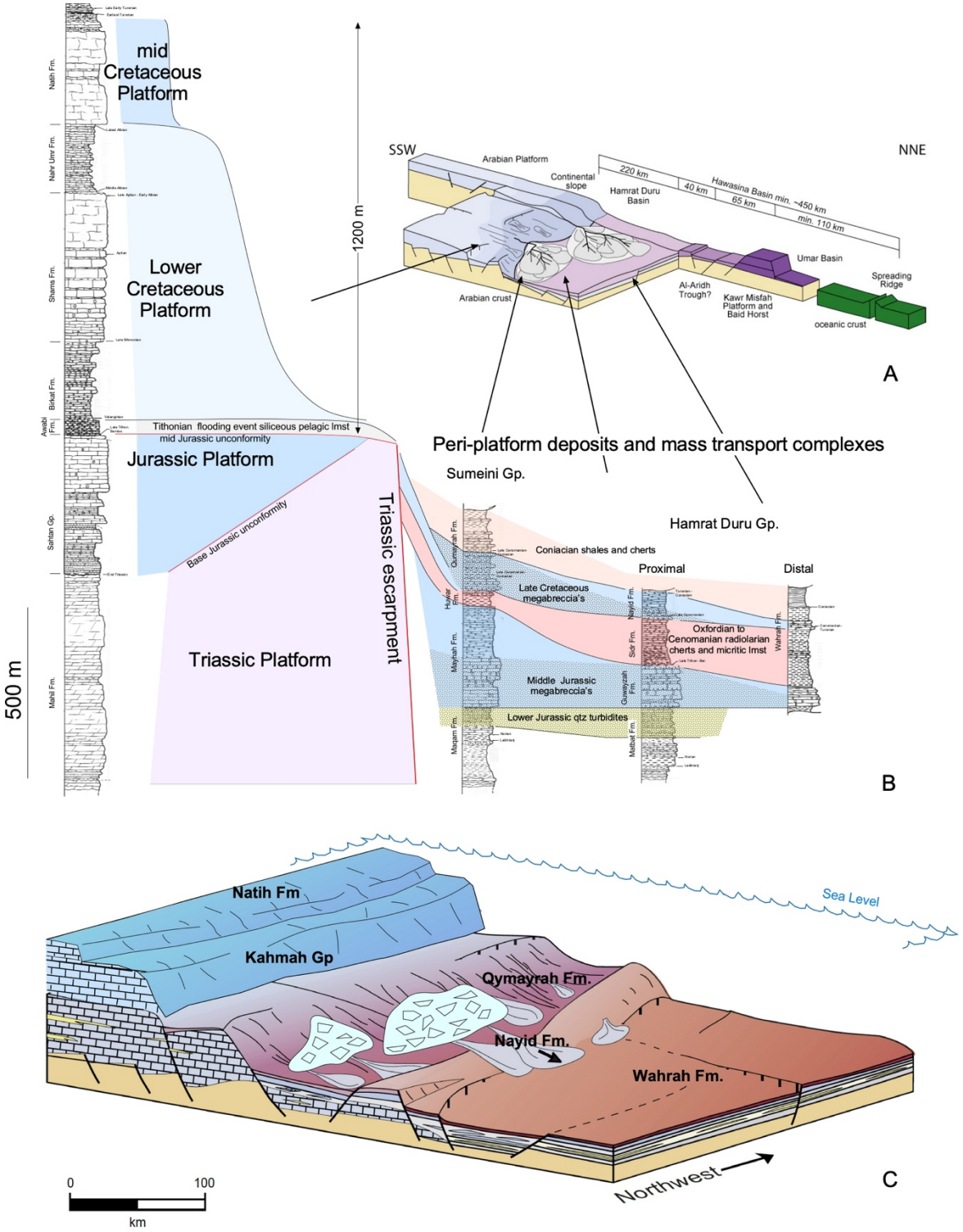


Figure 3-18 A: Reconstruction of Mesozoic Hawasina Basin, modified by Bauer et al. (2020) after Blechschmidt et al. (2004), showing widths of individual units after Béchennec et al. (1990). B: Schematic cross section based on the field work, showing geometry of Mesozoic platform margin. A steep escarpment was formed during the Triassic and platform growth during the Cretaceous added well over 1 km extra bathymetry. The Triassic escarpment was by-passed by reworked sediments and megabreccias during Jurassic and Cretaceous erosional events. Logs derived from (Le Métour et al., 1995b).

margin and development of escarpments already started in the Late Cenomanian. The

presence of Jurassic clasts in the basal part of the sequence (Upper Huwar Fm., Béchennec et al. (1992b)) and reworked Permian clasts in Albian-, more distal, sediments of the Hawasina (Sid'r Fm., Blechschmidt et al. (2004)) would suggest an even earlier, Late Albian onset of tectonic instability. Lack of matrix, the unstratified nature, and the major erosion at the base all suggest that the megabreccia beds are debris avalanches along submarine escarpments (Watts and Garrison, 1986). They are possibly related to inversion along pre-existing faults at the former passive margin (Callot et al., 2010). In Jebel Fayad, Coniacian megabreccias overlying deformed slope deposits possibly indicate active thrust tectonics or the presence of large olistoliths (Watts and Blome, 1990).

Figure 3-18 shows a reconstruction of the platform margin during the Cenomanian to Turonian. It shows an overall backstepping margin formed by a Triassic - Jurassic escarpment, a Lower Cretaceous aggrading platform margin (Kahmah Gp.) that did not reach that escarpment, followed by a backstepped Albian to Turonian platform (indicated as Natih Fm. but also including Nahr Umr Fm.). The base-of-slope carbonates of the Sumeini Group were deposited at the foot of the Triassic escarpment. Thicknesses of the autochthonous Mesozoic platform and the base of slope carbonates in the Sumeini Gp. suggest that the total bathymetric height along the margin was more than 1.2 km (not accounting for differential compaction).

3.4 Conclusions

1) There is no major uplift along the platform margin prior to obduction. The erosional truncation of some 1.5 km along the platform margin suggested in the early studies and which forms a major element in the models of the obduction history in literature is an artifact. This conclusion was based on the misinterpretation of then-undated

slope deposits overlying the Jurassic platform north of the middle Cretaceous margin as a younger, post-unconformity deposit, assigned to the Muti Fm. Not flattening sections along the base of these slope deposits but using instead the unconformity on the top of the platform created the impression of significant truncation of the platform margin.

2) The Mesozoic platform margin had its widest extent during the Triassic to Middle Jurassic and shows an overall backstep following Late Jurassic and late Albian flooding events. As a result, the continental margin, when it was approached by the nappe complex, consisted of three submarine escarpments: Triassic/Jurassic, Lower Cretaceous and middle Cretaceous with a total bathymetric relief of well over 1.5 km.
3) The preservation of the Cretaceous autochthonous platform margin slope deposits indicates that frontal thrust was at seafloor and moved up along the carbonate slope margin. Or perhaps better expressed, the down-going Arabian plate bent sufficiently downward to preserve these sequences from thrust truncation beneath the nappes.
4) On the epeiric platforms significant changes in the palaeogeography started to occur during the middle Cenomanian and are related to reactivation of basement structures underlying both the Lekhwair area and the Huqf axis. These coincide with the onset of the subduction and formation of the Semail ophiolite some 235 km to the north. The basement re-activation may be related to a change in regional stress that led to the initiation of subduction.
5) During the Turonian, the infill of the intra-platform basins on the epeiric platform consists of forced-regressive wedges prograding southward away from the epeiric platform margin in the north, which was likely subaerially exposed. The relative sea level changes were in the order of several tens of metres and were likely driven by

eustacy as these also occur in other regions. Minor distal siliciclastic input from the west resumed in the Turonian but could be associated with eustatic changes and does not necessarily indicate anything tectonic. However, the lateral stacking of these wedges to the south suggests these may be superimposed on an overall uplift in the north. This could be evidence of a Turonian back-bulge situation. In which case the forebulge at this time would have been very wide and beneath the current Oman Mountains in Jebel Akhdar.

6) The BAU above the Turonian wedges is associated with regional incision of 100-200m in a belt some 100-200 km wide south of the thrust front. This incision could be evidence of southward-migrating forebulge uplift.

The next chapter will discuss the subcrop patterns and erosional features along the BAU and the type of structural deformation that controlled these features.

4 The base Aruma unconformity (BAU) – forebulge erosion?

4.1 Introduction

The purpose of this chapter is to review the stratigraphic and sedimentological evidence for uplift along the Base Aruma Unconformity (BAU) and the subsequent drowning of the plate margin and assess this evidence in terms of the model of forebulge and foredeep. This work is based on detailed mapping of the subcrop and onlap patterns on the BAU and sedimentological and stratigraphic interpretation of the overlying transgressive deposits (detailed in Appendix 1). The objective is to determine the presence/absence of a

migrating or non-migration flexural bulge and the influence of re-activation of pre-existing geological lineaments as observed in Chapter 2.

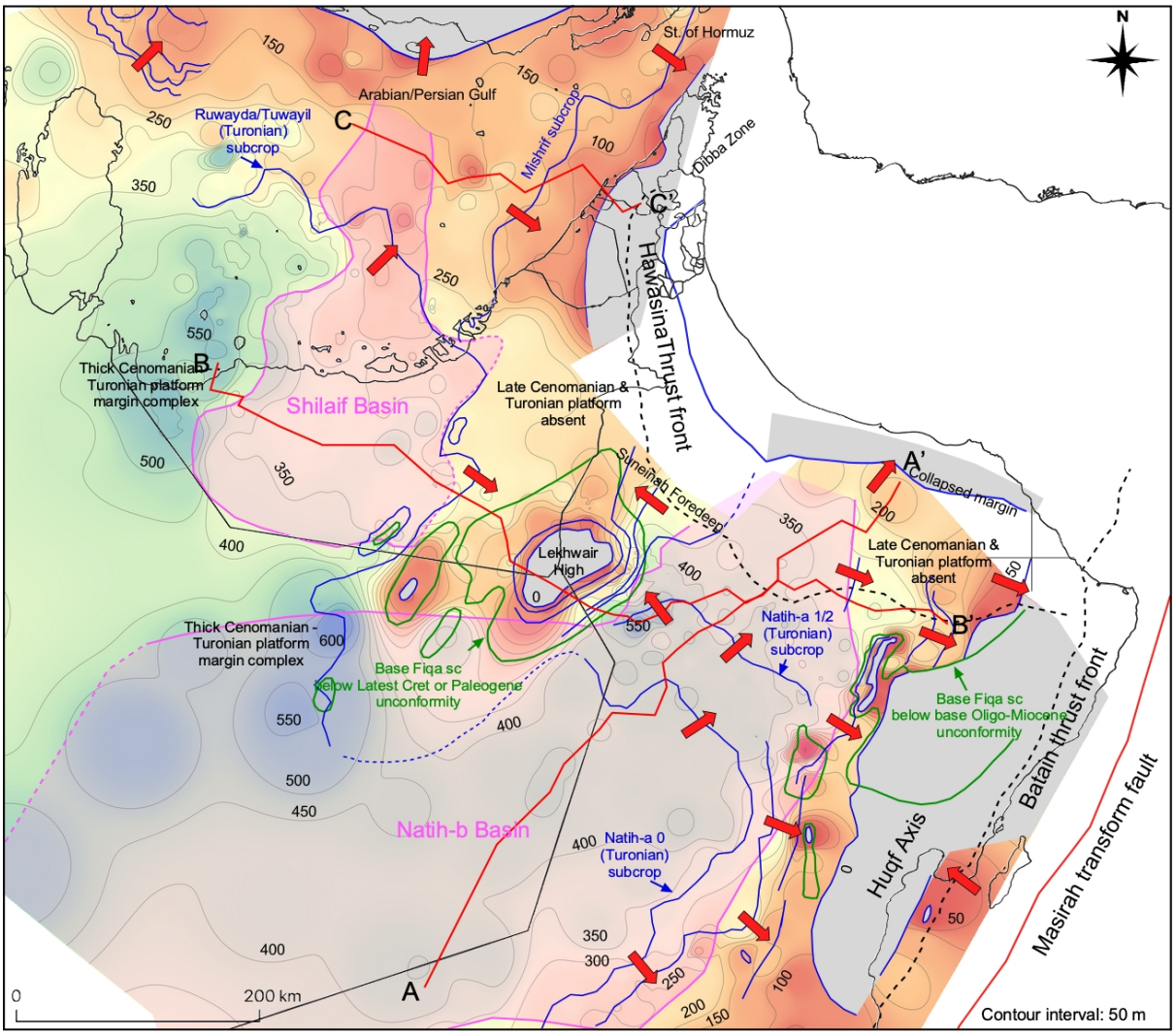


Figure 4-1 Map showing regional truncation, being the boundary between the Wasia and Aruma Groups, along the top of the Albian to Turonian platform. Red arrows indicate direction of increasing truncation, blue lines the subcrop of stratigraphical units and green lines the subcrop of the Fiqa foredeep sediments below Late Cretaceous or Neogene unconformities. The isochores are based on inverse distance gridding of well data and only show general trends. The data for the map has been compiled and reinterpreted from various studies: Al-Zaabi et al. (2010); Bromhead et al. (2022); Burchette and Britton (1985); Craigie (2015); Droste and Van Steenwinkel (2004); Franco et al. (2021); Franco et al. (2018); Murris (1980); Newell and Hennington (1983); Patton and O'Connor (1988); Piryaei et al. (2011). Cross sections are shown in Figure 3-6 and -7 (A and B) and Figure 4-3 A (C-C'). The figure shows two broad trends: the influence of a series of NE/SW trending highs and truncation towards the north or northeast.

4.2 Regional erosion of mid Cretaceous platform

The mid-Cretaceous carbonate platform is truncated by a major regional unconformity, the BAU, with uplift and erosion that is recognised over large parts of the Arabian Plate, in the Zagros, the Arabian Gulf area, Saudi Arabia and Oman (Harris et al., 1984; Murris, 1980). This unconformity is associated with the change from a passive to an active plate margin following the initiation of an intra-oceanic subduction zone in the southern Neo-Tethys ocean at 96.7 Ma (Robertson and Searle (1990); Searle et al. (2025). The unconformity is known as the "Wasia Aruma Break" in the Gulf area and Oman (Glennie et al., 1974; Patton and O'Connor, 1988; Robertson and Searle, 1990), the "Pre-Aruma unconformity" in Saudi Arabia (Cantrell et al., 2014; Le Nindre et al., 2008), and the "mid Turonian exposure surface" (mT-ES) in Iran (Mehrabi et al., 2022). It is the K150 Sequence Boundary (K150 SB) or the "Mid-Turonian unconformity" separating the middle Cretaceous AP8 from the Late Cretaceous AP9 tectonostratigraphic megasequence of Sharland et al. (2001).

An extensive review of biostratigraphic data around this unconformity by Simmons et al. (2025) shows that the youngest preserved rocks below the unconformity are middle Turonian in age c. 91.5 Ma (*Collignoniceras woollgari* ammonite zone or *Helvetoglobotruncana helvetica* planktonic foraminifera zone). The oldest rocks above the unconformity are within the same biostratigraphic zones. This would indicate a maximum duration of only 1-2 Myr. However, the palaeontological data points are scattered, and the minimum and maximum ages are not from the same localities. Offlapping geometries in the Lower Turonian and margin collapse in the Cenomanian (see previous section) suggest that the tectonic activity occurred over a longer period. The minimal age difference of rocks occurring below and above the unconformity is rather a strong indication that the

unconformity is diachronous or polygenetic: it could, for example, be related to eustatic sea level fall in some places or a migrating flexural bulge on others (examined below).

As concluded in the previous chapter, the major truncation along the Mesozoic platform margin in north Oman suggested in earlier studies (Glennie et al., 1974; Rabu et al., 1990) and shown in Figure 1-8 and 8, is here considered to be related to a combination of lateral facies variations from platform margin to slope with platform margin collapse and is not related to uplift associated with subaerial exposure.

Isochore trends for the Albian to Turonian carbonate platform show thickness variations of several 100 m.(Figure 4-1). These are caused by the combined effects of regional uplift, differential compaction related to facies changes and burial depth variations, salt diapirism and, in north Oman, valley incisions. On a regional scale the map shows that thinning of the Albian to Turonian platforms occurred along the major NE-SW trending highs of the Huqf axis, Lekhwair High, the Dibba zone and a possible axis in southeastern Iran along the Strait of Hormuz. Subcropping patterns clearly show that major thinning is related to truncation and (re-) activation of the highs during a pre-Aruma tectonic event (Figure 4-1). These highs were also active during later Cretaceous and Neogene deformation phases, and the superimposed unconformities make it difficult to assess the total amount of erosion specifically due to the pre-Aruma uplift. However, in those areas where the Aruma unconformity is directly overlain by Coniacian to Lower Santonian transgressive deposits it can be shown that the truncation was substantial.

Along the Huqf axis the BAU overlies the Natih Formation in the northwest but cuts down to the Neoproterozoic Nafun Group in the east. The truncation of the Natih below the base Aruma is clearly seen on seismic data (Figure 4-2). In the offshore Masirah Bay area

further east, well data show that the Aruma again overlies the Natih Formation (Beauchamp et al., 1995), suggesting that the main uplift was located in the eastern part of the Huqf High, close to the present day shoreline. Although earlier truncation events removed a lot of section in this area, it can be seen from a cross section on the geological map (Dubreuilh et al., 1992) that at least some 700 m of missing section can be assigned to the base Aruma event.

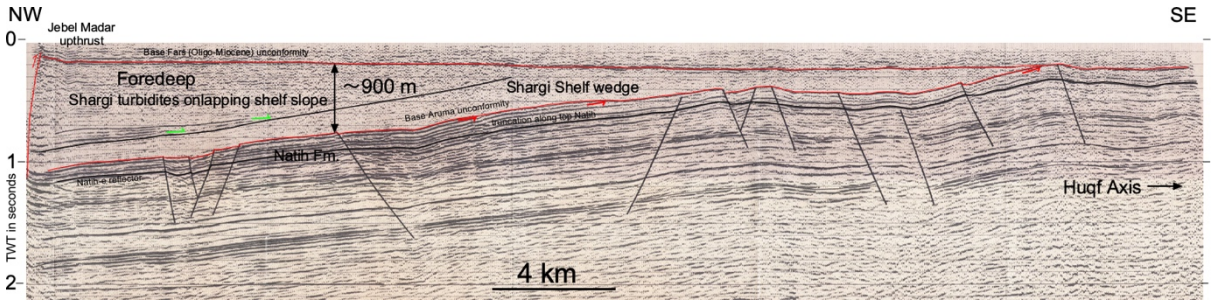


Figure 4-2 NW-SE trending vintage 2D seismic line from the Huqf axis in the east into the foredeep towards the Jebel Madmar up-thrust. A clear angular truncation of the top Natih below the BAU toward the SE suggests that the Huqf axis experienced uplift before flooding by foredeep sediments. The Lower Fiqa Fm/ Shargi Mbr. shelf wedge was deposited following the drowning, and on other lines in the area clinoforms indicate northward progradation into the foredeep. The reflectors onlapping on the shelf wedge are turbidites of the upper Shargi Mbr. The Late Cretaceous sequence is truncated beneath the Oligo-Miocene Fars Formation. The upper part of the foredeep infill (Upper Fiqa Fm. and Palaeogene Hadramaut Group) are not preserved, indicating a time gap of more than 35 Ma. Location: SL-1 in Appendix 4.

Further north along the same axis, south of Saih Hatat the unconformity reached the Nahr Umr Fm., as shown by well data. Outcrops at Wadi Minzif suggest at least 200 m additional erosion compared to nearby wells with complete sections.

Figure 4-2 shows a clear angular truncation of the top Natih below the BAU toward the SE suggests that the Huqf axis experienced uplift before flooding by foredeep sediments. The Lower Fiqa Fm/ Shargi Mbr. shelf wedge was deposited following the drowning, and on other

lines in the area clinoforms indicate northward progradation into the foredeep (i.e. towards the thrust front).

On the crest of the Lekhwair High both the Natih and Nahr Umr have been eroded, and the Aptian Shu'aiba Formation is overlain by the base Palaeogene unconformity, which overprinted the BAU (Figure 3-7). It is not possible to determine how much erosion is accounted for by the BAU. Significant thinning of the Shargi Mbr. below the base Simsima Mbr. on the flank of the high suggests that the main erosion occurred during an intra-Aruma event. However, well data along the flanks of the Lekhwair High show that at least some 100 m of erosion occurred pre-Aruma.

Wells drilled in the northern offshore of Qatar also indicate that some 200 m of the platform was truncated (van Buchem et al., 2014).

In the Straits of Hormuz and the northern Emirates erosion reached the Nahr Umr and was at least 200 m. Here Patton and O'Connor (1988) interpreted the truncation patterns as evidence for the development of an early peripheral swell located in a fixed position close to the edge of the platform margin (Figure 4-3). Best fit lines through the profile suggest a swell with a width of 150 km and a height of 244 m. However, the modelled flexural rigidity (D= 3.87 x 10^{22} Nm foredeep filled with water and D= 1.18 10^{22} Nm foredeep filled with sediments) associated with this profile is much lower than anticipated for a typical continental lithosphere. They suggested a combination of the effects of thermal age, a larger amount of lithospheric extension during the rifting of Neo-Tethys and horizontal compression by loading of the nappes. The Cenomanian/Turonian swell was buried below the foreland

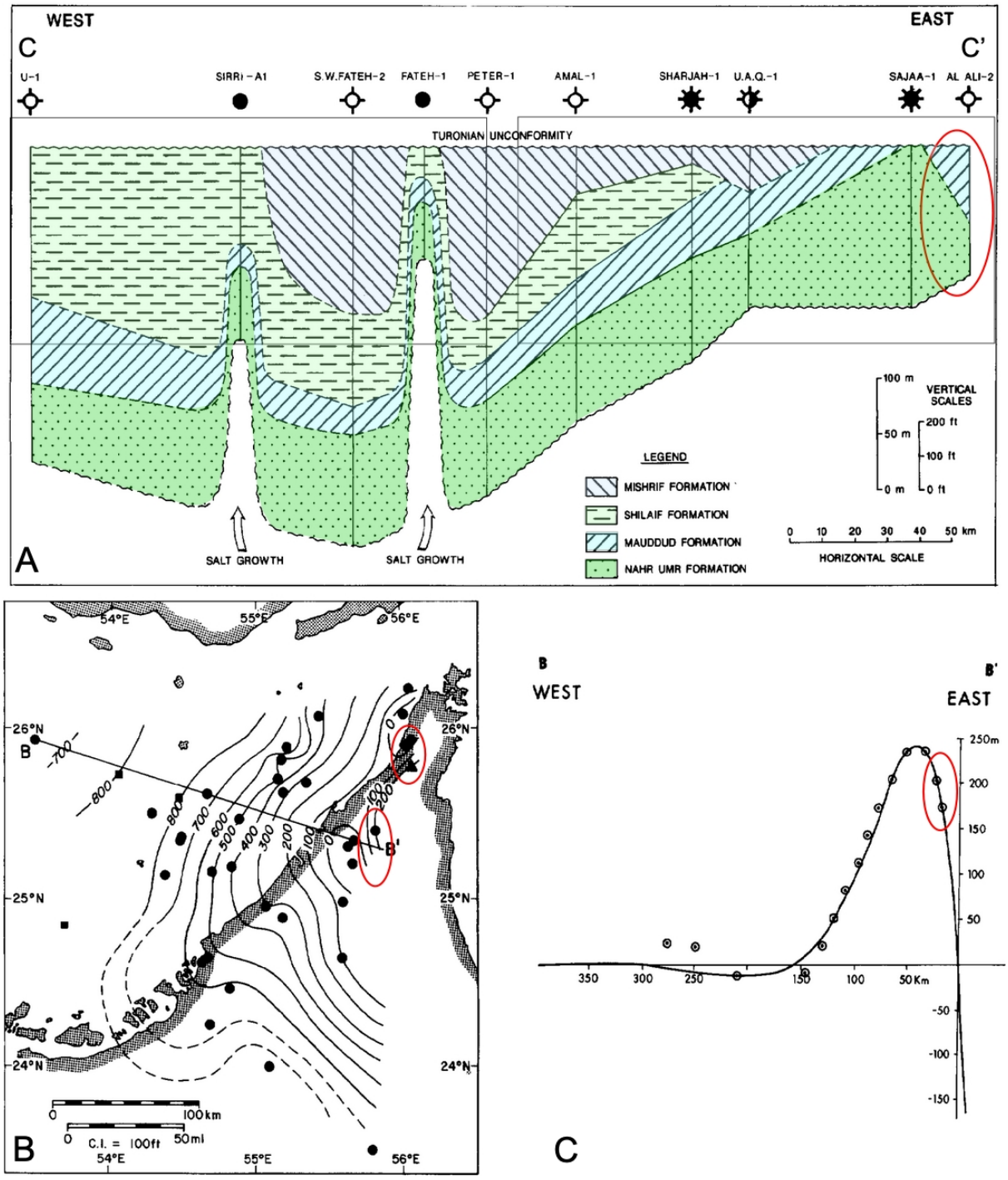


Figure 4-3 Flexural deformation and formation of peripheral swell in the UAE northern foredeep area A: Well correlation panel of Wasia Group flattened on the BAU showing regional thickness variations due to local salt tectonics and regional uplift in the east. The easternmost well suggests thickening east of the swell but it also shows unusual stratigraphy and facies. For location see Figure 4-1 and XS-12 in Appendix-4. B: Isopach map in feet of top Nahr Umr to BAU interval, red circles are areas where closure of the bulge is suggested, however the stratigraphic interpretation here is questionable, see text. C: Reconstructed structural profile of swell, see B for location. Modified from Patton and O'Connor (1988).

basin, following an abrupt migration of the flexure some 200 km towards the west, as thicker

continental crust was directly loaded by the allochthon during Coniacian times. The inferred forebulge geometry is based solely on the re-appearance of stratigraphy NE of the maximum truncation indicated by one well at the end of their cross section. This well, Al Ali-2, shows Mauddud Fm. overlying a much-thinned Nahr Umr Fm. It makes the swell very asymmetric to the east. The log response, lithology and thickness are very different from other wells in the area, which show a much more calcareous Nahr Umr and the interpretation of the Nahr Umr and overlying limestone is questionable. Sharp contacts between units may indicate thrusting. Further north, outcrops in Dhayah (Ras Al Khaimah, UAE) with Mauddud exposures are also suggested to be located east of the crest. However, a few km north of this area, the closest well penetrations that were used to define the crestal location, show that the Nahr Umr is cut by the Neogene. The suggested forebulge geometry in this area is questionable. A re-activation of a NE-SW basement lineament resulting in regional tilting is a more likely explanation. This explains better with the rigidity of the plate, and the discrepancy in timing, which is earlier than the Aruma foredeep formation. In the UAE and northeastern Saudi Arabia NW-SE anticlinal structures started to form during the Late Cretaceous (Figure 4-4, Johnson et al. (2005); Stewart (2016)). The deformation is thought to be related to reactivation by NW-SE compression of N-S trending basement lineaments by wrench faulting (Marzouk and Sattar, 1993; Marzouk and Sattar, 1994), or gentle inversion of deep-seated grabens (Johnson et al., 2002), or buttressing of sediments against pre-existing basement faults (Richard et al., 2017). Erosion below the BAU along the crests shows that some of these structures were already active during the Cenomanian-Turonian (Ali and Farid, 2016; Franco et al., 2018). Syn depositional structuration during this time is also indicated by the infill of salt withdrawal and structural depressions with thick (> 150 m) non-marine, ostracod-bearing clays and carbonaceous muds (Franco et al., 2021). Similar anticlinal structures also

occur in Oman, for example on the Lekhwair High and the Huqf Axis. Some tentative anticlinal trends in the Jebel Akhdar and Saih Hatat indicate folds with similar trends (Figure 4-4).

Away from the regional highs and the platform margin, thickness variations are more subtle (Figure 4-1). Over most of interior Oman the Natih platform thickness is between 400 – 450 m without clear trends. The Natih in the Oman Mountains outcrops is clearly thinner (200 m, Figure 4-1). As the stratigraphy seems complete, this could simply reflect increased compaction as these rocks were subject to burial of c. 12 km (Grobe et al., 2019) below the thrust complex, compared to depths of 1-1.5 km in the interior of Oman. Also, there is some stratigraphic thinning due to internal truncation and onlap of the lower and middle Cenomanian platform complex to the north. The correspondence of facies and thickness, namely thinner, more proximal, facies near the margin and thicker, basinal facies to the south, suggests a subsidence control. The increased subsidence of the platform interior may be related to isostatic sagging of the underlying Cretaceous carbonate interior platform, similar to what has been modelled for a Jurassic intra-platform basin further west by Aigner et al. (1989).

Thickness changes do not bring out a forebulge geometry. The main tests for a possible forebulge development are (1) subcrop patterns of the uppermost stratigraphic units in the Natih Fm. and (2) valley incisions away from the regional highs, observed on seismic.

4.3 Subcrop patterns

The base Aruma subcrop pattern between the Lekhwair and Huqf highs (Figure 4-1) is formed by Turonian depositional wedges prograding south-westward into the Natih-b intra-

platform basin that are truncated to the northeast (Figure 3-5 and -6, the wedges are within the unit labelled “Natih a/b platform complex”). These regressive wedges may themselves have been forced by uplift in the northeast (or they may onlap the platform rather than actually being truncated) but the cross section (Figure 3-6) indicates that the removed section could be more than 100 m.

In the Suneinah Foredeep area in NW Oman Boote and Mou (2003); Boote et al. (1990) show subcrop patterns of lower Natih members below the BAU, indicating truncation

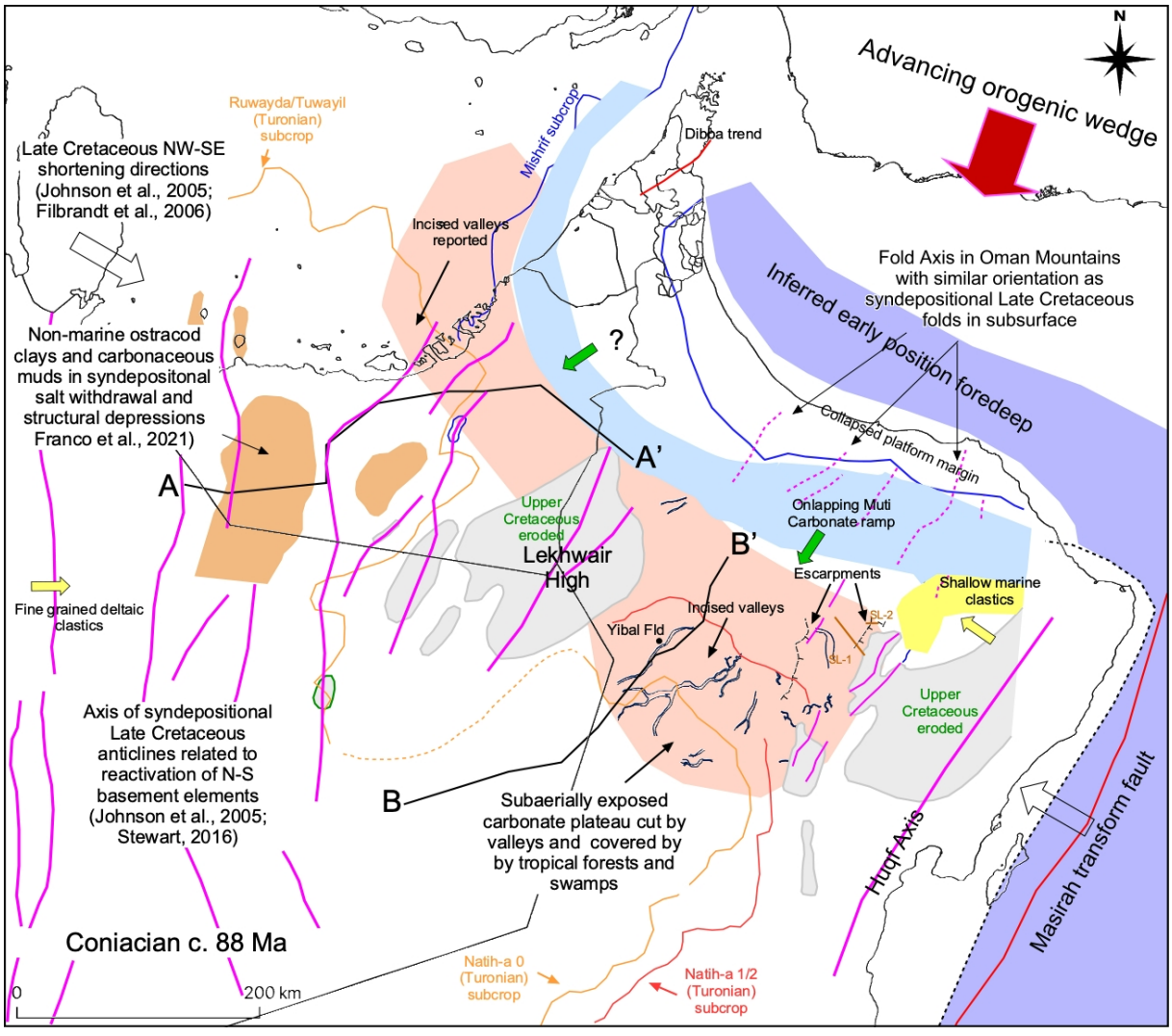


Figure 4-4 Palaeogeography and structural elements associated with the BAU during the Coniacian at c. 88 Ma. Location of seismic lines in black, SL-1 = Figure 4-2, SL-2 = Figure 4-6, Cross section A-A’ and B-B’ in Figure 6-4 and Figure 6-5.

towards the northeast. However, recent studies indicate that these subcrop patterns actually

follow NNE-SSW trends, with increasing truncation towards the Lekhwair High in the west and do not indicate uplift to the northeast (Butler and Al Shukaili, 2024).

In the eastern part of the UAE, west of the Shilaif basin, the platform carbonates are less than 300 m thick, much thinner than the 400 – 450 m in Oman. The carbonates probably are equivalent to Natih-e, and the upper Natih is absent due to differential uplift and erosion (O'Connor and Patton, 1986). However, data points are very limited and there is no data on the original thickness in this area or in the foredeep which could be used to determine any regional trends.

4.4 Valley incisions

Seismic data and closely spaced well correlations show a clear erosional topography along the top of the mid-Cretaceous carbonate platform (Droste and Van Steenwinkel, 2004; Filbrandt et al., 2006). 3-D Seismic mapping reveals a complex of deeply incised meandering channel systems along the top of the Natih Formation (Figure 4-5). The incisions can be up to 5 km wide, and some can be followed for more than 100 km (Figure 4-4). The large incisions cut down more than 150 m and are relatively straight, trending SSW-NNE in Central Oman. Branching of tributaries is suggestive of flow to the northeast. East of the Maradi Fault a more than 6 km wide channel system shows a S-N trend bending to the west in the north. An escarpment type feature on seismic mapped further west suggests that this valley system may be in an even wider N-S running depression.

Between the large incisions, which have a spacing of several tens of km, is a network of smaller channel systems which are more sinuous and have random orientations. They are up to a few 100 m wide and a few tens of metres deep. They show a km-scale spacing and drain into the larger incisions. Still smaller channels are likely to be present but are below seismic

resolution. The incisions have been observed in a belt c. 160 km wide that parallels the thrust front. They probably extend further north below the nappes, but no 3-D seismic data is available to confirm this.

Some abrupt changes in thickness at the margin of the incisions have been interpreted as erosional escarpments up to 80 m high (Figure 4-6). However, well calibration confirms that the apparent steepness of the incisions is simply due to the vertically

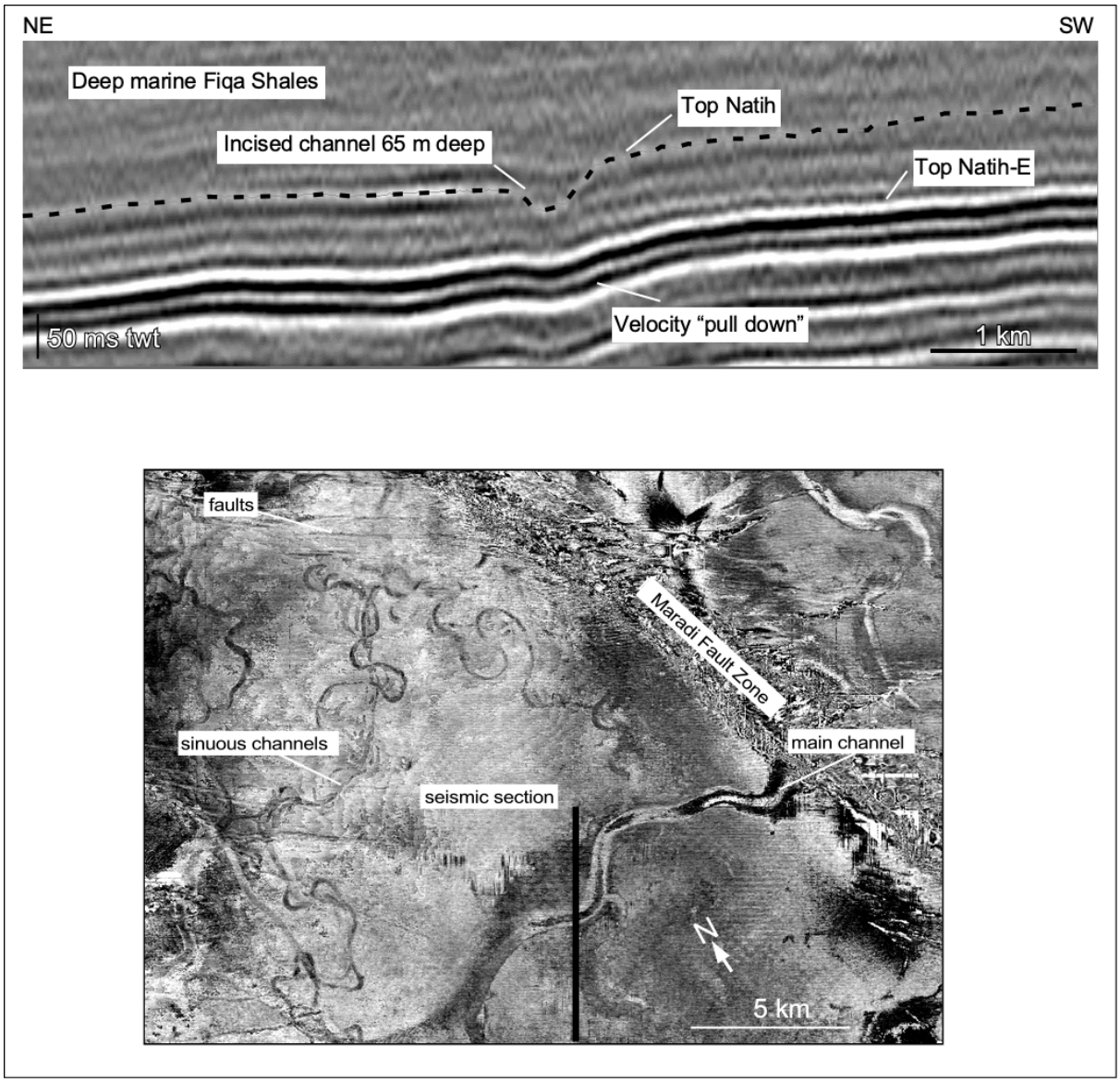


Figure 4-5 Channel complex cut into the top of the Natih Formation. Top: Seismic line through channel. Bottom: Amplitude map along time slice 44 ms TWT (c. 75 m). below Top Natih horizon in north Oman, showing a complex of narrow sinuous channels and wider northeast-southwest–trending main channel. TWT = Two-way travel time. Modified from Droste and Van Steenwinkel (2004).

exaggerated seismic display. Also, the seismic expression of the channels is enhanced by seismic velocity differences between the fast carbonate host rock and the slow shales of the infill, causing a “pull down” effect and a yet more enhanced depression in the time domain.

Well correlations in densely drilled oil fields show that the slopes are in the range of only a few degrees with a maximum of 12°, corresponding to a gradient of some 21% (Figure 4-7). The km-scale seismic channel belts actually represent a gentle fluvial valley topography, rather than canyons and may have looked very similar to present day chalk landscapes such as the Chilterns in the UK, shown in (Figure 4-8). During the Cretaceous Oman was in a tropical humid climate, as indicated by lignitic shales with plant fragments, and in the UAE coal deposits, overlying the BAU.

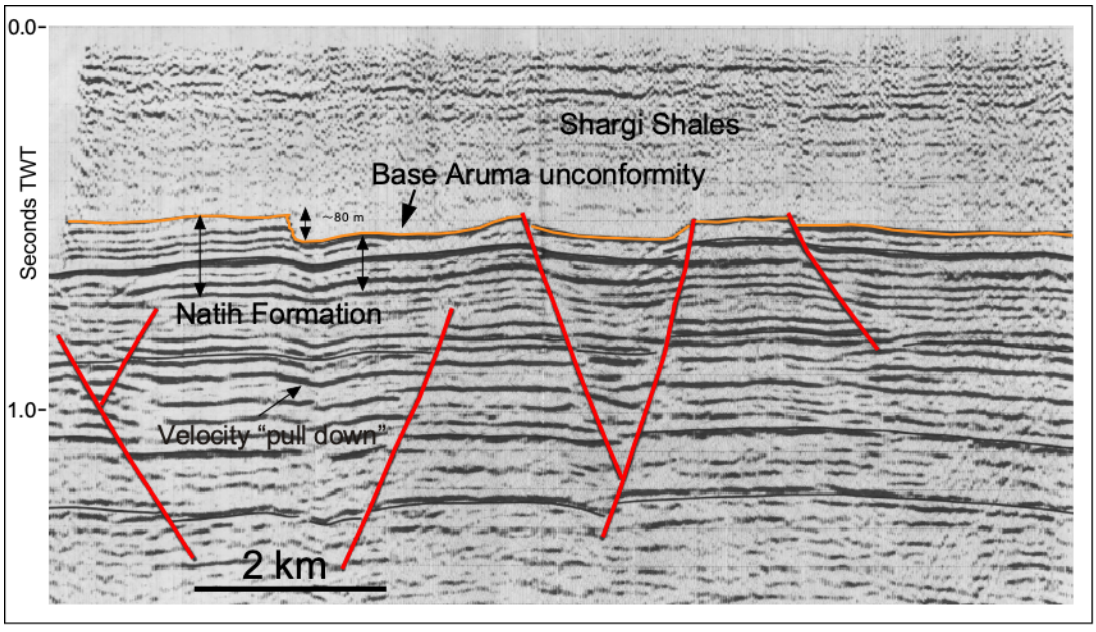


Figure 4-6 2-*D seismic line showing sharp truncation at top Natih. The drop of the top Natih is not related to faulting and associated with a clear thinning of the Natih interval. At lower levels a “pull down” effect due to velocity contrast between Natih carbonates and Shargi shales is visible. The “escarpment” is some 80 m high. TWT = Two-way travel time. For location SL-2 in Figure 4-4 and Appendix-4. Modified from Lidster and Horsfield (1984).*

3-D Seismic maps sometimes show cross-cutting of channel systems; these probably represent smaller rivers which entered the main valley from the flanks and then follow the

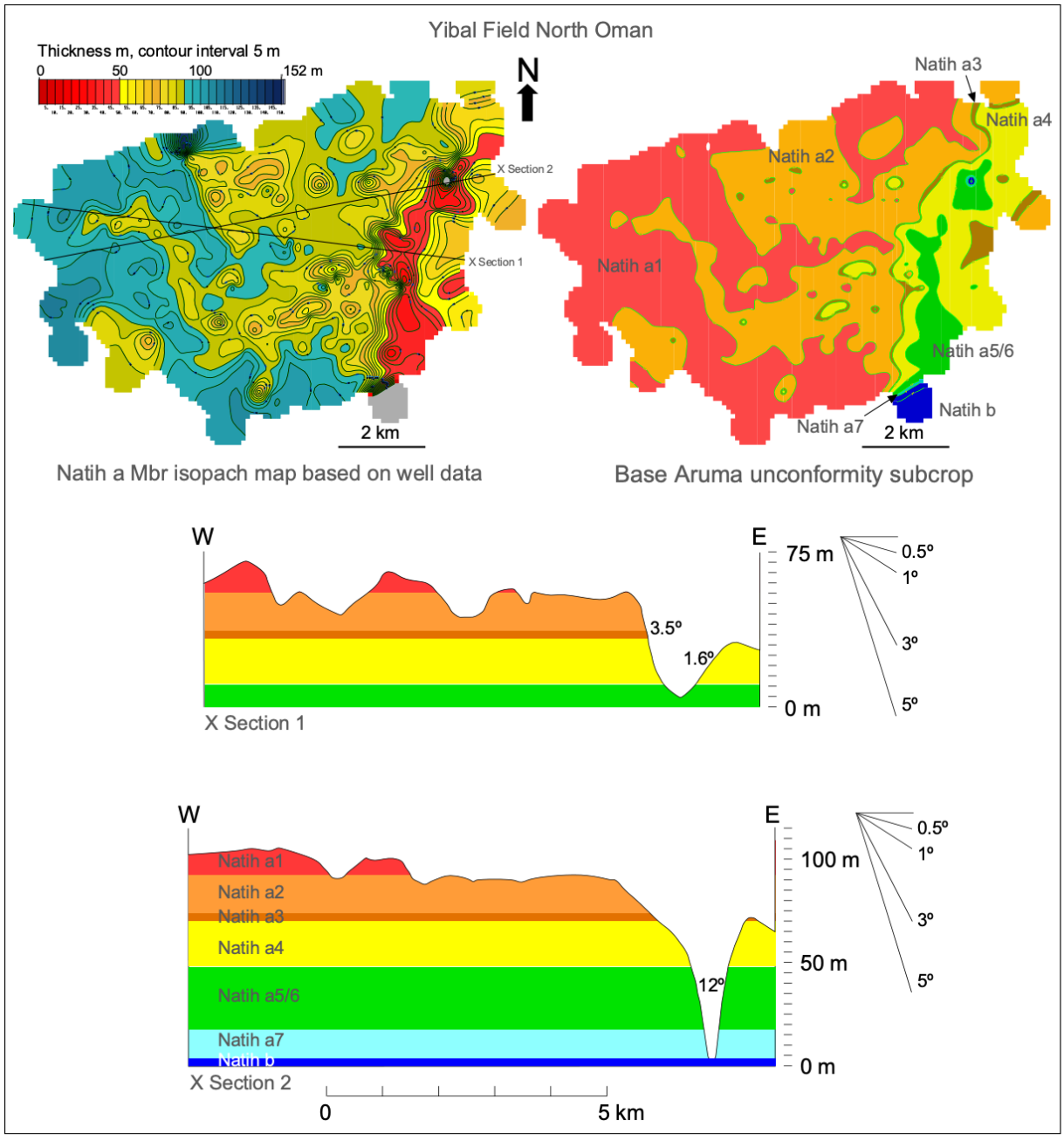


Figure 4-7 Illustration of erosional topography at the BAU in the Yibal Field in North Oman. The isopach map (upper left) of the Natih a member at the top of the Natih Formation and a subcrop map (upper right) of the BAU are based on a densely spaced (200 – 500 m) well dataset covering the field. The maps show the topography is formed by a network of channels cutting into the different Natih a reservoir units. The two cross sections in the lower part of the figure illustrate the topography along the BAU, assuming no structural deformation and the same amount of relative uplift across the field. (Location of cross sections is shown in upper left map). The channels cut down to some 120 m deep, in places removing the whole Natih-a member. The dips of the flanks of these channels are only a few degrees (compare with the scale on the right).

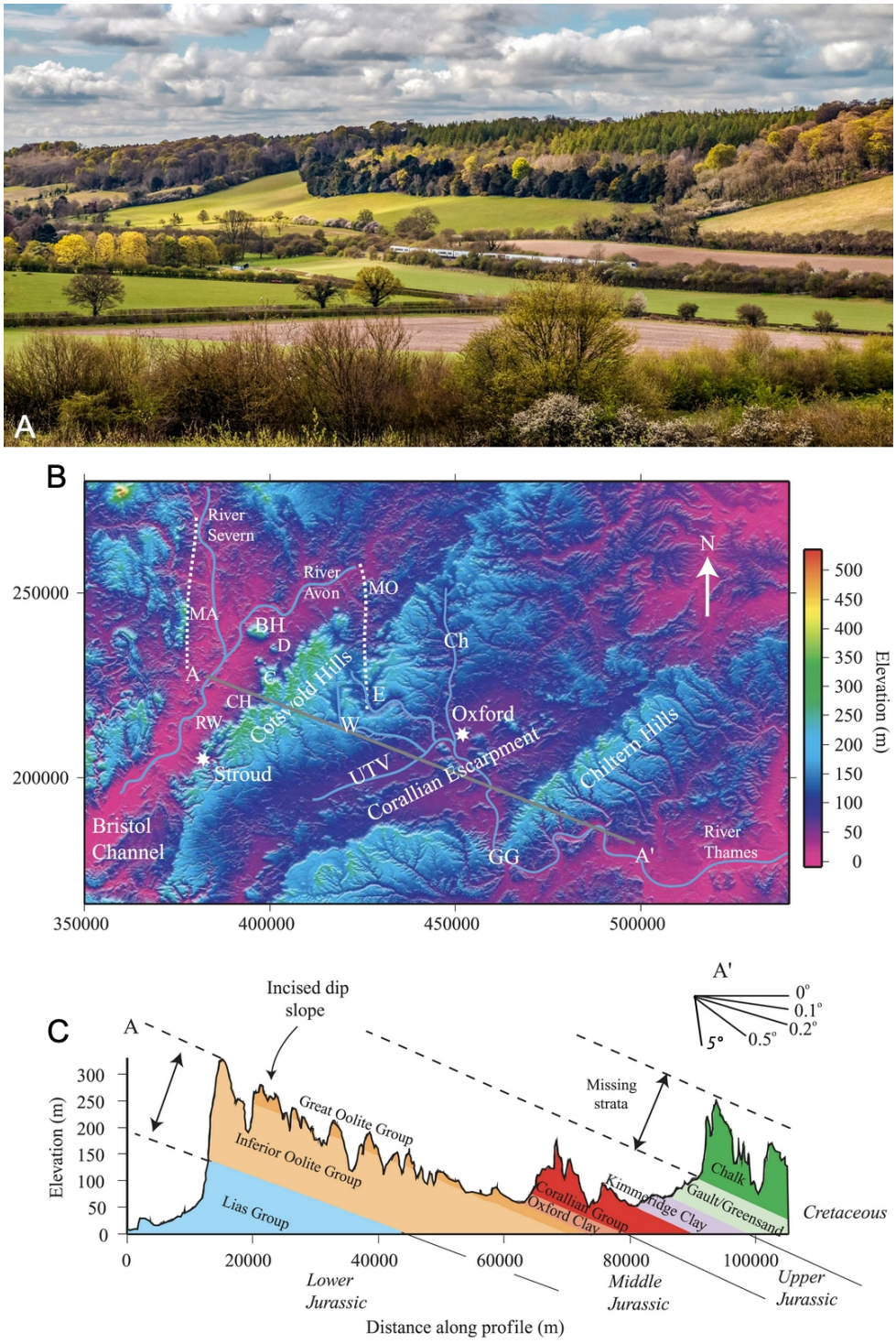


Figure 4-8 A: Photo of dry valley system cut into a chalk landscape at Bradenham, Chilterns, UK. The topography is very similar to that of the BAU on top of the predominantly muddy mid-Cretaceous Natih limestones in Oman. B: Topographic map from NEXTMap Britain DTM and C: a cross section of the Cotswold region, showing a valley relief which for up to 50% was controlled by flexural uplift. The valleys have a similar scale as those along the BAU in the Yibal Field shown in Figure 4-7. Photo by H. Mothersole from National Trust website: www.nationaltrust.org.uk. Satellite photo and elevation profile from Google Earth. B and C modified from Lane et al. (2008).

main valley, with incision into the valley floor.

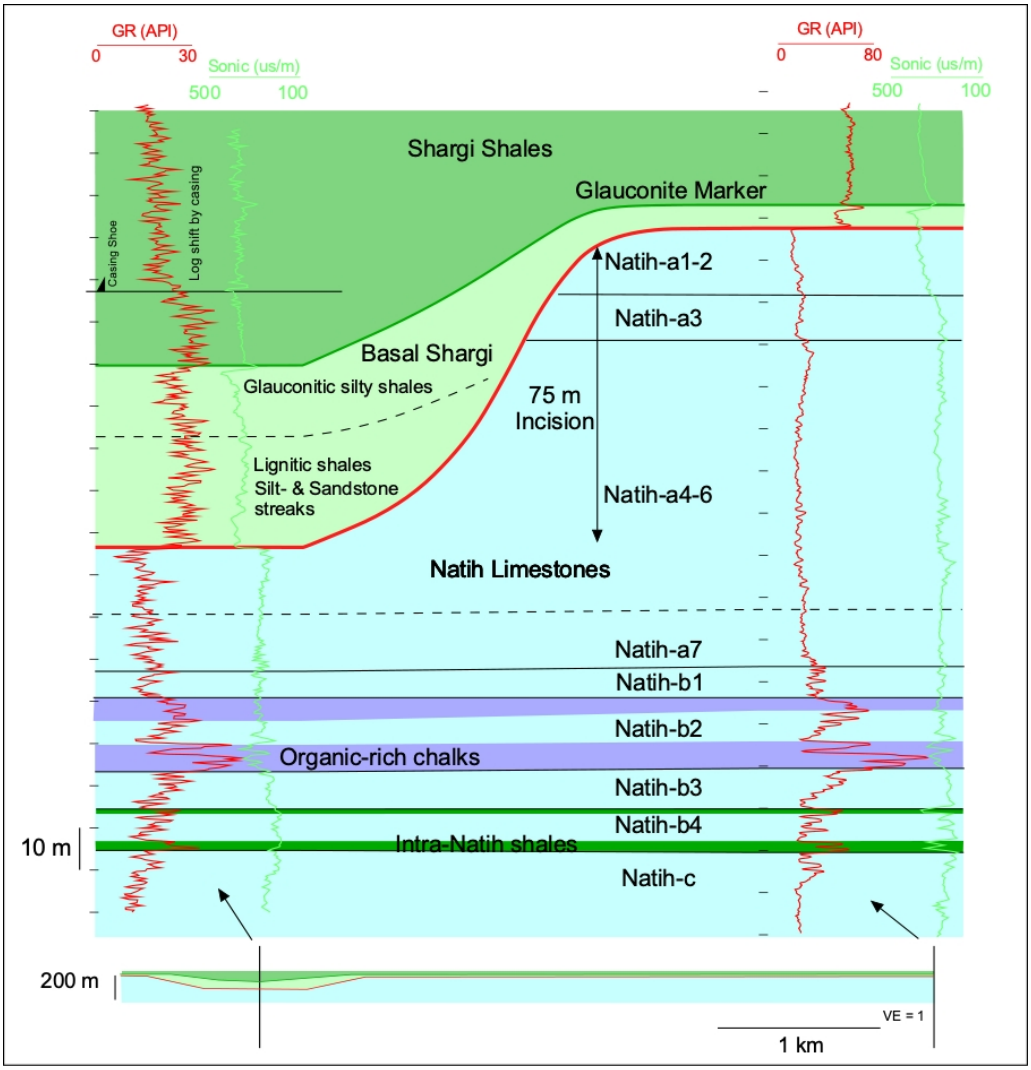


Figure 4-9 Well correlation showing the infill of the pre-Aruma topography by the basal Shargi in North Oman. The well on the left is located within a valley recognised on seismic. The valley is about 1200 m wide and can be followed over more than 80 km. The well on the right is located on the eroded carbonate platform interfluve flanking the valley. The present-day thickness of infill is less than the erosional topography because of differential compaction between the Natih limestones and the fine clastics of the basal Shargi. The serrated log response of the well in the incision is an acquisition artifact as the log was run through casing.

The basal sediments of the Aruma Group fill and onlap the valley topography (Figure 4-9). These shales are non-fossiliferous and contain up to 30% lignite, especially in the basal part. The shales also contain silt and sandstone streaks, which contain small planktonic foraminifera and traces of glauconite and pyrite. The shale interval is capped by an iron oolite-bearing, glauconitic claystone, which is overlain by normal Fiqa Fm. shales with

abundant planktonic and benthonic foraminifera. On well logs the infill is characterized by slightly lower gamma reading than for the Fiqa. The shales probably were deposited in a coastal lagoon/swamp with occasional influx of marine sands and silts. In the southern Arabian Gulf several metres of coal and palaeo-soils, rich in organic material, have been encountered on top of the Aruma unconformity. This suggests a humid climate with development of swamps, at least seasonally (Burchette et al., 2010).

The Fe oolite interval represent a major drowning and transgressive surface. The overlying Fiqa shales are deep water deposits.

Cores in the Fahud Field show karst-related in-situ breccias and a karstic pipe network with Fiqa shales extending down 10-15 m into the Natih. The lignitic material suggests that the exposed Natih platform was covered by vegetation. The patchy distribution of the oldest Coniacian sediments may be controlled by their deposition in lows formed by valley systems cut into the Natih carbonates. The sediments were deposited in restricted lagoonal settings in valley fills, at the onset of rapid submergence of the exposed Natih carbonates during the Coniacian to Santonian. Lack of siliciclastic input may explain the absence of any well-developed beach barrier system. Instead, a condensed sequence of glauconitic sands and chamositic ooids form the transgressive lag. The system may have looked like the present-day, sediment-starved, drowned river valleys in Kingsbridge shown in Figure 4-10.



Figure 4-10 Google Earth satellite image of Kingsbridge estuary in Devon, England, a recent analogue for the drowned river valleys during the onset of the base Aruma transgression. The large size of the estuary is related to little inflow of sediments through rivers. A similar situation can be expected during the Late Cretaceous transgression in Arabia, as the denudation of the slowly uplifted, relatively flat carbonate platform in a humid climate setting is dominated by chemical weathering (Ott et al., 2023).

Channels and possible sink holes and irregular karstic features have also been observed on seismic attribute maps along the BAU in the northern Abu Dhabi area (Franco et al., 2021; Neo, 1996; Vahrenkamp et al., 2015a). These channels show a NW-SE orientation. Neo (1996) also reports NW to SE trending channels up to 60 m deep and several km wide cutting into the top of the Mishrif Formation in a field located offshore Abu Dhabi City. The outline of the channels is based on horizontal well and 2D seismic data. The channels are filled with limestones, brecciated limestones and carbonaceous shales with abundant plant debris possibly filling smaller channels within the channel belt. Neo suggests the Upper Cenomanian - Turonian Ruwaydha and Tuwayil infill of the Shilaif Basin postdates the incision. However, as these two units are truncated by the BAU, they are related to earlier lowstand events, rather than the Aruma unconformity itself (therefore they are not shown in Figure 4-4). The orientation and depth of the channels suggest these channels, like those in Oman, may be related to the forebulge uplift.

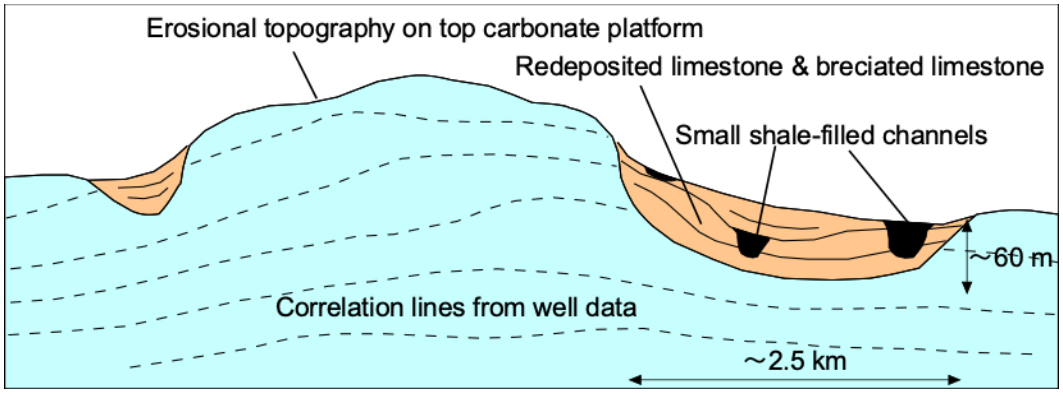


Figure 4-11 Geological model for channel topography and facies fill along top of Mishrif carbonates in an offshore field in the UAE. Figure shows present day structural configuration and has been modified from (Neo (1996).

4.5 Is the Lekhwair High a forebulge?

The Lekhwair High has been interpreted as a forebulge flexure in several subsurface studies (Boote and Mou, 2003; Boote et al., 1990; Loosveld et al., 1996; Warburton et al., 1990). However, it has been noted (Filbrandt et al., 2006) that the circular to elliptical subcrop pattern of the Mesozoic platform carbonates beneath its successive unconformities, including the BAU, does not support the notion of a linear peripheral bulge related to the emplacement of the allochthon. The objective of this section is to investigate whether this feature is related to Late Cretaceous flexural deformation or represents the reactivation of an older structural feature. This has been done by interpretation of a key seismic line and a geological cross section over the structure using well and seismic data, which is compared to the published section by Boote et al. (1990) used for the forebulge interpretation.

The cross sections are shown in Figure 4-12. The upper section is a correlation based on 4 wells, flattened on the Base Paleocene unconformity by Boote et al. (1990). This section orientation is SW-NE and runs from the northern crest of the high into the foredeep. The foredeep infill consist of Coniacian to Santonian shales of the Shargi Mbr., overlain by Campanian marls. The infill thins towards the Lekhwair High. The thinning has been interpreted to be related to uplift and erosion of the Lekhwair High during the late Santonian – early Campanian, followed by onlap of the later Campanian. This bulge postdates the BAU and is related to a younger unconformity between the Lower and Upper Fiqa. However, Boote et al. (1990) mention that their model is speculative due to ambiguities in seismic and well data. The suggested onlap between the two middle wells is inferred from seismic geometries which show flat reflections in the foredeep above a northward dipping sequence of the Mesozoic platform. Modern 3D Seismic studies in the Lekhwair and surrounding areas

highlight the presence of seismic artifacts in the 2D datasets. The Palaeogene section on the Lekhwair High is some 1200 m thick and a highly efficient multiple generator. These very

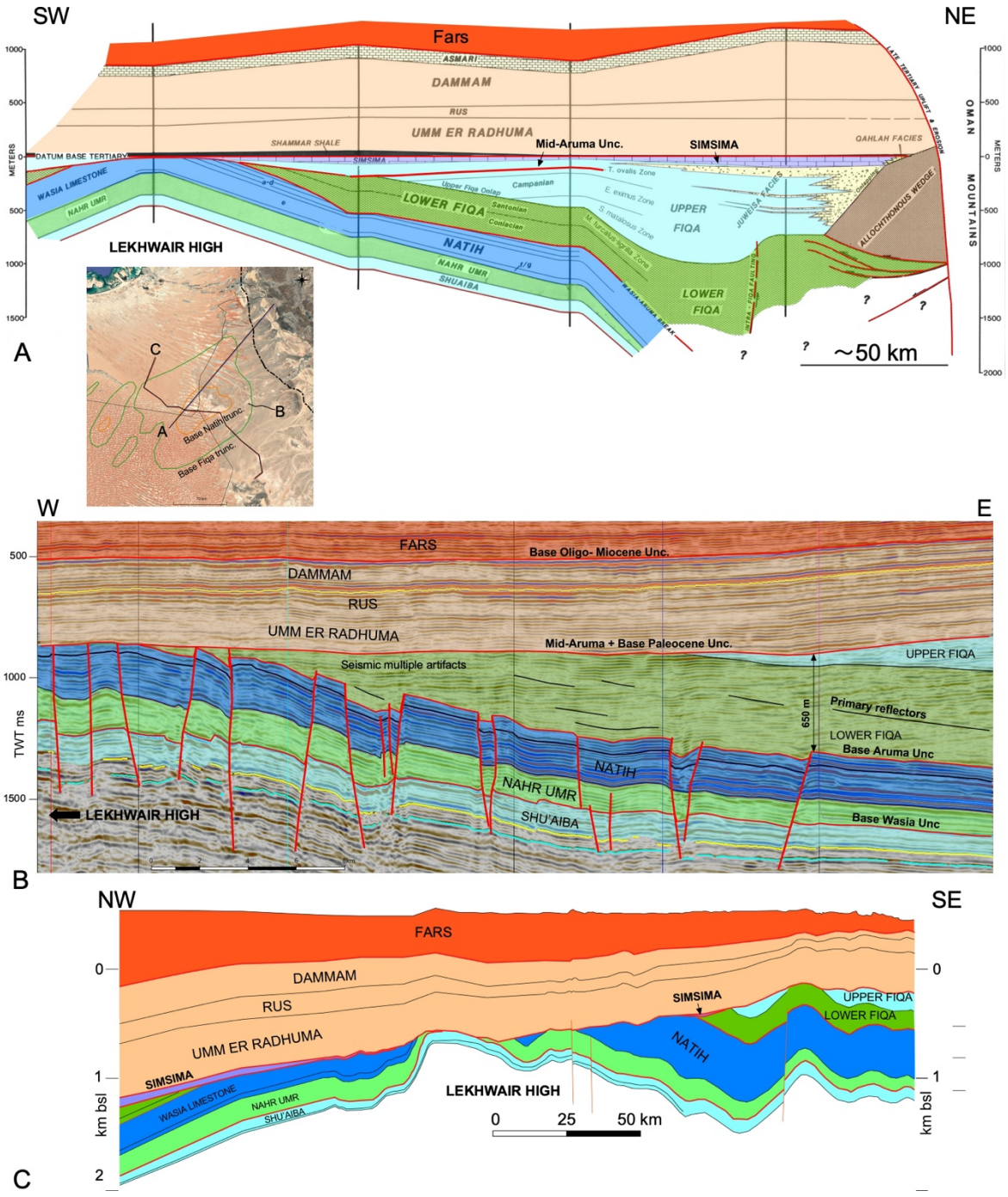


Figure 4-12 Geological and seismic cross sections of the middle and Upper Cretaceous across the Lekhwair High. A: Well-based cross section modified from Boote et al. (1990). Section has been flattened on base Paleocene unconformity. B: Re-interpreted seismic line east of the Lekhwair High showing primary reflectors and seismic multiples in foredeep fill. C: Section over southern part of Lekhwair High based on seismic and well data (20 wells). B and C based on own work. For location see Appendix-4 A=XS-13, B=SL-11 and C=XS-14.

strong multiples overprint much weaker reflections in the foredeep succession (Butler and Al Shukaili, 2023; Cullen, 1979; Hozayen et al., 2008; Melville et al., 2004).

This is illustrated in Figure 4-12 B by a seismic line east of the Lekhwair High re-interpreted for this study. The reflectors at the basal Fiqa still follow the Natih trend but in most of the overlying Fiqa the reflectors show a similar trend as in the Palaeogene overburden and – erroneously – seem to onlap the underlying sequence. However, some vague primary reflections can still be observed that are conformable to the top of the tilted reflections in the Natih and below. The prominent reflections in the foredeep fill are seismic artifacts. The thinning towards the Lekhwair High in the west is related to truncation between the Paleocene and the Campanian. On the eastern part of the section, it can be clearly seen that the Upper Fiqa marls (Arada Mbr.) are truncated at the top of the sequence. Wells located about 40 km to the SE in a similar position in the foredeep logged 1200 m of foredeep infill. This suggests the total erosion on the west side of the section likely exceeds 1 km.

The NW-SE depth section based on seismic and well data in Figure 4-12C also clearly shows that the main uplift and structuration of the Lekhwair High occurred in the uppermost part of the foredeep infill. On the west flank of the Lekhwair High a thin Simsima limestone is present below the base Palaeogene unconformity, on the east flank only a few scattered pockets have been reported. The base Simsima is conformable to the base Paleocene and clearly truncates the foredeep, as well as the mid-Cretaceous platform sequence. The Simsima itself is truncated by the Base Paleocene unconformity, which is due to a regional tilting event associated with uplift in the east. The approximate location of the mid-Aruma unconformity is indicated by the red line in the foredeep in Figure 4-12C.

In a 3D-seismic study over the crest of the Lekhwair High, Bazalgette and Salem (2018) observed NE-SW trending Jurassic normal faults, which they thought could be associated with a Triassic Jurassic rift event. They suggest these faults to have been reactivated during the Cretaceous, resulting in large wavelength, low amplitude folds with a NE-SW axis in the overlying Cretaceous carbonates on the high. According to Romine et al. (2004) and Al-Kindi and Richard (2014) the uplift of the high may be related to inversion of a Neoproterozoic graben along the Western Deformation front. On a more regional scale, as shown in Figure 4-12 C, it seems the high is located at the crest of a regionally tilted structure some 100 km wide, which seems to involve the western part of the Fahud Basement Terrane.

In summary, the late Campanian – early Maastrichtian timing of truncation as seen from seismic and well data, along with the circular to elliptical truncation patterns (Figure 4-1) do not support that the Lekhwair High is a peripheral forebulge. Instead, the main deformation occurred at the same time as the late Campanian – early Maastrichtian reactivation of structural highs in the UAE and Saudi Arabia (Franco et al., 2021; Melville et al., 2004; Powers, 1968).

4.6 Conclusions

1) There is evidence from thinning and truncation of minor structural deformation along a suite of large (hundreds of km) and small (km to tens of km) scale N-S to NE-SW trending anticlinal structures prior to and during the formation of the BAU.
2) There is little evidence for transverse structures, i.e. parallel to the advancing thrust front, other than the incision of broad valleys in a NE-SW trending belt in Oman.

3) There is no evidence for migration of structures away from the thrust front during the period Cenomanian through Santonian other than southward downstepping of Turonian lowstand wedges in a back bulge setting.
4) The largest amplitude active structures are related to pre-existing regional structural features. These were salt withdrawal structures in (from NW to SE) UAE, the Lekhwair High and the Huqf High.
5) The Lekhwair High is not a peripheral forebulge. The main deformation occurred well after the final emplacement of the nappes during a late Campanian – early Maastrichtian reactivation of a basement lineament.
6) In conclusion, the main subcrop patterns do not support development of major pre-Aruma forebulge uplift, they rather indicate reactivation of regional highs perpendicular to the thrust front.

The next chapter will discuss the distribution and nature of the transgressive deposits of the Turonian to Santonian Muti Fm. and basal Shargi Mbr of the Fiqa Fm. overlying the BAU. These record the drowning of the platform as it entered the foredeep.

5 Initial fill of the foredeep – The Muti Formation

5.1 Introduction

The objective of this chapter is to provide an overview of the stratigraphy, palaeogeography, and syndepositional tectonic history of sediments deposited during the initial development of the foreland basin. These sediments comprise the Muti Formation (Glennie et al., 1974) , which is bounded by the basal Aruma unconformity below

and the basal thrust of the obduction complex above, as well as its lateral equivalent in the subsurface south of the orogenic wedge in Oman: the basal part of the Shargi Member of the Fiqa Formation (Forbes et al., 2010).

This overview is based primarily on fieldwork conducted in the Oman Mountains, data from ten wells penetrating the Muti Formation in the foothill areas, and a comprehensive review of published outcrop and subsurface studies covering this stratigraphic interval. The chapter begins with a review of stratigraphic nomenclature and depositional interpretations from previous studies. This is followed by a description of the Muti Formation along outcrop transects, based on new fieldwork in the Oman Mountains and foothills, together with a review of subsurface data from Oman and the UAE. The final section presents new sedimentological and tectonostratigraphic interpretations of the Muti Formation along with an updated stratigraphic description. These interpretations form the basis for a newly proposed tectonostratigraphic model applicable to both outcrop and subsurface data.

5.1.1 Previous studies

5.1.1.1 Haremboure and Horstink (1967)

The Muti Fm. was originally defined by Haremboure and Horstink (1967) in an unpublished report by Petroleum Development Oman (PDO) as one of the formations in the Hawasina tectono-stratigraphic unit in the Jebel Akhdar, Nakhl, Saih Hatat, Hamrat ad Duru and Sufrat ad Dawh areas. This unit was considered to be autochthonous to parautochthonous and consisted of folded, more or less chertified shales with lenses of limestones, limestone conglomerates and calcareous sandstone. It was interpreted as slope to basinal deposits of ?late Santonian to ?early Campanian age, with a total thickness estimated at c. 440 m. They mention conglomeratic limestone lenses with a mainly

Cenomanian source and locally, whitish conglomerate boulders with abundant Permian fauna. In turbidites in the upper part of the formation reworked Jurassic fauna was also reported. In their definition, the Muti Fm. unconformably overlies Permo-Triassic to mid-Cretaceous platform deposits, locally with a ferruginous oolite on top of the Natih. It was overthrusted by the Hamrat Duru Tectono-stratigraphic unit, composed of limestones and

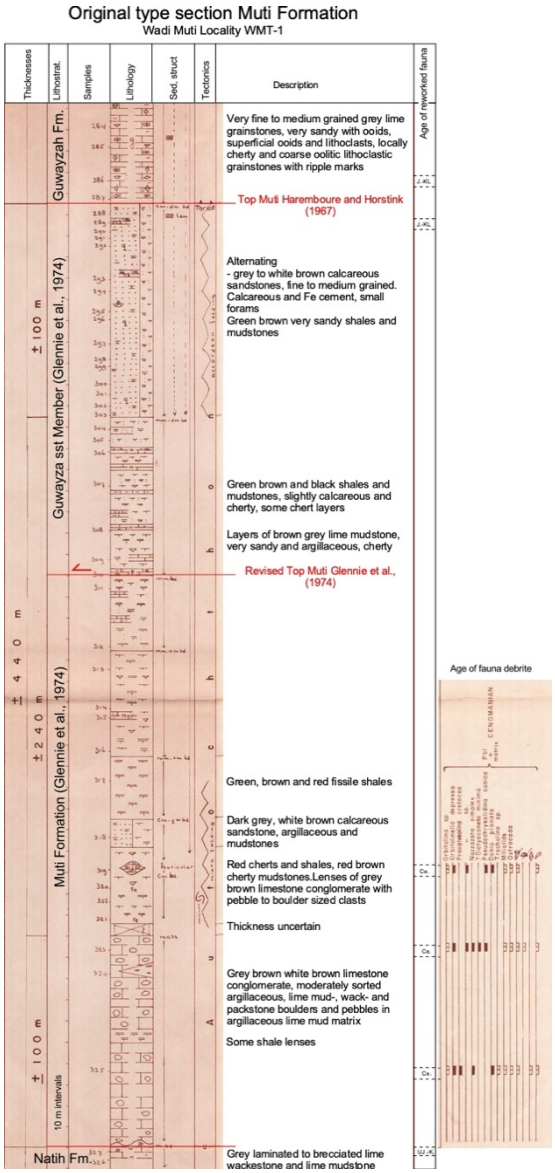


Figure 5-1 Original log of the Muti Fm. type section by Haremboure and Horstink (1967) which was also used for the re-definition of the formation by Glennie et al. (1974). The latter moved the siliciclastic turbidites in the upper part of the original Muti into the allochtonous Hamrat Duru Group as the 'Guwayza Sandstone Member.' The interval above the basal debrite is poorly exposed and deformed. The right column shows age dating of fauna from the debrite clasts which is Cenomanian. There are no data suggesting presence of Permian clasts in the debrite as indicated on the log shown in Glennie et al. (1974). Modified from Haremboure and Horstink (1967).

cherts with redeposited Jurassic fauna, and deposited in a slope to basinal setting. The section in Wadi Muti (Wadi Imti) was assigned as type locality, and the original section log is shown in Figure 5-1.

5.1.1.2 Glennie et al. (1974)

Based on biostratigraphic data showing an Early Jurassic to Late Triassic age for the sandstones in PDO's Upper Muti, Glennie et al. (1974) realised that the main thrust was in the scree below the turbidite unit and redefined the top of the Muti Formation at a difficult to locate thrust plane below the base of the turbidites. Hence, the turbidite unit was included into the allochthonous Hamrat Duru as the Guwayza Sandstone Member (Figure 5-1).

The Muti was defined as a flysch-like sequence of shales and marls with turbidites and conglomerates of Coniacian to Campanian age. The type section only contains a thick monomict debrite interval with Natih clasts at the base overlain by a poorly exposed interval containing shales, cherts and sandstones. However, the debrite shows strong lateral thickness changes and is not present over the whole area. In most areas the formation is dominated by indurated marls/shales with various amounts of fine-grained lithoclast debris, in places overlain by the debrites. Glennie specifically mentions that the Muti does not contain any debris derived from the Hawasina or Semail thrust sheets, but at the same time, report that some of the facies of carbonate pebbles in the formation are only known from lithoclasts in the allochthonous units. The absence of debris from the thrust stack is a key component of the Glennie model, which suggests that conglomerates were sourced from an uplifted and exposed shelf edge in the north before emplacement of the Hawasina and Semail thrust sheets (see Figure 1-8). Glennie et al. (1974) suggest the Muti is not only

restricted to the sub-thrust sequence as they also include Coniacian to early Santonian distal more siliceous facies in the Sumeini Group near Jebel Ghasnah and Dibba in the Muti as facies variations (Qumayrah and Riyamah facies respectively).

5.1.1.3 Robertson (1987a and b)

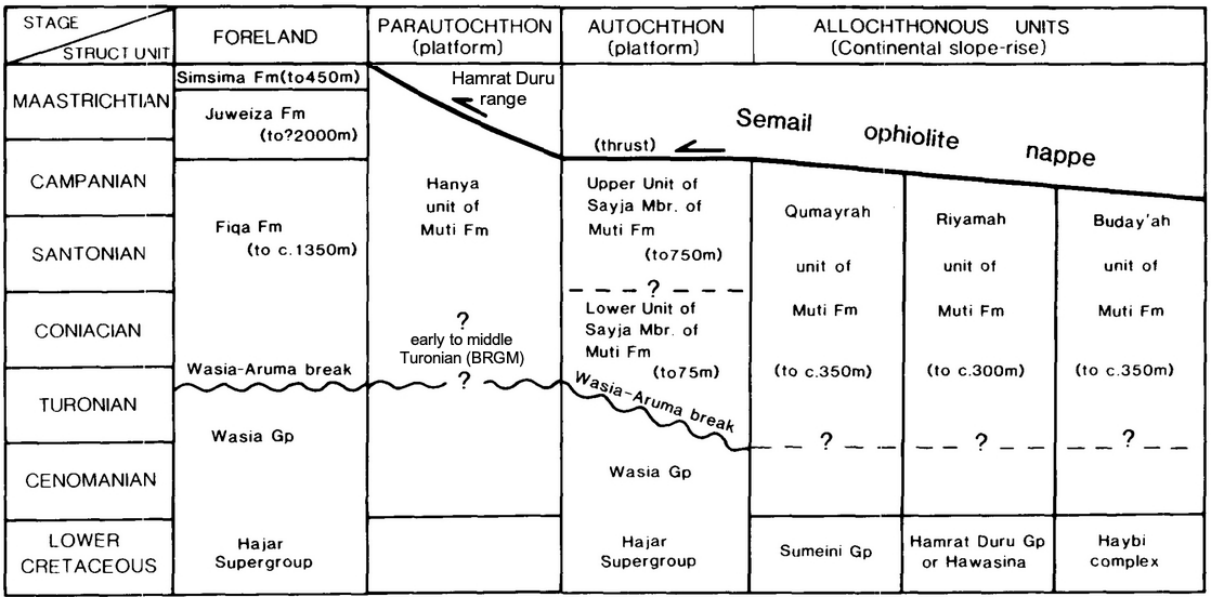


Figure 5-2 Stratigraphic subdivision of the Muti Fm. by Robertson (1987a). Modified from Robertson (1987a).

Robertson (1987a and b) presented a more detailed description of the Muti Formation. He expanded the extent of the Muti Formation across different tectonic units and proposed a subdivision into five age-correlative units (members) each occurring separately within the autochthonous and various allochthonous sequences (Figure 5-2). The Muti Fm. was considered to be syntectonic and formed during the transition of a passive margin to a foreland basin during the ?late Cenomanian to late Campanian (Figure 1-10). It includes carbonate platform, slope and abyssal plain sediments. Robertson's autochthonous Sayja unit is equivalent to the classical Muti overlying the Mesozoic carbonate platform described by Glennie et al. (1974). He subdivides this into a lower and upper interval (Figure 5-3). The lower interval is some 75 m thick. It consists of concretionary and argillaceous limestones

with some ferruginous and phosphatic deposits, bioclastic packstones with iron formation, which deepen upward into hemi-pelagic marlstone facies. His upper interval is up to 700 m thick and can contain a wide range of lithologies: non-calcareous shale, turbiditic quartzose siltstones and sandstones, calciturbidites, lithoclastic debris-flows and detached block of platform lithologies. Locally, up to 30 m thick megarudite horizons occur consisting of Natih-derived clasts. The upper Sayja of Robertson (1987) includes the whole Muti of the Glennie type section. Biostratigraphic data reported in his study suggests a Turonian – Coniacian age for the lower unit and a Santonian Campanian age for the upper part. The latter deposits were interpreted as slump sheets and debris flows deposited within a developing foredeep. They were inferred to have been derived from the downwarped autochthonous carbonate platform along the southern margin of the foredeep, as well as from basement scarps.

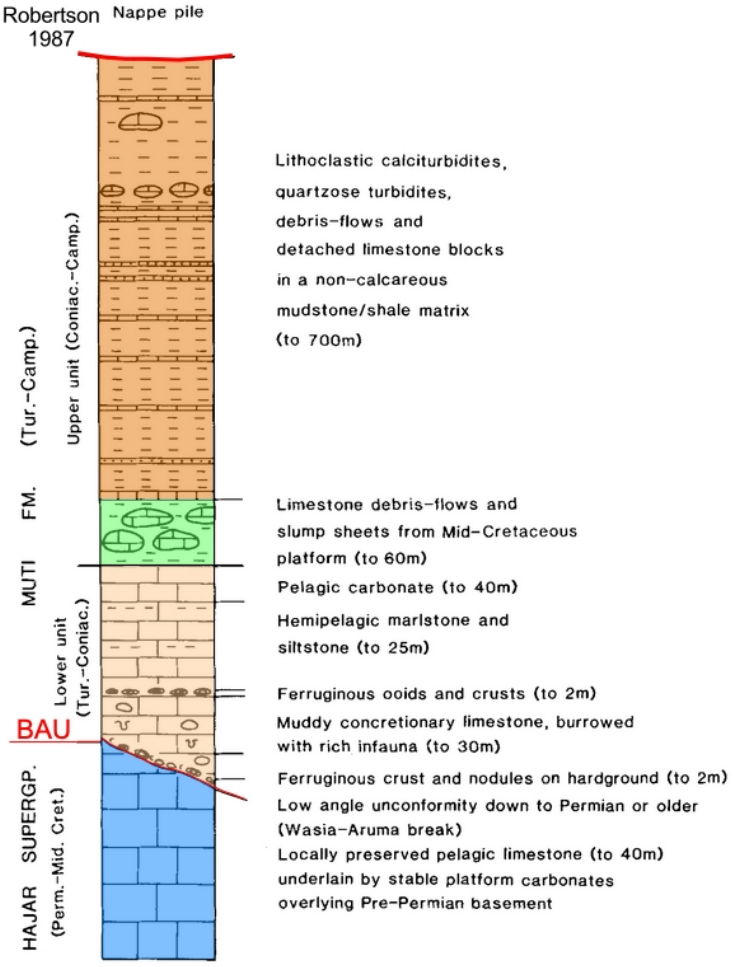


Figure 5-3 Type log for the Sayja Mbr of the Muti Fm. in the Samail gap area proposed by Robertson (1987b). Modified from Robertson (1987b).

Robertson's Hanya Unit consists of Upper Cretaceous sediments that are structurally located close to the sole thrust of the nappes in the Hamrat ad Duru area. These sediments occur near the base of, and within, the thrust-imbricated unit of the Hamrat Duru base-of-slope succession and are considered parautochthonous. The succession comprises a range of distal to marginal basinal facies, including ferruginous and oolitic limestones, calciturbidites, calcareous claystones and siltstones, chalks and calcareous shales, matrix-supported limestone conglomerates containing scattered quartz and basic extrusive rock grains, bedded cherts, and quartzose sandstones. Planktonic foraminifera in some calciturbidite beds suggest a probable late Santonian–Campanian age, however BRGM studies indicate early to middle Turonian ages for these outcrops (Janjou et al., 1986; Rabu et al., 1993). Robertson (1987a) also reported in situ patch reefs up to ~5 m long and ~3 m wide, containing coral debris. These reefs are interpreted to have formed on the nappe front, which was near sea level and locally emergent, shedding sediment. Most of the sediments of the Hanya Unit are interpreted as redeposited material derived mainly from a Mesozoic platform margin located to the west and southwest, with a minor terrigenous contribution from the advancing nappes.

The Riyamah unit overlies Lower Cretaceous slope and basin plain facies of the Hamrat Duru Group within the Hawasina Complex. This unit is also described in Cooper (1986, 1987 and 1990). It consists of Cenomanian radiolarian cherts and shales which in places are overlain by slumps, debris flows and calci-siliclastic turbidites containing thick calcirudite to coarse-grained calcarenites beds with Albian – Cenomanian carbonate clasts. These are interpreted as base-of-slope deposits lining the collapsed Mesozoic platform margin.

In the Dibba area a structurally higher interval with quartzose turbidites and diabase sills in non-calcareous shales, a mélange with detached blocks of shelf edge facies and of mafic lava and chert some 15 km in diameter is also included in this unit. Robertson (1987a) suggests the lave and chert blocks may have been derived from the oversteepened thrust front. Alternatively, these blocks could be intercalated thrusts with volcanics of the Haybi Complex as observed by Cooper (1987).

Other studies incorporate the Riyamah unit into the allochthonous Nayid Formation of the Hamrat Duru Group (BRGM geological maps, Blechschmidt et al. (2004)). Cooper (1990) suggests the Riyamah unit may be partly lateral equivalent to the Nayid Formation.

The Qumayrah unit overlies slope facies of the Sumeini Group and comprises calciturbidites, shales, and bedded radiolarian cherts, overlain by quartzose sandstones, conglomerates, redeposited limestones, and debris-flow deposits. Planktonic foraminifera indicate ages ranging from late Albian–early Cenomanian to Coniacian–Santonian and Campanian, while radiolarians suggest Albian–Cenomanian to Coniacian ages. The redeposited carbonate sediments were interpreted to have been derived from collapse of the upper slope of the Mesozoic carbonate platform. The terrigenous sediments were interpreted to have been sourced from an unknown uplifted continental basement along the continental slope.

The unit of the Qumayrah comprising terrigenous sediments is separated from adjacent sections by a major thrust, and its upper contact is strongly sheared. Locally, the upper part contains decametre-scale blocks of Hawasina cherts and Haybi volcanics, interpreted as sedimentary mélanges derived from the Haybi and Hawasina thrust sheets. However, other studies (e.g. Watts and Blome (1990); Watts (1990)) do not report siliciclastic sediments in

their Qumayrah Formation. This raises the possibility that the conglomerates and quartzose sandstones described by Robertson were misinterpreted and instead belong to a different thrust unit, such as the Hamrat Duru.

Detailed studies of the Qumayrah unit by Watts and Blome (1990) show in places an angular unconformity above folded Sumeini slope deposits. This unconformity is interpreted as recording either early folding and thrusting of the slope sediments during their incorporation into the orogenic wedge, or large-scale gravity sliding along an over-steepened slope (Watts, 1990; Watts and Blome, 1990).

The Buday'ah unit is interpreted as a sedimentary mélange with associated olistostromes incorporated within the Haybi Complex. It comprises material derived from the collapse of Permian-Triassic carbonate seamounts during their entry into the subduction trench.

As will be demonstrated below, Robertson's definition of the Muti Formation in terms of these five units is very broad. The units incorporated within the nappes (Buday'ah, Riyamah, and Qumayrah) are related to collapse of the epeiric platform margin and of seamounts, predating emplacement onto the epeiric carbonate platform. In the sub-nappe Sayja sequence, different types of redeposited sediments of varied origin have been grouped together, and the role of tectonic deformation within this interval is not recognised.

5.1.1.4 BRGM (1986 – 1992)

The BRGM geological mapping project of the Oman Mountains used the same definition for the Muti Fm. as Glennie et al. (1974). However, following 1:250,000-scale mapping, the Muti Formation was removed from the Aruma Group, which was restricted to post-nappe sediments. On these maps, the Muti Formation and the Wasia Group are included in the Hajar Unit, while outcrops mapped as the Fiqa Formation are assigned to the Aruma Group

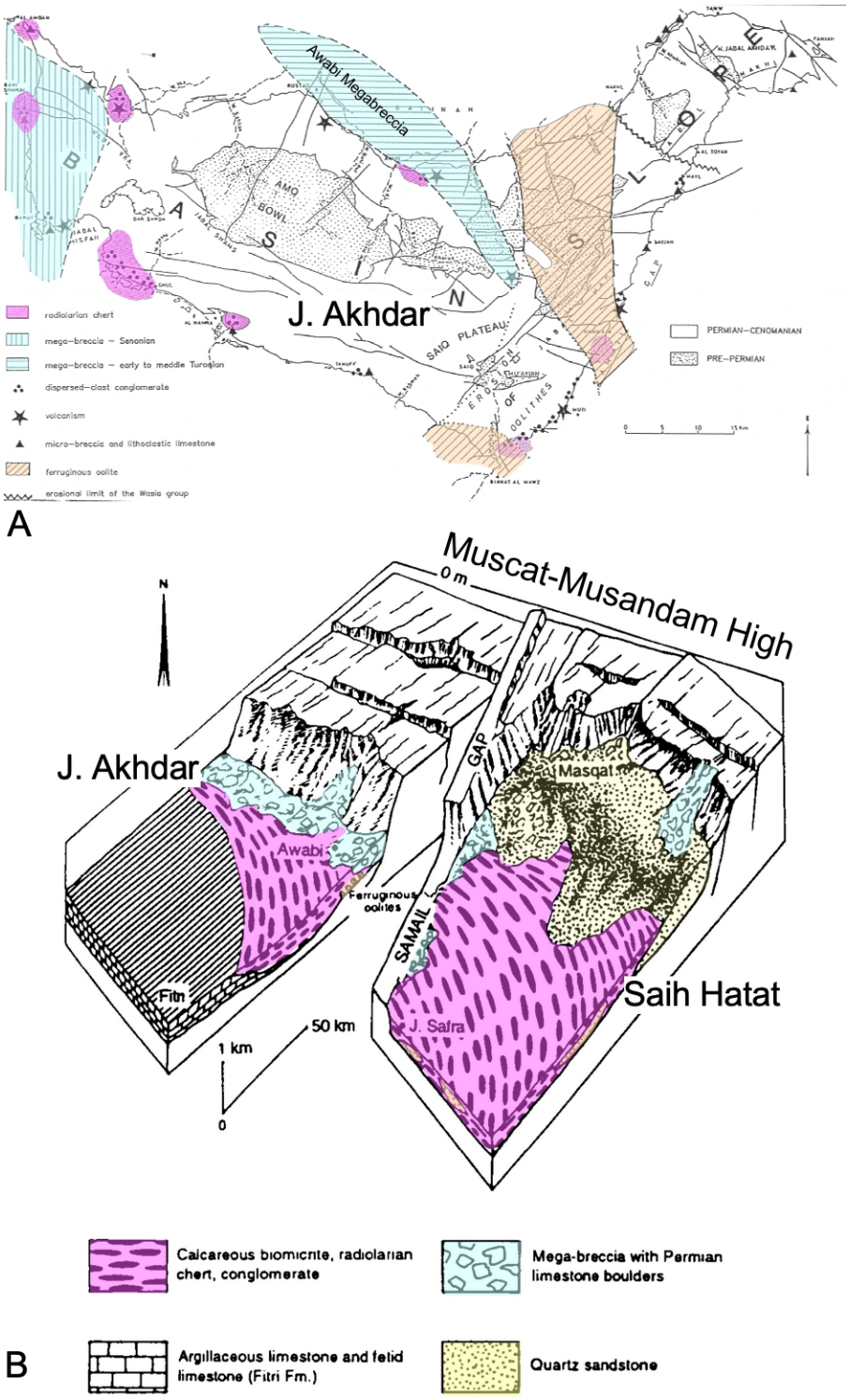


Figure 5-4 BRGM interpretation of the Muti facies distribution and palaeogeography during the Turonian A: Muti lithofacies distribution and palaeogeography in the Jebel Akhdar area. B: Block diagram of Muti intrashelf basin palaeogeography and sediment distribution (modified from Rabu et al. (1993). Note that this model was based on the concept of a Muscat–Musandam High. This interpretation relied in part on inferred major uplift and erosion, already refuted in Chapter 3, and in part on geophysical data (Ravaut et al., 1998). Subsequent publication of offshore seismic data (Levell et al., 2021) demonstrates that there is no geophysical basis for this feature.

(e.g. Béchennec et al. (1992c)). In a summary of the mapping project results by Rabu et al.

(1993), the Muti Formation was placed in a newly proposed Barut Group, which also encompasses parts of the subsurface Fiqa Formation that predate or were contemporaneous with nappe emplacement. This scheme was not adopted in the literature, and the Muti Formation is generally regarded as part of the Aruma Group.

The initial 1:100000 geological maps and associated memoirs issued in the late eighties (Rabu, 1988; Rabu et al., 1990) grouped a wide range of depositional facies into the Muti. Some of these units were later reinterpreted as not being part of the Muti and excluded in the 1:250000 geological maps of the early nineties. These units are the “Fitri Formation”, deep water limestones now recognised by the BRGM as the outcrop equivalent of the subsurface Natih b Member (Béchennec et al., 1992c), and recrystallized “reef” limestones in the northwestern part of the Samail gap, which are now considered to be the Shams/ Hassanat Formation of the Kahmah Group (Béchennec et al., 1992a).

The interval mapped as the Muti Formation includes a wide range of sediments, reflecting strong vertical and lateral facies variability (Figure 5-4). Planktonic foraminifera and radiolarians indicated an early Turonian to Santonian age range. The following facies were recognised by BRGM geologists (see Rabu et al., 1990; 1993):

- Planktonic foraminiferal and radiolarian mudstones containing lithoclasts derived from erosion of a pre-Turonian carbonate shelf. This is the most common facies and represents background sedimentation.
- Discontinuous intervals of monomict conglomerates composed of limestone pebbles derived from the Natih Formation. This facies is common in the Jebel Akhdar area.
- Intervals of radiolarian chert, which along the southern flank of Jebel Akhdar.

- Ferruginous oolites associated with yellow bioclastic limestones. This facies has not been recognised in the Saih Hatat area.
- Discontinuous intervals of breccia, microbreccia, and calcarenite within radiolarian-bearing biomicrites. In the Saih Hatat area, these are associated with sandstone-filled submarine channels containing reworked clasts from the Kahmah and Sahtan Groups, and Mahil Formation. The quartz sandstones occur as lenticular bodies up to 70 m thick and are interpreted as proximal turbidites filling submarine channels. As discussed in Section 3.3.1, the undated Saih Hatat sequence assigned to the Muti by BRGM more likely represents middle Cretaceous slope deposits.
- Widespread megabreccias of reefal limestone. Along the northern flank of Jebel Akhdar, the Awabi megabreccia unit extends for several kilometres in a NW-SE direction (Figure 5-4 A) and is associated with pillow lavas, tuff beds, and a radiolarian-bearing micrite at its base. Individual clasts can reach tens of metres in size and consist of karstified Permian platform carbonates. The matrix contains early to middle Turonian planktonic foraminifera. In other areas, similar breccias reworked into radiolarian cherts and volcanic units fill erosional channels cut into late Coniacian to early Santonian marls.

The Muti sediments were interpreted by BRGM geologists as deep-water deposits formed within an intrashelf basin bounded to the northeast by the inferred “Muscat–Musandam High” (Figure 5-4 B). This fault-controlled high was proposed to lie along the edge of the Mesozoic platform offshore of the present-day coastline and to have become active during the early Turonian. Redeposited sediments and megabreccias were interpreted to

have been sourced from fault scarps along the southern margin of this high. However, recent seismic studies indicate that no such offshore high exists (Levell et al., 2021).

5.1.1.5 Other studies

Following the above-mentioned studies, no new regional interpretations of the tectonostratigraphy or palaeogeography of the Muti Formation have been published. More recent publications are limited to short papers that focus on the sedimentology, petrography, and chemostratigraphy of scattered Muti outcrops in Jebel Akhdar ((Attar et al., 2022; Attar et al., 2024; Attar et al., 2026; Attar et al., 2025; Mattern et al., 2022a) and olistostromes related to the thrusting (Mattern et al., 2022b).

5.1.1.6 The Muti stratigraphy used in this thesis

The interval assigned to the Muti Formation in this thesis follows the original boundaries defined by Glennie et al. (1974) and restricts the unit to sediments deposited in the foredeep that are now located beneath or at the margin of the thrust complex. This stricter definition corresponds to the Sayja and Hanya units of Robertson (1987a), i.e. autochthonous or parautochthonous only. Other units mentioned by Robertson (1987a) preserved within the allochthonous units, which record the collapse of the platform margin and associated seamounts during various stages of nappe emplacement, are treated here as separate stratigraphic units forming part of the Sumeini, Hawasina and Haybi complexes.

5.2 Regional evaluation of the Muti in the Oman foredeep

This chapter presents the Muti Fm. outcrop and subsurface observations and interpretations conducted for this thesis. It begins with descriptions of outcrop transects in Saih Hatat, the Semail Gap, the southern flank of Jebel Akhdar, and the foothills, which represent the northernmost, most proximal, and likely oldest exposed parts of the foredeep in the Oman Mountains. This is followed by a discussion of the more distal subsurface

succession. The locations of the outcrops are shown in Figure 5-5. Detailed descriptions of the logged sections along each transect are provided in Appendix 1.

5.2.1 The Muti Fm. in Saih Hatat

The units mapped as Muti Formation by BRGM along the northern and eastern flanks of Saih Hatat are reinterpreted in this study as mid-Cretaceous slope deposits and are therefore discussed in sections 3.3.1.3-5. The section below describes only the interval overlying the reinterpreted BAU. Two major units have been recognised in this area during this study: a

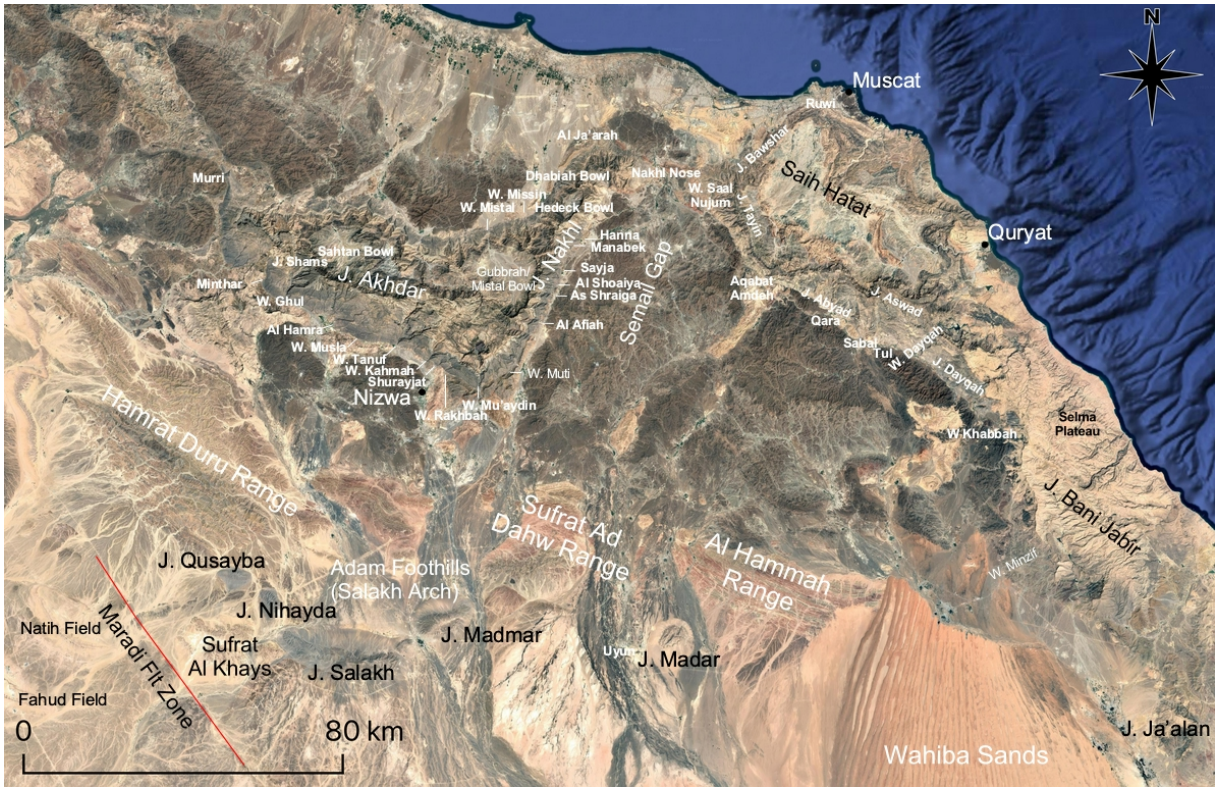


Figure 5-5 Muti Fm. outcrop localities in North Oman discussed in the text. See Appendix 1 for more detailed images.

basal bedded sequence conformably overlying the BAU and an upper chaotic mélange below the thrust complex.

5.2.1.1 Basal Muti interval

Undisturbed deposits on top of the BAU and the Wasia Group have only been observed in a few outcrops on the southern side of Saih Hatat.

5.2.1.1.1 Description

Near the village of Tul, at the confluence of Wadi Tayyin (Khabbah) with Wadi Daiqa, some 50 to 100 m of biscuit-coloured, strongly sheared, marls overly dark-grey-weathering peloidal to oolitic bioclastic grainstones of the Wasia Gp. (according to Glennie et al. (1974), BRGM mapped this outcrop as Kahmah Gp.). The top of the Wasia limestones is an iron-stained, pitted, surface, with some cavities and cracks filled with fine-grained red and black-

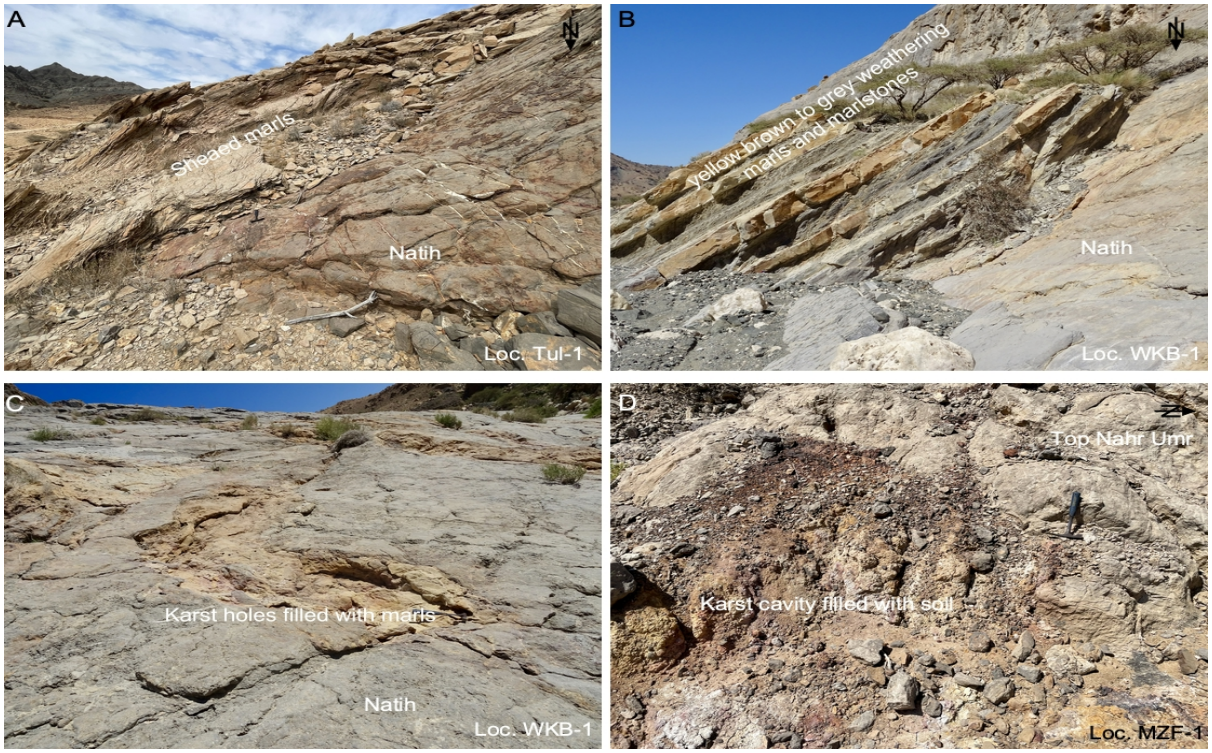


Figure 5-6 Photos of Muti outcrops south of Saih Hatat. A: Biscuit-coloured, strongly sheared marls overly dark grey weathering peloidal to oolitic bioclastic grainstones of the Wasia Gp. at locality Tull. B and C: Yellow-brown to grey weathered marls and marlstones overly a karstic surface on top of fossiliferous grey limestones of the Wasia Gp. at locality Wadi Kabbah (WKB) D: Soil development on top of Nahr Umr Fm. along BAU in Wadi Minzif. See Figure 5-5 for location.

sediment (Figure 5-6 A). This is a typical appearance of the BAU and is likely a top Natih karstic surface covered by an Fe-stained hardground surface during a subsequent transgression. The overlying Muti marls show a dm- bedding, defined by more and less resistive intervals of marls and marlstone.

Some 30 km to the SW, at the foot of the Jebal Bani Jabir, a 100+ m thick package of yellow brown to grey weathered marls and marlstones overlies a karstic surface on top of

fossiliferous grey limestones (Figure 5-6 B). The limestones are assigned to the Kahmah Group on the BRGM geological map, but the presence of radiolitid rudists observed during the present study indicates an Albian to Cenomanian age equivalent to the Natih. The top of the limestone is stained reddish with an overall smooth surface truncating bioclasts in the underlying limestone. Locally this surface shows cracks and m-scale depressions filled with reworked limestone pebbles from the underlying beds, suggesting karst cavities (Figure 5-6C). Marls dominate the overlying section. The interbedded marlstone beds are a few dm to about a metre thick. Their base is sharp and the top is transitional into the marls and burrowed. Along the western foot of the Salma Plateau in the Ibra area Peters et al. (2005)

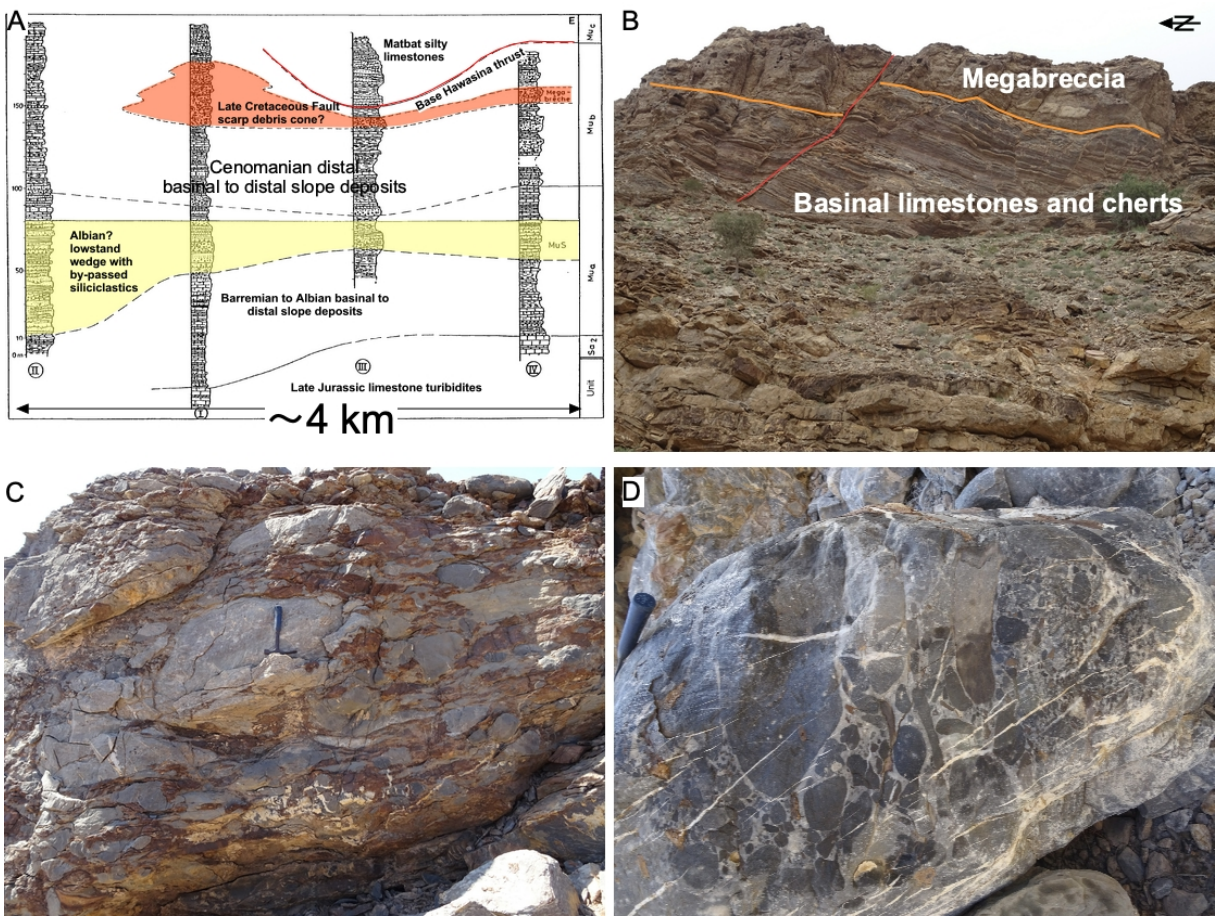


Figure 5-7 Megabreccia bed in Wadi Saal, western flank Saih Hatat. A: E-W correlation of outcrops by Le Métour (1988), showing pinch-out to the west (see Appendix for location). B: Megabreccia in sharp contact with basinal limestones. C: Poorly sorted limestone and cherty limestone clasts, which show some flattening by shearing. D: Polymict, poorly sorted conglomerate with calcite cemented pores.

report a 80 – 100 m thick Muti section, composed of yellow-to-reddish-weathered, greenish silty shales. Only the lowermost 10 m is carbonate rich and has a grey-black colour in fresh cuts. In places some black limestone conglomerates are present in the basal part.

Some 35 km further south, at the entrance of Wadi Minzif, 15 km north of the Wahiba sands, the BAU cuts down into the Nahr Umr. This too was associated with subaerial exposure. A basal conglomerate and varicoloured palaeosol horizon can be seen (Figure 5-6 D). These are overlain by some 10 – 15 m of yellow brown marls, which are siltier and interbedded with beige, very fine-grained calcareous quartz sandstones in the upper part. This section is truncated by folded, dark brown to green sandstones and limestones of the Hamrat Duru Gp.

In the Wadi Saal Nujum area the Cretaceous slope and basinal deposits below the BAU are overlain by calcarenites and calcareous shales with several-metres to tens-of-metres thick channel fills, containing polymict breccias with blocks of Cretaceous rudist limestones, cherty limestones, cherts, Jurassic oolitic limestones and sandstones, and Triassic dolomites (Figure 5-7. The matrix consists of pinkish calcareous silt to marl, but in places there is no matrix between the clasts, and the cavities are filled with sparry calcite. The breccia forms a wedge that pinches out towards the west (Le Métour, 1988). The megabreccias are truncated by the base Hawasina thrust and the basal contact is also often sheared. Similar polymict breccias have also been observed further south near Sabal (loc SWH-1) and Wadi Qara.

5.2.1.1.2 Biostratigraphy basal Muti interval

The marls near Tul contained siliceous sponge spicules, radiolarians, rare possible *Oligosteginas* and abundant planktonic foraminifera (Le Métour, 1988). The latter include: Heterohelicids, Hedbergellas, *Marginotruncana gr. sigali*, *Marginotruncana gr. renzi – paraconcavata*. These indicate a late early Turonian to Santonian age range in the Mikrotax

database (Huber et al., 2016). But a younger, mid to late Turonian age was interpreted by Le Métour (1988), based on the absence of *Dicarinella primitiva-concavata*. The Mikrotax database (Huber et al., 2016) suggests the latter species also occurs in the late Turonian (*Marginotruncana schneegansi* zone). Thus, based on its absence, the maximum age is upper early Turonian for the basal Muti in this area. The Muti in Wadi Minzif contains inoceramids and ammonites (*Thomasites* and *Gauthiericeras*) indicating a Turonian age according to Peters et al. (2005). These data suggest deposition of the Muti in this area occurred during the Turonian and may have continued until Santonian.

5.2.1.1.3 Interpretation basal Muti interval

Basal marls and shales

The marls with pelagic fauna represent a deep-water sequence with little input of shallow-water–derived sediment. Because these deposits directly overlie a karstified surface, a rapid deepening event is inferred in the Saih Hatat area during the Turonian–Santonian. The presence of minor siliciclastic material in the south reflects proximity to the exposed Huqf Axis.

Megabreccias

The absence of matrix suggests that the megabreccias were deposited along very steep slopes and probably are fault-scarp debris cones. The mixing of a wide range of clasts from different stratigraphic levels, and the subangular to rounded shape of the clasts could indicate the footwall of the fault scarp was subaerially exposed. Apart from the fault scarp itself, clasts were likely also derived from more distant sources by rivers incising into different stratigraphic levels of the uplifted footwall.

The pinch-out towards the west in the Wadi Saal Nujum area points to NNW-SSE trending normal faults that bound the NW side of the Saih Hatat dome just east of the outcrops. The

fault trend is likely to overlie a basement lineament that was re-activated before emplacement of the nappes. These deposits are similar to the limestone breccias and conglomerates of the Ausaq Fm., which is considered to be an equivalent of the Muti Fm in the NE-SW trending Dibba zone in the Musandam area Cooper et al. (2016); Robertson et al. (1990). There, the onset of the obduction caused a collapse of a platform margin along a re-activated lineament.

An alternative interpretation is that these megabreccias were derived from exposed thrusts that incorporated fragments of the Permo–Cretaceous platform. The presence of such thrusts is indicated on geological maps of the Saih Hatat area, northeast of the outcrops described here (Le Métour, 1988; Le Métour et al., 1992b; Le Métour et al., 1986b). In this scenario, the megabreccias would form part of the upper Muti mélange interval. Further detailed structural mapping of the western flank of Saih Hatat is required to test this interpretation.

5.2.1.2 Upper Muti mélange

5.2.1.2.1 Description

In the Ruwi area, an interval mapped as the Muti Formation is tectonically overlain by a slab of Triassic Mahil Formation Dolomite, which is in turn overlain by Sahtan Group siliciclastic rocks. The Muti Formation comprises a mélange of intensely folded, sheared, and partially recrystallised metasedimentary rocks (Le Métour, 1988; Le Métour et al., 1992b; Le Métour et al., 1986b). These rocks predominantly include siltstones and yellow silty carbonates that have been recrystallised into grey-green, yellowish-beige, or pinkish schists and calc-silicate schists, and some blocks of metabasalt, probably from the Haybi Complex.

Locally, the mélange contains beds and rafts of turbiditic coarse quartz sandstones and conglomerates, with carbonate and siliceous pebbles, as well as lenses, boulders, and blocks

of recrystallised, possibly reefal, limestone. The sandstones are comparable to turbidites in the Cretaceous succession of the Wadi Saal–Nujum and Quriat areas. This suggests the mélange represents a mixture of Hawasina and Haybi units together with autochthonous Cretaceous slope deposits.

Around the Saih Hatat dome chaotic mélanges below the thrust complex have been mapped as Muti on the most recent 1: 250.000 scale geological maps (Béchennec et al., 1992a; Le Métour et al., 1992b). However older 1: 100.000 scale maps by BRGM (Le Métour

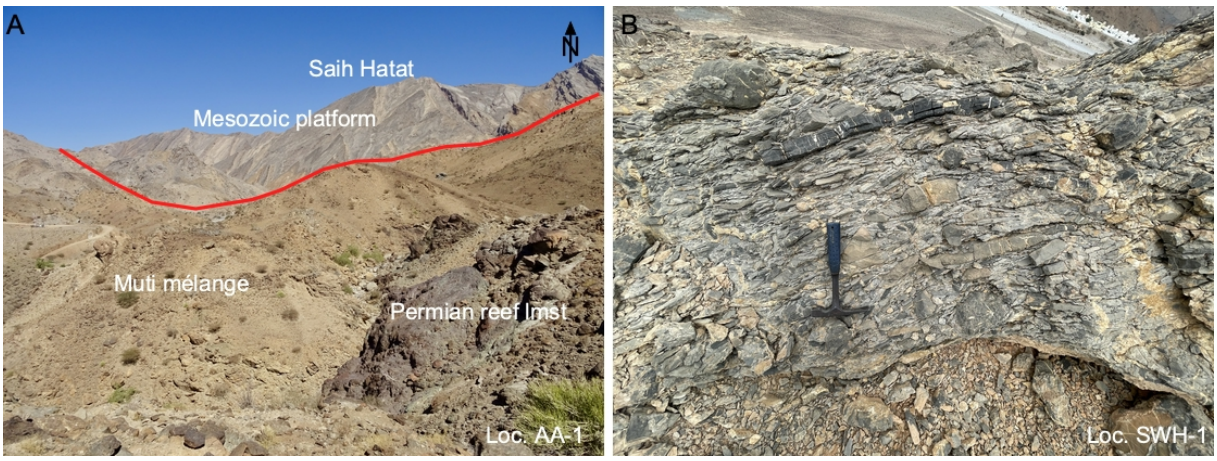


Figure 5-8 A: Field aspect of Muti mélange in Aqabat Amdeh area. B: Rafts of megabreccia's within Muti mélange near Sabal village along Wadi Hamadah.

et al., 1986b; Villey et al., 1986) and Glennie et al. (1974) mapped most of this as part of the Hawasina and Haybi complexes. Outcrops at Aqabat Amdeh, Wadi Qara and Quriat show a chaotic sequence with silicified mudstones and cherts, purple-black shales, bioclastic and lithoclastic limestones, blocks of dolomitic limestones with Permian corals, and polymict conglomerates and breccias with boulders and rafts up to some 50 x 100 m of recrystallised reefal limestones, platform dolomites, and cherts (Figure 5-8). The sequence also contains limestone blocks of, probably Cretaceous, debrites and slope deposits. A thickness of some 500 m is indicated on the geological map in the Wadi Qara area (Le Métour et al., 1992b). The contact with the basal Muti marls is not exposed.

5.2.1.2.2 Interpretation

The chaotic nature and mixing of fragments with affinities to the Hawasina and Haybi thrusts and Cretaceous slope deposits suggest this unit was deposited initially as a sedimentary mélange along the frontal part of the thrust complex. These deposits were subsequently underthrusted below, and mixed with, materials from the advancing nappe stack.

5.2.2 The Muti Fm. in the Semail Gap and Jebel Nakhl (a North-South section)

These outcrops are located along the eastern dip slope of Jebel Akhdar and Jebel Nakhl in the Semail gap. The dip slope along the Semail Gap is strongly faulted. The major faults are normal faults trending WNW–ESE, with relative displacements of several tens to up to 100 m. Smaller faults, with displacements of up to a few tens of metres, are oriented NNW–SSE. These structures pre-date folding of the Jebels and have been described by Al-Wardi and Butler (2007), Al-Wardi (2006), and Scharf et al. (2019).

Figure 5-9 shows a cross section of the logged sections through the Muti Fm. along a north-south transect. Two main units are recognised: a lower, undisturbed limestone and marl sequence conformable with the BAU, and an upper mélange interval. The lower Muti Formation occurs in a series of discontinuous, commonly biscuit-coloured, flat-iron outcrops resting on the limestones of the Natih Formation. Preservation appears to be fault-controlled and restricted to grabens, which limited truncation beneath the upper Muti mélange or the overlying thrust complex. This suggests that at least some of the faulting pre-dated the obduction.

5.2.2.1 Basal Muti interval

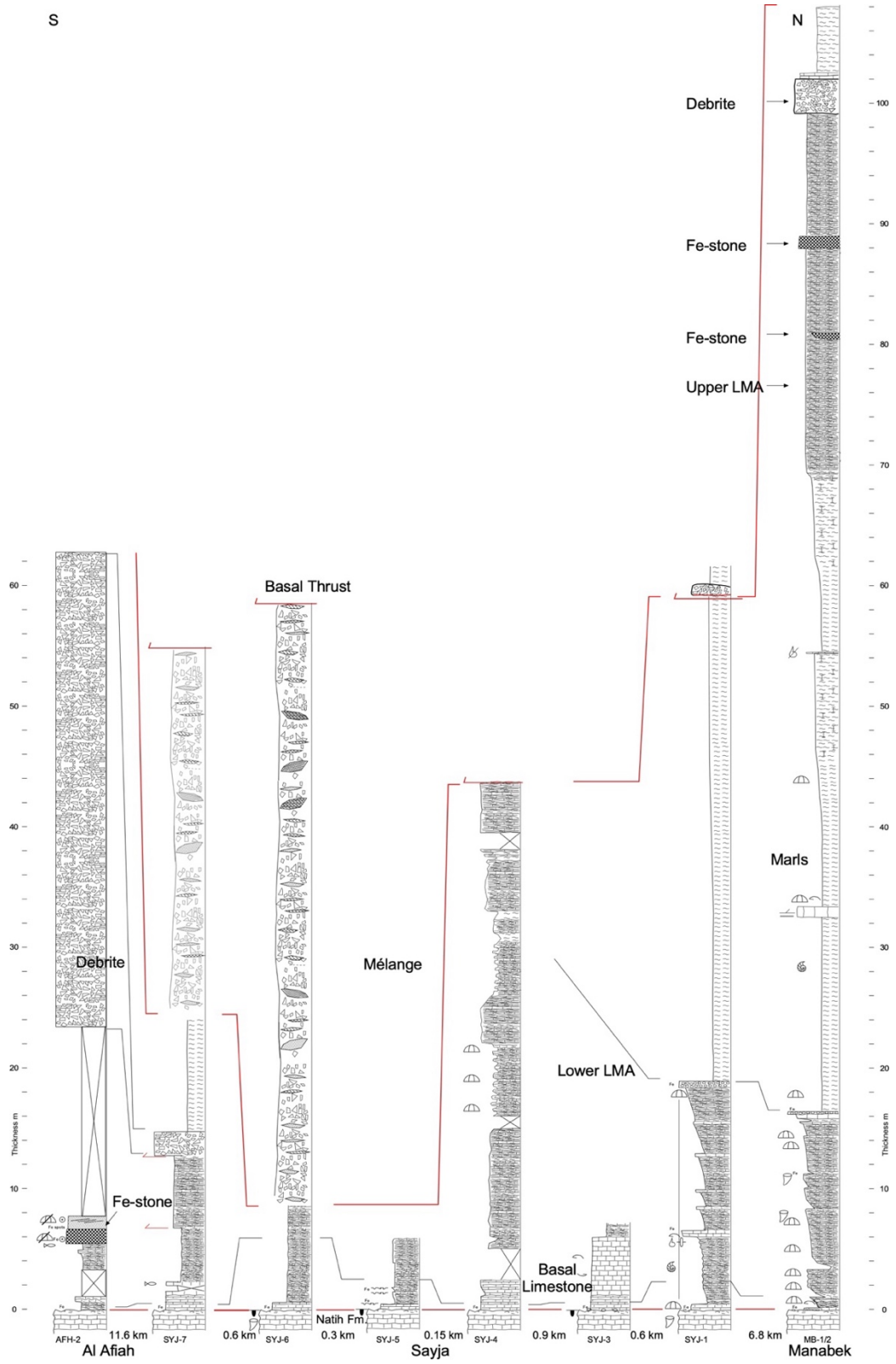


Figure 5-9 Section through the transgressive basal Muti along the Semail Gap. The logs are limited upwards by exposure, accessibility, or, in most cases, the basal thrust (in red). For detailed descriptions of sections see Appendix 1, for outcrop localities see Figure 5-5.

The lower unit comprises a succession of limestones and marls, locally overlain by debrites and olistoliths (Figure 5-10 A, B), and corresponds to the basal Sayja and lowermost part of the upper Sayja of Robertson (1987b) (see Figure 5-3).

5.2.2.1.1 Description

Basal limestones

The basal limestones and marls show a typical biscuit-like weathering colour and are up to 100 m thick. At the top they are either eroded by debrites of the upper part of the

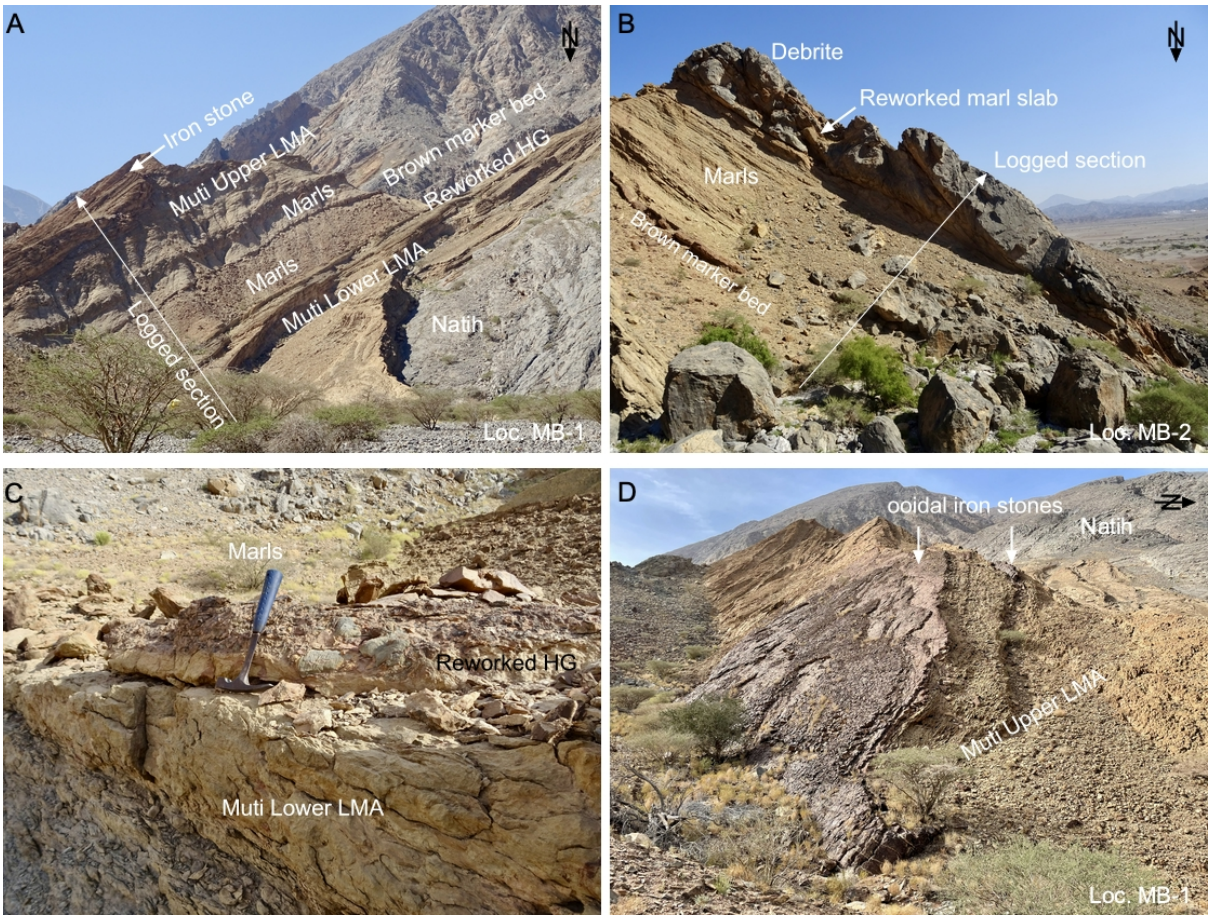


Figure 5-10 A and B The proposed new Muti type section at Manabek South (locality MB-1 to MB-2), overlying Natih dip slope. LMA = limestone marl alternation. C: Reworked hardground capping Lower LMA interval below marls. D: Oolitic ironstone beds in the upper part of the Muti section. Note sharp contact of ironstone bed with Upper LMA facies.

sequence or truncated along the base of the mélange or thrust complex. The thickest and stratigraphically most complete sections are in the Sayja / Manabek area.

Here the sequence consists of a basal limestone, and a lower and upper limestone marl alternation (LMA) package separated by marls (Manabek locality, see Figure 5-9). The burrowed limestone-marl alternations contain abundant well-preserved echinoids, ammonites, bivalves and rare rudists fragments. The sequence contains iron-stained hardgrounds and in the upper part iron-rich calcarenites and oolitic ironstone beds (Figure 5-10). The ironstone intervals form lens-shaped bodies that can be up to 2 m thick and consist of dm-scale beds of red brown oolitic pack- to grainstone with shale pebble conglomerates, containing some green clasts and reworked marl clasts. The beds fine upward and contain black phosphatized burrows or fossils, ferruginous pellets and ooids, all in a fine red ferruginous matrix. Some of the iron-rich sediments partly infill burrows in the underlying limestone.

There are strong lateral variations in thickness in the basal Muti, related to onlap to the south (not visible in Figure 5-9 as the section is flattened on top Natih) and because of truncation below the debrites or the detachment surface along the mélange below the thrust complex, which makes the sections variably incomplete. The limited data suggest some lateral facies variations, as the marls may grade into LMA facies towards the south. Ironstones occur in the upper LMA in the north but also occur on top of the basal LMA in the south.

In the southern part of the Semail gap, at the sections in As Shraiga and Al Afiah (Loc. AFH-2) the lower LMA has been reduced in thickness to a few metres below an erosively based, nearly 2.5 m thick, fine, bioclastic, iron-rich calcarenite. The bed is thick-bedded and

consists of an amalgamated bedset with low-angle and cross-lamination and contains intraclasts from the underlying LMA. It also contains black-coated iron ooids, chamositic ooids, echinoid fragments, oyster fragments, fish teeth, phosphate, benthic foraminifera and scattered quartz grains. The absence of hardgrounds and the sharp base suggest that the chamositic ooids and phosphate in this bed were not formed in place. The condensed sediments were probably reworked from shallower, more elevated areas, possibly by storms.

Poor exposures along the northern flank of Jebel Akhdar, 2.5 km east of Wadi Mistal (MST-2), show a Muti facies similar to that in the southernmost Semail Gap. The top Natih is an irregular iron-stained surface, covered locally by a basal conglomerate and a 10 – 20 cm thick burrowed oolitic ironstone with (composite) iron oolites, glauconite and echinoderm fragments. Above the basal ironstone is an LMA. Isolated fallen blocks suggest that this may have been overlain by a 2 m thick ironstone bed. Higher in the sequence light-brown marls are truncated by several m of brownish Muti debrites with Natih clasts.

Debrites

In several outcrop localities the limestone and marl sequence has been truncated or been completely removed beneath a debrite interval. The basal contact of the debrites is a sharp surface, in places overprinted by bed-parallel sliding. In Al Shoaiya and Wadi Muti, the debrites directly overly the Natih limestones along a stepwise erosional surface related to local removal of discrete Natih limestone beds.

In outcrop they show a typical brownish / greenish-grey weathering colour and a relatively smooth, undulating, weathering surface. The thickness of the debrite unit varies from a few to more than 100 m. Despite showing strong lateral thickness changes, some of the debrite layers can be followed for about 1 km.

The debrites are very poorly sorted and the clast size ranges from a few mm to decametre sized rafts floating in a fine-grained matrix (Figure 5-11). They are mostly structureless although slump and slide structures can be seen in places. Most of the debrites

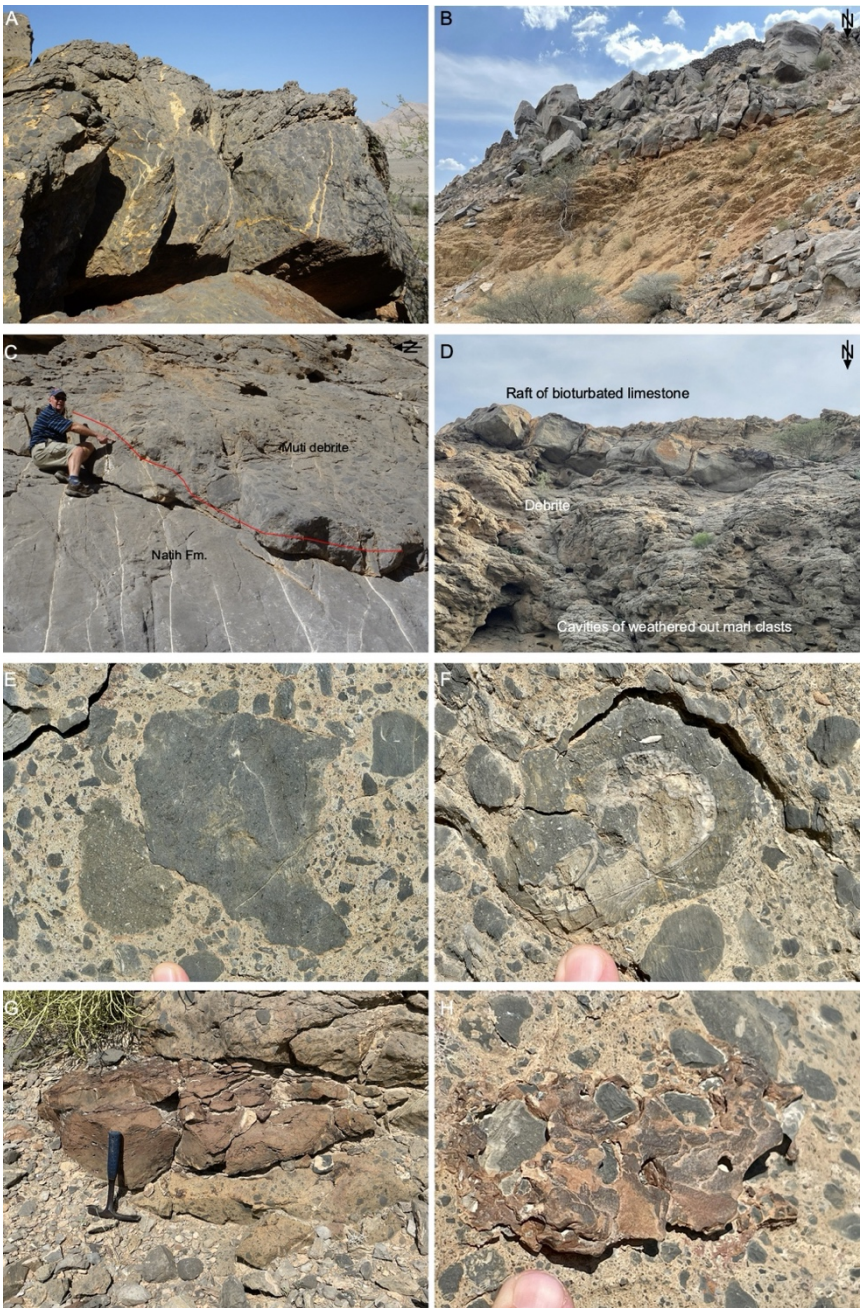


Figure 5-11 Outcrop photos of Muti debrites. 2 m thick debrite interval showing layering with coarser and finer clast. B: Sharp-based debrite overlaying Muti marls. C: Erosional contact debrite with Natih limestones. D: 2 m thicks raft of bioturbated limestone within Muti debrite. E: Poorly sorted Natih limestones clasts in debrite. F: Clast with rudists and praealveolinids from the mid-Natih. G: Muti iron-rich calcarenite clast in debrite. H: Fragment of the top Natih exposure surface in debrite. Location of photos: A Wadi Missin, Loc. WMS-3, B and F W. Kahmah West Loc. WK-2, C Wadi Muti, Loc. WMT-1, D Al Hamra Loc. AH-4E and F Sayja, Loc. SYJ-7.

are monomict and dominated by dark grey, cm-sized, angular limestone clasts derived from the Natih. Different Natih facies are represented. Clasts with abundant praealveolinids and large radiolitid rudists suggest that they were derived from levels as deep as the middle Cenomanian Natih c and uppermost Natih-e interval, at least 150 m below the top Natih. Usually, a few Muti-derived clasts are present, such as biscuit-coloured marls, bioclastic calcarenites with oysters, iron oolites and quartz sandstone. However, in As Shraiga (loc SGA-3, see Appendix 1) a light orange-brown weathering debrite is entirely composed of Muti clasts. It is most likely that the intra-debrite matrix consists of reworked Muti LMA and marls, as the Natih predominantly consists of cemented limestones.

5.2.2.1.2 Biostratigraphy

Little data is available on the biostratigraphy of the section in the Semail Gap. Robertson (1987b) mentions a Turonian age for a sample from the Sayja section based on the possible presence of *Praeglobotruncana* (= *Helvetoglobotruncana* in Mikrotax) *helvetica* (Bernoulli, private communication). Other ages mentioned for the lower unit without a specified location are Coniacian – Santonian ('Hedbergella", Heterohelids and one double-keeled Globotruncanid) and a Santonian to Campanian age for a horizon close to the top of the Lower Sayja based on planktonic and benthic forams (M. Harte, private communication). According to Robertson (1987b) deposition took place during the Turonian to Coniacian.

5.2.2.1.3 Interpretation of basal Muti interval

The abundant hardground surfaces and upward deepening trend from shallow open-marine carbonates to hemipelagic marls indicate that the basal Muti Formation represents a transgressive sequence overlying the karstified top of the Natih carbonates. The most complete section at Manabek suggests that this deepening comprises a retrogradational stacking pattern of shallowing-upward cycles. Sharp-based bioclastic and iron-rich

grainstones, with minor fine-grained siliciclastic input, are not interpreted as in situ deposits but rather as reworked transgressive sediments and palaeosols introduced by storm events.

Limestone breccias with matrix-supported floating clasts are interpreted as cohesive debris flow deposits (Gani, 2004). The clasts are derived from Natih and Muti strata, sourced from fault scarps exposed on the seafloor. This relationship is observed in several outcrops along the southern flank of Jebel Akhdar and on seismic lines in the Hamrat ad Duru area, which will be discussed in Sections 5.2.3 and 5.2.6.1.3.

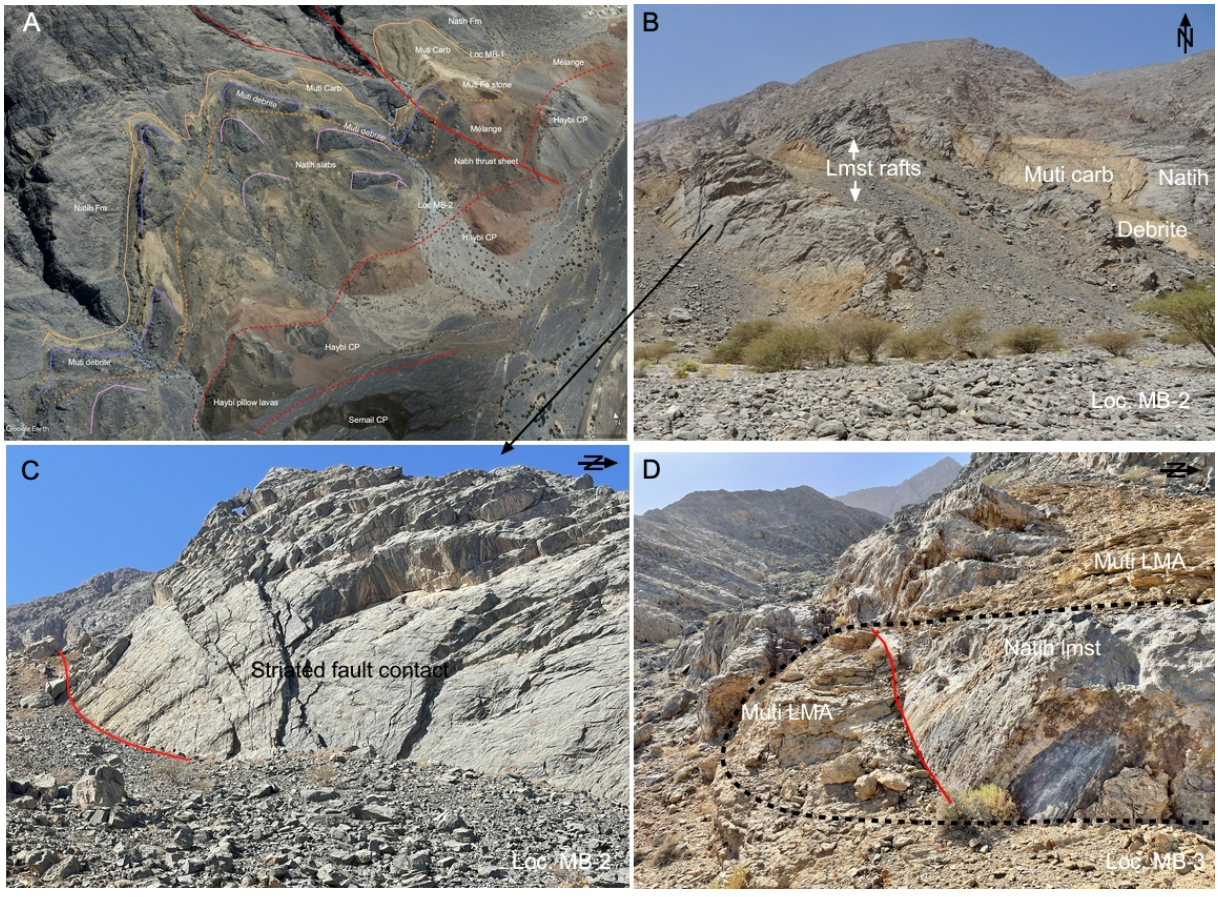


Figure 5-12 A and B: Slabs of Natih limestones encased in Muti marl south of Manabek (loc MB-2), Semail gap, striated surfaces (C) suggest these are collapsed fault scarps D: Block (dashed line) containing Natih and Muti in fault contact between Manabek and Hanna at locality MB-3, just below mélange with Hawasina blocks.

5.2.2.2 Olistoliths

5.2.2.2.1 Description

In Manabek a 200 thick interval in the Upper Muti contains huge, bedded limestone blocks, some of which are more than 150 m long and over 20 m thick. They occur above a debrite and are encased in biscuit-coloured, silty marls. This interval extends for nearly 1.5 km to the southwest along the flank of the Jebel. The upper contact of these blocks with the marls is a smooth surface, formed by a siliceous iron crust. In places striations can be seen. The blocks show abundant calcite veining. The lower contact is also a sharp planar surface but does not show iron staining or calcite veins. The blocks consist of fine-grained, light blue to grey weathered limestone, with orbitolinid and praealveolinid fragments. The latter suggest these are derived from the Natih Fm. Erosive contacts with debrites, with clasts up to 10 cm diameter and with similar lithology as the main block, can be seen locally. Some blocks contain both Natih and Muti strata separated by a striated fault contact (Figure 5-12).

5.2.2.2.2 Interpretation

The large rafts of bedded Natih limestones are interpreted as derived from collapsed, or cut-off, fault walls. The iron-stained surface truncating these beds may have been part of a fault plane. Alternatively, these blocks may have been sheared off pre-existing horst blocks (footwall cut-offs; see Butler et al. (2006)) during thrust emplacement. In this case, they could also be regarded as part of the overlying mélange. Robertson (1987) mentioned slivers of platform carbonates within the Muti Fm. in the Semail Gap area but related these to normal faulting linked to late culmination collapse of the Jebel. However, the structural position below the thrust complex indicates that the faulting occurred before nappe emplacement.

5.2.2.3 Upper Muti mélange



Figure 5-13 Outcrop photos of the Muti Mélange. A and B: Thrust contact between folded cherts and Muti debrite, in Muti type section (Loc WMT-1). C-D Tectonic mélange in Sayja area (Loc. SJ-4). The Muti, mélange and Haybi Complex can be clearly seen by the colour differences in the landscape. The Hamrat Duru is not present in this area, but rafts of this unit occur within the mélange such as bedded cherts of the Sid'r and folded, conglomeratic, oolitic limestone beds of the Guwayza Fms. Large blocks of Muti limestones also occur in the tectonic mélange. E: Google Earth Satellite photo of SJ-4 locality clearly showing large blocks (marked by arrows) in the mélange.

Along the Semail gap and the nose of Jebel Nakhl a poorly exposed, strongly deformed mélange up to 150 m thick separates the Muti sediments from the Hawasina or Haybi thrusts or the metamorphic sole of the Semail Ophiolite (Figure 5-13). The main outcrops are in the Manabek, Sayja, and As Shraiga sections. This unit corresponds to the upper parts of the upper Sayja unit described by (Robertson, 1987b), see Figure 5-3.

5.2.2.3.1 Description

The base of the mélange is often poorly exposed but typically marked by the sudden appearance of poorly exposed, red, non-calcareous, silky shales. Similar shales have been described from the Upper Permian to Triassic Jilh Formation in the lower part of the Hamrat Duru Group (Béchennec et al., 1992a; Rabu et al., 1986), and may have been reworked from these strata. Alternatively, these shales may represent a very deep water Muti facies.

Where exposed, the base of the mélange is marked by a sheared zone. In the northern Semail Gap (Farasha, locality FRS-2) and northern Jebel Nakhl (Al Ja'arah, Locality AJ-5) the mélange is in direct contact with the autochtonous Cretaceous carbonates. In Farasha the contact comprises a sheared interval a few metres thick containing up to metre-sized brownish-grey–weathering cherty limestone blocks. These blocks are flattened and stretched along a north–south axis (195–15) within a greenish-grey calc-silicate schist matrix. The grey limestones are bioclastic and contain crinoids, shell fragments, lithoclasts, and mud chips, and locally include Cretaceous platform facies. Above the sheared interval, rafts of folded biscuit-coloured Muti marls occur showing top to the SW shearing (locality THM-2).

At the southern end of the Semail Gap, in the type section of the Muti Formation at Wadi Muti (Wadi Imti; locality WM-1), a sheared surface was observed at the top of the lower Muti debrites, forming a razor-sharp contact between the basal debrite and overlying cherts and folded shales (Figure 5-13 A, B). Haremboure (Figure 5-1) noted in the original

description that this interval is disturbed, with slumping and micro folding, but did not recognise the shear zone.

Along the Semail gap, the silky shales provide the matrix for intermixed rafts and blocks of various lithologies (Figure 5-14):

1. Thin-bedded, flaggy, greenish-grey limestone turbidites with sharp bases, lamination, and rippled tops with iron-stained laminae and crusts. These are likely also derived from the Al Jil Fm.
2. Brown-weathered, oolitic polymict conglomerates containing rounded to sub-rounded pebbles of light, yellow-brown limestone marls, blue-grey limestone, and rusty brown limestone. The matrix is iron-rich and very hard. This facies occurs in the Guwayza Fm. of the Hamrat Duru Gp.
3. Very coarse to medium-grained, poorly sorted, calcareous quartz sandstones with limestone clasts of the Guwayza Fm.
4. Rafts of light brown weathering, very hard, siliceous limestones and decimetre bedded cherts with strong cleavage. These are likely remnants of the Sid'r Fm. of the Hamrat Duru Gp.
5. Pillow lavas, derived from the Haybi Complex or base of the Hamrat Duru Gp.
6. Blocks of Natih limestones.
7. Sheared beds and lenses of folded debrite beds and folded rafts of biscuit-coloured marls and limestones of the Muti Formation. The rafts in the mélange can be several tens of metres thick.

At Al Ja’arah, the mélange forms a series of isolated limestone hills composed of carbonate slope deposits that protrude from the alluvial plain that covers poorly exposed



Figure 5-14 Heterogeneous clast compositon of Muti mélange at locality SGA-1. A: Rafts of thin-bedded limestones with chert from the lower Sidr Maiolica facies B: Polymict breccia beds of the Guwayza Fm. C: Folded limestone beds D: Folded Muti debrite beds E: Polymict breccia beds of the Guwayza Fm F: Pillow lavas from the Hamrat Duru or Haybi thrust complex.

red to orange silky shales situated between the mid-Cretaceous dip slope and ridges of the Hamrat Duru nappes. These deposits have previously been interpreted as the Muti Formation, Sayja Member (Cooper, 1986).

The shales are tightly to isoclinally folded and strongly sheared, and locally the contact with the underlying dip-slope limestones is observed to be a ductile shear zone. The shales consist of very slightly calcareous to non-calcareous, greenish-grey, micaceous—locally silky—red-brown shales (claystones) with interbedded siltstones. They contain decimetre-long lenses of harder, coarser siltstone forming centimetre- to decimetre-thick beds, as well as isolated decimetre-sized, locally folded blocks and rafts of grey bioclastic limestone containing rudist fragments.

Along the basal contact of the mélange with the Cretaceous slope deposits, altered volcanic rocks occur together with greenish-grey limestone conglomerates and typical Guwayza conglomerates of the Hamrat Duru Group, the last characterised by a red shale matrix and bedded cherts. The limestone ridges are encased in red-brown to greenish shales. In most areas, the limestones are strongly sheared and display NW–SE–striking, top-to-the-NE isoclinal folds.

The limestone units include metre-scale debrite beds intercalated with bedded limestones and calcareous shales to marls. Clasts within the shales consist of disrupted layers of redeposited, shallow-water–derived sediments from an Albian to Cenomanian carbonate platform. These deposits represent slope sediments that were sliced into the mélange and mixed with shales and sandstones derived from the overlying Hamrat Duru nappes. Although poorly exposed, the mélange may attain a thickness of up to ~800 m.

5.2.2.3.2 Interpretation

The chaotic fabric and mixing of fragments derived from different thrust sheets suggest that this unit originated as a sedimentary mélange formed by debris flows along the frontal part of the thrust complex. These deposits were subsequently overridden and incorporated into the thrust stack. Some lower Muti fragments and middle Cretaceous slope deposits may have been reworked from thrusts involving Muti sediments or may represent thrust slices at the base of the stack.

5.2.3 The Muti Fm. on the South flank of Jebel Akhdar (an E-W section)

The southern flank of Jebel Akhdar forms a southward-dipping slope of approximately 20–30°. This dip slope is cut by a high density of faults belonging to a Late Cretaceous WNW–ESE–trending fault system. Individual faults are up to ~5 km long and display vertical offsets exceeding 100 m (Al-Kindi and Richard, 2014; Filbrandt et al., 2006; Filbrandt et al., 2007). These normal faults were subsequently tilted during uplift of the mountain range.

Figure 5-15 shows a cross-section of the logged sections through the Muti Formation along an east–west transect. The succession comprises a lower limestone interval, up to a few tens of metres thick, overlain by marls containing debrites. A mélange interval, similar to that observed in the Semail transect, is exposed in a quarry in Wadi Mu'aydin but is otherwise poorly exposed or absent (Figure 5-16).

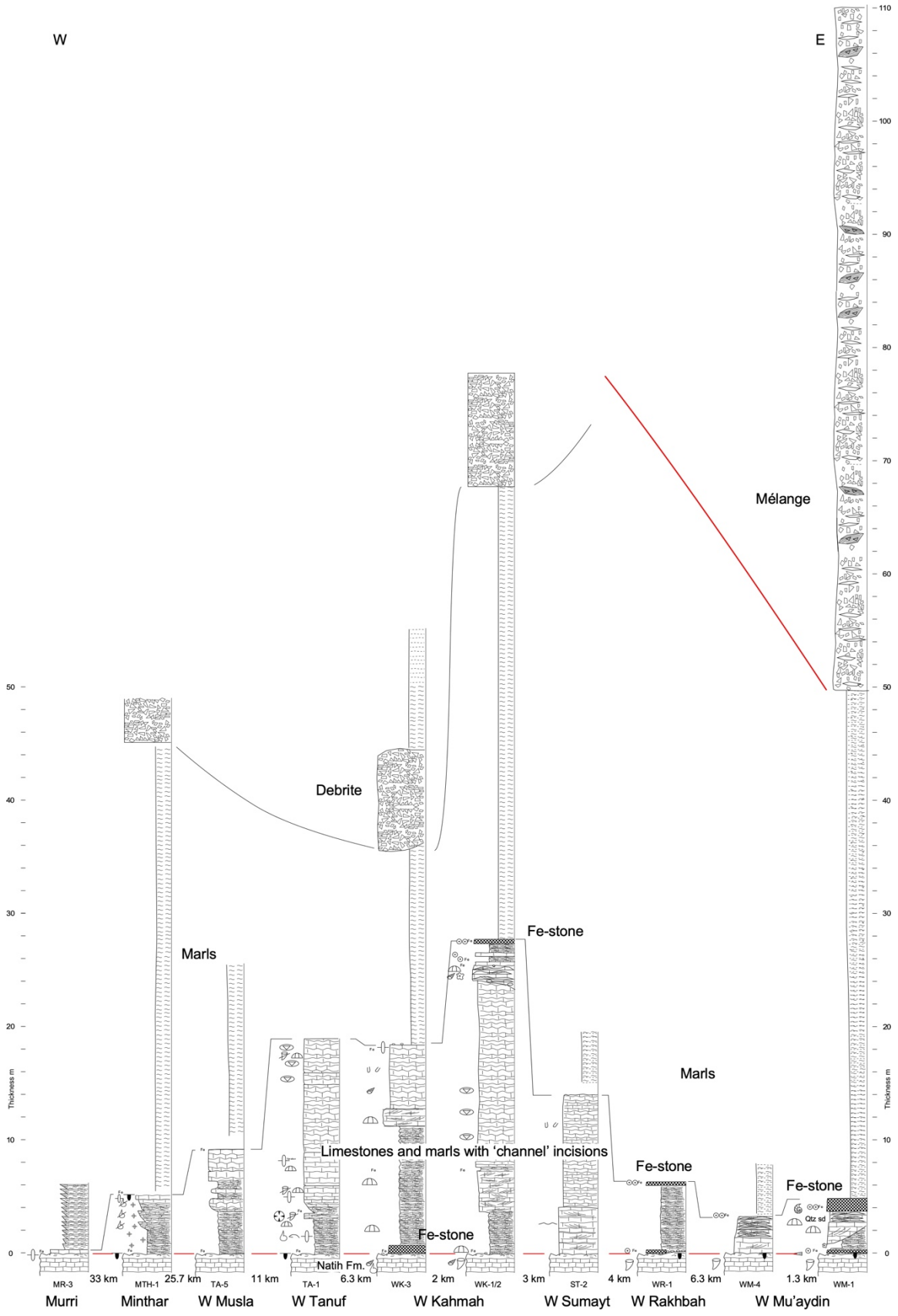


Figure 5-15 Section through the basal Muti along the southern flank of Jebel Akhdar. Red line is the base of tectonised mélange. For outcrop localities see Figure 5-5.

5.2.3.1 Basal Muti interval

The literature presents differing interpretations of the location of the BAU (and the top of the Natih Formation) along the southern flank of Jebel Akhdar. As discussed at the end of this section, the present outcrop study suggests that the BAU corresponds to a planed-off erosional surface separating shallow-marine carbonates of the Natih Formation from an overlying high-energy transgressive limestone interval (Figure 5-16 and Figure 5-17).

5.2.3.1.1 Description

Basal limestones

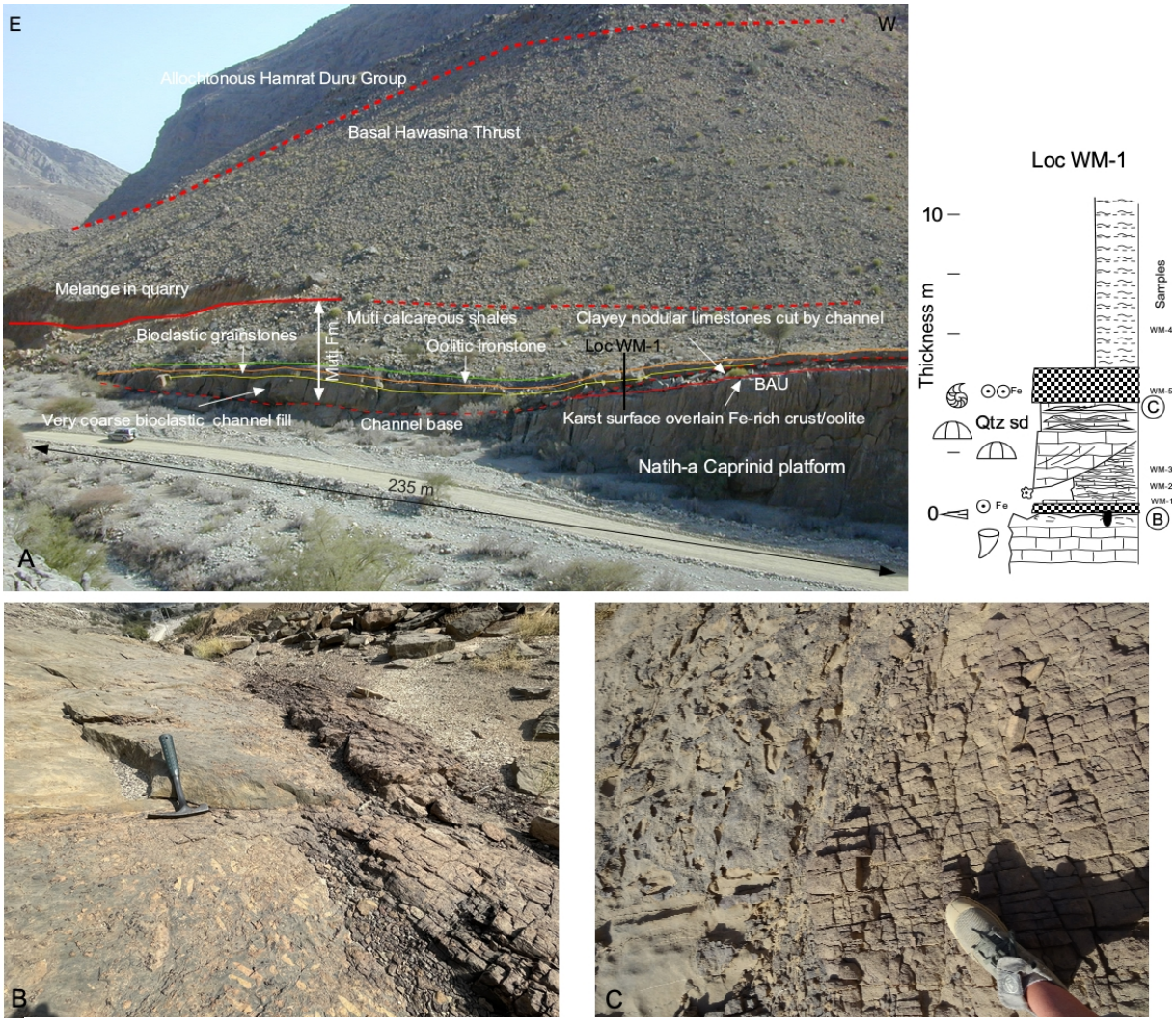


Figure 5-16 Muti Formation outcrops in Wadi Mu'aydin (locality WM-1). A: Overview of the outcrop section showing the logged stratigraphic section. B: Basal Aruma Unconformity capping shallow-water Natih limestones, defined by a planed erosional surface that sharply truncates fossils and is overlain by a thin ironstone bed. C: Bioturbated, condensed surface beneath the upper ironstone bed, previously identified as the BAU in some studies (see discussion in 5.2.3.1.4). The locations of photographs B and C are indicated on the log in A.

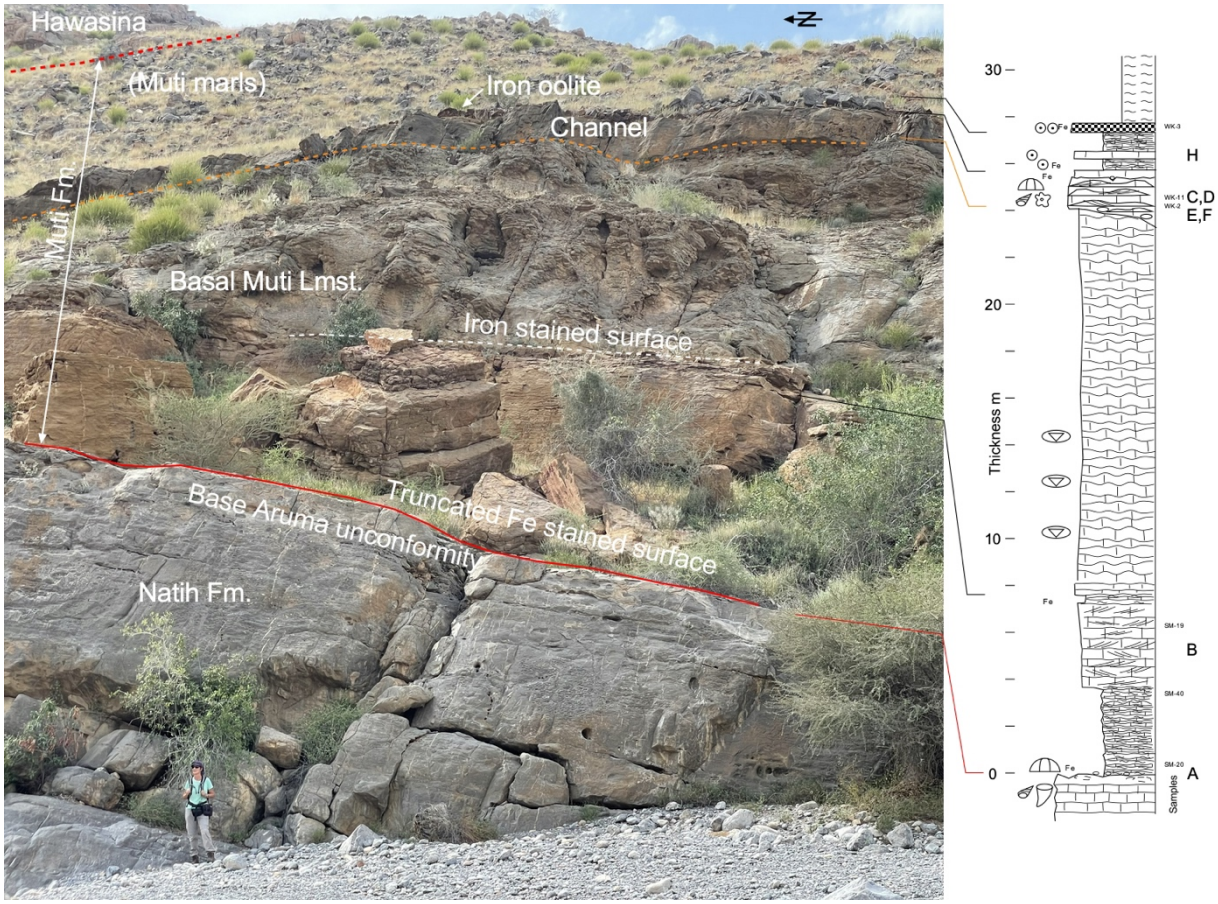


Figure 5-17 Basal Muti section in Wadi Kahmah, locality WK-1. Letters next to log refer to photographs shown in Figure 5-18.

Along the southern Jebel Akhdar transect, the top Natih is a sharp, pitted, iron-stained erosion surface, which in places has a brecciated appearance with a brown matrix. It shows a cm to dm scale topography, and in places is overlain by ferruginous ooids or conglomerate layers with cm-sized reworked clasts (Figure 5-18A). Rudists along the top

Natih surface have been truncated, and cavities are filled with light brown sediment (Figure 5-16 B). In Wadi Mu'aydin it is overlain by lag deposits with belemnites below the lower ironstone.

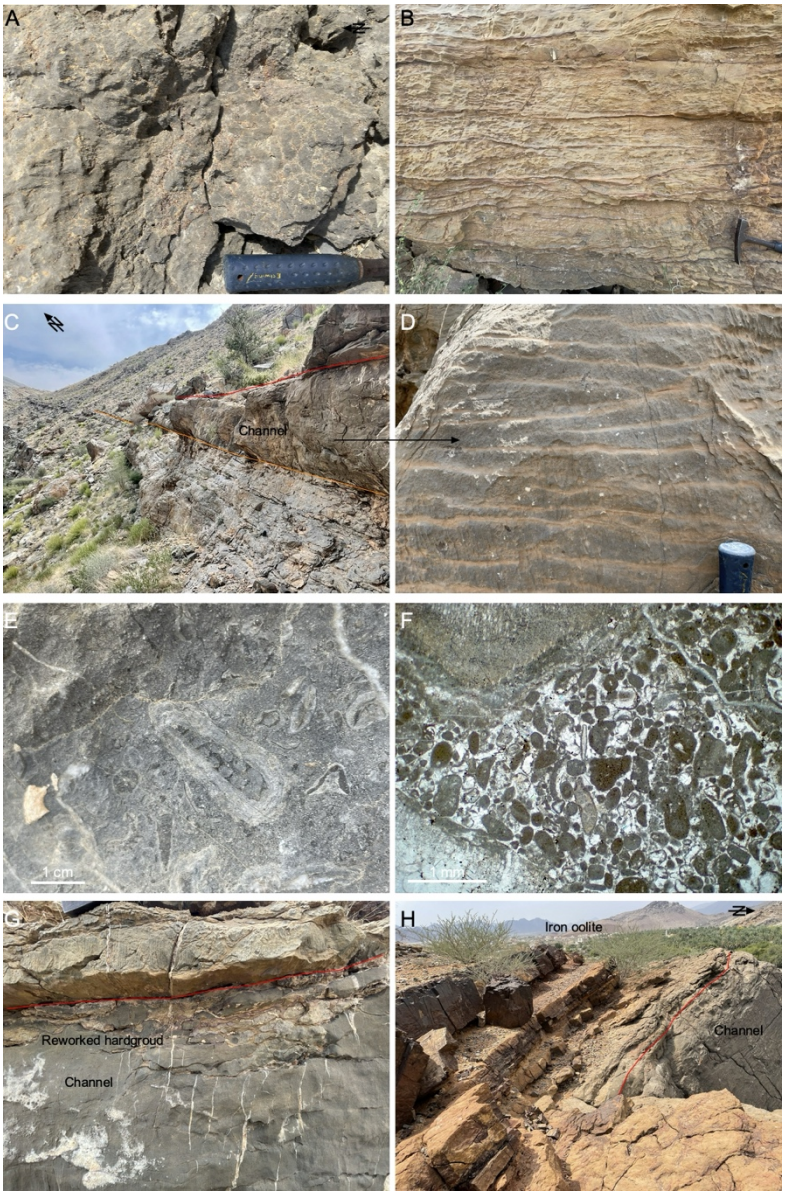


Figure 5-18 Muti facies in Wadi Kahmah locality (WK-1). A: Basal conglomerate on top of Natih. B: Hummocky to swaley and cross-bedded calcarenites in basal Muti interval. C: 'channel' incision in uppermost Muti. The 'channel' pinches-out to the north and thickens to more than 5 m to south. D: 'Channel' fill consisting of lenticular-bedded limestones with low angle cross-lamination. E: Coarse bioclasts within 'channel', mainly gastropods and oncoids with a gastropod nucleus. F: Thin section photomicrographs (normal light) of 'channel' fill showing a peloidal grainstone with micrite-coated bioclasts, echinoids, and shell fragments (Sample WK-11) FOV 4.9 mm. G: Reworked hardground / karstified surface along top of 'channel'. H: Top of Muti carbonates formed by 2 m of iron rich, burrowed limestones overlying the 'channel' fill. Interval is capped by the "upper" iron oolite. For location of photos see Figure 5-17.

The overlying basal Muti limestones show strong lateral variations in thickness from 0 to 28 m. The sequence starts with a few metres of poorly exposed biscuit-coloured marls. This is overlain by m- bedded, yellow-brown weathered, fine-grained bioclastic limestones and nodular, cm-bedded, grey, bioclastic limestones. The beds are very fossiliferous with well-preserved echinoids, lamellibranch and radiolitid rudist fragments, oncoids, gastropods and isolated corals (Figure 5-18E). Thin sections also show micritized benthic foraminifera and peloids, planktonic foraminifera and small calcispheres (Figure 5-18 F). In places the wavy to nodular-bedded limestones contain cm to dm-sized chert nodules. The bioclastic limestones show low angle, hummocky to swaley cross stratification, cross-bedding and wave ripples (Figure 5-18 B). In places they show clear vertical, spreiten-filled, burrows. Within the sequence are incisions up to 5 m deep (Figure 5-18 C, D) filled by well-sorted, lenticular and cross-bedded grainstones containing cm-sized calcareous silt clasts from the underlying units. The upper part of the limestone sequence in Wadi Kahmah is a 1 m thick interval of intensively burrowed iron-rich grainstones with some iron ooids and hardgrounds (Figure 5-18 G).

The top of the limestone sequence is formed by an up to 1.5 m thick, coarse-grained, iron-rich, grainstone with iron ooids and black phosphatic clasts, or, in the west, an iron-stained burrowed interval (Figure 5-18 E). This contains micritic lithoclasts with rudist debris and benthonic foraminifera, rounded bioclasts as well as some planktonic foraminifera in the matrix. The ironstone is sharply overlain by biscuit-coloured marls; in Wadi Mu’aydin there is a lag deposit with ammonites at this level.

Along the western part of the transect this basal Muti limestone interval is reduced to only a few metres of nodular limestones interbedded with marls capped by an iron-stained burrowed surface.

Debrites

The basal limestone and ironstone interval is sharply overlain by a monotonous succession, several tens of metres thick, of biscuit-coloured to greenish-yellow marls with faint bedding. These grade upward into poorly exposed beige- to greenish-grey, non-calcareous silty shales. The succession contains sharp-based, laterally discontinuous debrite intervals that locally reach several tens of metres in thickness. The debrites are similar to those observed in the Semail Gap: they are very poorly sorted, and the clasts—derived from the basal Muti Formation as well as the Natih Formation—range in size from a few millimetres to decametre-scale rafts floating in a fine-grained matrix.

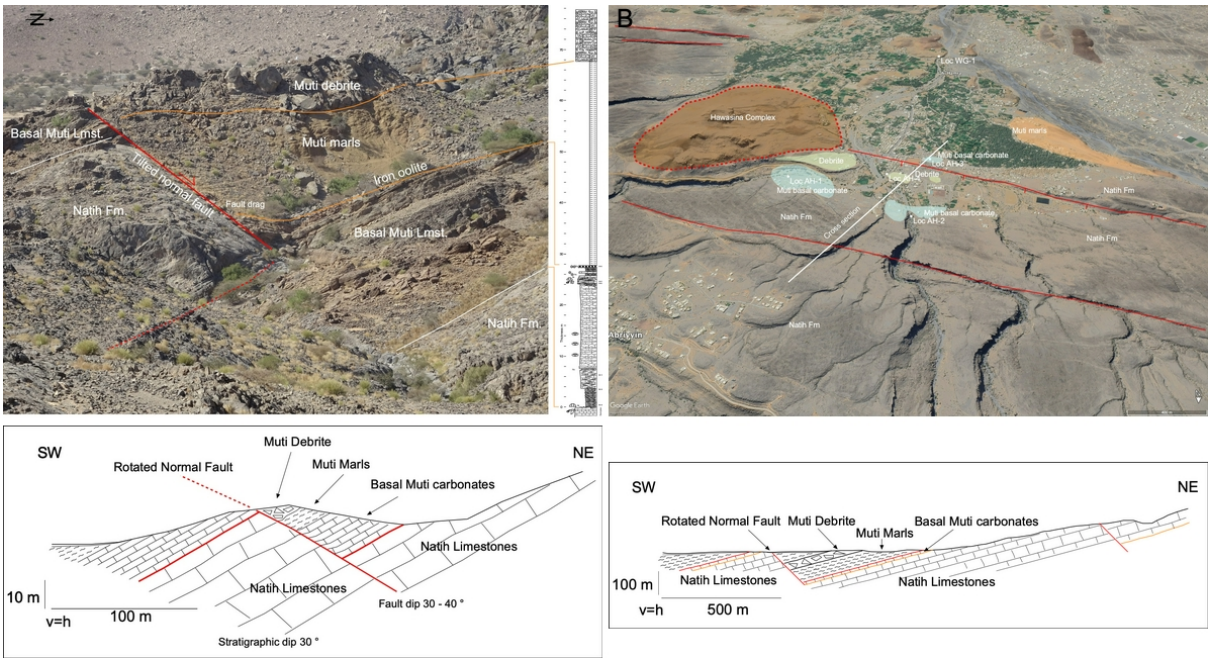


Figure 5-19: Muti debrites associated with fault scarps. A: Overview photo and section log of locality WK-2, showing displacement of Muti Formation along tilted normal fault. B: Overview and cross section of Al Hamra area showing Muti debrites on the hanging wall of a fault displacing both the Natih and the Muti carbonates. White line is location of the cross-section.

In Wadi Kahmah (loc WK-2 see Appendix-1) debrites occur on the footwall of an E-W trending normal fault (Figure 5-19 A). The fault has an apparent throw of more than 60 m and emplaces Muti marls against the Natih Formation. Clay smearing suggests faulting occurred relatively early, before deep burial. The lower Muti and Natih clasts in the debrite on the hanging wall indicate fault scarp erosion along the uplifted footwall. An interval of marls below the debrite on the hanging wall indicates that faulting occurred after the main drowning event and took place in a deep-water setting.

In the Al Hamra area (loc. AH-4 see Appendix) a debrite interval of at least 35 m thick, some 105 m above the base of the Muti marls, occurs on the hanging wall of a major E-W trending fault, with a throw of > 200 m (Figure 5-19 B).

Along the road up to Jebel Shams (loc JS-3 see Appendix-1) debrites abut a W-E trending fault scarp about 40 m high, showing fault scarp retreat of some 95 m to the north (Figure 5-20). The debrites are part of a body covering an area of c. 20 by 12 km. The source for such a large amount of debrite may be a major E-W trending fault, indicated with a throw of several 100 m, some 7.5 km north of these outcrops.

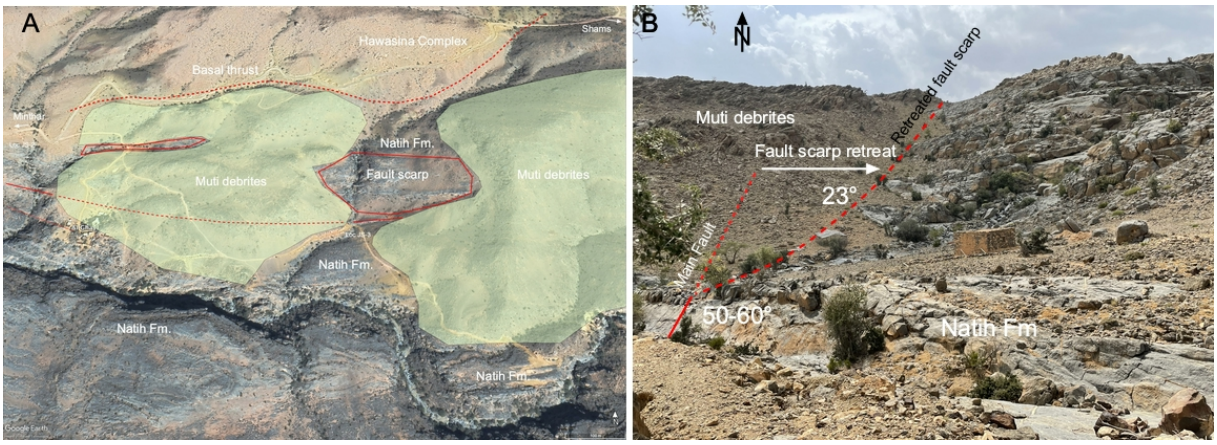


Figure 5-20 Muti debrites along fault scarp in Al Ghayl along the road to jebel Shams. A: Google Earth satellite picture showing a Natih outlier created by a fault scarp cut into the Natih Fm. and covered by Muti debrites (green overlay). B: Detail of fault scarp retreat at locality JS-3.

5.2.3.1.2 Biostratigraphy

In the middle of the basal limestone interval of the Muti Fm. on the Jebel Akhdar Plateau Smewing (1985, unpublished work) reports the presence of the larger benthic foraminifera *Rotalia skourensis* (now considered to be *Rotorbinella skourensis* (Simmons et al., 2025)), which is also known from the Ilam Fm in Iran. The Ilam is considered to be Coniacian to Santonian in age, though some studies suggest that planktonic foraminifera and nannoplankton indicate that the basal part could be late-middle to late Turonian in age (Hosseini et al., 2024). Smewing (1985) also mentions that argillaceous limestones of the basal Muti in the Wadi Ghul area were dated Santonian – Campanian, based on planktonic foraminifera by Robertson's Research.

A shallow core hole some 64 m deep was drilled in 1960 by PDO in Wadi Mu'aydin near WM-1 and sampled the lower part of the Muti marls and some 6 m of the underlying Muti limestones for palynology (Heward, 2005). The samples were barren for palynology, but pelagic microfauna showed these shales to be late Santonian - early Campanian in age (Kapp and Llewellyn, 1965; Wilson, 2000). A sample of the marl below the debrite in the quarry at WM-1 had poorly preserved nannofossils of Santonian to mid Campanian age (sample WM-4, M. Simmons pers. comm. 2025). A sample of the marl below the debrite in the Wadi Kahmah area (loc KM-3) had poorly preserved nannofossils of late Coniacian – mid-Campanian age (sample WK-5, M. Simmons pers. comm. 2025). Unpublished work by Smewing (1985) mentions that lime mudstones from between Al Hamra and Tanuf have been dated as Turonian – Coniacian and Santonian based on nannofossils, and that calcareous mudstones of the Muti in the Al Hamra area have been dated as 'probable Santonian' based on foraminifera, all by Robertson's Research.

Taken together, these data suggest that at least part of the basal Muti limestone sequence is Santonian in age but that the very basal part could be older. Also, some of the overlying marls are Santonian in age but could extend into the middle Campanian.

5.2.3.1.3 Interpretation basal Muti interval

Basal limestones

The basal Muti Formation along the southern Jebel Akhdar transect comprises an upward-deepening succession of bioclastic and iron-rich grainstones and marls, with minor fine-grained siliciclastic input. It overlies a major unconformity that truncates the underlying Natih limestones. This unconformity represents a transgressive ravinement surface that removed the upper part of the karstified Natih limestones and their associated soil cover (Figure 5-16 B).

Sedimentary structures—including low-angle hummocky to swaley cross-stratification, cross-bedding, wave ripples, and scour-like incisions within the grainstone units, indicate storm deposition on a shallow shelf. The sharp upper surface, marked by iron oolites and hardground development and overlain by hemipelagic marls, records a major deepening event. Overall, the basal Muti is developed in a more proximal facies than the LMA in the Semail Gap.

Debrites

Limestone breccias with matrix-supported floating clasts are interpreted as cohesive debris-flow deposits (Gani, 2004). Outcrops along the southern flank of Jebel Akhdar clearly demonstrate that these deposits are fault-related. Clasts derived from the Natih and Muti formations are interpreted to originate from syndepositional fault scarps exposed on the seafloor. The biostratigraphy suggests these faults were active during the Santonian – middle Campanian. The orientation of these extensional faults, parallel to the obduction front,

suggests that they may be related to extension associated with downwarping of the platform as it entered the foredeep.

5.2.3.1.4 Controversy over the precise location of the BAU

Along the southern flank of Jebel Akhdar, the biscuit-coloured Muti marls and shales are separated from typical Natih limestones by a few metres thick interval of limestones and marls which can be both under- and overlain by dark brown ferruginous oolite beds (Figure 3-8 A, Figure 5-16 and Figure 5-17). In literature there are different interpretations of the stratigraphic position of the BAU with respect to this sequence. Some authors place it at the iron oolite bed at the base of this sequence and others at the base or top of the upper iron oolite. This is important because if one of the higher boundaries is chosen it would imply that there were substantial depositional changes already in the upper Natih prior to the unconformity. Glennie et al. (1974) did not mention this interval, but PDO geologists placed the base of the Muti / top Natih contact at the base of the marls on top of the upper oolitic ironstone (Haremboure and Horstink, 1967; Kapp and Llewellyn, 1965). In the extensive regional studies of the Natih in North Oman published by van Buchem et al. (2002), Grélaud (2005) and Razin et al. (2021) the base of the Muti is placed at the base of this upper iron oolite bed or if absent, the base of the overlying marls . The interval below is interpreted by them as the uppermost sequence of the Natih Formation, of inferred Turonian age. The same pick is also used by Sharland et al. (2001). A recent study by Mattern et al. (2022a) in Wadi Mu'aydin places the base Muti back at the top of the upper iron oolite bed. Alternatively, BRGM studies during the geological mapping of Oman place the base Muti in the Mu'aydin area at the basal erosional / exposure surface overlain by the lower iron oolite bed and interpret the interval above this as a transgressive basal unit of the Muti Formation (Béchennec et al., 1992c; Hutin et al., 1986; Philip et al., 1995; Rabu, 1988). Robertson

placed the boundary also at the erosional unconformity surface below the lower ironstone in both the Wadi Mu'aydin area and in the Wadi Kahmah section (although, confusingly, in

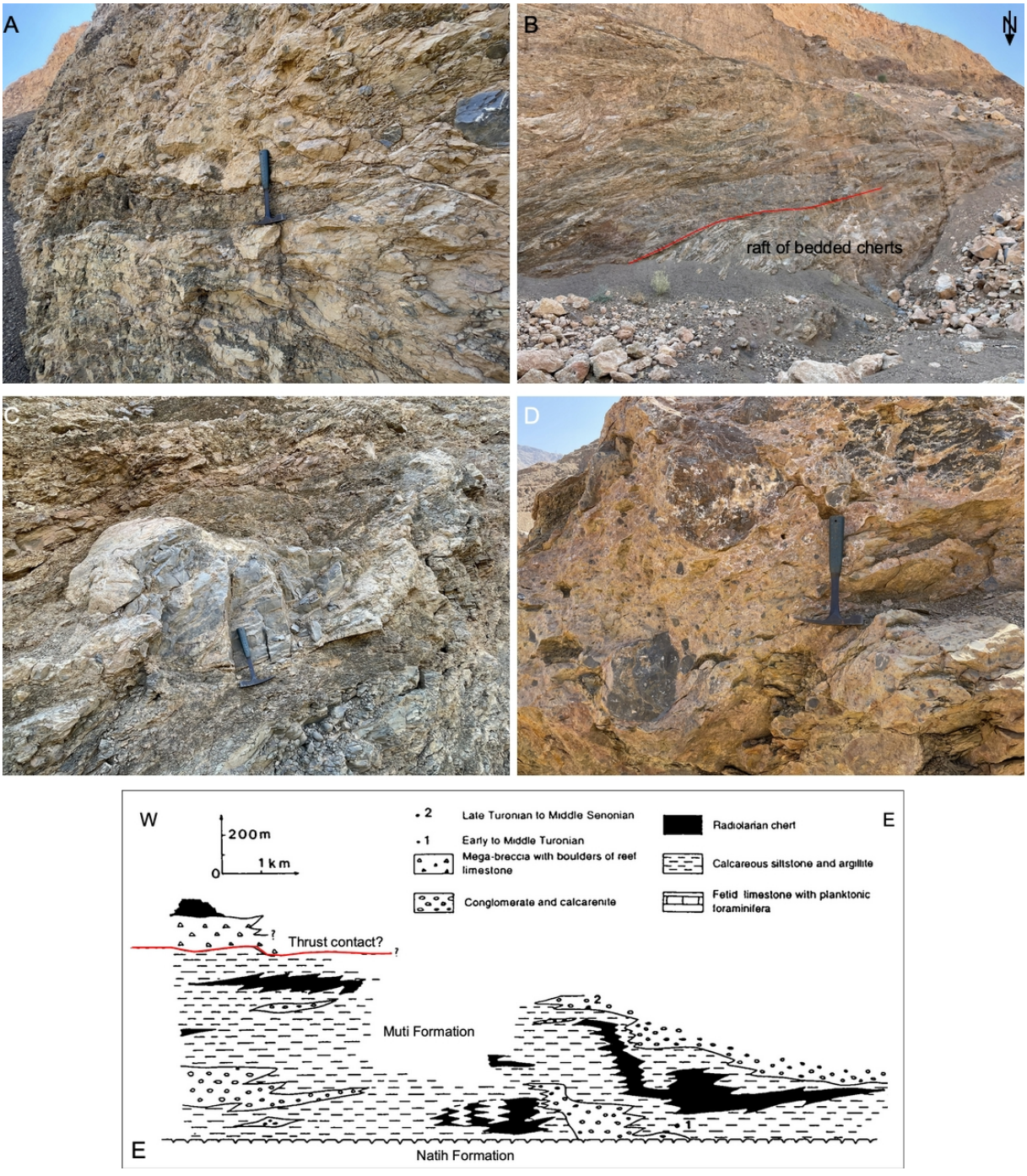


Figure 5-21 Wadi Mu'aydin debrites with large shale clasts in central part of quarry (A), m-scale rafts of bedded cherts (B), slumped limestone debrite beds and injection structures (C) and limestone clasts floating in a poorly sorted shale and marl matrix (D). E: BRGM model of lithofacies variation in the "Muti" Formation along the south flank of Jabal Akhdar (between Wadi Nakhr and Jabal Misfah, along road to Jebel Shams). It shows kilometre scale mega lenses of debrite, megabreccia and bedded cherts. Modified from Rabu et al. (1993).

the log for Mu'aydin shown in his figures the base Muti is indicated at the base of the marls (i.e. the top of the upper iron oolite)) (Robertson, 1987b; Robertson, 1988).

The present study agrees with the interpretations of BRGM workers, and the unconformity is readily identified in the Wadi Mu'aydin section beneath the lower iron-oolite bed as a planed-off erosional surface that cleanly truncates fossils (Figure 5-16 B). Accordingly, in this study the limestones and marls underlying the upper iron-oolite unit are assigned to the Muti Formation. This major unconformity can be recognised along the entire southern Jebel Akhdar transect and is similar in scale and character to those observed in the Semail Gap sections, the southern Saih Hatat sections, and at the base of the Aruma Group in the subsurface. In contrast, the bedding surface below the upper iron-oolite unit and underlying the marls, previously suggested as the BAU in the studies cited above, shows evidence of condensation but lacks clear indications of significant truncation (Figure 5-16 C).

5.2.3.2 Upper Muti mélange

5.2.3.2.1 Description

In Wadi Mu'aydin the mélange is very well exposed in a small shale quarry (Loc. WM-1). Some 25 m above the upper ironstone, the Muti marls are overlain by folded beige to greenish-grey coloured, non-calcareous, silty shales c. 20 m thick. The contact is poorly visible due to folding. This unit is overlain by a chaotic interval, about 60 m thick, consisting of free-floating clasts of cm to dm-sized, blue-grey limestones and rafts of calcareous shales, thin-bedded cherts and folded Muti debrites that can be more then 10 metre in size (Figure 5-21). These very poorly sorted clasts are floating in a very fine-grained, calcareous shale matrix, which shows soft-sediment deformation and injection structures, suggesting overpressure. Despite the proximity to the basal thrust there is little evidence for tectonic shearing, though some of the contacts between rafts are planar sheared surfaces (Figure

5-21D). The shale rafts show an elongated wedge-shaped outline, possibly flattened by compaction. The debrite interval is overlain by non-to slightly calcareous, brown, silty shales which contain folded rafts of polymict conglomeratic limestones of > 5 m diameter. The conglomeratic limestones and cherts are reworked from the allochthonous Hamrat Duru Gp. The shales are overlain by folded turbidite quartz sandstones of the Triassic Matbat Fm. The contact is not exposed but the lateral continuity of the overlying sandstones suggests these are located above the basal thrust.

5.2.3.2.2 Interpretation

The presence of soft-sediment deformation and slumping, combined with the absence of well-developed shearing fabrics, suggests that this unit represents a sedimentary mélange. The occurrence of folded rafts containing Muti debrites indicates that these deposits postdate faulting. The mixing of fragments derived from different thrust sheets further suggests that the unit formed by debris flows along the frontal part of the thrust complex and was subsequently overridden by the advancing thrust stack.

5.2.4 The Muti Fm. in Jebel Madar (siliciclastic supply from the east).

In Jebel Madar south of the eastern foothills (Al Hammah Range) of the Oman Mountains (see 1.4.5), the top Natih has been eroded down below the BAU into Natih-b equivalent slope facies and is thus Cenomanian in age (van Buchem et al., 2002; van Buchem et al., 1996). Along the flanks of the Jebel, the basal Muti is exposed in scattered outcrops.

5.2.4.1 Description

The top of the Natih is a karstified surface with dissolution holes and some red staining. It forms an irregular surface, which is overlain by some 40 m of bioturbated and cross-bedded sandstones (Figure 5-22). Along the base, cm-sized limestone clasts from the Natih Fm occur in the sands and Béchennec et al. (1992c) mention that the basal part of the sandstone

interval contains reworked benthic foraminifera of late Cenomanian age. The sand interval consists of 3 coarsening-upward cycles each some 10 – 15 m thick. The basal part of these cycles consists of a few metres of yellowish-grey coloured, fine-grained, moderately to poorly sorted sandstones with scattered coarse quartz grains, which are strongly bioturbated with only faint bedding. In the upper part of the cycle the bioturbated sandstones are interbedded with brown-grey weathering, ferruginous, calcareous, sharp to erosively based, up to 20 cm thick sandstone beds. These contain north-directed dm scale cross-bedding and ripples. The sands are fine to coarse-grained and well to poorly sorted with single and composite quartz grains, glauconite, abundant shell and echinoid fragments, brachiopods, large gastropods, benthic foraminifera, rudist fragments, calcispheres and *Hedbergella*-type planktonic foraminifera. These sandstones are overlain by at least 50 m of yellow marls containing pelagic foraminifera (Razin et al., 2021). The sandstone/marl contact is not exposed but occurs over a short interval and seems to be sharp.

In wells a few tens of km from these outcrops the equivalent of these sands is a sandy interval at the base of the Shargi Mbr. (Lower Fiqa Fm.) with variable thickness (from 0 to 40 m) and variable lithology. The interval can consist of yellow-brown ferruginous sandstones and siltstones with glauconite, silty shales, limestones with quartz, glauconite and carbonaceous matter. One well reported an ooidal ironstone with glauconite in a siliceous silty clay matrix. This ironstone overlies claystones and shales with locally sandy and glauconitic limestone interbeds, grading to calcareous, coarse-grained sandstones with lithic clasts.

5.2.4.2 Biostratigraphy

A sample of the marls contained nicely preserved nannofossils, of late Coniacian to Santonian age (M. Simmons pers. comm). Planktonic foraminifera and nannofossils suggest a

Coniacian – Early Santonian age range for this interval in a well located 20 km south of the outcrops.

5.2.4.3 *Interpretation*

The sedimentary structures and fauna both suggest a shallow marine, mixed carbonate siliciclastic setting for this basal Muti of the Jebel Madmar area. The cross-beds, shell lags and strong bioturbation point to an offshore transition zone with proximal storm deposits. These sediments fill a remnant topography cut into the top Natih. The lithoclasts may have been derived from the Natih. The transition into the marls represent a major drowning event and an end to the influx of siliciclastics.

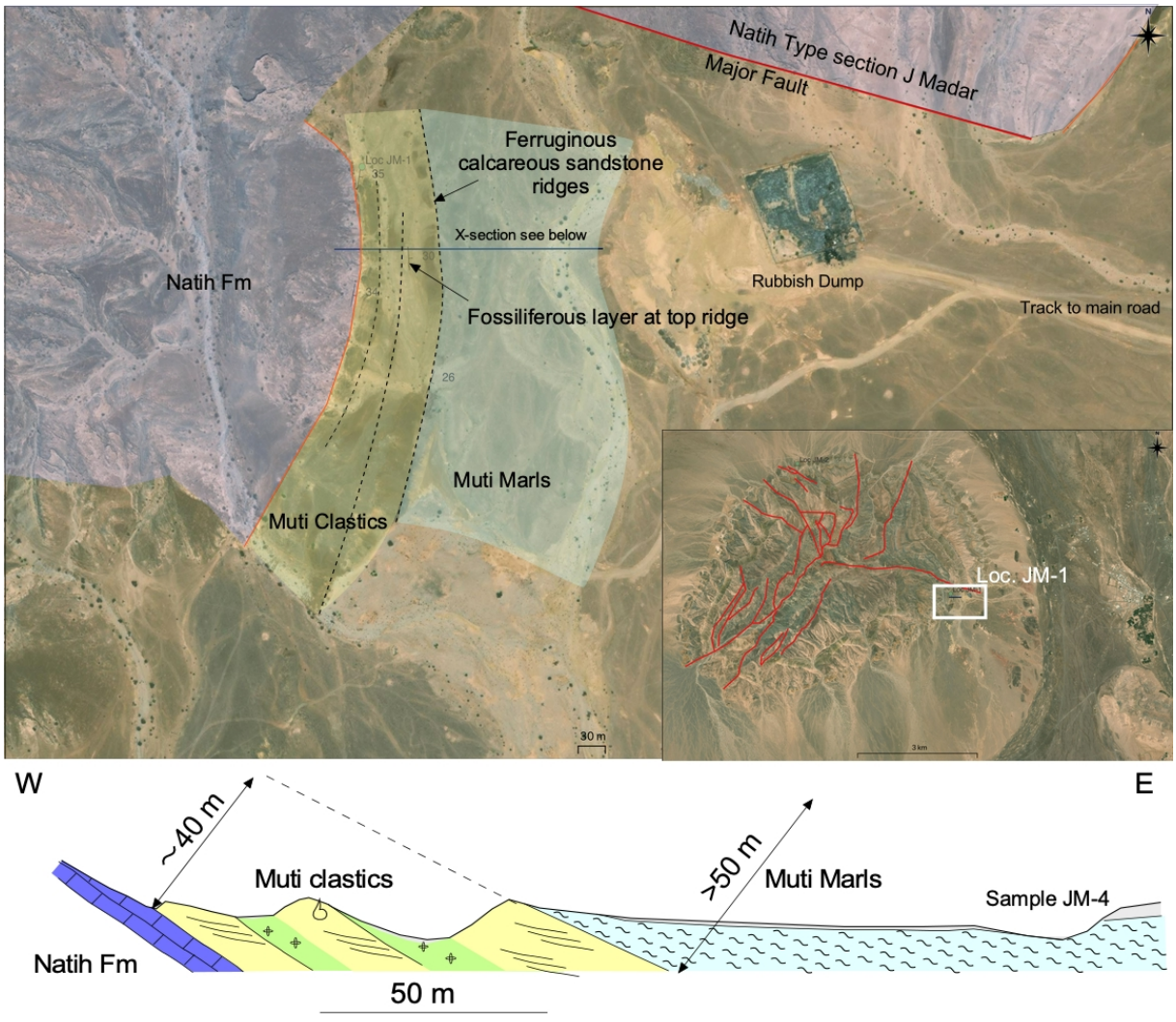


Figure 5-22 Jebel Madar Locality JM-1. Poorly exposed basal Muti clastics and marls. Location of cross-section is indicated on map. Inset Jebel Madar, fault patterns from Claringbould et al. (2013).

Some studies (Grélaud, 2005; Razin et al., 2021) suggested a lagoonal or estuarine setting. However, the fully open marine fauna, echinoids and planktonic foraminifera all suggest an unrestricted deeper water setting. Béchennec et al. (1992c) interpreted these deposits as turbidites, but the sedimentary structures indicate a much shallower, higher energy setting.

The only available sources for these coarse-grained siliciclastics are the Lower Palaeozoic or Neoproterozoic clastics, or basement, exposed along the Huqf axis to the west and southwest of this area.

5.2.5 The Muti Fm. in the Salakh Arch

Scattered Muti outcrops occur along the base of the dip slope of the anticlines and wadi incisions on the alluvial plain.

5.2.5.1 Description

In Jebel Qusayba the Muti Fm. overlies a ferruginous top Natih surface and starts with some 10 m of ferruginous bioclastic calcarenite, which is sharply overlain by marls with planktonic foraminifera of Coniacian age, and carbonate debrites (Razin et al., 2021). On the nearby Jebel Nihayda some 3 m of ferruginous arenite, capped by a ferruginous oolitic calcarenite bed, overlies the ferruginous hardground on top of the Natih (Béchennec et al.,

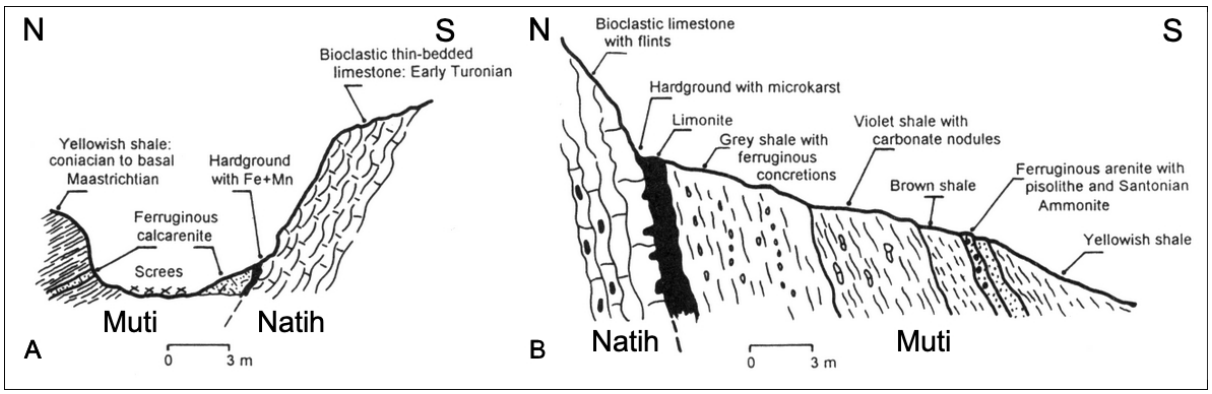


Figure 5-23 Basal Muti sections along A: the northern, locality SA-,3 and B: the southern, locality SA-4, flanks of Jebel Salakh showing lateral facies and thickness variations over a distance of some 10 km. Modified from Béchennec et al. (1992c).

1992c). Higher up in the sequence olive-green marls with ammonites are exposed below wadi gravels. Below the marls is a 30 cm thick dark, rusty-brown coloured bed with round, cm-sized pebbles of bioclastic silty limestone with gastropods and shell fragments. Other pebbles are pisoids with concentric internal laminations. The pebbles are pitted and contain borings. They occur in a red muddy matrix with bioclasts and shells some of which also contain borings. The pebbles contain cracks filled with red matrix; some cracks follow the clast outline and look like spalling. Plant remains have been found in reddish, more silty deposits.

In Jebel Salakh Fe/Mn hydroxide concretions up to 10 cm long are locally present along the top of the Natih Fm. On top of this hardground, there are patchy exposures of a 1-2 m thick, dark rusty brown, ferruginous, calcarenite, which in places contains ferruginous ooids and pisoliths (Figure 5-23 A). This calcarenite locally also fills cracks in the top of the Natih carbonates. In other areas the Natih is overlain by ferruginous lime mudstones rich in planktonic foraminifera. These are overlain by poorly exposed reddish- yellow, non-calcareous shales with rare, decimetre thick beds of ferruginous calcarenite.

On the southern flank of Jebel Salakh, the basal Muti consists of a 15 m thick interval of grey, violet and brown shales, overlying a limonite crust covering the top Natih Fm. (Figure 5-23B). These shales are capped by a ferruginous arenite with pisolites and a Santonian ammonite (Béchennec et al., 1992c). This unit is overlain by yellowish shales. This section is like the basal Shargi interval in the subsurface to the south.

Approximately 150 m above the base of the Muti Formation, a debrite interval several tens of metres thick occurs, containing sub-rounded, poorly sorted limestone blocks up to 10 m across. All clasts are derived from the upper part of the Natih Formation (Hanna

and Smewing, 1996). These debrites are overlain by poorly exposed shales, and intervals containing the debrites form isolated hills protruding from the alluvial plain on the northwestern side of the Salakh anticline.

5.2.5.2 Biostratigraphy

In Jebel Salakh planktonic foraminifera in shales some 8 m above the base Muti suggest a Coniacian to earliest Maastrichtian age (Béchennec et al., 1992c). Higher up in the sequence a latest Coniacian to early Santonian age, based on planktonic foraminifera, was derived from the shales associated with the debrites (Béchennec et al., 1992c). In Jebel Qusayba planktonic foraminifera of Coniacian age have been reported from marls in the basal Muti by Razin et al. (2021) but without any detail on the components. On the southern flank of Jebel Salakh a Santonian ammonite is mentioned by Béchennec et al. (1992c). These ages suggest that the basal Muti transgression occurred within the latest Coniacian to Early Santonian time interval, just like in the Jebel Madar area.

5.2.5.3 Interpretation

The bored pebbles, pisoids, varicoloured shales with plant remains and abundant hardgrounds indicate a transgressive coastal to shallow setting with reworked sediments from the soil originally covering the Natih Fm. The pisoids were probably derived from a pisolitic soil.

The debrites most-likely are associated with fault scarps Similar intervals containing debrites and rafts of Natih limestone have been encountered in wells located on the hanging wall adjacent to a fault scarp in the Fahud Field, located some 70 km SE of the outcrops.

5.2.6 The Muti Fm. in Hamrat ad Duru Range

The Hamrat ad Duru foothills expose the frontal part of the orogenic wedge. Muti strata are encountered both in outcrop and in wells drilled in this area. Seismic lines from the area provide critical insights into the depositional architecture and structural deformation of the upper part of the Muti Formation.

5.2.6.1 Description

5.2.6.1.1 Basal Muti

Wells drilled in the southern Hamrat ad Duru Range indicate that the thicker Muti limestones exposed along the southern Jebel Akhdar extend some 75 km further to the SW. Here, the karstified top Natih surface is overlain by up to 25 m of silty calcareous claystones with pelagic bivalves, and a microskeletal wackestone with multiple firmgrounds and incipient hardgrounds towards the top. These are overlain by up to a few metres of glauconitic, oolitic, packstones to grainstones. The limestone interval only occurs in a cluster

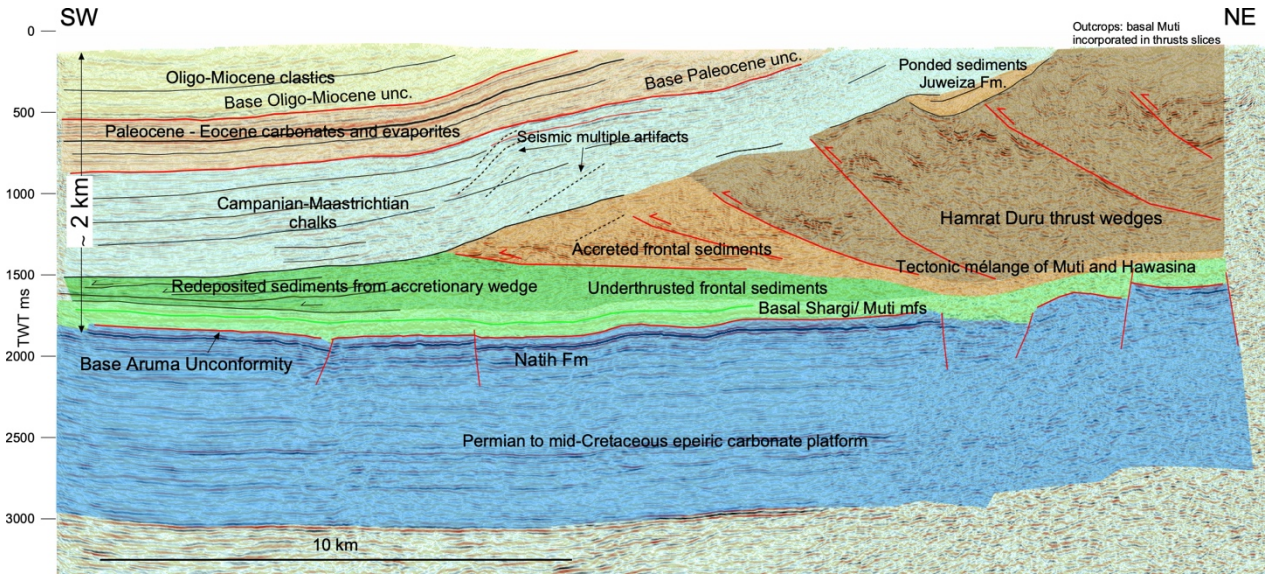


Figure 5-24 Seismic line across the frontal thrust south of the Hamrat ad Duru range. This is a re-interpretation of a section in Warburton et al. (1990) and Boote et al. (1990). It shows some sediment shedding from the orogenic into the foredeep (dark green). These are incorporated into the frontal thrust and underthrusted below the orogenic wedge. Also, the upper part of the transgressive Muti/ basal Shargi (light green) has been sliced into the tectonic mélange at the base of the thrust wedge. Location is shown on Figure 6-2 and SL-7 in Appendix-4.

of wells below the Hamrat ad Duru range and is absent in surrounding wells where the top Natih is simply covered by a glauconitic iron oolite.

5.2.6.1.2 Upper Muti mélange

Blocks of typical Muti facies (ferruginous oolitic grainstones, Natih-derived debrites, thin-bedded siltstones and marls), together with blocks of mid-Cretaceous turbidite deposits, units of the Hamrat Duru Group, cherts and Permian-Triassic reefal limestones occur in an Upper Cretaceous shale matrix in the southern part of the Hamrat ad Duru range (Hanna, pers. comm. 1994, Béchennec et al. (1992c). This mélange also occurs as slivers between the imbricated thrusts. These have been described as the Wadi Hafr unit (Hanna, 1990), Hafar Fm. (Warburton et al., 1990; Warburton et al., 1986) and Hanya Unit (Robertson, 1987a). Erosion and collapse occurred along the thrust front which incorporated basal Aruma sediments (Hanna, 1990; Warburton et al., 1990).

5.2.6.1.3 Seismic data

Deformation along the thrust front and incorporation of basal Fiqa/Muti into the thrust stacks has also been observed on seismic (Boote et al., 1990; Warburton et al., 1990; Warburton et al., 1986). In places, underthrusting at the leading edge of the thrust has led to thickening of the lower Fiqa/Muti shales to as much as twice their original thickness (Boote et al., 1990).

A seismic line through the frontal thrust along the southern edge of the Hamrat ad Duru range, which was used in a study by Warburton et al. (1990), is re-interpreted in Figure 5-24. It shows a progradational wedge in front of the thrust complex, which extends 10 km into the foredeep. According to Warburton, a well drilled into this sequence further east of the section suggests that this wedge consists of hemipelagic mudstones. To the north this wedge merges into the deformed allochthon, becomes affected by thrusting and is partly

underthrusted at the leading edge of the allochthon. The wedge and allochthon are draped by Late Cretaceous chalks. Progradational geometries suggested for this interval by Warburton are based on misinterpretation of steep dipping multiple reflectors from the Palaeogene overburden.

5.2.6.2 Interpretation

Based on the similarity of the lithology and facies to the outcrops in Jebel Akhdar, the basal Muti is interpreted as a transgressive succession with shallow marine storm deposits. The facies distribution in the outcrops and subsurface suggest a tentative N-S trending belt and could indicate some structural control on the location of the carbonate ramp (Figure 5-25).

Seismic data from the frontal part of the orogenic wedge show the presence of a

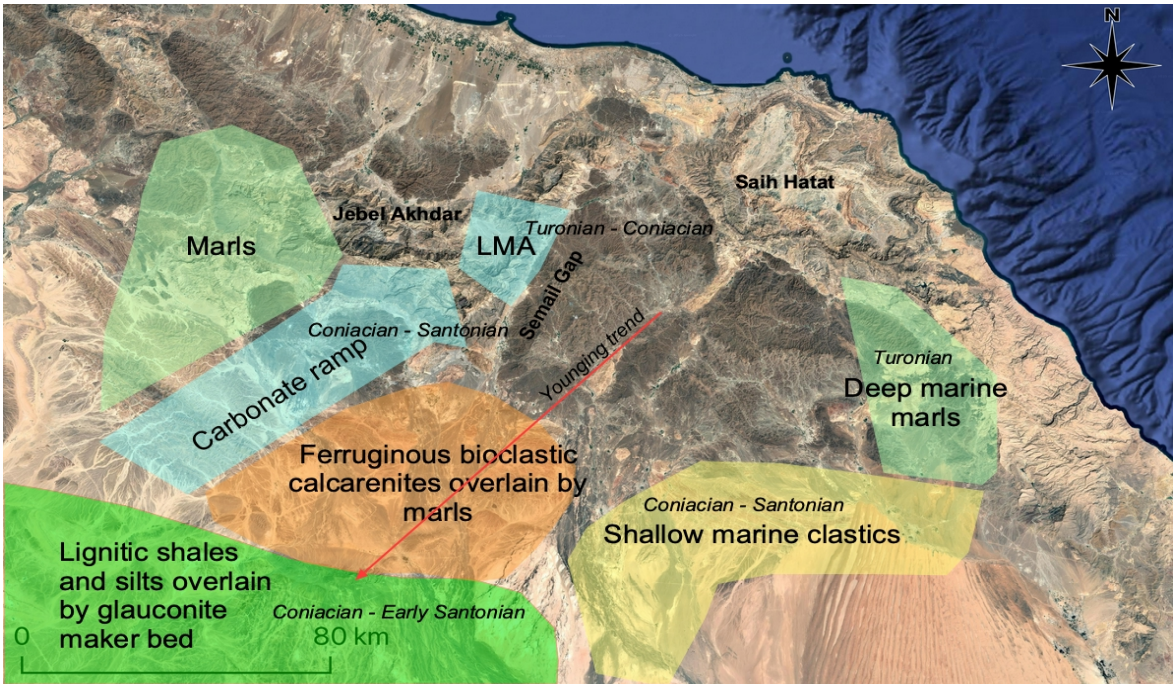


Figure 5-25 Facies and ages of Muti Fm. directly overlying the BAU in the Oman Mountains and frontal ranges. The facies belts in Jebel Akhdar and Semail show a similar orientation as basement trends and indicate some structural control. Uplift and erosion along the Huqf axis sourced the siliciclastics in the southeast. Limited biostratigraphic data show a tentative younging to the south.

sedimentary mélange composed of sediments eroded from the thrust stack and deposited in front of the wedge. Both seismic data and outcrop observations indicate that these

sediments were progressively incorporated into the wedge together with slices of the upper Muti Formation.

5.2.7 The Shargi Mbr (Muti equivalent) in the foredeep

In the subsurface south of the frontal ranges the BAU is overlain by the Shargi Mbr., a thick shale unit at the base of the Fiqa Fm. of the Aruma Group. This unit is located south of the orogenic wedge and the lateral equivalent in the foredeep of the Muti Fm.

5.2.7.1 Description

The basal part of the Shargi consists of dark lignitic shales and silts with ostracods followed by glauconite-rich shales with thin intervals of chamositic oolites. Terrestrially derived miospores and rich blooms of *Botryoccus spp*. have been reported from this interval suggesting influx of fresh-brackish water (Osterloff et al., 2001). In many wells in North Oman a glauconite-rich interval of sands and siltstones and chamositic oolites, the "glauconite marker", occurs some 3 to 40 m metres above the base (Forbes et al., 2010). This is overlain by deep water shales. Cores in the Fahud Field show karst-related, in-situ breccias along the top of the Natih Fm. and a karstic pipe network filled with Shargi shales penetrating down 10-15 m into the Natih. On seismic sections the basal beds of the Shargi are parallel to the top Natih.

5.2.7.2 Biostratigraphy

In several wells in North Oman ostracod faunas were encountered that suggest a Coniacian age for the basal part; the overlying glauconite marker bed has been dated as early Santonian (Filbrandt et al., 2004; Forbes et al., 2010; Osterloff et al., 2001; Packer, 2002). This interval has a similar facies and age as the Laffan Fm. in the UAE subsurface.

5.2.7.3 *Interpretation*

The basal Shargi consist of brackish water, lagoonal to estuarine deposits filling the erosional topography along the top Natih. The glauconite marker represents the final drowning event. The absence of transgressive shoreface deposits is related to the lack of siliciclastic sediment input from the exposed carbonate platform. Brackish water and rapid subsidence may have inhibited the onset of major carbonate production.

5.2.8 Impact of syndepositional faulting on basal Shargi: the Fahud Fault

Subsurface studies have shown that the basal Shargi is affected by syndepositional faulting (Al-Kindi and Richard, 2014; Boote et al., 1990; Filbrandt et al., 2006; Richard et al., 2017). Similar faulting has also been suggested along the southern flanks of Jebel Akhdar (Al-Kindi and Richard, 2014; Filbrandt et al., 2006; Filbrandt et al., 2007). A well-documented subsurface example illustrating the impact of this faulting on basal Shargi stratigraphy is the Fahud Fault (Figure 5-26), which is discussed in this section.

5.2.8.1 *Description*

The WNW-ESE trending Fahud Fault zone is located 50 km south of the thrust front. It is 90 km long and the upthrown northern side forms the structure of the Fahud and the Halban oil fields (Tschopp 1967; Harris and Frost 1984; Filbrandt et al., 2006; Al Kindy and Richard 2014). The apparent throw is nearly 1000 m, and the fault extends down to the top of the Ara salt, with some dextral strike-slip movement (Loosveld et al., 1996; Al Kindy and Richard 2014). Biostratigraphic data suggest the fault was active during the latest Santonian to Campanian (Filbrandt et al., 2006). The Fiqa sediments are 750 to 900 m thicker on the downthrown block (Tschopp 1967). Well and seismic data suggest limited (300 m) erosion of the Fiqa foredeep fill prior to the deposition of the Paleocene Shammar shale (Filbrandt et al., 2006). The main inversion along the fault, with some sinistral movement, occurred during

the Neogene, with more than 1000 m uplift of the Cretaceous (Filbrandt et al., 2006; Kindy and Richard 2014). The carbonates in the footwall acted as a rigid block, while the Fiqa shales on the hanging wall were squeezed into an anticline.

Well penetrations and high-resolution seismic data show erosion of the Natih carbonates along the crest of the footwall. In places the cut-out reaches as deep as the Natih-c Member, which suggests up to c. 150 m of erosion. Also, the glauconite-bearing interval at the base of the Shargi, which is present over large areas in north Oman on the flanks of both the footwall and the hanging wall of the Fahud fault, is absent from the crest. This suggests erosion took place after deposition of the lower Shargi. A 40 m thick redeposited limestone interval has been encountered 90 m above the top of the Natih Formation in a well drilled on the hanging wall along the fault zone. Cores show debrites with 10 cm clasts and rafts of Natih-a to basal Natih-b and middle -c members, intercalated with slivers of Shargi shales. Well log and cutting data in another well, located on the downthrow block some 3 km from the fault zone, shows a 12 m thick limestone interval within the Shargi, some 6 m above the top Natih, which may also represent redeposited sediments derived from the fault crest. Core through

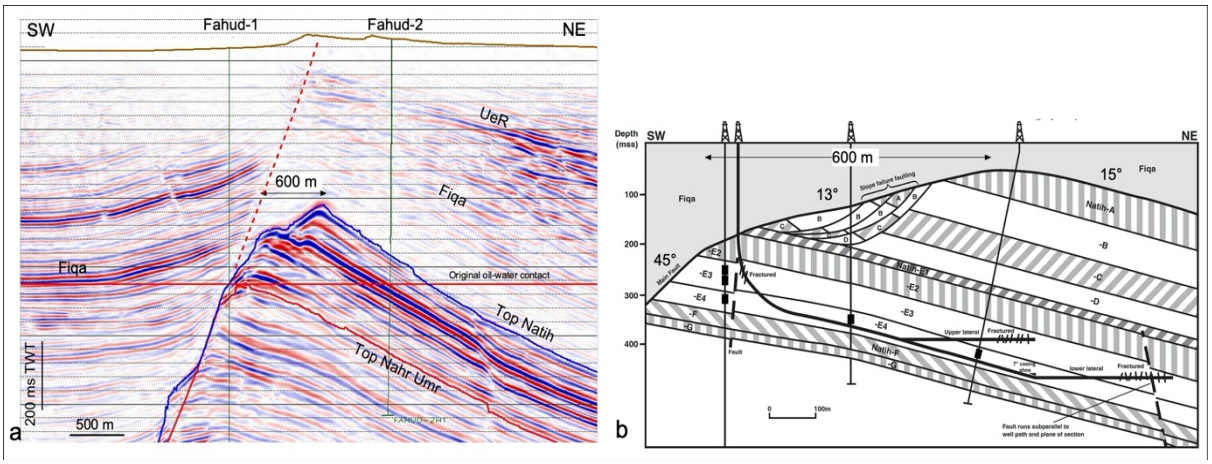


Figure 5-26 Seismic (a) and geological interpreted (b) cross section throught the Fahud structure in North Oman. The sections show more than 150 m of erosion along the crest of the footwall, resulting in a fault scarp retreat of some 600m. Modified respectively from Heward et al. (2006) and Nicholls et al. (1999).

the upper part of the Natih on the footwall show in-situ breccias / brecciated horizons, which may represent the initial stages of scarp collapse.

5.2.8.2 Interpretation

Some faults along the crest of the structures have been interpreted as slope failure faulting along the retreating escarpment. These listric faults probably sole out into intra-Natih shale beds (Nicholls et al., 1999). The total retreat was nearly 600 m, the overall slope of the escarpment along the crest some 15°.

5.2.9 Base Aruma transgression in the western foredeep (UAE)

5.2.9.1 Description

In the western foredeep in the central UAE the BAU is overlain by green to grey-brown shales of the Laffan Fm., which are slightly calcareous and contain thin streaks of limestones ((Alsharhan and Kendall, 1995). The fauna is dominated by ostracods and shows a low diversity, suggesting restricted environmental conditions. In offshore NE Abu Dhabi and western Dubai several metres of coal and palaeosols rich in organic material overlie a major karstified top Mishrif limestone surface, with caves and valleys or dolines filled with breccias and soil-derived material (Burchette et al., 2010). In eastern and northern parts of Abu Dhabi ferruginous ooids and rounded phosphatic nodules are common at the base. The upper part has a more diversified fauna with abundant ostracods, thin-shelled bivalves, benthic foraminifera such as miliolids and alveolinids, dasyclads and rare corals and gastropods.

The Laffan shales generally vary in thickness from 75 m to less than 15 m and are thicker in the western part of the Shilaif basin than the east. In places, thicker sequences of > 150m are related to syndepositional salt-withdrawal subsidence (Burchette et al., 2010; Franco et al., 2021). The contact with the overlying Halul limestones is conformable and probably these units interfinger and are partially laterally equivalent (Alsharhan et al., 2014; Franco et al.,

2021). The shales disappear towards the Lekhwair High due to Late Cretaceous and younger truncation and also towards the foredeep in the NE (Alsharhan and Kendall, 1995). In the latter, the unit is not recognised anymore due to shaling-out of the overlying Halul limestones and is therefore included in the Fiqa Fm. But at the base there are a few tens of metres of interbedded glauconitic limestones and shales, and in places conglomerates with reworked reddish soil. Based on the limestone lithology the conglomerates were erroneously included into the top Natih in the original interpretations.

5.2.9.2 Biostratigraphy

Palynology indicates a Coniacian to Santonian age (Hopping and Standring, 1969); ostracods indicate a Coniacian age (Alsharhan and Nairn, 1990).

5.2.9.3 Interpretation

The Laffan is considered as deposited in a deltaic setting, sourced from the west following a major transgression over the exposed mid-Cretaceous epeiric carbonates (Alsharhan and Nairn, 2003; Alsharhan and Nairn, 1990). Isopach maps indicate a depocentre over the western edge of the Shilaif Basin (Franco et al., 2021). Geometries, shown on a regional well-based cross section (Vahrenkamp et al., 2015a), suggest a tilting of the basin due to uplift in the east, which could indicate a back-bulge setting. This will be discussed in the next chapter. These clastics are covered by a thin veneer of shallow marine carbonates forming the landward edge of the Halul Formation as the transgression continued.

5.3 Lower Muti summary and discussion

The lower Muti interval consists of a transgressive limestone marl succession of variable thickness which locally is intercalated or overlain by debrite deposits.

5.3.1 The basal Muti transgression

1) The basal Muti sequence overlying the BAU shows strong lateral variations in lithology and depositional setting. These range from non-marine to brackish water lignitic shales and coals, coastal to open marine limestones and marls with varying amounts of siliciclastics, reworked and condensed intervals with glauconitic, ferruginous and phosphatic deposits and deep marine shales (Burchette et al., 2010; Forbes et al., 2010; Franco et al., 2021; Robertson, 1987a; Robertson, 1987b; Robertson, 1988). In all areas the sequence shows a clear deepening upward trend.

2) The abundant supply of iron is likely from the reworking of palaeosols that covered the exposed Natih carbonate platform and the Arabian continent to the SW. Similarly, oolitic ironstones in the basal Nahr Umr Fm. are associated with the major Late Aptian unconformity (Droste, 2010b; Raven et al., 2010; Robertson, 1988). However, in the case of the Muti, a source linked to ophiolite formation cannot be excluded. Sediments in ferruginous crusts and nodules associated with hardgrounds along the top Natih and within the basal Muti show a high Cr content and presence of biotite which points to mafic or ultramafic source (Robertson, 1988).

3) The BAU around Southern Jebel Akhdar has in the past been mis-picked. It was picked along a limestone marl contact but is located lower in the upper part of what was interpreted as the uppermost Natih Fm. It is now placed at the top of a weathered and karstified surface that was planed-off by a high energy coastal retreat to form a ravinement surface. The overlying sequence, containing high energy carbonate sands with erosionally based high-energy, shallow water, current-formed limestone bodies, is part of the Muti transgressive deposits.

4) The basal Muti in the Oman Mountains consists of an upward deepening sequence of limestone-marls alternations, bioclastic and iron-rich grainstones and marls with some fine siliciclastic influx. These are intercalated with abundant hardground surfaces. The top of the sequence is a sharp contact with overlying marls, often associated with an iron oolite bed.

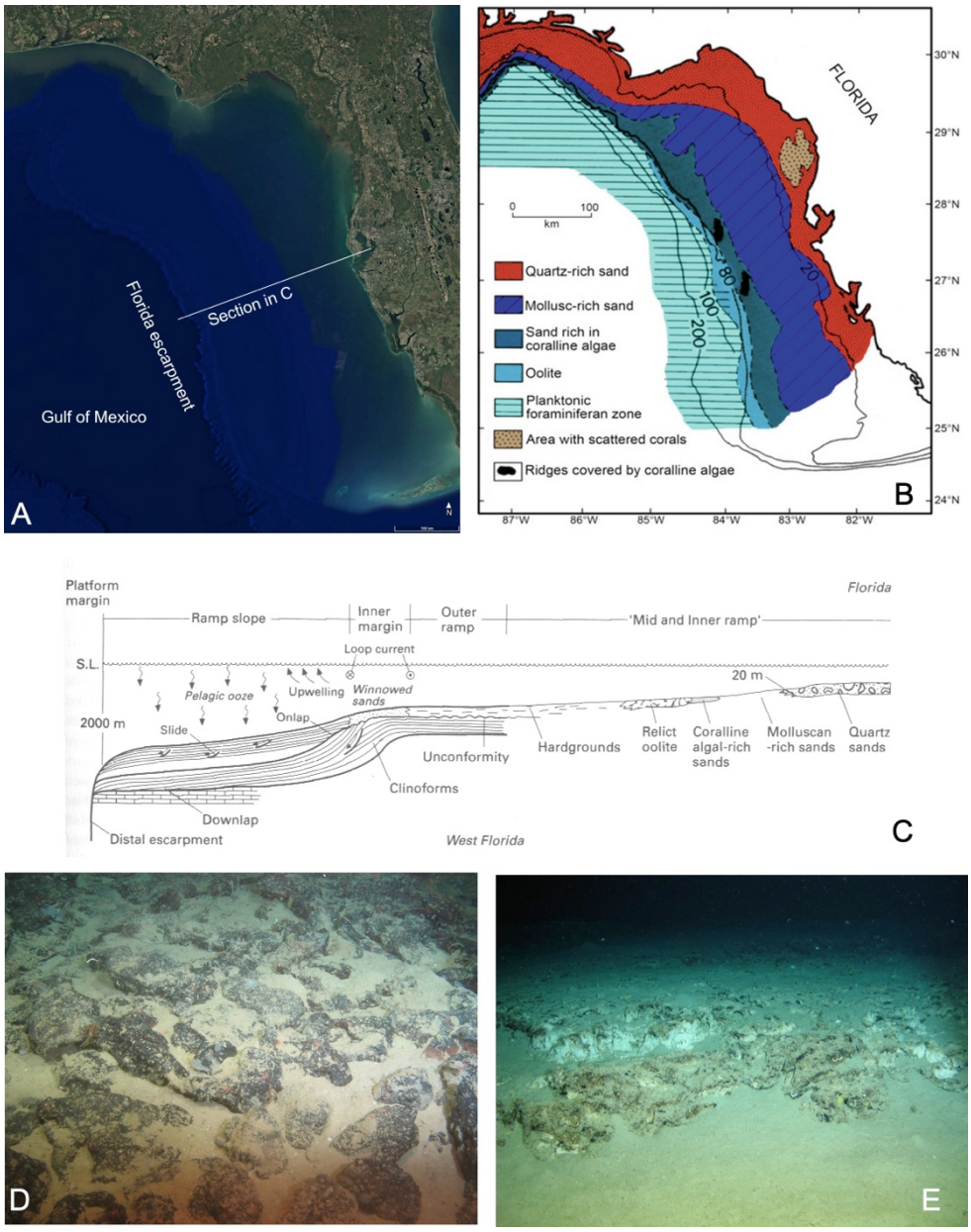


Figure 5-27 The present-day carbonate ramp of the West Florida shelf is a basal Muti analogue. A: Satellite map of Western Florida Shelf. B: Basic map of surface facies (Davis (2017) modified from Sellwood (1986)), C: Schematic cross-section of the carbonate ramp (Wright and Burchette (1996) modified from Mullins et al. (1988)). D: Exposed hardgrounds and E; Fe-Mn crust along sea floor (Ling et al., 2016)

5) In the east the transgressive deposits consist of shallow marine, mixed carbonate-siliciclastics. The siliciclastic input and the lack of lower Muti condensed horizons is in marked contrast to any other Muti section thus far described. This fact emphasises the sediment starvation in the rest of the basin and the continuing role of the Huqf High. It hints at a longitudinal – limited – siliciclastic sediment supply for the foreland basin. The overall deepening motif of the Muti Formation is nevertheless still present.

6) The basal part of the Muti equivalent in the subsurface south of the Mountains, the lower Shargi Mbr., consists of dark, lignitic brackish water shales and silts with ostracods, followed by glauconite-rich shales, with thin intervals of chamositic oolites. The features described above are very similar to the present-day carbonate ramp overlying a drowned karstified carbonate platform of the West Florida shelf as shown in Figure 5-27. Here too, the shelf is sediment starved because little sediment is delivered to the shelf by rivers. The West Florida shelf sediments consist of a mixture of relict and actively formed deposits with abundant hardgrounds, and the Holocene sediments seldom exceed 1 m in thickness (Sellwood, 1986). Lack of carbonate sediments is the result of current erosion and winnowing and the currents may be too strong to allow reef development (Ling et al., 2016).

7) A shortage of siliciclastic input, as well as of contemporaneous detrital bioclastic input resulted in a sediment starved basinal setting. The platform carbonate factory had been shut down, first by emergence and later by rapid drowning.

8) In the Oman Mountains facies belts in the basal Muti show a similar orientation as basement trends and indicate inherited structural control. The carbonate ramp along the eastern part of Jebel Akhdar continues into the subsurface along the Semail

trend. Uplift and erosion along the Huqf axis sourced the siliciclastics in the southeast (Figure 5-25).

9) Limited biostratigraphic data show a tentative younging to the SW (Figure 5-28). The earliest sediments are Turonian pelagic marls SE of Saih Hatat. Further south the sediments overlying the BAU are Coniacian to Early Santonian in age. The onlap to the south is suggestive of rotational subsidence related to the approach of the foredeep.

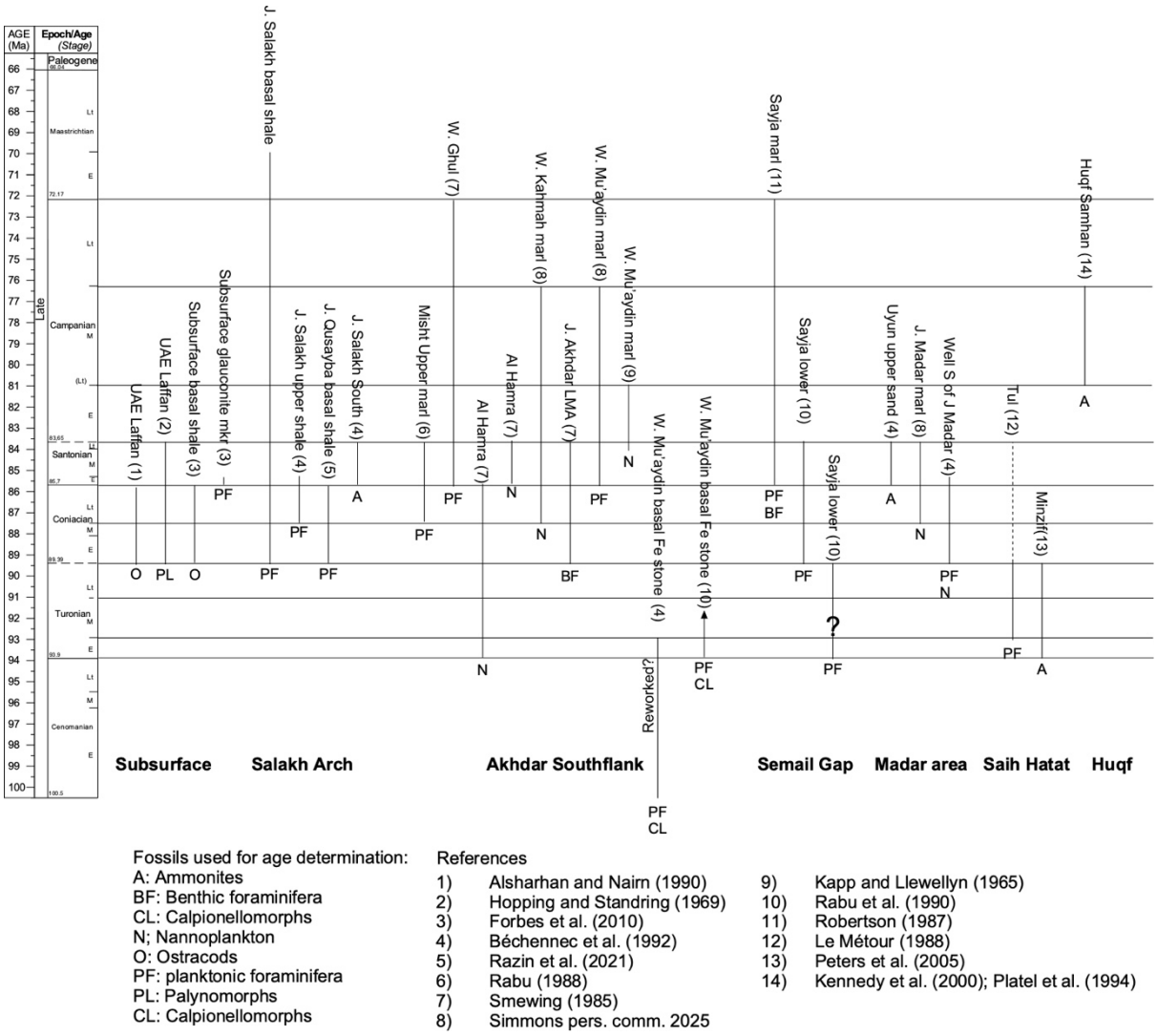


Figure 5-28 Biostratigraphic data for the Muti Fm. Bars show age range indicated by the fossil content, the actual age of the sample is somewhere within this interval. No detailed analysis of these interpretations has been done, and the zonation schemes of different fossil groups are poorly calibrated which makes the interpretations very tentative. Overall, most samples fall within the Coniacian to Santonian, only the Saih Hatat area shows clearly older, Turonian, ages. Simmons et al. (2025) bracketed the BAU palaeontologically as corresponding to 92.5 ± 0.25 Ma (their Fig 7).

10) The deeper water Muti Fm. marls may range in age up to mid Campanian. If so, this indicates extremely slow rates of deposition (ca 10m/Myr), which is in line with the abundant sedimentological evidence for condensation.

11) In summary, the lower Muti Fm. represents a sediment starved transgressive sequence covering a karstified carbonate platform. It is characterised by slow sedimentation rates, abundant winnowing and erosion, allowing full bioturbation and oxidation.

5.3.2 The debrites

The upper part of the basal transgressive Muti Formation commonly contains debrite deposits in outcrop. The characteristics of these debrites, and their relationship with structural deformation of the platform during subsidence into the foredeep, are summarised in this section.

5.3.2.1 Late Cretaceous faulting associated with the Muti debrites

The appearance of the debrites in the Muti broadly coincides with a period of faulting, salt diapirism and reactivation of basement lineaments during the Santonian to Early Campanian, that is recognised in the subsurface of North Oman and the UAE (Al-Kindi and Richard, 2014; Boote et al., 1990; Filbrandt et al., 2006; Johnson et al., 2002; Marzouk and Sattar, 1993; Marzouk and Sattar, 1994; Melville et al., 2004; Richard et al., 2017; Silva et al., 1996). These subsurface studies recognise the formation of two fault families (Figure 5-29):

1) a conjugate set of E-W to ESE-WNW and NW-SE to NNW-ESE faults, which resulted in a pervasive rhombic, fish-net pattern in some areas.

2) NW oriented growth faults with a component of strike slip.

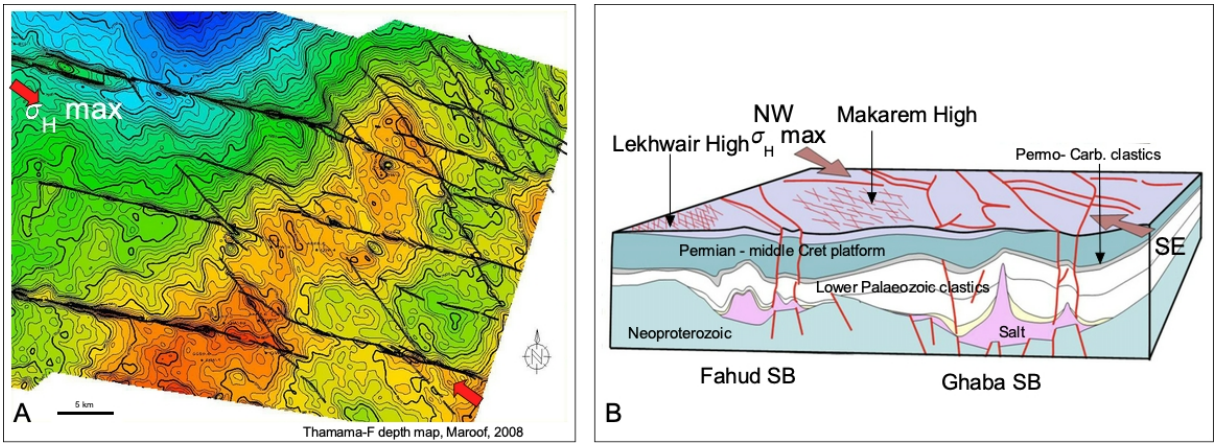


Figure 5-29 Late Cretaceous deformation A: Depth map of top Thamama F (Habshan) over the western flank of the Lekhwair-Mender High, SE UAE. The contour interval is 15 ft. The pervasive transpressional conjugate fishnet faults suggest NW-SE maximum horizontal stress. The gentle NE-SW trending low relief dome is thought to be related to Jurassic seated NE-SW reverse faults, also indicating NW-SE maximum horizontal stress. Map modified from Richard et al. (2017). B: Schematic distribution of Late Cretaceous deformation. The fishnet faults are developed over regional highs with little or no salt cover. In the salt basins there is reactivation of salt diapirs, formation/ reactivation of transtensional faults, often with salt thickening into the footwall. Modified from (Al-Kindi and Richard, 2014).

5.3.2.1.1 The conjugate faults

The conjugate faults affect the basal Upper Cretaceous Shargi shales down to the Permo-Carboniferous clastics where they merge. The faults do not cross the entire Fiqa Formation in the basins and tip-out upwards below the Upper Campanian-Maastrichtian. They are detached from the basement and not linked to any basement features. The vertical offsets are generally a few tens of m but can be up to 150 m. Very little horizontal displacement was observed, it is probably less than or equal to vertical the displacement. The angle between the arrays is about 65-70°, and the inferred maximum horizontal stress orientation from the kinematic indicators is, for most of the faults, NW-SE (125-135°). The fishnet pattern is well developed, planar both vertically and horizontally, and uniformly distributed over regional basement highs, where the salt is thin or absent. The deformation is more irregular in the salt basins. Richard et al. (2017) suggest that the fishnet pattern on the highs is related to the

activation of numerous detachments, like marls and shale intervals, in the absence of salt, to accommodate the larger scale deformation.

On the flanks of Jebel Akhdar the faults associated with the debrites expose similar fault trends as the subsurface Late Cretaceous WNW–ESE fault systems, with faults up to 5 km long and vertical offsets in excess of 100 m (Al-Kindi and Richard, 2014; Filbrandt et al., 2006; Filbrandt et al., 2007). These faults are thought to have formed during the same deformation phase. However, the fracture fill and diagenesis of these structures is different, due to their significantly greater burial depths and also reactivation during the doming and uplift of the Jebel.

5.3.2.1.2 The NW oriented growth faults

The NW oriented growth faults occur in the salt basins and were active during the early stages of foredeep development. Some of these have very large offsets of 200 to 1000 m and affect the entire succession down to the Lower Palaeozoic Haima Group (Fahud, Maradi, Burhaan, Habiba-Khatmah and Natih Faults). Although they are detached above the salt, some may be reactivated basement faults. Salt moved from the hanging wall to the footwall, leading to footwall uplift along many of these major faults. The average extensional strain for all faults is 5% across North Oman in a NW-SE direction (Filbrandt et al., 2006). As discussed in Chapter 2, it is likely that the salt basins extended to the north below the obduction complex, and similar faults are expected to have affected the platform and early foredeep fill here as well.

5.3.2.1.3 Interpretation

The tectonic deformation of the Permian to middle Cretaceous carbonate platform in northern Oman and the UAE during the Late Cretaceous is the result of a combination of NE-SW extension and NW-SE compression (Al-Kindi and Richard, 2014; Filbrandt et al., 2006;

Loosveld et al., 1996; Richard et al., 2017). The NE-SW extension is readily related to the downwarping of the continental crust below the obduction complex and the formation of the foredeep. The extension is accommodated by NW-SE trending normal faults. The origin of the NW-SE compression is less clear but has been suggested to be related to a counter-clockwise rotation of the Greater Indian plate relative to the Africa/Arabian plate due to the separation of India/Madagascar from Antarctica starting at 133 Myr during the Early Cretaceous (Bazalgette and Salem, 2018; Gaina et al., 2015; Tuck‐Martin et al., 2018). Combined with the NE-SW extension, this resulted in the initiation and re-activation of conjugate strike slip faulting. The transtensional faulting also caused a renewed phase of salt halokinesis. The NW-SE compression initiated local inversion of Jurassic and older fault lineaments. Richard et al. (2017) suggest that the absence in the foreland of NE-SW compression related to the thrusting may be related to overpressures of the sediment in the Hawasina nappes which may have acted as a detachment layer. This allowed subduction of

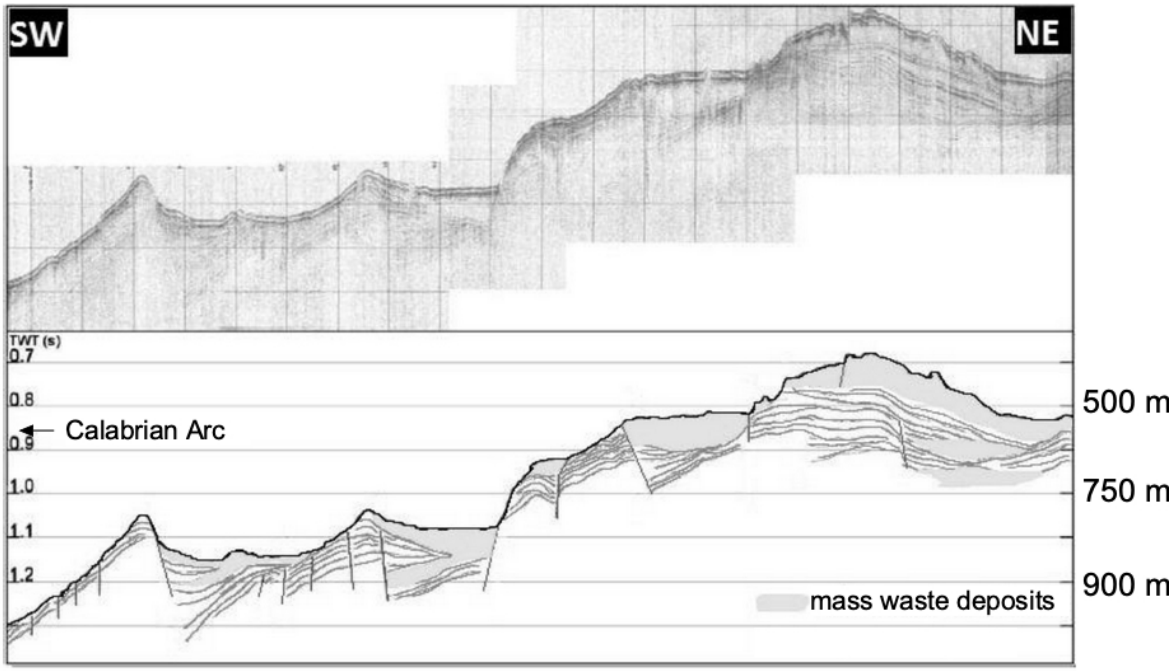


Figure 5-30 Sparker profile over the foreland basin formed by the Apulian ridge, showing large active faults associated with mass flow deposits. Modified from Pellegrini et al. (2012).

the Arabian plate margin below the ophiolites without generating NW-SE compressional stresses in the foreland.

5.3.2.2 *Present-day analogues for Muti fault scarps*

The outcrop coverage and the limited high resolution subsurface data do not allow a detailed 3-D picture of the Muti fault scarps and debrites. Hower, recent studies using high-

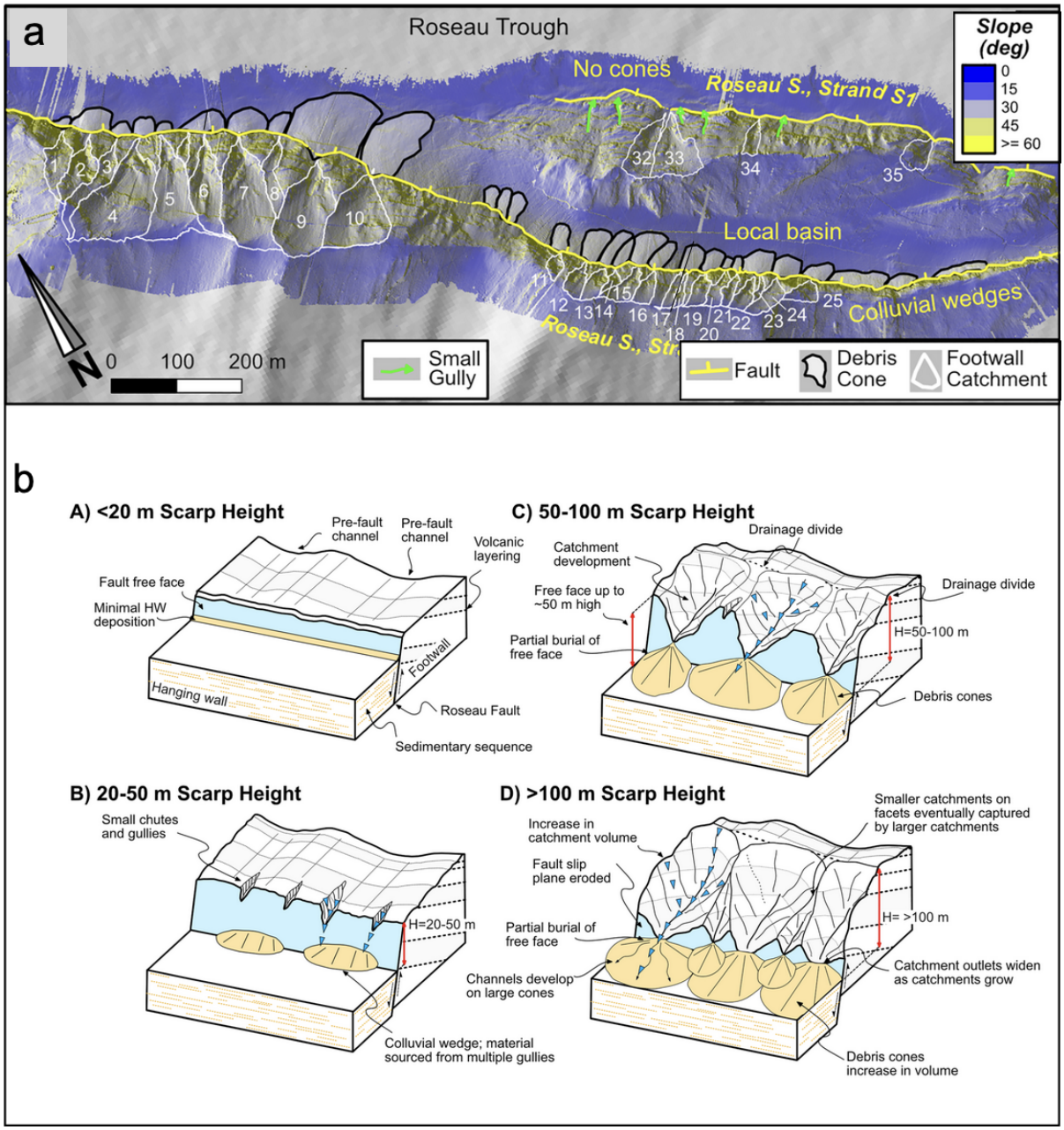


Figure 5-31. Footwall catchments and debris cones along the Roseau Fault some 1000 m below sea level in the Lesser Antilles volcanic arc. The colours indicate slope gradient. b) Fault scarp evolution with increasing fault throw. The light blue colour indicates the exposed fault surface. With increased escarpment height the fault surface is eroded by mass wasting and slope retreat of the footwall. Modified from Hughes et al. (2021).

resolution bathymetric and imagery datasets can serve as analogues for the geometry and evolution of these systems. Four analogue examples of fault scarps, and what can be learned from them, are described below: (1) the Apulian ridge in the Apennine and Hellenic fold-and-thrust belt, (2) the Roseau Fault in the Lesser Antilles, (3) The Monte Marine Fault along the eastern Mediterranean continental slope, and (4) Fault-related carbonate breccias in Natih outcrops, Jebel Qusayba.

5.3.2.2.1 Apulian ridge in Apennine and Hellenic fold-and-thrust belt

High-resolution bathymetric data of the Apulian ridge, which forms the foreland basin to the Apennine and Hellenic fold-and-thrust belt, shows numerous active fault scarps, up to several 100 m high, associated with submarine mass-wasting deposits (Figure 5-30, Pellegrini et al. (2012)).

5.3.2.2.2 Roseau Fault in the Lesser Antilles

Hughes et al. (2021) describe fault scarp evolution based on high-resolution bathymetric datasets and video imagery of an up to 160 m high submarine fault scarp in a volcanic sequence along the Roseau Fault in the Lesser Antilles. They observed catchment areas on the footwall: erosional cirque-like amphitheatres that capture mass-wasted material from their flanks and funnel the eroded material off the scarp to debris cones at the foot of the scarp (Figure 5-31A). In their example mass wasting starts as the scarp height reaches 20 – 40 m (Figure 5-31 B). Material is shed along several small chutes and gullies along strike into a colluvial wedge close to the fault scarp. With further scarp growth gullies start to deepen and erode into the footwall. They form catchments from which material is shed into radial debris cones on the hanging wall. Where the scarp height grows to more than some 100 m, the catchments enlarge and start to interact. The exposed fault surface gets eroded to a slope of some 30 – 40° and covered by redeposited sediment. Angular rubble and boulders on the

debris cones suggest most of the erosion is by rockfall. The fault scarp retreat is about 150 m; the debris cones extend a few tens to 100 m from the fault scarp (Figure 5-32). The surface slope of the debris cones varies between some 20 and 40°. Rubble and fine sediment also fill channels and drape the bedrock in the catchment areas. The total width of the belt where debrites occur in this degradation complex is 100 - 250 m.

Similar processes and evolution are likely to have affected the Muti Formation. Apart from the fault scarp height, the amount of erosion and retreat is likely also affected by the

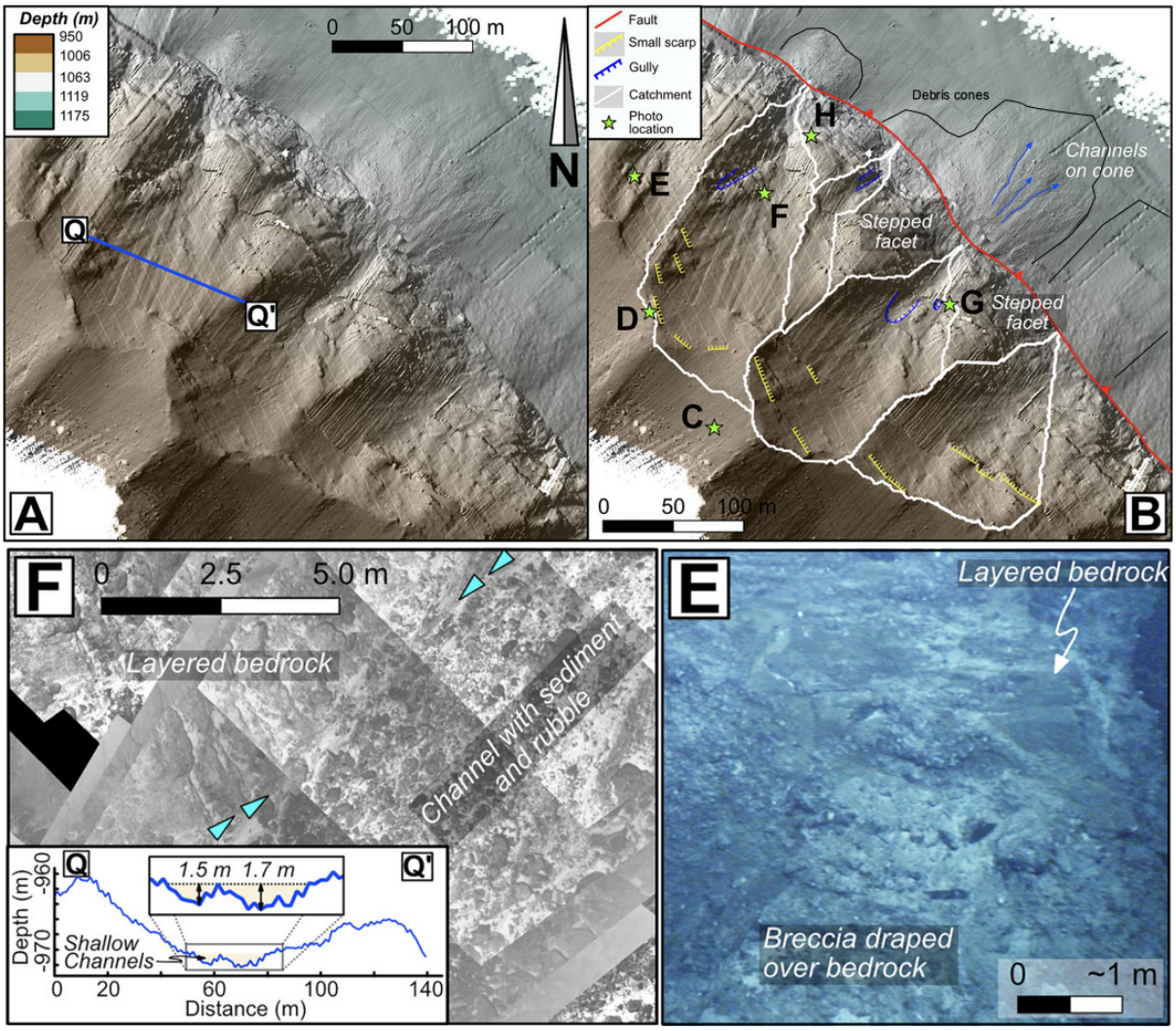


Figure 5-32 Detail of footwall catchment areas and footwall cones along the Roseau Fault catchment area (catchments 7, 8, 9 and 10 in Figure 5-31). A) Shaded relief map with interpretation shown in B) Outline of catchment areas and detrital cones. Images E) and F) show sediment and rubble in the catchment area overlying eroded bedrock (location shown on B). Profile Q-Q" shows cross section through channels in catchment (see A for location). Modified from Hughes et al. (2021).

lithology exposed at the fault scarp: initially hemipelagic marls and shales or shallow marine limestones of the Muti Formation, but with increased fault throw also the more resistant shallow water limestones of the Natih Formation.

5.3.2.2.3 Fault scarps along the eastern Mediterranean continental slope

Mapping of landslides and fault scarps along the eastern Mediterranean continental slope show that landslides and surface rupturing in an active faulting system may post or predate each other (Katz et al., 2015). The landslide deposits derived from updip faults may cover earlier active faults or may be re-faulted during a later stage of deformation.

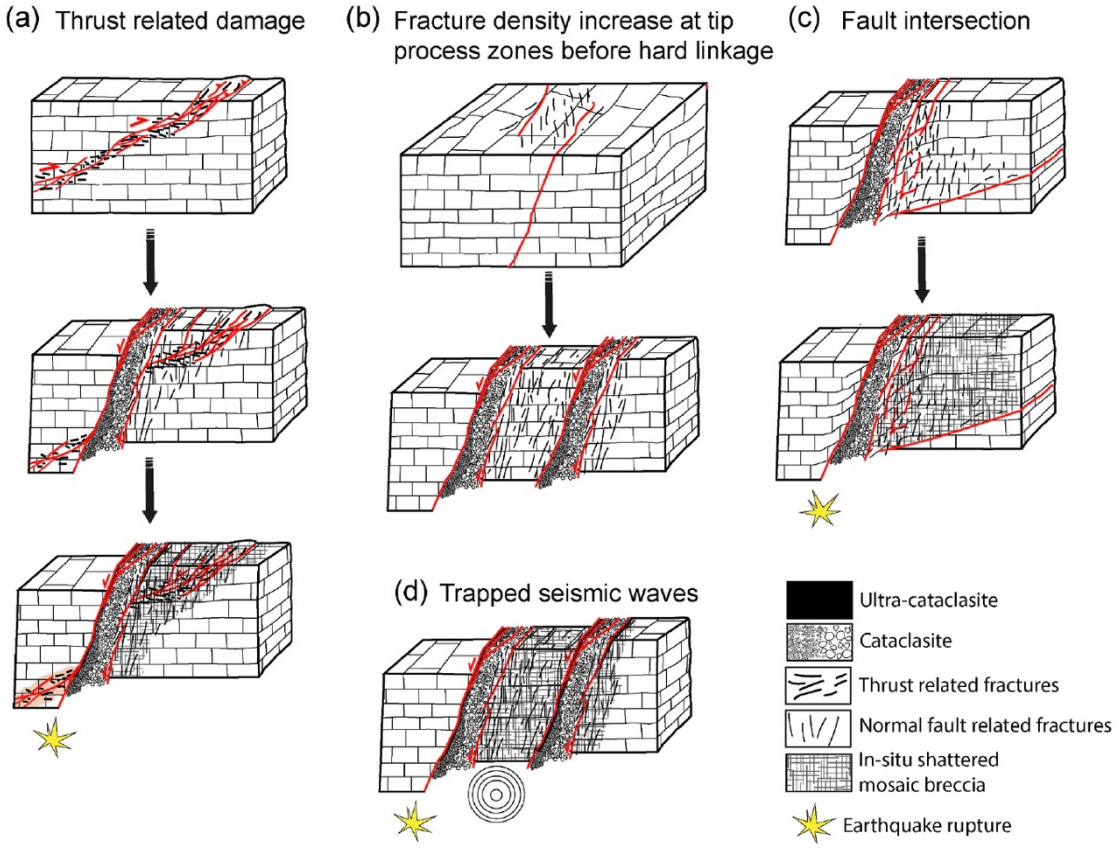


Figure 5-33. 3D-block diagrams showing possible development of in-situ shattered mosaic breccias along the Monte Marine Fault in the Italian Apennines (Cortinovis et al., 2024). (a) Thrust-related inherited damage. (b) Fracture density increase in the overstep region of normal fault segments. (c) Mechanical interaction at fault intersection between low-angle thrust fault and high-angle extensional faulting. (d) Trapped seismic waves between overlapping extensional faults. Models (b) and (d) may be applicable to the formation breccias in the Natih carbonates that were later reworked into the Muti debrites.

The angular clasts in the debrites most likely have been sourced from in-situ shattered mosaic breccias along the faults activated by seismic events during the subduction. Cortinovis et al. (2024) describe large volumes of mosaic carbonate breccias with thicknesses of 50 – 100 m within fault zones in the Italian Apennines that are thought to be associated with the propagation of earthquake ruptures (Figure 5-33).

Similar carbonate breccia bodies have been described by Balsamo et al. (2016) interposed between fault cores and damage zones in the Natih outcrops on Jebel Qusayba (Figure 5-34 A and B). These bodies range in thickness between some 10 cm to 7 m and

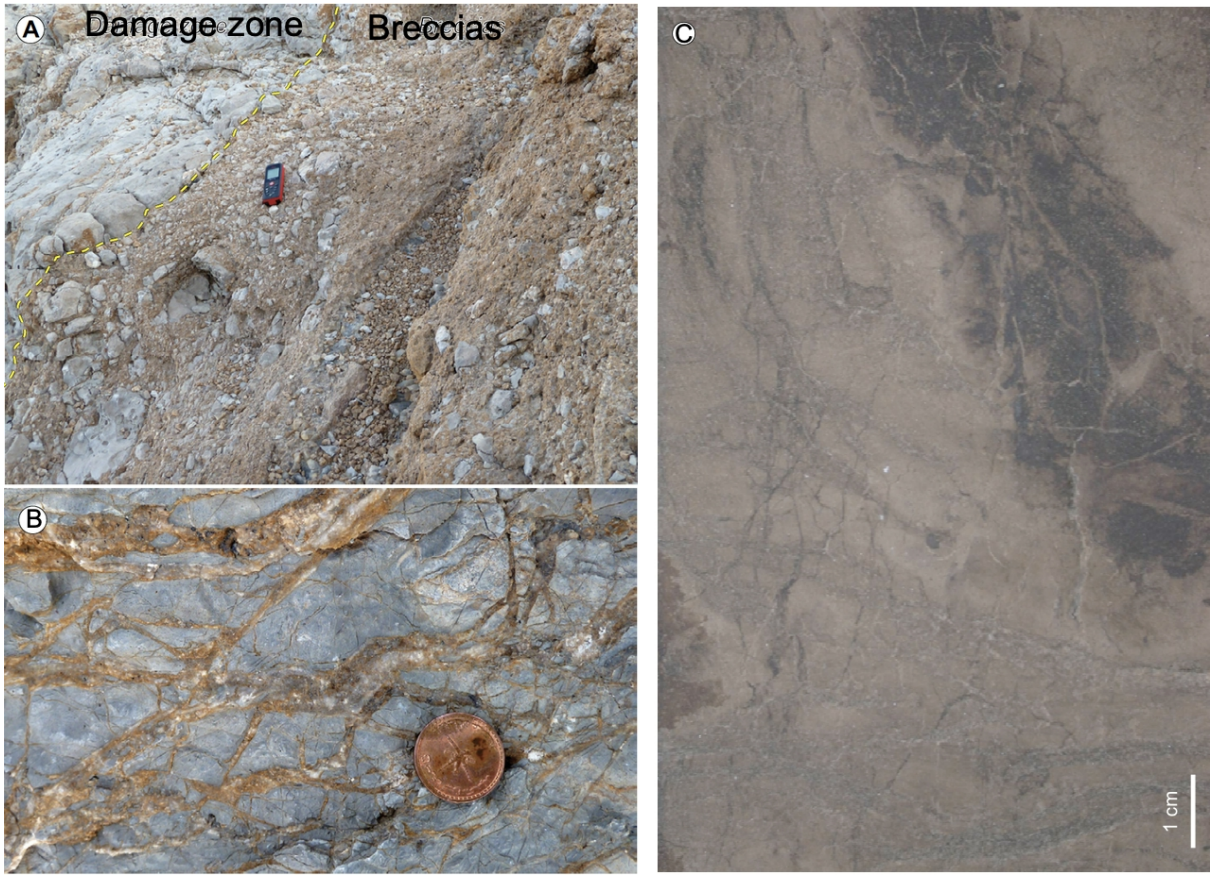


Figure 5-34. Examples of in-situ brecciation of Natih limestones. Damage zone and dilation breccia (A) and mosaic breccia with angular carbonate fragments (B) associated with faults in Jebel Qusayba outcrop. Modified from Balsamo et al. (2016). C: Hairline fractures and in situ brecciation in a subsurface core of one of the fractured Natih fields in North Oman. The clasts have a similar shape to those in the Muti debrites.

consist of highly angular fragments ranging in size from a few millimetres to ~1 m, forming a

"jigsaw" texture. Hairline fractures and in situ breccia's have also been observed in subsurface Natih cores in some of the fractured Natih fields in North Oman (Figure 5-34C).

5.3.2.2.4 Summary of learning from analogues

1. Submarine faults scarps are common in foreland basins. These can be hundreds of m high and are associated with mass wasting.
2. Erosion along the fault scarp already starts after a few tens of m throw and the retreat can be several 100 m
3. Material eroded from the retreating scarp is deposited in debris cones at the foot of the fault and can extend several hundred m into the basin.
4. The landslide deposits derived from updip faults may cover earlier active faults or may be re-faulted during a later stage of deformation.
5. The angular clasts in the debrites most likely have been sourced from *in-situ* shattered mosaic breccias along the faults activated by seismic events during the subduction.
6. In-situ brecciation in the Natih Fm. near faults has been observed both in cores and outcrops.

5.3.2.3 Conclusions

1. The debrites in the Muti Fm. are derived from fault scarps exposed along the sea bottom. Most of these scarp-front deposits consist of cohesive debris flow deposits, which have floating angular clasts derived from the Natih and Muti Fms. The onset of faulting is in the Santonian and predates the emplacement of the nappes at the fault scarp. The faults are formed by extension during bending of the drowned platform as it entered the foredeep. They show an overall NW-SE strike.

2. Some debrites along the western flank of Saih Hatat are polymict conglomeratic megabreccias that also contain clasts of Permian, Triassic and Jurassic sediments. The clasts are often rounded, and conglomerates lack matrix, suggesting possible subaerial exposure of very steep slopes. These deposits are interpreted as fault scarp debris cones. The faults must have throws of many hundreds of metres and are thought to be related to re-activated basement lineaments. The tentative orientation, based on pinch-out of the breccia, is NNW-SSE perpendicular to the strike of the nappes. Similar deposits occur along the NE-SW trending Dibba zone, which is a similarly inherited structure in the Musandam area.
3. Active faulting associated with mass wasting is responsible for the redeposited sediments derived from the autochthonous platform within the Muti Fm. These processes are related to faulting and fault re-activation along the top of the carbonate platform as the platform enters the foredeep and is overridden by the frontal thrust wedge. This process has also been described in various present-day, subduction-related analogues in foredeep settings such as landslide complexes offshore Costa Rica (Harders et al., 2013).

5.4 The Upper Muti mélange summary and discussion

5.4.1 Discussion and analogues

Mélanges along convergent margins are widely regarded as polygenetic, resulting from the interplay of tectonic, sedimentary, and diapiric processes (Festa et al., 2010). Sedimentary mélanges typically form through slope instability and mass wasting into the trench, whereas tectonic mélanges result from intense shearing. Diapiric mélanges are

commonly linked to the escape of overpressured fluids. Tectonic overprinting generally represents the final stage, reworking primary fabrics and obscuring earlier sedimentary features. Festa et al. (2010) argue that most mélanges in convergent settings originate predominantly from mass-transport and diapiric processes, with a lesser contribution from tectonic shearing.

The Upper Muti mélange exhibits evidence for both sedimentary and tectonic processes:

Sedimentary processes

- In Wadi Mu'aydin, slumped limestone debrite beds, injection structures, and limestone clasts floating within a poorly sorted shale–marl matrix indicate deposition under overpressured conditions. No evidence for tectonic shearing is observed within this interval (Section 5.2.3.25).
- Permian–Triassic reef blocks derived from exotics within the Haybi Complex also occur within the Upper Muti mélange in the Hamrat ad Duru Range, approximately 25 km southwest of the Haybi Complex thrust front. A tectonic origin for these blocks is difficult to reconcile; they are more plausibly interpreted as having been eroded from the advancing Haybi Complex, redeposited ahead of the thrust front, and subsequently overridden by the Hamrat Duru nappes (Section 5.2.6.1.2).
- Seismic profiles across the frontal thrust indicate the presence of a sedimentary wedge along the leading edge of the thrust complex (section 5.2.6).

Tectonic processes

- Large Natih olistoliths in the Manabek area incorporate fault scarps juxtaposing Natih and Muti sediments, suggesting footwall cut-offs associated with thrusting (Section 5.2.2).
- Rafts of Cretaceous slope deposits within the Muti mélange near Al Ja'arah, NW of Jebel Nakhl, are interpreted as thrust slices detached from the platform margin (Section 3.3.2.2).
- Underthrusted slices of the allochthon into the Muti marls as is clearly shown by the imbricated slab of Permo-Triassic limestone thrusted into the Muti marls near Sayja in the Semail gap (locality SJ-2, see Appendix-1).

This suggests that this unit originated as a sedimentary mélange formed by debris flows, slumps and slides along the frontal part of the thrust complex. These deposits were subsequently overridden and incorporated into the thrust stack with the addition of tectonically derived exotic blocks.

The depositional geometry and subsequent deformation of the mélange are clearly illustrated on seismic data published by Warburton et al. (1990) and discussed in section 5.2.6.1.3 and Figure 5-24. These data show a frontal wedge of redeposited sediments extending out in front of the thrust stack, which was progressively accreted and underthrust as it is overridden by the advancing wedge. Some lower Muti fragments and middle Cretaceous slope deposits may have been redeposited from thrusts involving Muti sediments, or may represent thrust slices incorporated at the base of the stack.

Comparable features have been documented in a Miocene orogenic wedge offshore Sabah and Palawan (Ilao et al., 2018; Morley, 2024). There, 2D and 3D seismic data show extensive debris flows shed from the wedge: some are preserved undeformed in front of the

wedge, whereas others have been overridden and incorporated into the wedge. In addition, the wedge contains highly imbricated sedimentary units composed of material derived from the lower plate mixed with sediments deposited onto, and derived from the growing wedge, including mass-transport complexes.

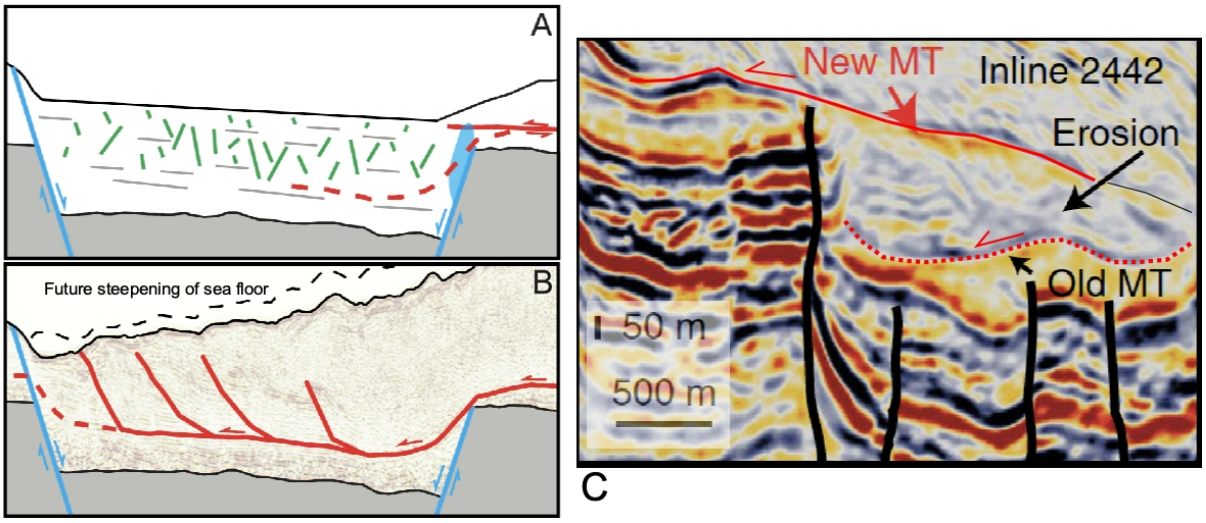


Figure 5-35 Impact of normal faulting on the near-trench detachment propagation. Schematic model of early stages of step down into a graben (A) and step out of graben (B) modified from (Boston et al., 2014). C Example of up-stepping of the detachment in front of an horst block in the Costa Rica subduction zone, MT = Megathrust. This results in erosion along the base of the upper plate and transfer of sediments of the accreted wedge and mélange to the lower plate. Modified from Edwards et al. (2018).

Sedimentary mélanges are common in accretionary wedges and form through sliding, slumping, debris flows, and debris avalanches triggered by slope oversteepening and instability at the wedge front (Festa et al., 2010). Oversteepening of the slope could be caused by increased friction along the down-going plate and thickening of the wedge by internal deformation (Critical Taper Theory: Davis et al. (1983)). This can be related to irregular sea floor topography caused by a seamount or faulting (Figure 5-35). Subduction of irregular seafloor topography may also trigger earthquakes, which in turn can induce slope collapse in other parts of the wedge (Xu et al., 2025).

As an analogue, the work of (Marroni and Pandolfi, 2001) on the early Paleocene subduction zone in the Northern Apennines, suggests that major faulting of the subducting plate caused extensive erosion along the wedge front and redeposition of sediments in debris flows and slide deposits on the faulted lower plate. These sediments were subsequently subducted and incorporated into the frontal wedge.

Edwards et al. (2018) and Kirkpatrick et al. (2020) show with 3-D seismic data over the present day Costa Rica subduction zone that large (> 200m throw) exhumed faults entering the frontal part of the accretionary wedge can induce jumps in the location of the basal thrust to a downdip position for landward dipping faults, or updip position for seaward dipping faults. In the latter case parts of the frontal wedge material are transferred to the subducting plate. This results in a tectonic mixing of elements of the thrust complex with the top of the underlying autochthon.

Similar features can be expected along the basal thrust in Oman, where fault-related debrites observed in Muti Formation outcrops, together with subsurface seismic data, indicate that the downgoing plate had an irregular seafloor topography related to faulting. In addition, pronounced seafloor relief also developed along the shelf edge at the backstepping Mesozoic platform margins discussed in Chapter 3 (Figure 3-18). Large rafts of bedded Natih limestones and basal Muti sediments within the mélange may have been detached from pre-

existing horst blocks (footwall cut-offs; see (Butler et al., 2006)) or from the platform margin during thrust emplacement.

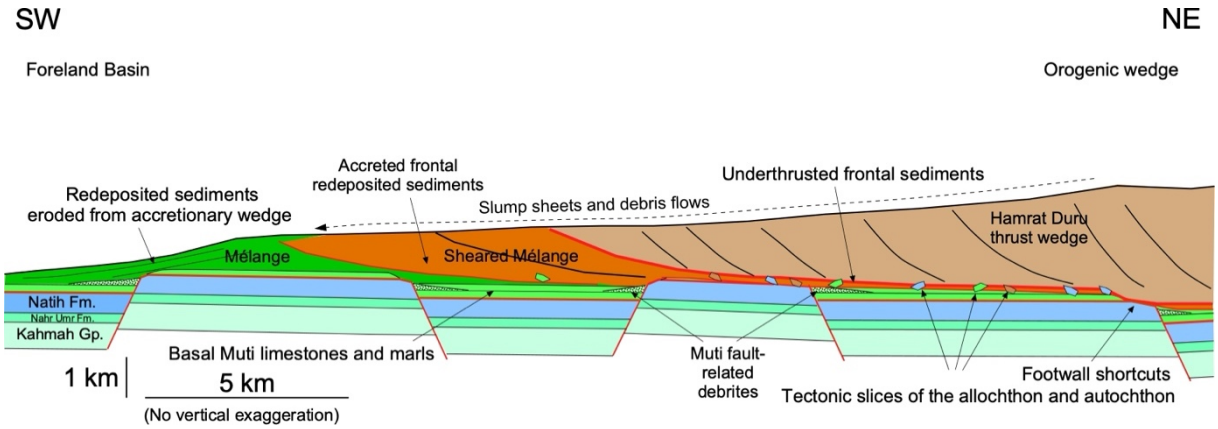


Figure 5-36 Schematic model for the Muti debrites and mélange. The Muti debrites (grey wedges) are derived from submarine fault scarps. The Muti mélange initially consists of slump sheets and debris flows sourced from the thrust complex. This sedimentary mélange (dark green) becomes sheared and mixed with slivers of the underlying Muti as it is underthrusted below the thrust complex. The cross section is based on the seismic line across the frontal edge of the thrust front shown in Figure 5-24, integrated with outcrop observations from Jebel Akhdar.

This mélange model also explains the strong vertical, and rapid lateral, facies variations in the Muti Fm. along the south flank of the Jebel Al Akhdar, as shown in Rabu (1988) and Rabu et al. (1993), see Figure 5-21 E. Also, the presence of pillow lavas in the Muti Fm. is better explained as rafts from the overlying thrust complex than as contemporaneous volcanics, which is difficult to explain in a foredeep setting.

5.4.2 Conclusions

1. The polymict assemblage of redeposited sediments overlying the transgressive Muti Formation on the platform has been interpreted in previous studies as synorogenic deposits derived from an inferred uplifted carbonate platform margin in the north (Glennie et al., 1974; Rabu et al., 1990; Rabu et al., 1993; Robertson, 1987a; Robertson, 1987b). However, detailed outcrop observations and subsurface data demonstrate that this interval instead comprises a sedimentary mélange of blocks

and rafts derived from the allochthon, mixed with rafts sourced from the underlying Muti and Natih formations.

2. This sedimentary mélange formed at the frontal edge of the thrust stack and was supplied by debris flows, slumps, and slides eroding the frontal part of the thrust complex. Incorporation of material from the autochthon, including sediments of the Muti Formation, may have occurred where the thrust complex cut through elevated areas of the seafloor. These deposits were subsequently overridden and incorporated into the thrust stack. With continued deformation, the sediments evolved into a tectonically sheared mélange, forming a discontinuous sheet along the base of the thrust complex exposed in the Oman Mountains.
3. This new interpretation significantly simplifies previous tectono-stratigraphic models, as it does not require kilometre-scale uplift of the platform margin.

5.5 Updated stratigraphic description of the Muti Formation

Based on the regional evaluation the stratigraphic description of the Muti Formation has been updated as follows.

5.5.1 Author

The Muti Formation was originally described by Haremboure and Horstink (1967) in an unpublished report of Petroleum Development Oman (PDO) and subsequently by Glennie et al. (1974). Robertson (1987a) later expanded the definition of the formation and proposed a subdivision into five age-equivalent units (members) occurring in in both the autochthonous and allochthonous sequences. One of these members, the autochthonous Sayja Member, was decribed in greater detail by Robertson (1987b).

5.5.2 General definition

The Muti Formation comprises sediments associated with the Late Cretaceous drowning of the epeiric carbonate platform and the emplacement of the nappe complex. These sediments are now preserved either between the basal Aruma unconformity and the thrust complex or along the toe of the frontal thrust. Contrary to the original definition of Glennie et al. (1974) and Robertson (1987a), the unit defined here also includes redeposited debris derived from the nappe complex.

5.5.3 Type locality

The type locality of the Muti Formation established by Glennie et al. (1974) is located in Wadi Muti near the village of Imti (Loc. WMT-1; WGS84: 58.0861615°E, 23.4655471°N). However, this section exposes only the upper part of the formation, as the characteristic basal transgressive sequence observed elsewhere is truncated. In addition, the upper part of the section and the contact with the Hamrat Duru thrust complex is largely obscured by scree and poorly exposed.

A more representative reference section is exposed at Sayja (locality SYJ-7; WGS84: 57.8671663°E, 23.2007827°N), which provides a more complete overview of the succession including the mélange. Additional sections illustrating the regional lateral variability of the basal Muti Formation include Manabek (MBK-1/2; WGS84: 57.9117252°E, 23.2737106°N), which preserves the thickest and most complete basal transgressive sequence; Wadi Kahmah (WK-1; WGS84: 57.5398094°E, 23.0187025°N), showing development along the southern flank of Jebel Akhdar; Wadi Khabbah (Loc. WKB; WGS84: 58.9794901°E, 22.8411501°N), representing the Saih Hatat area; and Jebel Madar (JM-1; WGS84: 58.1693095°E, 22.3855826°N), where the succession records siliciclastic influx near the Huqf axis.

5.5.4 Lithology and facies interpretation

The Muti Formation consist of the two main units: a lower, overall transgressive shallow- to deep-marine succession deposited on the karstified and drowned platform and an upper chaotic mélange.

The transgressive interval consists of interbedded limestones and marls which in the east are intercalated with shallow marine quartz sandstones. Locally it contains oolitic ironstones. In the upper part of this interval, erosionally based poorly sorted debrite beds occur. The debrites consist of redeposited Muti and Natih sediments derived from submarine fault-scarp erosion along extensional faults formed during subsidence into the foredeep. Locally the debrites truncate the basal transgressive deposits and rest directly on the Natih limestones.

The mélange contains a diverse assemblage of reworked lithologies derived mainly from the Hamrat Duru Group and the Haybi Complex. These include thin-bedded greenish-grey limestone turbidites likely sourced from the Al Jilh Formation; oolitic polymict conglomerates and calcareous quartz sandstones characteristic of the Guwayza Formation; siliceous limestones and bedded cherts interpreted as remnants of the Sid'r Formation; pillow lavas derived from the Haybi Complex or from the base of the Hamrat Duru Group; and Permo–Triassic reefal limestone blocks derived from the Haybi Complex. In addition, blocks of typical Muti facies (ferruginous oolitic grainstones, Natih-derived debrites, and thin-bedded siltstones and marls) as well as Natih limestones are present.

The mélange matrix consists of non-calcareous, commonly reddish, silky shales. The basal contact of the mélange is commonly poorly exposed but can be inferred from the appearance of reddish silky shales beneath the scree. However, clear detachment surfaces are locally observed in outcrops along the Semail Gap.

The mélange comprises debris-flow deposits, slumps, and slide blocks formed along the frontal part of the thrust complex. These deposits were subsequently overridden and incorporated into the thrust stack. In the Manabek area of the Semail Gap, olistoliths exceeding 100 m in size, derived from the Natih and Muti formations, occur. These are interpreted as fragments derived from collapsed or cut-off fault walls during nappe emplacement. At Al Ja'arah, rafts of Middle Cretaceous slope facies have been tectonically sheared into the mélange.

5.5.5 Thickness

The thickness of the Muti Formation is highly variable due to syndepositional faulting, tectonic truncation beneath the nappe complex, and internal truncation along a detachment surface at the base of the Upper Muti mélange. Well data indicate a thickness ranging from approximately 150 to 800 m beneath the southern margin of the orogenic wedge. Some tectonic thickening may have occurred as a result of underthrusting, possibly increasing the original thickness by up to a factor of two (Boote et al., 1990).

Outcrop sections record a maximum thickness of approximately 100 m for the basal Muti Formation. The Upper Muti mélange exposed along the Semail Gap is about 50 m thick; however, Robertson (1987b) reported thicknesses of up to 700 m in other areas, such as Saih Hatat.

5.5.6 Boundaries

The base of the Muti Formation is defined by the basal Aruma unconformity. In most areas, the succession overlies the Natih Formation. In the eastern foredeep, however, the unconformity locally cuts down into the Nahr Umr Formation. Along the Huqf axis Muti deposits can overly subcropping rocks as old as Neoproterozoic. Along the northern flanks of Jebel Akhdar and in Saih Hatat, the base of the Muti Formation is defined by the shear zone

at the base of the Upper Muti mélange and tectonically overlies Triassic to Cretaceous platform and slope deposits.

The top of the Muti Fm. is often difficult to locate, as the upper Muti is typically poorly exposed and covered by scree, with only isolated blocks protruding. It is therefore picked at the base of the structurally and stratigraphically more coherent (and mappable) units of the thrust complex.

5.5.7 Age

Limited biostratigraphic data, calibrated with seismic stratigraphy in the foredeep, suggest that the lower Muti Formation most likely ranges in age from the middle Turonian to

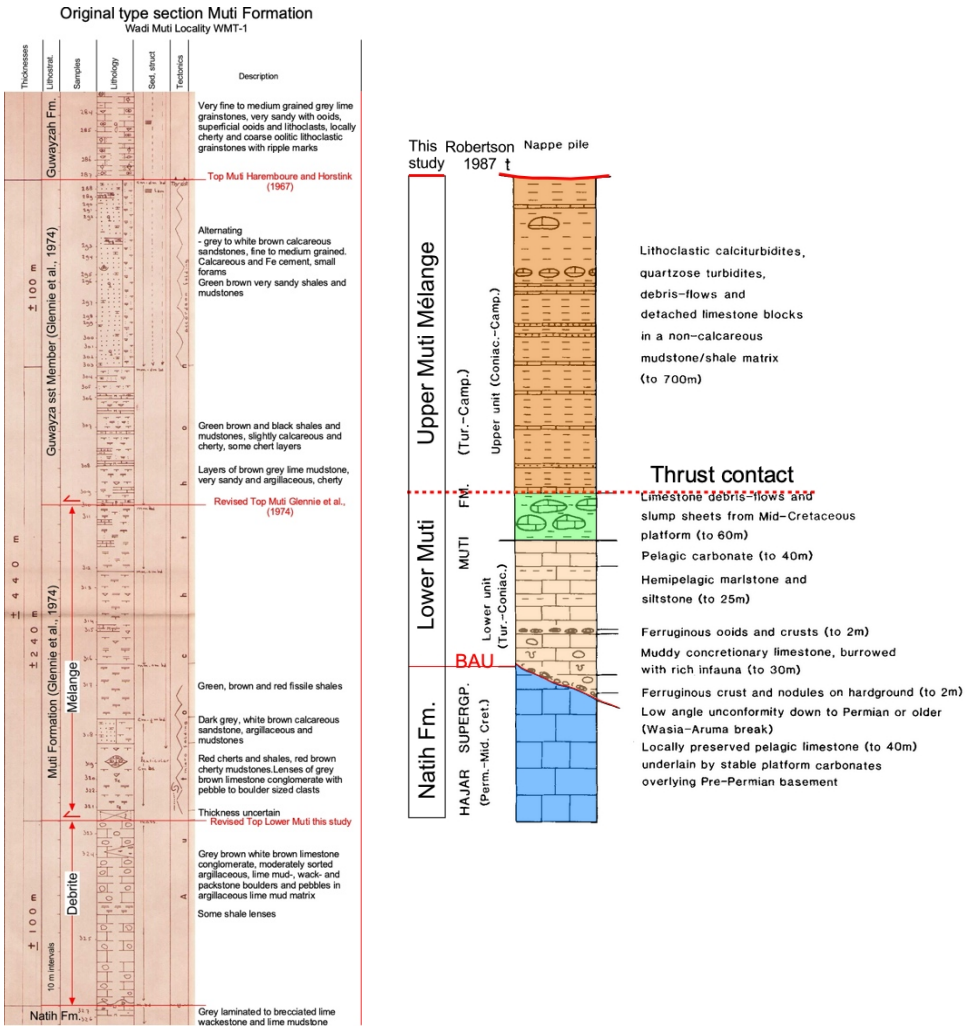


Figure 5-37 Reinterpreted Muti stratigraphy in this study plotted on type section of Glennie et al. (1974) and Robertson (1987b).

early Santonian. The data indicate a tentative southward younging trend resulting from onlap. The earliest sediments are Turonian pelagic marls southeast of Saih Hatat, whereas further south, the sediments overlying the basal Aruma unconformity are of Coniacian to early Santonian age. The age of the mélange is not well constrained; however, a Santonian age is inferred based on the Coniacian–Santonian ages obtained from the basal sequence.

5.5.8 Remarks

Glennie et al. (1974) mention that conglomerates in the Muti contain clasts from Permian to Cretaceous shallow-water carbonates and some radiolarian chert pebbles but no igneous debris. The present study shows that this does not apply to the debrites in the lower part, which are made up of only Cretaceous clasts. Though Glennie et al. (1974) specifically mention that the Muti does not contain any debris derived from the Hawasina or Semail thrust sheets, their study does mention that some of the facies of carbonate pebbles in the formation are only known from lithoclasts in the allochthonous units.

In the Muti Formation type section described by Glennie et al. (1974), the base of the mélange is located above the debrite interval (Figure 5-37). In the composite type log for the Muti Sayja Member presented by Robertson (1987), this boundary lies above the limestone debris beds identified in the basal part of his Upper Sayja.

The Sayja unit of Robertson (1987b) corresponds to the entire Muti Fm. as defined by Glennie and in this study, and therefore does not constitute a meaningful stratigraphic subdivision.

In the Hamrat ad Duru Range, the mélange has been described as the Wadi Hafr Unit (Hanna, 1990), Hafar Fm. (Warburton et al., 1990; Warburton et al., 1986) and Hanya Unit (Robertson, 1987a). These deposits are now assigned to the Upper Muti mélange.

The Qumayrah unit of the Muti (Robertson, 1987a) has been elevated to formation rank (Qumayrah Fm.; Watts and Blome (1990); BRGM mapping studies) and is variably assigned to either the Aruma Group (Watts and Blome, 1990) or the Sumeini Group (Béchennec et al., 1993a). The collapsed platform-margin deposits in this formation represent lowstand deposits associated with the BAU.

The Riyamah unit of the Muti (Robertson, 1987a) has been incorporated into the Najd Formation (Rabu et al., 1993; Béchennec et al., 1993). Its upper part represents a distal equivalent of the Qumayrah Fm. but is difficult to define and map as a separate unit.

The Awabi Megabreccia mapped by the BRGM (Rabu et al., 1990; Rabu et al., 1993) and Buday'ah unit of (Robertson, 1987a) represent depositional mélanges formed during earlier stages of thrusting that were later incorporated into the thrust stack. The Buday'ah unit has not been adopted in later work; it is regarded as part of the Haybi Complex (Robertson and Searle, 1990) and represents a facies described from various structural settings within the Al Aridh, Kawr, and Umar groups (BRGM: Béchennec et al. (1993a); Rabu et al. (1993).

The outcrops mapped as Muti in Wadi Saal/Nujum and Quriat area of Saih Hatat have been reinterpreted in this study as Lower Cretaceous slope deposits (see 3.3.1.3). An interval mapped by BRGM as Natih Fm. along the southern flank of Jebel Akhdar, has been included into the Muti (see 5.4).

The "Ruwi mélange" (Searle et al., 2004) represents a composite unit comprising Lower Cretaceous slope deposits and a tectonised mélange, and is here included within the Upper Muti mélange.

In subsurface studies, the Muti Fm. is generally not recognized as a distinct stratigraphic unit, as the capping thrust surface is absent south of the thrust complex. The

interval laterally equivalent to the Muti Fm. is assigned to the lower part of the Shargi Member of the Fiqa Fm. (Forbes et al., 2010), and in some studies is referred to as the Lower Fiqa Shales (Boote et al., 1990; Warburton et al., 1990). Locally, the top of this interval can be identified on well logs by a gamma-ray spike associated with glauconite, and on seismic data as a downlap surface. However, lithological distinction from the overlying Shargi/Fiqa shales is often difficult. Consequently, the Muti Fm. as a stratigraphic unit is effectively restricted to areas overlain by the orogenic wedge.

5.6 Conclusions

Re-evaluation of the syntectonic sedimentary succession associated with the obduction complex onto the Arabian margin indicates that it comprises three main tectonostratigraphic units:

(1) Lowstand succession. A lowstand succession associated with the Base Aruma Unconformity deposited along the continental slope and basin, sourced from a collapsing platform margin as it was uplifted and tilted into the foredeep during the ?Cenomanian to Coniacian. This unit comprises the megabreccias and turbiditic limestones of the Qumayrah and Riyamah Formation (Robertson, 1987a; Watts, 1990) which were subsequently incorporated into the thrust stack and now form parts of the Sumeini and Hawasina nappes, respectively. At Al Ja'arah In rafts of the slope facies have been sheared into the Muti mélange.

(2) Transgressive platform-to-basin succession. A transgressive shallow- to deep-marine succession deposited on the karstified and drowned platform, which became affected by extensional faulting during subsidence into the foredeep. This unit consists of the basal Muti

marls and limestones, shales and sandstones together with fault-related debrites, deposited during the Turonian to early Santonian.

(3) Depositional mélange. A depositional mélange initially emplaced along the frontal edge of the thrust front and subsequently incorporated into the thrust stack evolving into a tectonically sheared mélange during obduction in the Coniacian to Santonian. The mélange comprises blocks and rafts derived from the allochthon, mixed with sheared blocks from the underlying Muti and Natih formations. In the subsurface of northern Oman, the mélange conformably overlies the basal Muti Formation along the present-day thrust front; however, in areas overlain by the orogenic wedge, it is separated from the basal Muti by a previously unrecognised detachment surface and forms a discontinuous sheet along the base of the thrust complex.

The revised definition of the Muti Formation presented in this thesis retains fundamentally the same conceptual lower and upper boundaries as originally defined by Glennie et al. (1974), emphasizing that the unit represents the stratigraphic interval above the basal Aruma unconformity (BAU) and below the thrust stack. However, a key aspect of this study is the reinterpretation of the redeposited sediments within the Muti Formation as a fault-related debrite unit and a thrust-derived mélange. This interpretation significantly simplifies previous tectono-stratigraphic models, as it does not require kilometre-scale uplift of the platform margin. The proposed new model for the evolution of Oman's foreland basin is discussed in Chapter 7.

6 Syn- and post-obduction infill of the foredeep

6.1 Introduction

The stratigraphy and stratal geometries of the post-obduction foredeep fill are based on subsurface data alone; there are only very few and poorly exposed outcrops in the foothills. Furthermore, as the interval was of little interest for petroleum geology the data coverage in the subsurface tends to be relatively poor.

The sediments that fill in the foredeep belong to the Aruma Group. The Aruma Group overlies the mid-Turonian unconformity (BAU) and is unconformably overlain by the middle Paleocene shales of the Shammar Member of the Umm er Radhuma Formation. The Aruma shows strong lateral changes in thickness due to foredeep subsidence, uplift of structural highs during the Late Cretaceous deformation and regional tilting, uplift and erosion in the Oligocene at the base of the Fars Group.

In the subsurface the group is subdivided into the Coniacian to Campanian Fiqa Fm. and the Maastrichtian Simsima Fm. (Figure 3-1), which are described by Hughes Clarke (1988) and Forbes et al. (2010). The Fiqa Fm contains a basal shale unit, the Shargi Member, overlain by or laterally interfingering with carbonates of the Arada Member. As will be discussed later, siliciclastic sands and silt occur in the Shargi Mbr., especially in the eastern part of the foredeep.

The Simsima consists of shallow marine limestones and dolomites and disconformably overlies the Fiqa. In the absence of biostratigraphic data the Simsima is

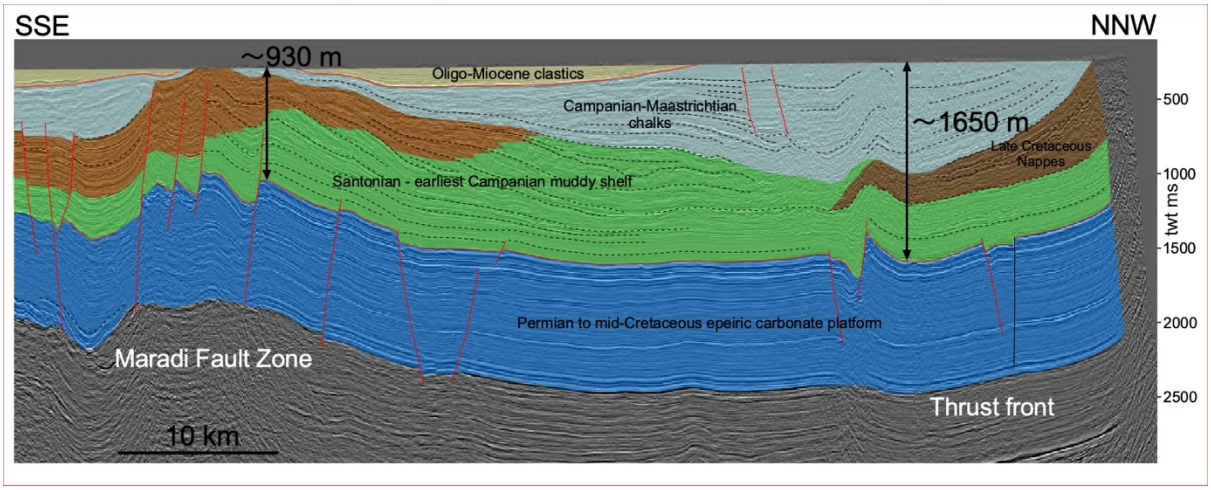


Figure 6-1 Vintage seismic section showing the infill of the foredeep in Central Oman. The Upper Shargi consists of a muddy shelf prograding from the south and mostly predates the final emplacement of the nappes. It is onlapped by a chalk sequence after an abrupt cessation of clastic supply in the late early Campanian. Neogene uplift can be clearly seen both in the thrust belt and the Maradi Fault zone in the south. Location SL-5 on Figure 6-2 and Appendix-4.

difficult to distinguish from the carbonates of the Arada Member. Also, the distribution of the Simsima in the subsurface is patchy.

In the foredeep area, some studies divide the Fiqa Fm. into a lower and upper Member (Boote and Mou, 2003; Boote et al., 1990; Warburton et al., 1990). The Lower Fiqa (Lower Shargi Mbr.) is age-equivalent to the Muti Fm. in the Oman Mountains and has been discussed in Chapter 5. This unit starts with Coniacian to Santonian shales that were deposited during the flooding of the exposed carbonate platform and the emplacement of the nappes. The Upper Fiqa consists of Campanian to lower Maastrichtian marls and coarse

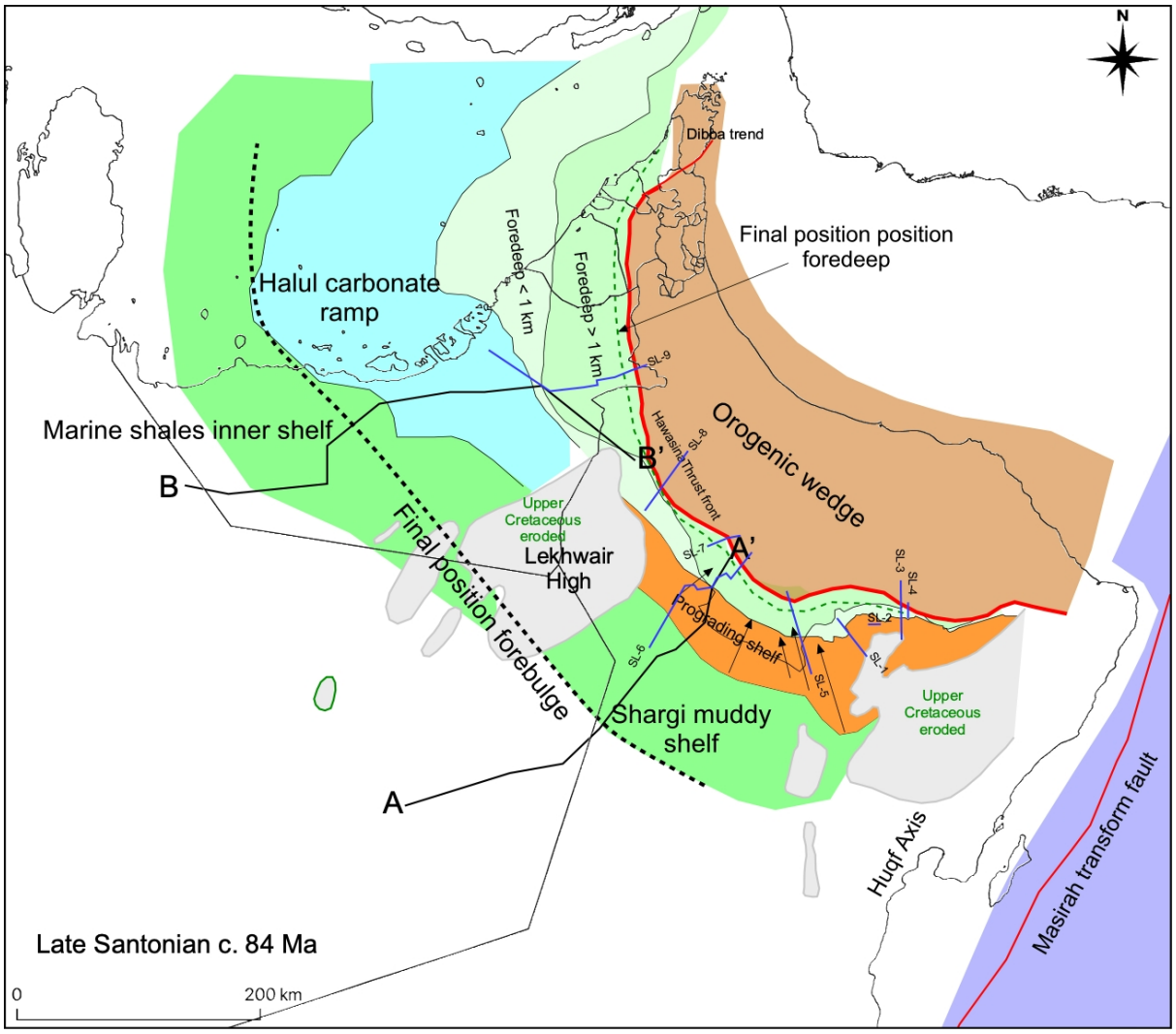


Figure 6-2 Palaeogeography during the late Santonian showing the initial infill of the Aruma Foredeep with the Shargi muddy shelf in the SE and the Halul carbonate ramp in the NW. Both prograded into the foredeep, away from the final position of the forebulge. Cross section A and B are shown in Figure 6-4 and Figure 6-5. Blue lines are locations of seismic sections discussed in Chapter 7.

lithoclastics that were deposited in the foredeep after nappe emplacement.

6.2 Santonian palaeogeography and forebulge location

6.2.1 Santonian palaeogeography

The upper part of the Shargi, which overlies the flooding surface formed by the glauconite marker bed mentioned in Chapter 5, consists of massive dark shales rich in planktonic and benthic foraminifera and with occasionally silty horizons and plant fragments (Forbes et al., 2010). Well logs and lithology over this interval suggest a very monotonous sequence. However, seismic sections show inclined geometries, clinoforms: dipping and

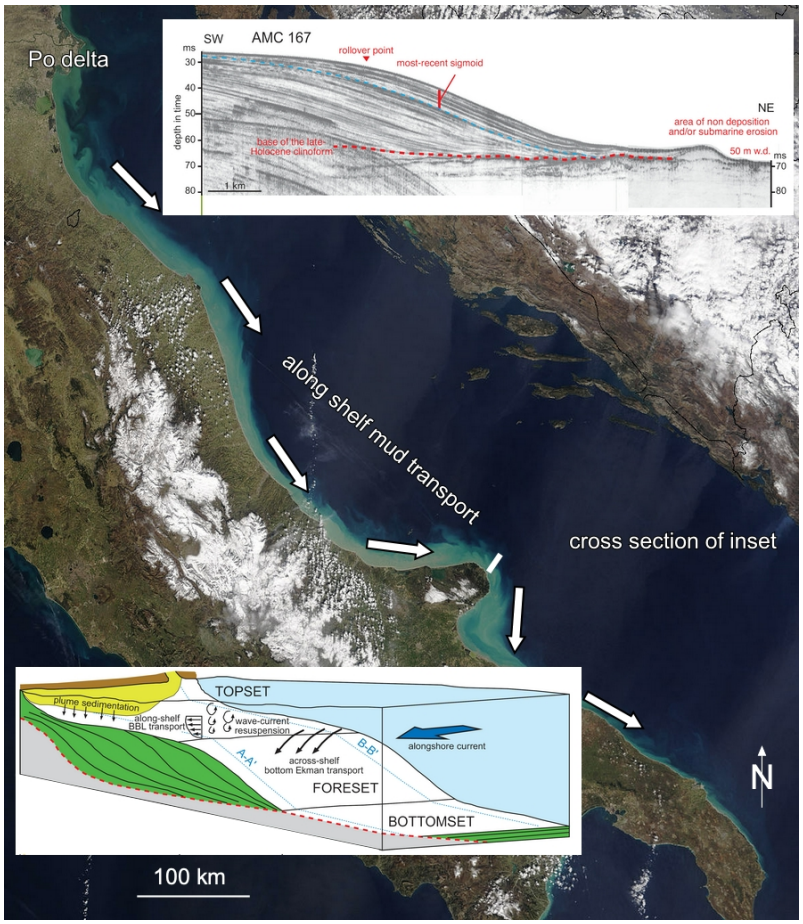


Figure 6-3 Prograding muddy shelf sourced by longshore currents along the eastern coast of Italy. The progradation into the Adriatic Sea is caused by offshore directed bottom currents. Modified from Droste (2010b),Satellite Photo: NASA, diagrams from (Cattaneo et al., 2004).

downlapping to the north onto the basal Shargi (Figure 6-1). This interval is Santonian to earliest Campanian in age and was interpreted as a mud-prone, prograding, delta complex

(Filbrandt et al., 2004). Mapping shows that the progradation occurs in a belt parallel to the foredeep margin as part of a prograding muddy shelf (Figure 6-2). The sediments are likely sourced by longshore transport from the exposed Huqf axis in the east. Like the mud belts along the Adriatic coast, (Cattaneo et al., 2004) reworking by off-shore directed bottom currents results in a prograding clinoform geometry (Figure 6-3). The maximum thickness of the progradational shelf wedge is about 900 m; the sediments fill up a bathymetry created by normal faulting.

The shelf prograded c. 100 km to the north from central Oman and reached an area 10 – 40 km south of the thrust front. The distal basinal sediments of the shelf are now located below the thrust complex.

In the western foredeep, located in the UAE, the margin consists of carbonate ramp limestones and slope marls (Harris et al. (1984), see Figure 6-2). This interval forms the Halul Fm., equivalent to the Ilam Formation in Dubai and Iran. The ramp limestones contain nodular bioclastic wacke- to packstones, with smaller and larger foraminifera and common echinoids, in places rudist pack- and grainstones with corals and stromatoporoids, and a slightly deeper facies with dasycladacean green algae and *Oligostegina*. The slope marls are rich in calcareous nannoplankton and planktonic foraminifera. The lower part of the Halul consists of argillaceous pyritic limestones and is transitional into the Laffan Formation. The Halul is Santonian in age but could extend both into the late Coniacian and basal Campanian (Alsharhan and Nairn, 1990; Piryaei et al., 2011).

The Halul limestones form a NE-SW trending shoal with some shallow water patch

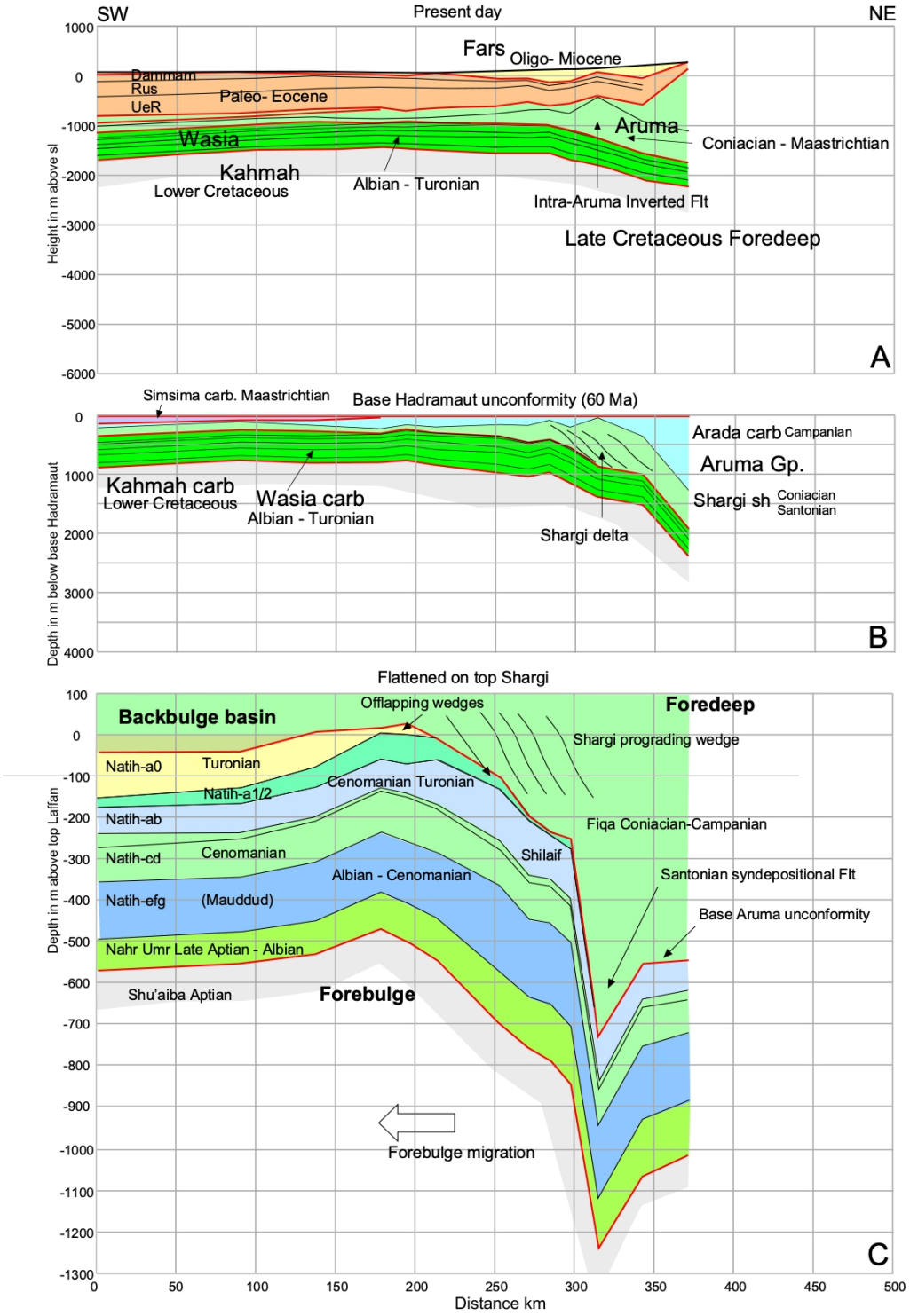


Figure 6-4 Geological cross section across the foreland basin in N. Oman, based on well data. For location: section A-A' in Figure 6-2 and XS-15 in Appendix-4. A: Present-day cross section from Cretaceous to recent. B: Same section flattened on top Cretaceous carbonate platform, showing the progradation of the Shargi shelf into the foredeep. C: Same section flattened at top Shargi, demonstrating a forebulge from which a muddy shelf progrades out into the foredeep. Truncated Turonian carbonate wedges prograding to the southwest are presently located in the foredeep but were originally deposited in the back-bulge basin. (see Chapter 4).

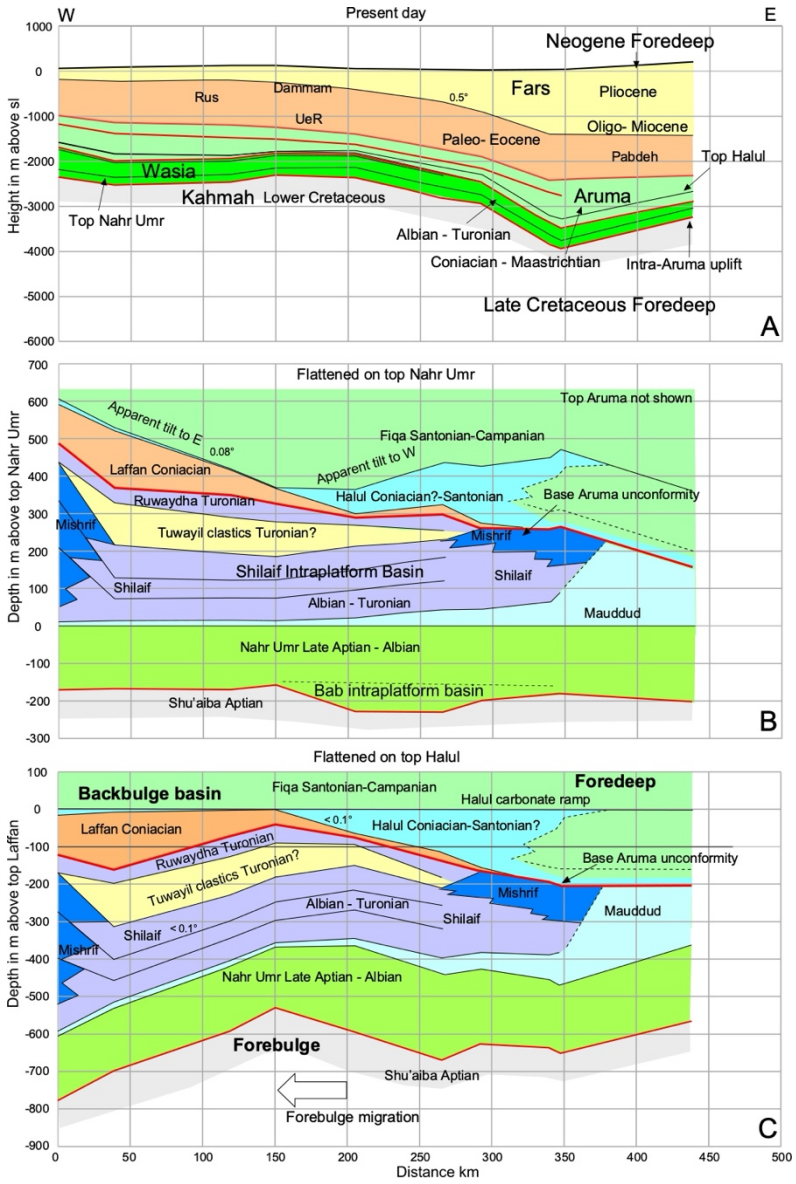


Figure 6-5 Geological cross section across the foreland basin in the UAE, based on well data. For location: section B-B' in Figure 6-2 and XS-16 in Appendix-4. A: Present-day cross section from Cretaceous to Recent showing the superposition of the Late Cretaceous and Neogene foredeep successions. B: Cretaceous section flattened on top Nahr Umr, illustrating the architecture of the Albian to Turonian carbonate platform. The platform along the western margin of the Shilaif basin reaches a thickness of more than 400 m; on the eastern margin the thickness is only 200 m. The subtle eastward dip of the Tuwayil and Ruwaydha infill of the basin compared to the base of the carbonate platform sequence suggests that uplift in the east may already have started at the end of the Cenomanian. The thicker Laffan shale in the west, overlying the unconformity, could indicate a westward shift of the depocentre due to uplift in the east. C: Inferred geometry at base Fiqa (top Halul) time, assuming that the Halul forms a flat carbonate ramp along the western margin of the foredeep. (Section flattened on top Halul in west and base Simsima – top Aruma east of 350 km distance). In this configuration, the Halul is onlapping a bulge with eroded Mishrif and Ruwaydha platform carbonates. The Laffan Fm. is considered to be partially equivalent to the Halul (Franco et al., 2021) and fills remnants of the Shilaif intra-platform basin to the west. Note that the dips in the figure are very low, in the order of 0.1°. Consulted publications: Vahrenkamp et al. (2015a), Franco et al. (2021) and Murris (1973).

reefs on salt-related highs (Franco et al., 2021). It reaches a maximum thickness of about 150

m. Towards the NE it pinches-out into deep water deposits of the Fiqa. To the SW it thins into a less than 30 m thick argillaceous limestone interval separating the Fiqa and Laffan Fms. This NE prograding carbonate ramp forms an isolated wedge along the foredeep margin. Towards the southeast the Halul is truncated below the base Simsima and base Hadramaut unconformities along the Lekhwair High. East of the Lekhwair High, in Oman, the Halul is not present, and the Santonian consists solely of a mud-prone shelf wedge.

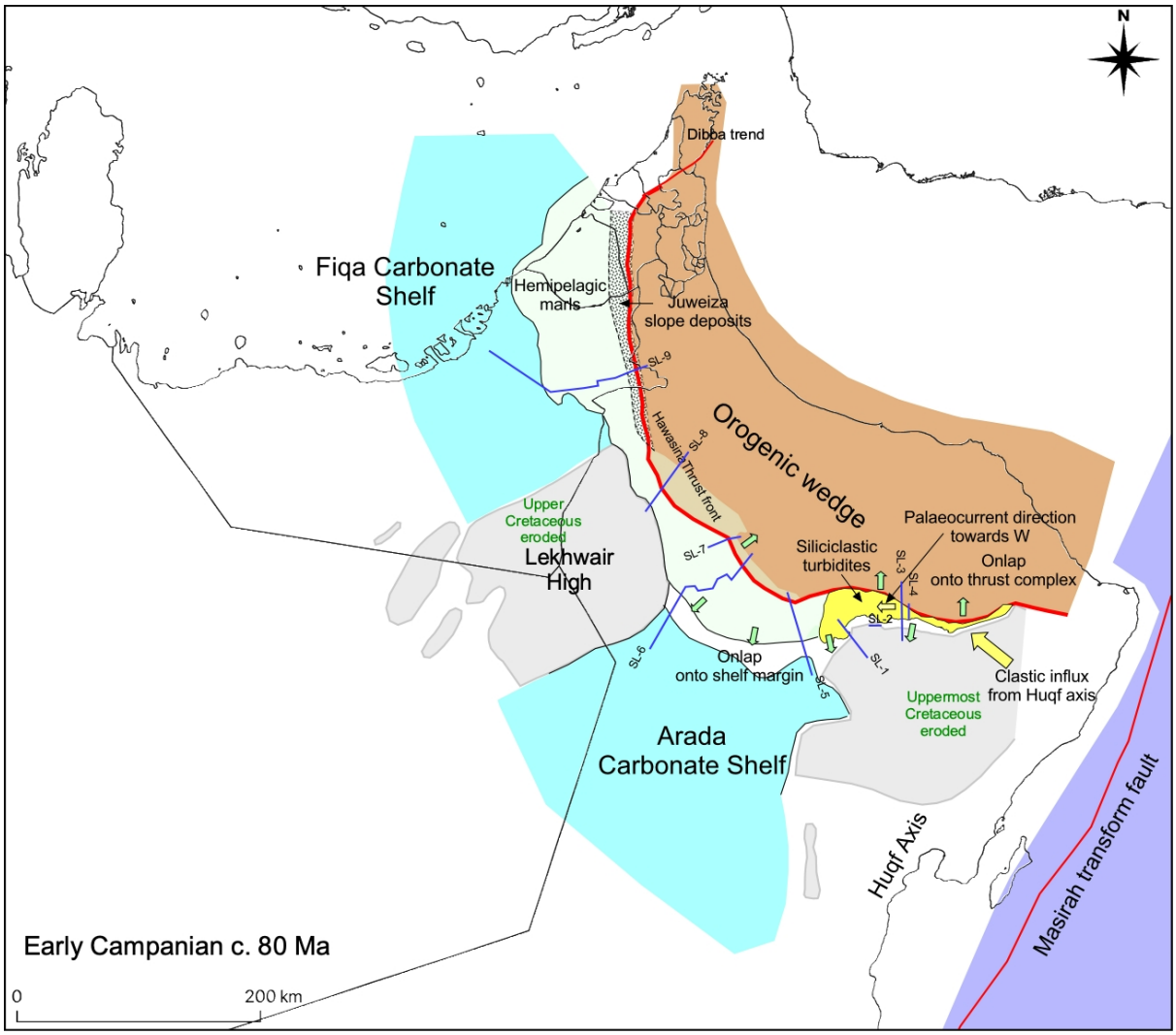


Figure 6-6 Palaeogeography during the early Campanian showing the infill of the Aruma foredeep by a carbonate shelf. In the east note the influx of siliciclastics, which were deposited as turbidites forming an axial fill of the basin. Cross sections A and B are shown in Figure 6-4 and Figure 6-5. Blue lines are locations of seismic sections discussed in Chapter 7.

6.2.2 Forebulge morphology

Both the Shargi and Halul shelves prograde into the foredeep and show wedge-shaped geometries thinning up depositional dip towards south and west. Flattening on the glauconitic flooding surface along the top of these wedges brings out a forebulge-shape topography in the underlying sequence (Figure 6-4 and Figure 6-5). The bulge separates a region with progradation into the foredeep from a depocentre with more restricted sedimentation. This bulge is interpreted as the final position of the forebulge and is located 160 – 250 km in front of the frontal thrust. In Oman, the pinch-outs of the Turonian lowstand wedges are now located downdip of the bulge in the foredeep. These were originally formed in a back bulge setting, when the bulge was located further north. This set of stratal geometries suggest a forebulge migrating to the west (open arrow on Figure 6-4 C).

6.3 Early Campanian

During the end of the Santonian the shelf progradation stopped and the shelf wedge shows erosion along the margins. In Oman the margin of the Shargi shelf wedge has been cut by deep canyons, channels and slump scars, suggesting slope collapse and sediment by-pass during the early Campanian (Filbrandt et al., 2001). Seismic shows that the eroded slope is onlapped by a sequence of clastics, consisting of interbedded clay, silt- and sandstones (Faya Formation, Forbes et al., 2010). These are turbidites and also onlap the nappes to the north and fill in the foredeep (Figure 6-6 and Figure 6-7). These stratigraphic relationships show that the nappe emplacement ended in the early Campanian. Chemostratigraphic and heavy mineral studies suggest that the sands are derived from the Permo-Carboniferous Haushi clastics, which were exposed in the Huqf area (Higgins & Howarth, 1997). In the upper part the clastics also contain igneous clasts from the ophiolite.

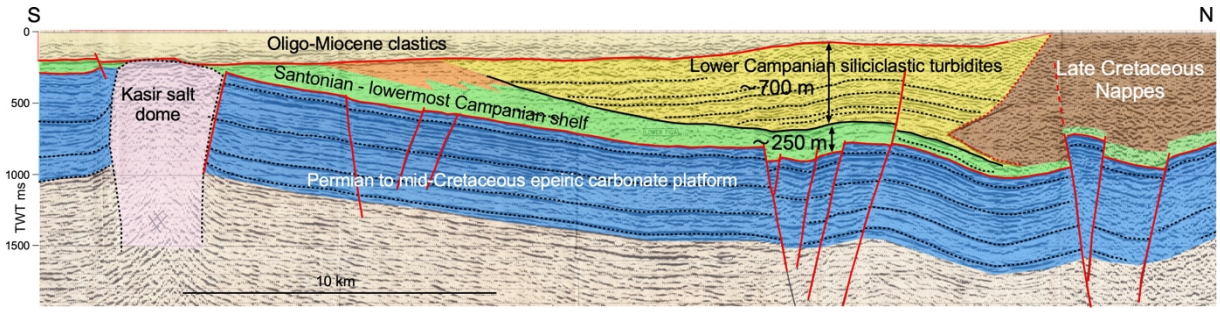


Figure 6-7 Vintage seismic line through eastern part of the foredeep, showing Lower Campanian siliciclastic turbidites (yellow) onlapping both the lower Shargi muddy shelf (green) and the thrust complex (brown). The foreland basin fill is truncated below the base Oligo-Miocene unconformity, which is related to uplift along the Huqf axis. For location: SL-3 in Figure 6-6 and Appendix-4.

The onlapping sandstone sequence outcrops in the Jebel Madmar area (Figure 6-8). In Uyun (Locality JM-3) it consists of brown-grey weathered, flaggy, sharp-based, bioclastic quartz sandstones beds interbedded with poorly exposed yellow marls. Along the base of the beds are lithoclasts of Fiqa marls. The sandstone beds are generally up to 30 – 50 cm thick. Some beds show low-angle to parallel lamination and hummocks and swales along the bedding surface. Some beds are strongly bioturbated. At the bottom of the beds there are abundant casts of a variety of burrows, as well as parabolic flute casts. The main current direction indicated by the casts and cross-bedding is from the east. The hummocks and swales and absence of Bouma sequences point to storm deposition rather than turbidites in this area.

The second outcrop is located further into the foredeep, at Sufrat ad Dawh. This outcrop consists of turbidites: well-bedded, graded quartzose sandstones with Bouma B to D sequences. They are interbedded with siltstones and poorly exposed, weathered, slightly calcareous shales to marls. Some beds are strongly bioclastic. Sole marks, mostly flute casts, indicate a westerly flow. These turbidites are deposited into a basin with a background deposition of hemipelagic calcareous shales to marls. The finer grain size, thinner bedding, absence of storm-wave structures, and the larger proportion of shales all suggest a more

distal setting compared to Uyun (located some 38 km to the SE). This fits the observed current directions and is also confirmed by cores in a well drilled 100 km WSW from Sufrat ad Dawh. This core showed very distal, silty turbidites, interbedded with bioturbated calcareous claystones with planktonic and benthic foraminifera.

In summary, the sandstones at Sufrat ad Dawh are interpreted as turbidites sourced from exposed Palaeozoic clastics on the Huqf High in the south and east. In the Jebel Madar area outcrops of these sands suggest a shallower marine setting, with storm deposits along

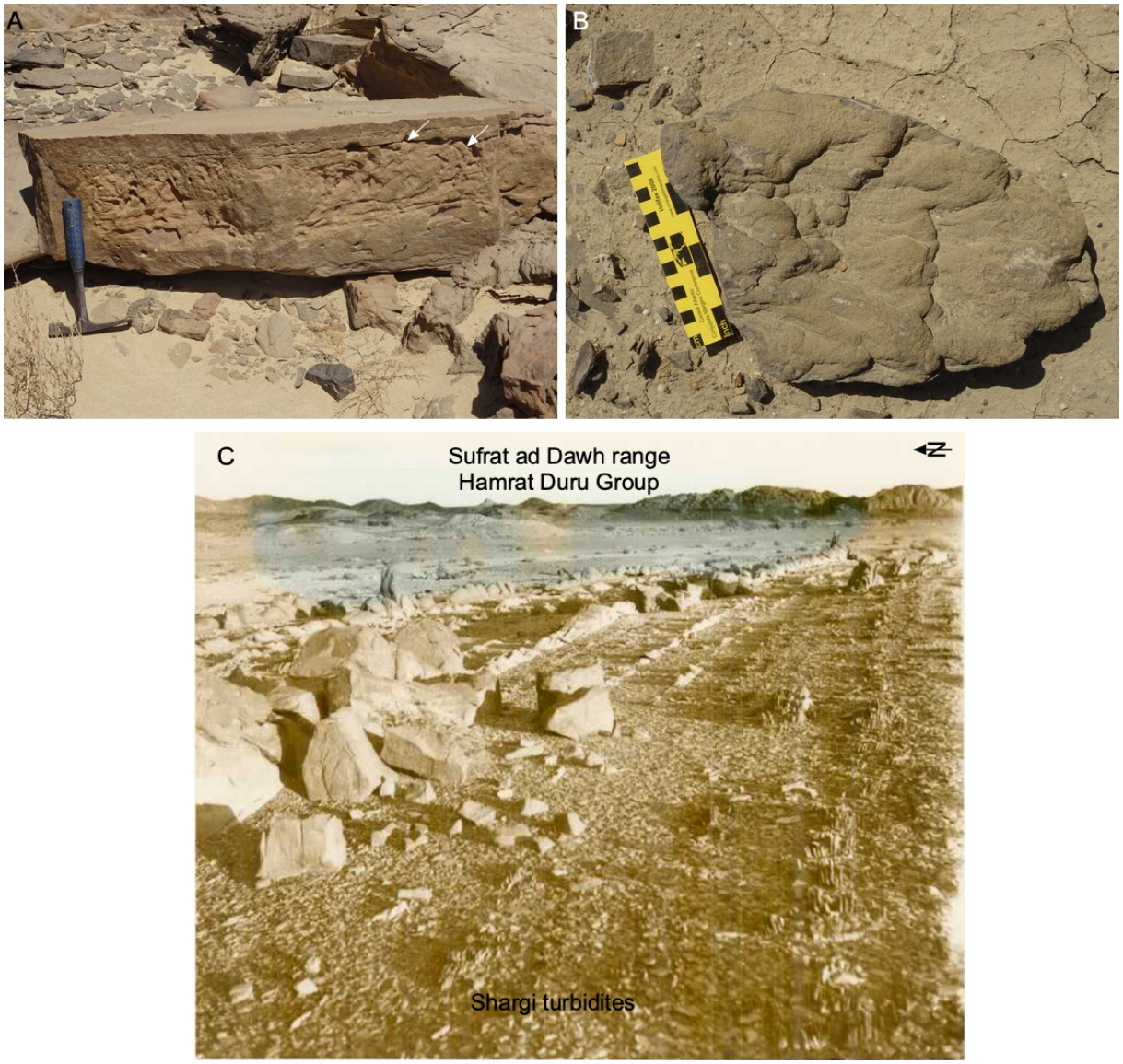


Figure 6-8 Outcrop of middle Shargi sandstones: storm deposits at Uyun. A: Composite sandstone bed with, in the middle, faint cross-bedding (arrow) destroyed by burrowing. B) Parabolic flute casts at base of bed. C: Turbidites in the Sufrat ad Dawh Range. Photo from Haremboure and Horstink (1967).

the southern margin of the foredeep. Incision and bypass of the delta was caused by tectonic tilt and uplift of the Huqf High.

The top of the Halul in the UAE is a sharp contact with the overlying calcareous shales of the Fiqa Fm., which locally contains abundant glauconite in the basal part. Seismic attribute maps offshore Qatar show a 40 km wide belt with low sinuosity bifurcating channel systems of 2-3 km in width (Figure 6-9 A, Pink et al. (2008); van Buchem et al. (2014)). These have been interpreted as tidal channels in a back-barrier position (Pink et al., 2008) or fluvial incisions influenced by foreland formation (van Buchem et al., 2014). Channel fill deposits have also been observed in cores of the Ilam Formation in the UAE (Boichard et al., 2001). These channels can be 20 to 35 m deep, 1.5 to 2 km wide and more than 17 km long. They erode into mud-supported shelf carbonates and are filled with alternating peloidal benthic foraminiferal grainstones and laminated skeletal packstones. Boichard et al. (2001) suggest that these are either marine infills of paleo-valleys or vertically stacked tidal channels.

An alternative interpretation is that these are gullies related to synsedimentary deformation of the carbonate ramp margin and slope, related to faulting and tilting, as it entered the foredeep. An analogue may be the Eocene Oligocene carbonate ramps in the Browse Basin in NW Australia, where seismic channels have been observed that are very similar to those on top of the Halul in Qatar (Figure 6-9 B-E, Rankey (2017)). These are

thought to have been initiated by platform margin-parallel synsedimentary faulting (Rinke-

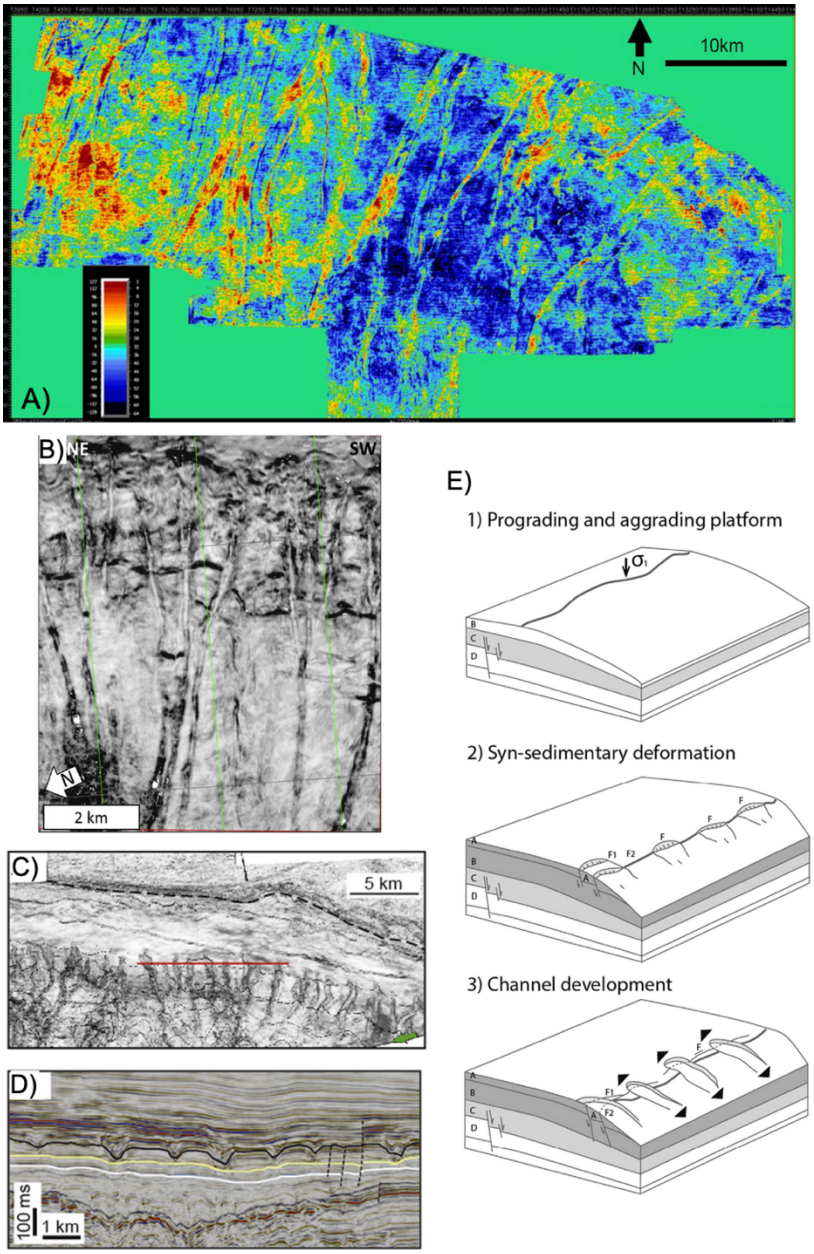


Figure 6-9 A: Seismic attribute map showing north-south oriented, low-sinuosity, bifurcating channels in the Halul offshore Qatar. Flow is interpreted to be toward the foredeep, here located in the north. Modified from Pink et al. (2008). B: Seismic attribute map of slope gullies on a Miocene carbonate ramp in the Browse Basin on the Australian North West Shelf, with a very similar morphology of those in the Halul shown in A. Modified from Rankey (2017). C: Seismic attribute map along the top of a Miocene carbonate ramp in the Browse Basin, showing slope channels along the platform margin. The dashed line shows position of reef front. Modified from Rinke-Hardekopf et al. (2018). D: Seismic section parallel to the margin, showing the gullies and synsedimentary faults. Location of the section is indicated by the red line in C. Modified from (Ninkabou et al., 2021); Rinke-Hardekopf et al. (2018). E: Model showing initiation of submarine channel systems due to synsedimentary deformation along a carbonate ramp margin for the Miocene succession in the Browse Basin by Rinke-Hardekopf et al. (2018). In this model high rates of platform progradation cause an additional vertical load ($\sigma 1$) on unconsolidated slope and basinal sediments. Differential compaction leads to the development of extension faults along the margin. Gullies are formed by downslope and headward erosion by erosional currents along the fault scarps.

Hardekopf et al., 2018). In the case of the Halul, instability of the margin and channelling could be due to tectonic tilting as it entered the foredeep.

Post Halul/Pre-Fiqa tectonic activity is also suggested by Ali and Farid (2016) who interpreted an angular unconformity at the base of the Fiqa on the crest of structural highs in the onshore UAE area. They suggest this is related to flexural uplift during ophiolite obduction.

The collapse of the Halul muddy shelf margin in the early Campanian was followed by a major flooding event and the formation of an extensive Arada/Fiqa carbonate shelf (Figure 6-6) along the southern margin of the foredeep. Sedimentation in the foredeep was dominated by hemipelagic marls with some influx of sediments eroded from the thrust complex (Juweiza Fm., first clastic influx from the north).

6.4 Late Campanian to Maastrichtian – The Simsima Fm.

The upper part of the Aruma Group, the Simsima Fm. consists of locally dolomitized, shallow water limestones (Glennie et al., 1974). The tentative regional palaeogeography for the Simsima is shown in Figure 6-10. However, the Simsima platform is much more differentiated than shown on this map with carbonate shoals growing on structural highs prograding into depressions with the laterally equivalent hemipelagic carbonates often assigned to the Fiqa. It represents the final infill of the foredeep in Oman. However, the foredeep in the eastern UAE persisted into the Palaeogene as the Pabdeh Basin (Ali et al., 2013; Swire et al., 2022).

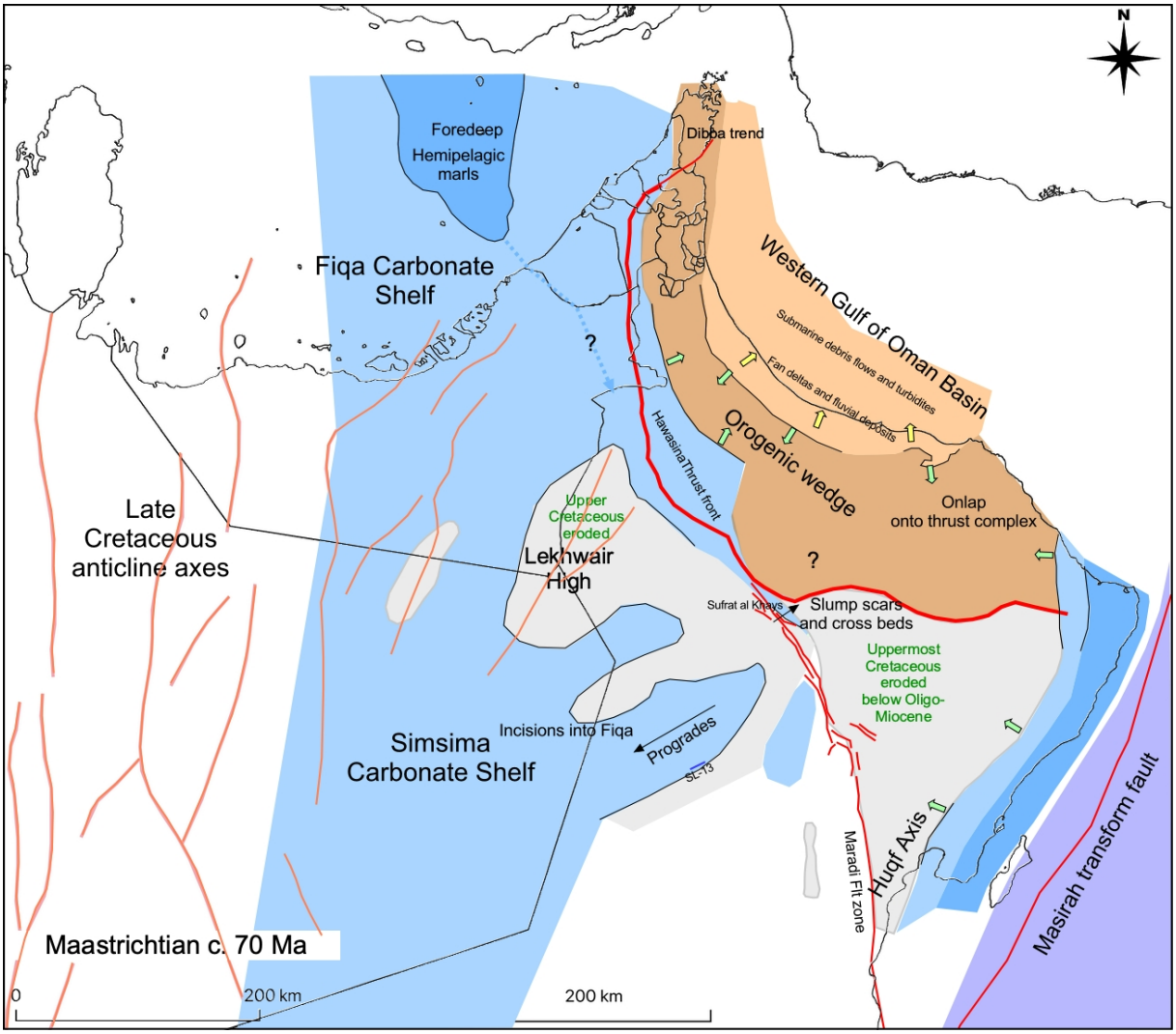


Figure 6-10 Palaeogeography during the Maastrichtian showing predominantly shallow-water carbonate deposition south of the orogen. Anticlinal structures in the UAE and Saudi Arabia formed through gentle reactivation of N–S-trending basement structures resulting from regional WNW–ESE compression. The Simsima in Oman has a very patchy distribution due to infill of Late Campanian incisions and truncation below the base Paleocene and base Oligo-Miocene unconformities. To the northeast, the Western Gulf of Oman Basin formed with major influx (more than 4 km) of late Campanian to Maastrichtian sediments sourced from the obduction complex. The outline of the deepest part of the remnant foredeep basin in UAE from Franco et al. (2021) is shown in dark blue. Late Cretaceous fold axes from Johnson et al. (2005) and Stewart (2016).

6.4.1 The Simsima in the UAE and Saudi Arabia

The base of the Simsima is not well known, but forms a significant regional unconformity associated with angular truncation in the UAE (Figure 6-11) and Saudi Arabia (Franco et al., 2021; Melville et al., 2004; Powers, 1968) and with valley incisions in Oman (Al Mahrooqi et al., 2000). This unconformity is related to the growth of anticlinal structures formed by gentle

reactivation of N–S-trending basement structures during regional WNW–ESE compression (Ali and Farid, 2016; Hozayen et al., 2008; Johnson et al., 2005; Stewart et al., 2016).

6.4.2 Simsima age

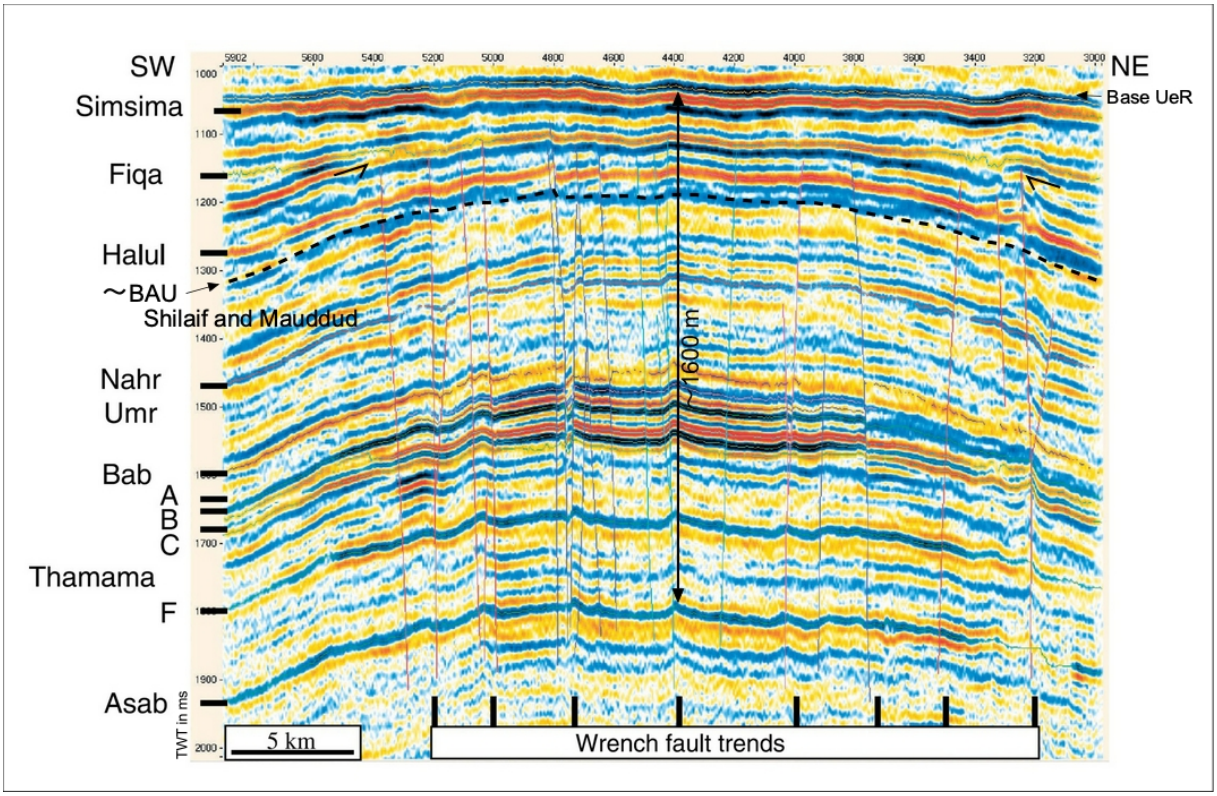


Figure 6-11 Seismic line through an oilfield onshore the UAE showing Late Cretaceous deformation. The base Aruma unconformity (BAU) on top of the Shilaif Fm. is about 25 ms below the top Halul reflector and indicated by the dashed black line. The seismic does not show major truncation at this level. This large anticline clearly predated the base Simsima unconformity with major truncation on the flanks. Wedging in the lower part of the Simsima suggest some syndepositional deformation. The base UeR unconformity does not show major truncation on this section. The wrench faults cutting the anticline affect the lower Fiqa and deeper intervals but not the Simsima suggesting a Campanian age for the faulting. Throws on the faults are up to 40 m. Vertical scale is two-way-travel time (TWT) and section has been strongly vertically exaggerated. Modified from Melville et al. (2004).

The age assigned to the Simsima in the Oman subsurface is Maastrichtian (Forbes et al., 2010; Hughes Clarke, 1988). The Simsima age in the UAE subsurface, mentioned in publications, varies from middle to late Maastrichtian, in places possibly early Maastrichtian (Alsharhan and Nairn, 1990) to late Campanian – Maastrichtian (Ali and Farid, 2016). In the outcrops of the Oman Mountains the Simsima shallow water carbonates and the underlying

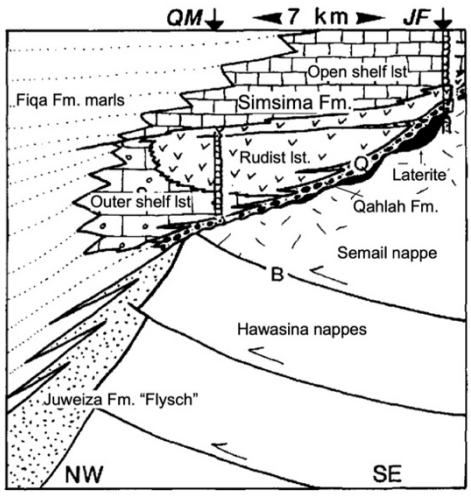


Figure 6-12 Stratigraphic relationships of Simsima, Qahlah, Juweiza and Fiqa formations in the northern Oman Mountains. Figure modified from Skelton et al. (1990), QM = Qarn Murrah and JF = Jebel Faiyah. outcrop sections discussed in their paper.

marginal to non-marine siliciclastics of the Qahla Formation that onlap the nappes have been interpreted as early to late Maastrichtian (Nolan et al. (1990); Skelton et al. (1990), Figure 6-12). Abdelghany (2003); (2006) suggest a late Campanian to Maastrichtian age based on benthic and planktonic foraminifera.

6.4.3 Simsima outcrops in Oman

Outcrops of the Simsima are restricted to the northern Oman mountains, the southeastern edge of Saih Hatat and along the Huqf axis in the east. A detailed description of the Simsima in outcrops is provided by Nolan et al. (1990) and Skelton et al. (1990). The limestones are very fossiliferous and form a deepening upward sequence from beach to shoreface to open shelf conditions (Skelton et al., 1990). They were deposited on a differentiated sea floor topography with topographic highs and lows (Vennin et al., 2000). Together with the underlying continental to shallow marine clastics of the Qahlah Fm. the Simsima forms a transgressive sequence that onlaps the obduction complex. In places the Qahlah is absent and the limestones, often with a basal conglomerate, directly overly the Samail or Hawasina nappes. The Simsima is up to 200 m thick, although truncated by a low-angle regional unconformity. It is overlain by Paleocene pelagic limestones. In the NW foothills of the Oman Mountains, the Simsima is overlain by slope deposits of the Muthaymimah Formation, deposited along the margin of the Pabdeh basin (Nolan et al.,

1990). Glennie et al. (1974) estimated a thickness of up to about 450 m on the western flank of the mountains north of Ibri but provides no further details.

6.4.4 Simsima distribution

The Simsima forms a widespread continuous interval over the Rub al Khali basin in the UAE and Saudi Arabia (Hughes Clarke, 1988). In the eastern UAE there is a gradual pinch-out (Alsharhan and Nairn, 1990). This is related to a lateral facies change to deep water marls of the foredeep (Franco et al., 2021). Only scattered occurrences of the Simsima limestones have been reported from the subsurface in Oman. Here it overlies marls of the Arada Mbr. of the Fiqa Fm. The interval is poorly documented and may not always have been identified, as it is lithologically difficult to distinguish on logs from the Campanian Arada (Forbes et al., 2010). Another challenge is that the Simsima may contain reworked Arada sediment, derived from the intra-Aruma unconformity. Unfortunately, biostratigraphic data is often not available, as the interval is located well above the interval of interest in most exploration wells. The limited distribution may also be facies related, as the deeper water equivalent of the limestones is formed by the upper Fiqa marls. Also, regional uplift and tilting during the base Shammar removed the Simsima over large areas.

In the Central Oman subsurface, west of the Ghaba Salt Basin, an intra-Aruma unconformity has been recognised based on well log correlations and seismic data (Al Mahrooqi et al., 2000; Van Vliet, 1983). The seismic shows an incision 150 to 200 m deep infilled locally with clinoforms, indicating progradation to the west, dipmeters suggest 10° to WSW (Van Vliet (1983), Figure 6-13). Regional mapping indicates the incisions trend NE-SW. Well data show that the infill consists of limestones and marls with palynomorphs and a very low content of microplankton. The upper part contains glauconitic calcareous shales with

plant remains. The palynomorphs of the upper part of the infill suggest a Maastrichtian age but nannoplankton over the whole interval indicates a late Campanian age (KN10) (Osterloff et al., 2001). The wedge cuts into and onlaps Campanian aged soft marls, which have also been reworked into the infill and may explain the late Campanian nannoplankton ages. In updip areas graben-like features that may represent valley feeder channels were identified (Al Mahrooqi et al., 2000). The complex is thought to represent an incised slope margin sourced by an elevated area in the east related to inversion of the Ghaba Salt Basin and uplift along its eastern flank (Al Mahrooqi et al., 2000). The infill and surrounding Aruma marls are capped by a peneplane surface of the base Palaeogene unconformity. As a result, the distribution of the Maastrichtian strata is very patchy and restricted to remnants of the incised valley fills.

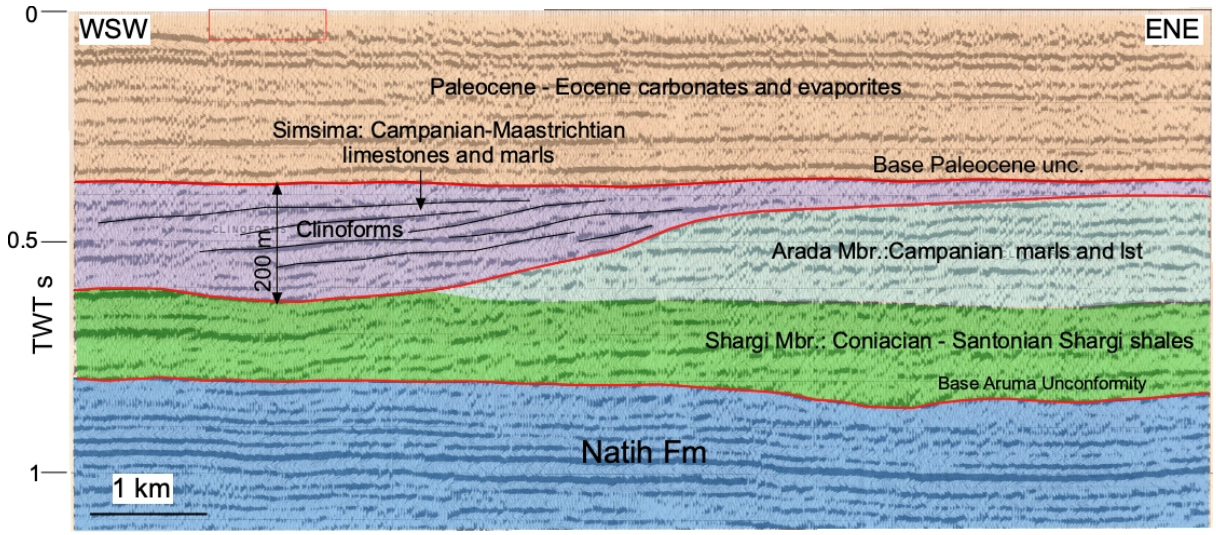


Figure 6-13 Vintage seismic section from central Oman showing incision of Simsima (purple) into the Fiqa Fm. (green). The top of the Simsima is a peneplained surface at the base of the Paleocene. For location: SL-13 in Figure 6-10 and Appendix-4. Modified from Van Vliet (1983).

In the Sufrat al Khays area, west of Jebel Salakh, and along the Maradi Fault, bioclastic calcarenites and calcirudite debris flow deposits with broken-up and brecciated carbonate blocks, slumped chalk and subordinate interbedded green marls overlie marls of

the Upper Aruma Gp. (Béchennec et al., 1992c; Hanna and Smewing, 1996). The clasts are reworked from shallow and deep marine Campanian and Maastrichtian sediments. The interbedded marls indicate a latest Maastrichtian age (Béchennec et al., 1992c). Channel shapes and cross-bedding indicate palaeocurrent directions towards the north, northeast and east. A slump scar indicates a northeastern dipping palaeoslope (Hanna and Smewing, 1996). These deposits are derived from a carbonate platform located in the southwest of Sufrat al Khays area. The mixture of clasts of different ages suggests a major relative sea level drop in the latest Maastrichtian. It is not clear whether this is associated with a eustatic fall, or with fault related uplift along the Maradi Fault zone just west of the outcrops (Figure 6-10).

6.4.5 Late Campanian to Maastrichtian in the "Western Gulf of Oman Basin"

On the north side of the orogenic wedge a deep basin, the "Western Gulf of Oman Basin" formed during the Campanian (Levell et al. (2021); Ravaut et al. (1997); Ravaut et al. (1998), Figure 6-10). This was filled with a 2-4 km thick sedimentary sequence sourced from the orogenic wedge during the Campanian and Maastrichtian (Levell et al., 2021; Ninkabou et al., 2021). This consists of fan delta to fluvial deposits of the Al Khawd Fm. and submarine debris flow and turbidites of the Thaqab Fm. and their basinal equivalent slope and base-of-slope deposits. The polymict Al Khawd conglomerates unconformably overly the Semail ophiolite and contain ophiolite and chert clasts from the thrust complex.

In the upper part of the sequence, near Saih Hatat, clasts of carbonates from the autochthonous platform occur, as well as Lower Palaeozoic meta sedimentary quartzites of the Amdeh Fm. (Nolan et al., 1990). This indicates major uplift of Saih Hatat during the Late

Cretaceous after ophiolite obduction. These sediments are late Campanian to late Maastrichtian in age (Levell et al., 2021).

The Thaqab Fm. is described in Nolan et al. (1990). It consists of a basal unit of well bedded, coarse cobbly conglomerates derived from the orogenic wedge. This unit is overlain by a monotonous sequence of shales with thin turbidite beds. The upper part consists of sandy bioclastic limestones interbedded with shales, lithic sandstones and conglomerates. The clasts include rudist and oyster fragments, as well as debris from the Semail Ophiolite, Hawasina and Haybi Complex. Well data show that the basinal equivalent of the Thaqab Fm. consists of mudstones and marls with some cherts, limestones and radiolarites (Levell et al., 2021; Ninkabou et al., 2021).

The Upper Cretaceous sedimentary fill of the "Western Gulf of Oman Basin" shows that major erosion occurred during the Campanian and Maastrichtian along the northern margin of the orogenic wedge. However, along the southern edge, sediments derived from the orogen are limited to the Juweiza Fm., which rims the northern margin of the foredeep and does not extend far into the foredeep.

6.5 Paleocene

The foreland basin fill is capped by a widespread peneplained surface which is overlain by middle Paleocene (Selandian), grey calcareous shales and marls of the Shammar Member at the base of the carbonate dominated Umm Er Radhuma Formation (Forbes et al., 2010). Forbes et al. (2010) mention that some old studies suggested an older Danian age, but that this is subject to debate and needs re-evaluation. More recently an early – middle Palaeocene (Danian – Selandian) age has been suggested for the basal Shammar in the Lekhwair area (Al Hajri and Gomez-Perez, 2019). The youngest subcropping unit below this

unconformity are late Maastrichtian carbonates of the Simsima Formation, suggesting a hiatus of some 4 Myr.

6.6 Conclusions

1. The infill of the foredeep consists of two major progradational cycles: the first cycle is from Santonian to Early Campanian, the second cycle from Campanian to Maastrichtian.
2. The sediments filling the foredeep are predominantly derived from the craton; there is little sediment coming from the orogenic wedge.
3. The first phase of infill during the Santonian consists of a prograding muddy shelf in the eastern foredeep (Oman) and a carbonate ramp in the western foredeep (UAE). The fine clastics in Oman are sourced from the Huqf axis and transported by alongshore currents to the west.
4. The Santonian progradation ends with an erosional surface during which the shelf margin is cut by deep canyons, channels and slump scars. During the early Campanian coarse siliciclastic sediments from the Huqf High enter the eastern foredeep and are deposited as turbidites. They onlap the shelf margin as well as the front of the nappe complex. They contain some ophiolite debris in the upper part. The stratigraphic relationship suggests that the nappes were in place during the early Campanian.
5. Following a regional flooding the second phase of infill consists of a prograding Campanian carbonate platform. The infill of the basin centre is by hemipelagic carbonates that onlap the orogenic wedge.

6. This platform is truncated by a major erosion surface with large incisions during the late Campanian. This is related to a major regional tectonic event associated with re-activation and uplift along basement lineaments. The unconformity is overlain by shallow marine Maastrichtian carbonates. The latter have a very patchy distribution due to truncation below the base Palaeogene and younger unconformities.

7 Foreland basin evolution

The objective of this chapter is to summarise the evolution of the Oman foreland basin based on the work presented above. This is achieved through the presentation of several seismic sections across the foredeep, palaeogeographic maps, reconstructed geological cross-sections illustrating the evolution of obduction, and a chronostratigraphic cross-section (Wheeler diagram) which integrates observations from both outcrop and subsurface data and allows comparison between the timing of stratigraphic events and geochronological constraints from the obduction complex. This is followed by a discussion of the key factors controlling sediment input into the foredeep. Finally, the Oman foreland basin is compared

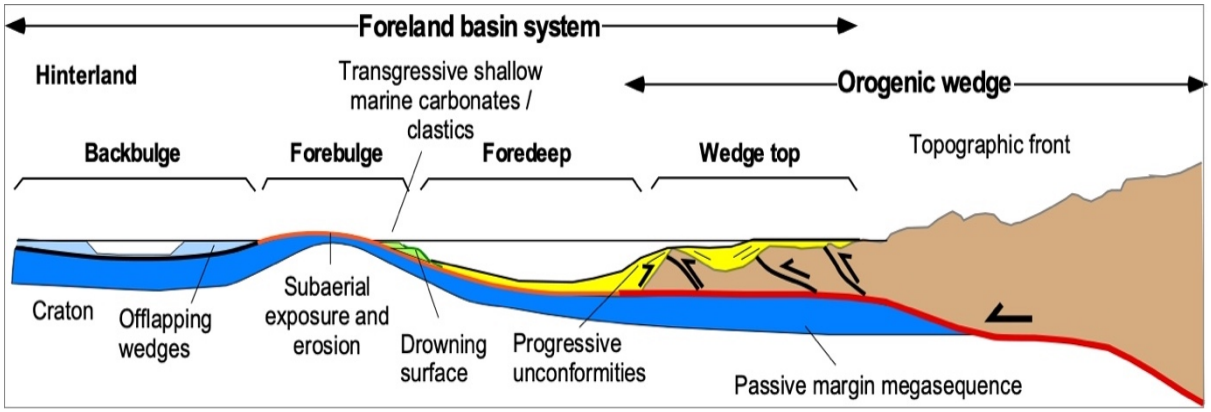


Figure 7-1 Schematic diagram for a classical foreland basin model. Through time the different depozones migrate towards the hinterland. The main infill of the foredeep (yellow) is by sediments derived from the uplifted orogenic wedge. Figure modified from DeCelles and Giles (1996).

with the classical foredeep model, and a revised model for obduction-related settings is proposed.

7.1 The classical model of a foreland basin.

The development of a foreland basin system is related to flexural bending of the lower plate by the loading of the advancing orogenic wedge (DeCelles and Giles (1996); see also review by Watts (2023)).

The classical model of a foreland basin system is based on continent-to-continent collision and retro-arc settings, and the question is if this model is applicable to the ophiolite obduction in Oman.

The classical model is shown in Figure 7-1. It consists of several depozones: a wedge top basin above the orogenic wedge, a foredeep in front of the orogenic wedge, a forebulge (area of uplift) and a backbulge basin. These zones of uplift and subsidence will migrate towards the hinterland during the emplacement of the orogenic wedge, leading to complex stratigraphic patterns. In the early stages subsidence may exceed sediment input and the foreland basin is underfilled (Figure 7-2). However, as more sediments enter the basin from the growing and uplifted thrust wedge, the basin becomes progressively filled with a sedimentary wedge onlapping both the forebulge and the orogen.

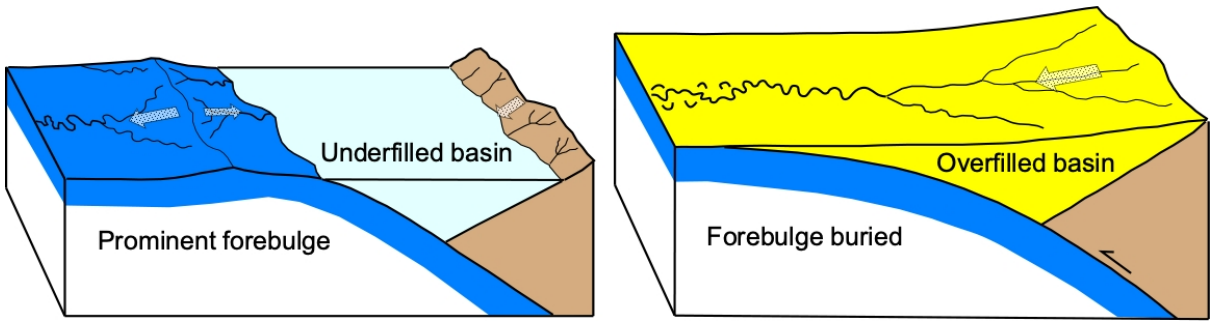


Figure 7-2 Infill stages of classical foredeep. An early underfilled basin and forebulge (left) is progressively filled and covered by sediments derived from the rising orogen (right). Modified from Crampton and Allen (1995).

A review of underfilled foreland basins by Sinclair (1997a) identifies a common diachronous lithostratigraphic succession of three units (the “underfilled trinity”). This comprises: (1) a lower transgressive unit of shallow-marine limestones and sandstones, commonly overlying a basal unconformity (thickness 0–2500 m; average ~550 m); (2) a middle unit of pelagic mudstones (thickness 50–4000 m; average ~830 m), deposited following basin drowning linked to flexural subsidence; and (3) an upper unit of deep-water turbiditic sandstones, commonly referred to as “flysch” (thickness 45–4000 m; average ~2000 m), derived from the advancing thrust stack. These units migrate cratonward and are progressively overthrust by the advancing orogenic wedge.

This succession is followed by an overfilled “molasse” stage, consisting of shallow-marine to continental deposits that onlap both the orogenic wedge and the cratonic margin. This stage reflects increased sediment supply from the orogenic wedge, commonly attributed to uplift and exhumation following slab break-off (Sinclair, 1997b).

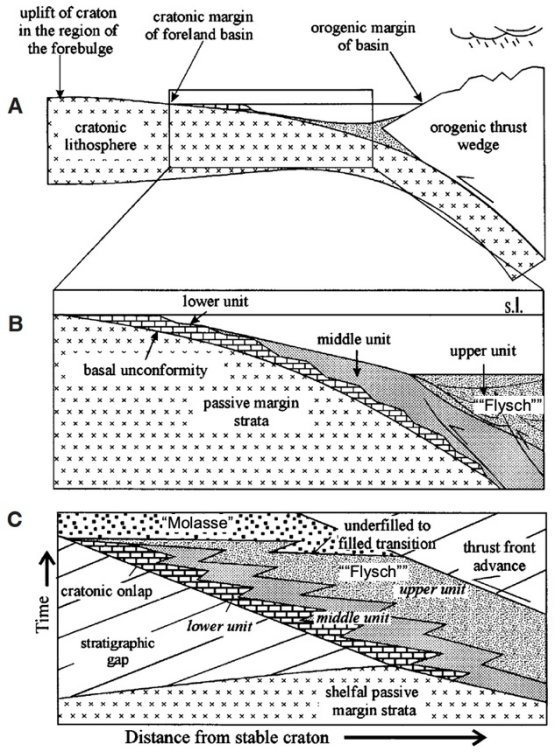


Figure 7-3 Typical stratigraphic evolution of a peripheral foreland basin. The initial underfilled stage comprises a tripartite succession (“underfilled trinity”): (1) a basal shallow-marine transgressive interval capped by a flooding surface, (2) deep-water mudstones, and (3) siliciclastic turbidites derived from the orogenic wedge. This is succeeded by an overfilled stage of shallow-marine to continental deposits sourced from the uplifted orogen. Modified from Sinclair (1997)

7.2 The Oman foredeep

7.2.1 Impact of basement lineaments

Figure 7-4 shows the areas of the foredeep where the thickness of the preserved Cretaceous infill exceeds 1 km (pink). The changes in width show that Oman's foreland basin is segmented. The segments align with the basement lineaments discussed in Chapter 2 and

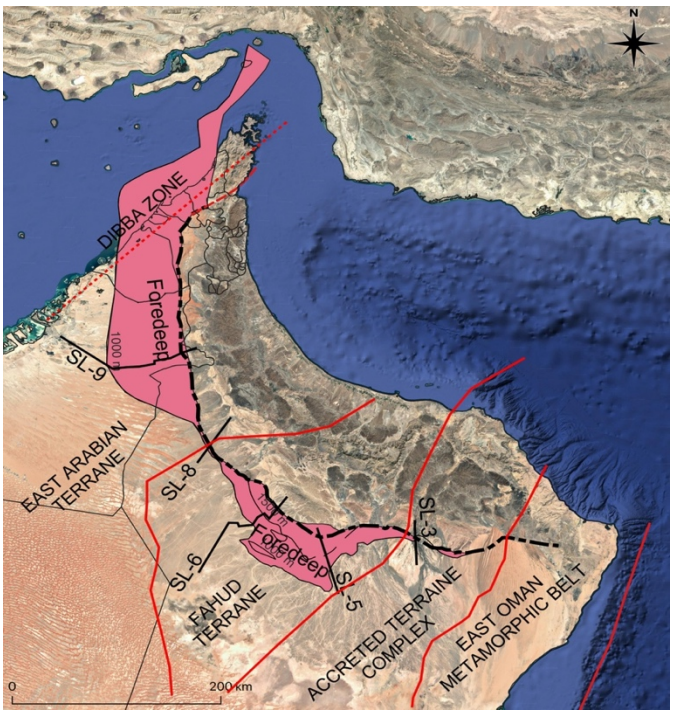


Figure 7-4 Outline of the foredeep (where fill > 1 km thick) compared to the location of Neoproterozoic basement lineaments.

indicated as red lines on the Figure 7-4. This suggests that re-activation of the NE-SW trending Neoproterozoic basement structures affected the shape and as discussed in the next section, the infill of the foredeep as well as potentially its later uplift and erosion.

7.2.2 Lateral changes in foredeep fill: seismic transects

The infill of these basin segments contains very little sediments eroded from the orogenic belt; only – limited – sediment supply came from the hinterland and most of the fill is hemipelagic, deep water ooze (chalk). Yet, the different basin segments show significant lateral changes, both in thickness and in nature. This is illustrated by Figure 7-5, which shows

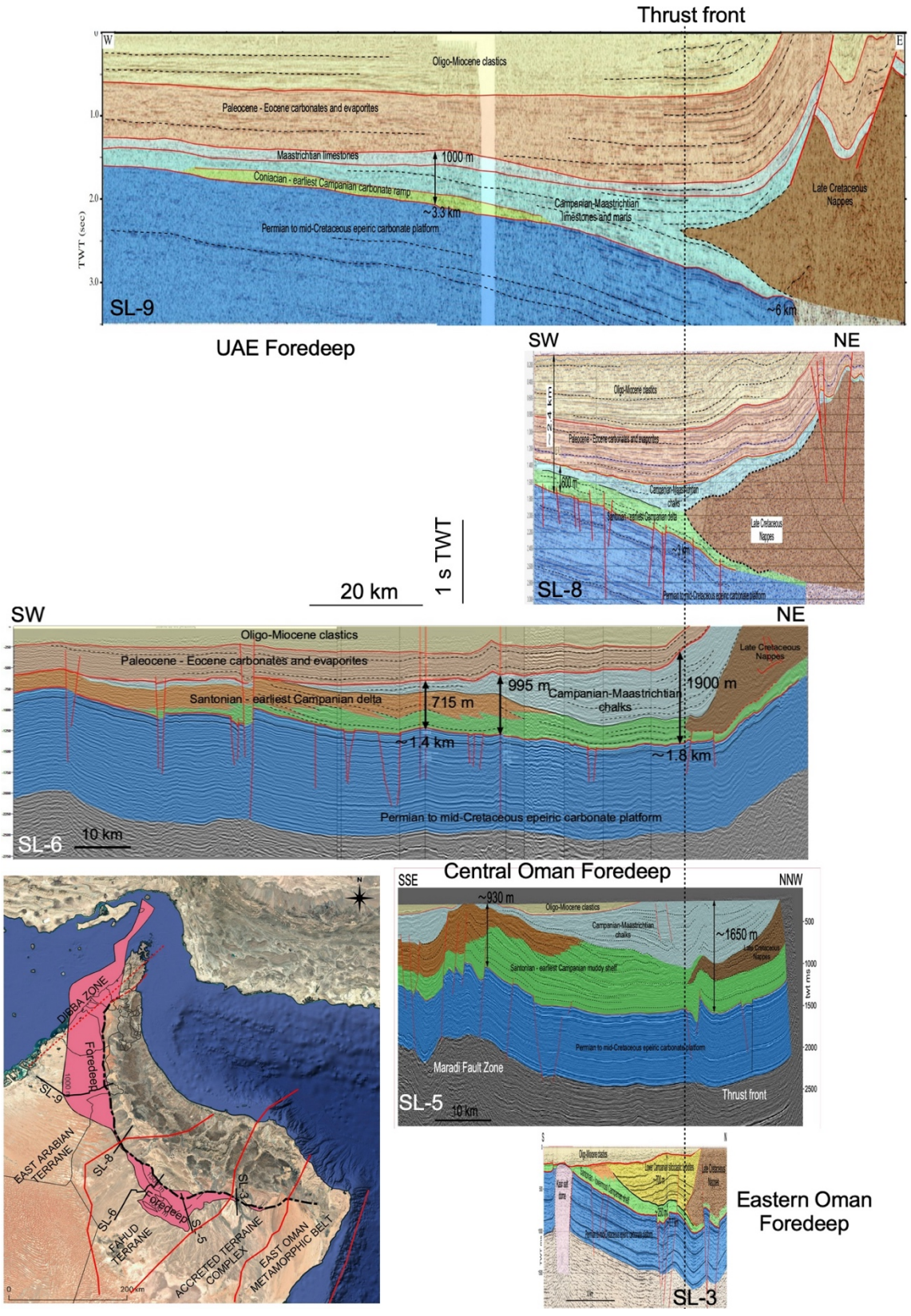


Figure 7-5 Transect of re-interpreted vintage seismic line across the foredeep illustrating lateral changes of the infill and thickness of the foredeep (based on nearby well penetrations). All lines have the same scale. Note only the frontal part of thrust complex is covered. The tilting of the infill over the frontal thrust is related to the Neogene compressional event. Line SL-9 modified from Ali et al. (2013). Line locations also shown in Appendix 4.

a series of scaled seismic profiles along the foredeep, from the UAE to eastern Oman,

calibrated with well data for the lithological interpretation.

In the central foredeep area (sections SL-5 and SL-6) the basin fill consists of two units: (1) a northward prograding Santonian muddy shelf system overlain by, (2) Campanian to Maastrichtian chalks and limestones. The muddy sediments of the shelf are derived from the hinterland, probably by longshore transport from the Huqf axis, as discussed in Chapter 7. The overlying (deep-water) chalky limestones represent the only active carbonate deposition in the basin, as the exposed carbonates from the forebulge are at this time being dissolved by subaerial leaching.

Further east (section SL-3) there are also two units: (1) the shelf system as in the central area (here truncated by the Oligo Miocene unconformity), but in this area the shelf system is overlain by (2) early Campanian siliciclastic turbidites rather than hemipelagic carbonates. These turbidites are sourced along depositional strike (or longitudinally) from uplifted Palaeozoic and older strata from the Huqf Axis (see Chapter 7) in the east. Only the very upper part of the turbidite fill contains some redeposited sediments from the orogen. The topmost part of the foredeep (Late Campanian and younger) has not been preserved due to Late Cenozoic erosion.

In the western foredeep (UAE, sections SL-8 and SL9) the Santonian lower shelf unit thins and pinches out, which reflects the increasing distance from the Huqf source area in the east. Here the sequence becomes dominated by limestones and marls. In Oman the top of the foredeep fill consists of shallow water carbonates of the Simsima Fm., whereas in the UAE the western foredeep was not completely filled during the Cretaceous and deep-water sedimentation persisted into the Palaeogene.

7.2.3 Integration of stratigraphic and structural framework

To compare the timing of structural and stratigraphic events the stratigraphic data collected in this study have been plotted in a 500 km long chronostratigrapic cross section

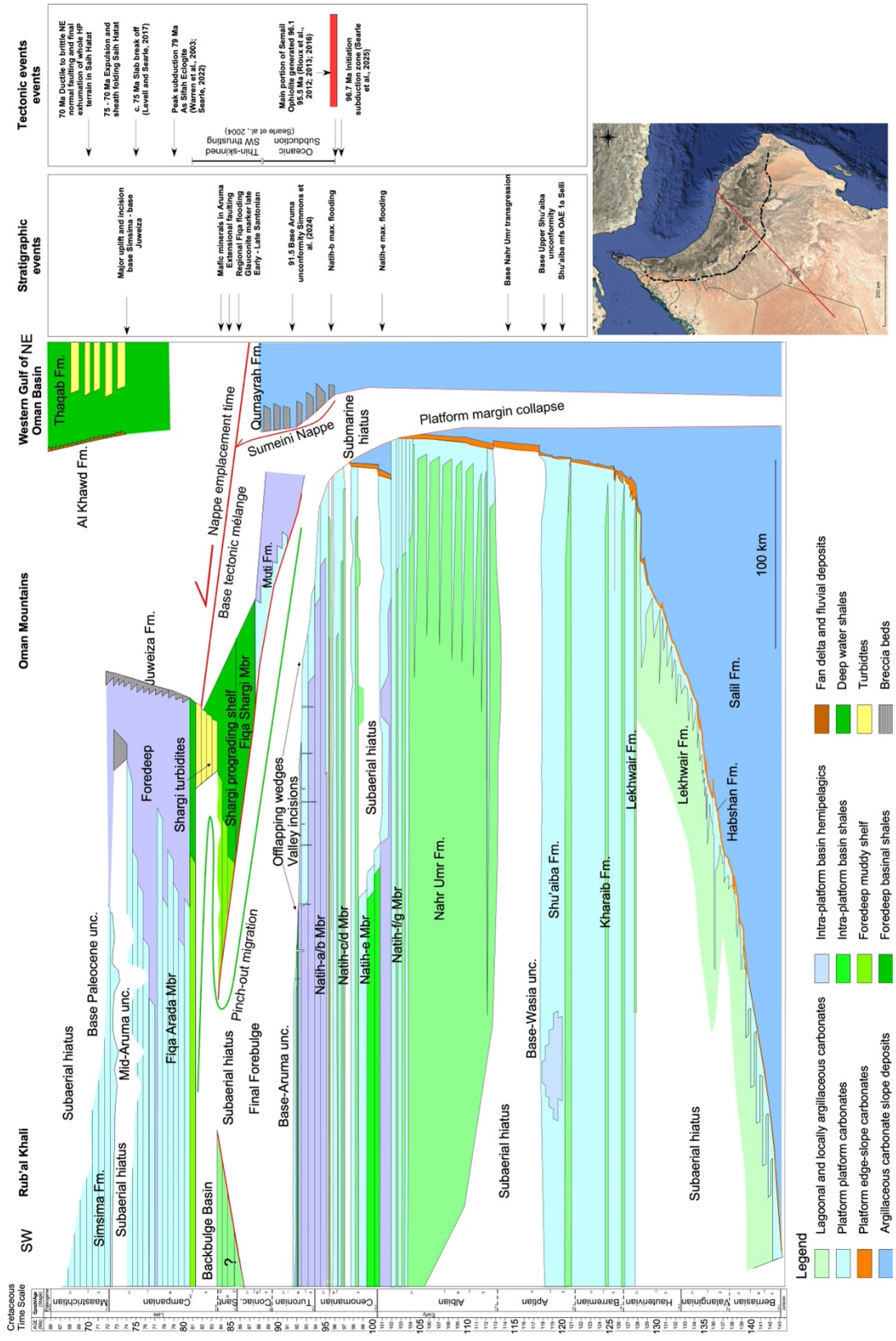


Figure 7-6 Chronostratigraphic cross section (Wheeler diagram) from the Gulf of Oman to the Rub'al Khali Basin. Own work based on well and seismic observations, apart from Early Cretaceous which is based on Dujoncquoy et al. (2018).

(Wheeler diagram), from the Oman mountains to the Rub'al Khali area (Figure 7-6). This

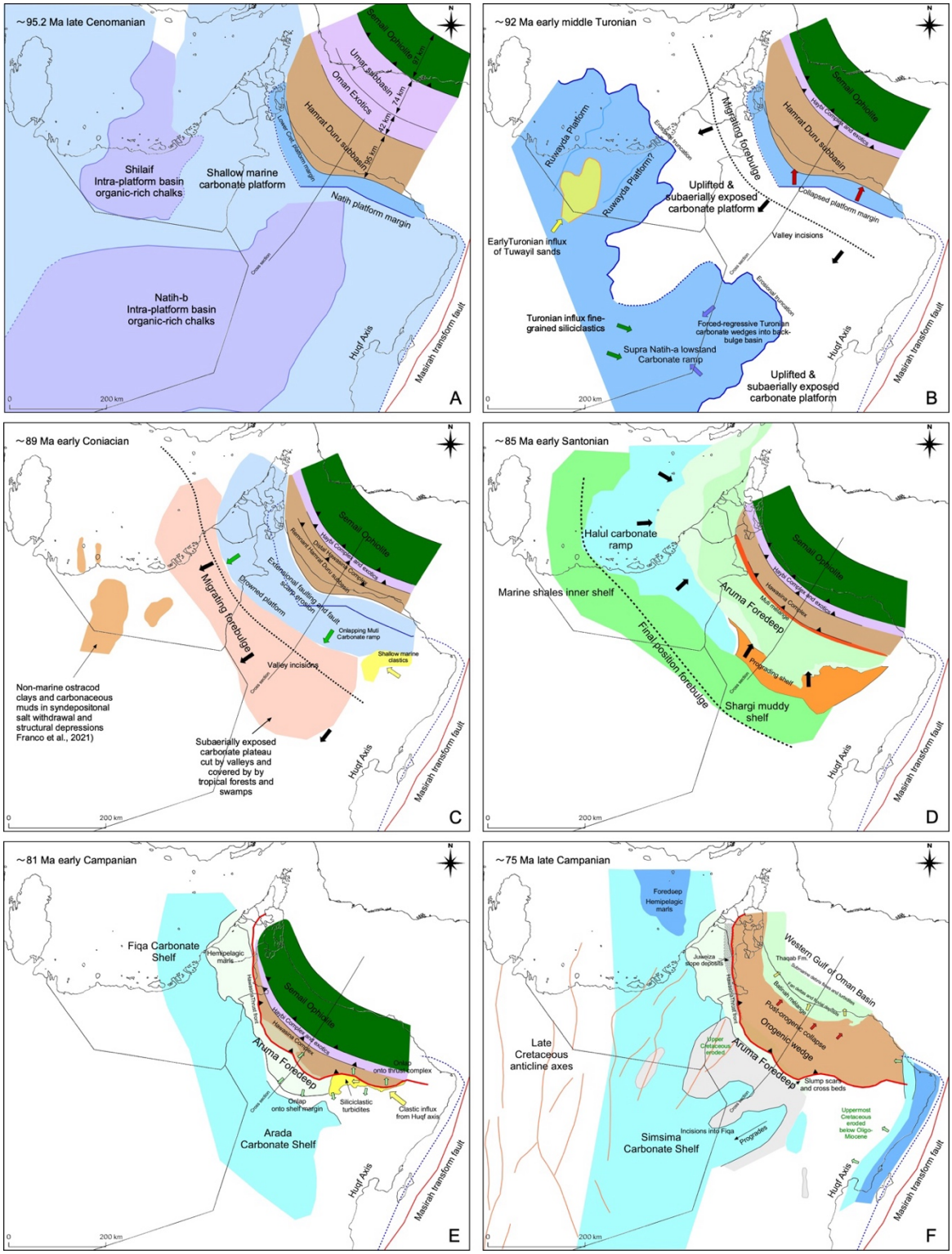


Figure 7-7 Middle–Late Cretaceous palaeogeographic reconstructions illustrating the obduction history of the Semail ophiolite. Restored widths of the Hawasina Basin and convergence rates are based on estimates from Najafi et al. (2026). Cross section is shown in Figure 7-8. Note in "F" the orogenic wedge is treated as a single unit. This because details of the uplift and erosion pattern, and hence the outcrop patterns of the individual thrust sheets in the Late Campanian, post emplacement, are not yet fully known.

diagram has been constructed using well and seismic observations and outcrop data. Although the age uncertainties are large due to limited age control, the stratigraphic patterns are consistent for the whole area. The stratigraphic and tectonic events are listed on the right side of the figure. The evolution of the different obduction stages is further illustrated

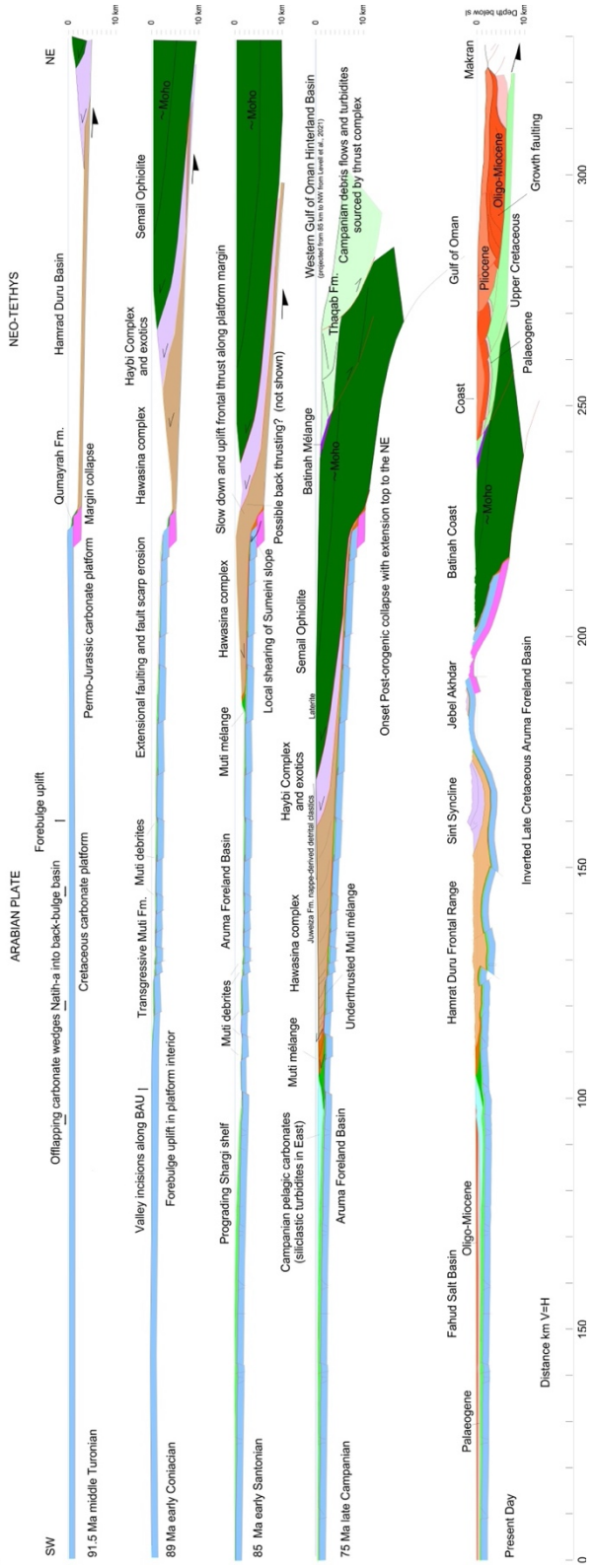


Figure 7-8 Middle–Late Cretaceous restored cross sections illustrating the obduction history of the Semail ophiolite. For location, see Figure 7-7 and XS-18 in Appendix 4. Restored widths of the Hawasina Basin and convergence rates.

through a series of palaeogeographic reconstructions and 1:1 restored cross-sections shown in Figure 7-7 and Figure 7-8. The estimated convergence rates and restored widths of the different parts of the Hawasina Basin used in these figures are based on a recent extensive review of all published data by Najafi et al. (2026). A more schematic tectonostratigraphic evolution, showing additional detail on the foreland basin evolution, is presented in Figure 7-9.

7.2.3.1 Early Cretaceous carbonate platform progradation

During the Early Cretaceous (Kahmah Gp.) the sequence consists of a northward prograding carbonate shelf (Salil, Habshan, Lekhwair sequence) controlled by eustatic sea level changes and there is no evidence for major tectonic events. Lack of accommodation space resulted in very strong progradation. The late Aptian – early Albian subaerial hiatus between Shu'aiba Fm. and Nahr Umr Fm. indicated on the platform has been linked to a eustatic sea level drop (Ben Chabaane et al., 2025; van Buchem et al., 2010), but in southern Oman the hiatus is also related to an inversion in the SOSB. This may be linked to activity along the transform margin in the East (see Chapter 3.2.1).

7.2.3.2 Mid Cretaceous – initiation of platform subduction

A strong differentiation on the platform with the development of intra-platform basins and lowstand wedges becomes apparent during the Cenomanian (Droste, 2010a; Droste and Van Steenwinkel, 2004). The depositional cycles have been related to eustatic changes, with local tectonic overprint (Bromhead et al., 2022). This time interval in the Cenomanian (98 – 94 Myr), marked by intra-platform basin differentiation, corresponds to the initiation of subduction and formation of the Semail ophiolite at least ~235 km to the north (Najafi et al.,

2026) (Figure 7-7 A and Figure 7-9 A). The tectonic stress regime that led to the subduction initiation may have caused the palaeogeographic changes on the carbonate platform.

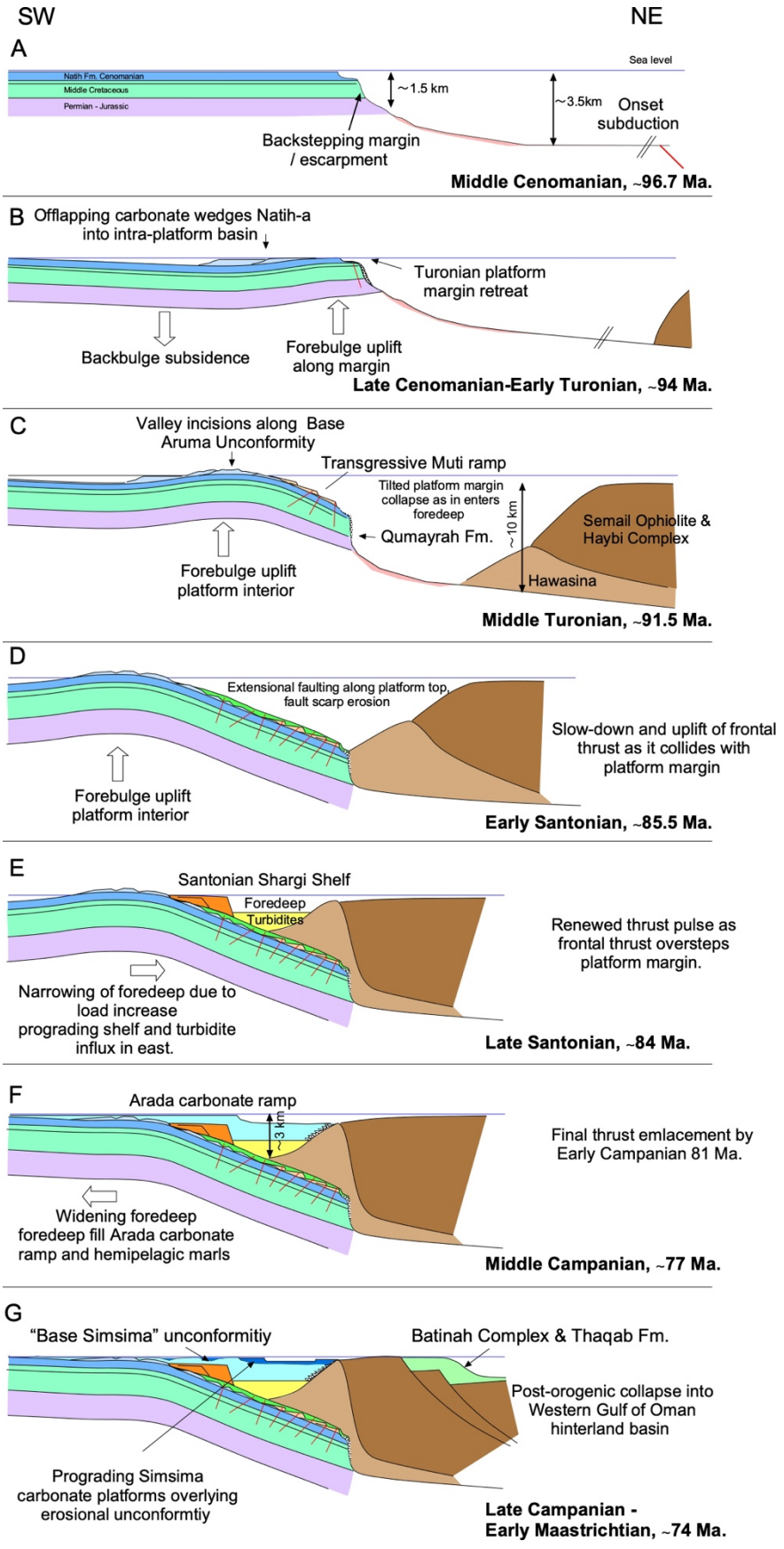


Figure 7-9 Cartoon showing tectono-stratigraphic evolution of the Oman foreland basin from Cenomanian to Maastrichtian. Not to scale.

7.2.3.3 Base Aruma Unconformity

The mid-Cretaceous epeiric platform was truncated by the mid-Turonian Base Aruma Unconformity (BAU; c. 92.5Ma), related to tectonic uplift preceding the emplacement of the nappes (Glennie et al., 1973; Simmons et al., 2025). Offlapping wedges and valley incisions indicate forebulge uplift and migration (Figure 7-7 B and Figure 7-9 B, C). Uplift along the Lekhwair High and Huq Axis are related to basement re-activation presumably triggered by differential flexural responses to the advancing thrust wedge. Somewhat earlier, during the latest Cenomanian, when the thrust front was ~150 km NE of the margin, collapse of the Mesozoic platform margin began with deposition of the Qumayrah Fm. at the foot of the escarpment which continued until the Coniacian (Watts, 1990). The margin instability was likely caused by tectonic tilting into the foredeep. The margin collapse along the uppermost part of the platform formed by the Natih Fm. could have occurred on the NE flank of a flexural bulge in the downgoing plate. However, due to the inherited bathymetry of a steep margin, uplift above sea level and subaerial exposure was likely limited (Crampton and Allen, 1995).

7.2.3.4 Drowning of the platform, Late Cretaceous

After the presumed passage of the forebulge (the hard evidence of valley incisions into the top Natih is only available from south of the mountains but widespread karstification of the top Natih does indicate uplift of several tens of metres) the BAU on the platform was onlapped by the Muti transgressive carbonate ramp and further south by the basal Shargi deepening-upward interval of lagoonal to marginal marine to open marine shales (Figure 7-7 C and Figure 7-9 C). The rapid drowning of the Muti carbonates may be related to adverse environmental conditions that hampered the initiation of the carbonate factory, including

brackish conditions during initial flooding, influx of fine clastics from the Huqf axis in the east, and high subsidence rates leading to deepening below the euphotic zone. Fault scarps associated with debris cones develop along the top of the platform during bending of the drowned platform as it entered the foredeep (Figure 7-9 D).

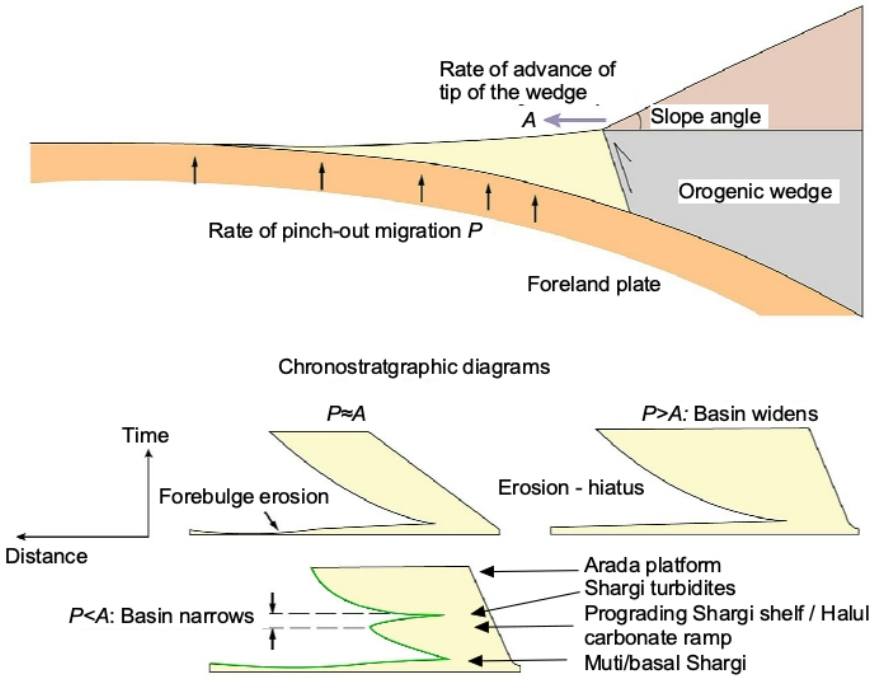


Figure 7-10 Influence of rate of advance (A) of the tip of the orogenic wedge and the pinch-out migration (P) on foreland basin width. Narrowing of the foreland basin can occur during increased advance of the orogenic wedge. Positions of the units of the Fiqa Fm. as indicated on the Wheeler diagram, green line in Figure 7-6. Modified from Allen and Allen (2013).

Based on seismic data and gravity modelling, the Aruma foredeep reached water depths of approximately 3 km (Ismaiel et al., 2025). The distribution of the most distal facies in the Muti Fm., containing bedded radiolarian cherts and fine-grained turbidites, suggest the deepest part of the foredeep was located below the frontal nappes in the Hamrat ad Duru range (Rabu et al., 1993).

A depositional mélange (Upper Muti Fm.) consisting of blocks and rafts derived from the allochthon was deposited along the frontal edge of the thrust front and was

subsequently underthrust, evolving into a tectonically sheared mélange at the base of the thrust stack (Figure 7-7 D).

The onlapping sequence on the forebulge is interrupted during the Santonian by a phase of progradation into the foredeep by the Shargi shelf in the eastern and the Halal carbonate ramp in the western foredeep (Figure 7-7 D and Figure 7-9 E). The progradation ends with, possibly subaerial, erosion associated with further channel incisions along the margin and, in the eastern foredeep, an influx of (Shargi) siliciclastic turbidites from the Huqf axis (Figure 7-9 E). This is followed by a second flooding and the development of the Arada carbonate platform (Figure 7-9 F). The turbidites contain minor amounts of reworked ophiolite debris and onlap the thrust complex. This ties the final nappe emplacement to the early Campanian.

7.2.3.5 Nappe emplacement and effect on basin fill – Late Cretaceous

The pinch-out/onlap migration trend ((Allen and Allen, 2013) in the foredeep indicated by the green line in the lower drawing of Figure 7-10 shows that southward migration of the foredeep experienced a northward shift during the late Santonian – early Campanian. This indicates a narrowing of the foredeep. A narrowing of the basin has been observed in other foreland basin systems such as the Carboniferous Appalachian Foreland (Tankard, 1986) and the Oligo- Miocene North Alpine Foreland Basin (Sinclair et al., 1991). These shifts have been interpreted to result from either stress relaxation (following a halt in the thrust advance) in a viscoelastic lithosphere, or thickening of orogenic wedge loading on an elastic plate (see Figure 7-10 and discussion in Allen and Allen (2013) and references therein). In the latter case, stratigraphic modelling by (Flemings and Jordan, 1990) suggests that the overall migration of the pinch-out towards the hinterland can be punctuated by periods of migration

of the forebulge and depositional progradation towards the thrust front at the onset of thrust cycles.

In the Oman foreland basin, an early and major obstruction to the thrust stack would have been the steep, > 1 km high, carbonate margin discussed in Chapter 3 (Figure 3-12). Buttressing of the thrust complex against a possible shelf edge promontory has been suggested for the large-scale duplex and complicated backthrust structures in the thrust complex located in the Hawasina window by Searle and Cooper (1986). This is likely to have caused a temporary slowdown of thrusting and thickening of the orogenic wedge, followed

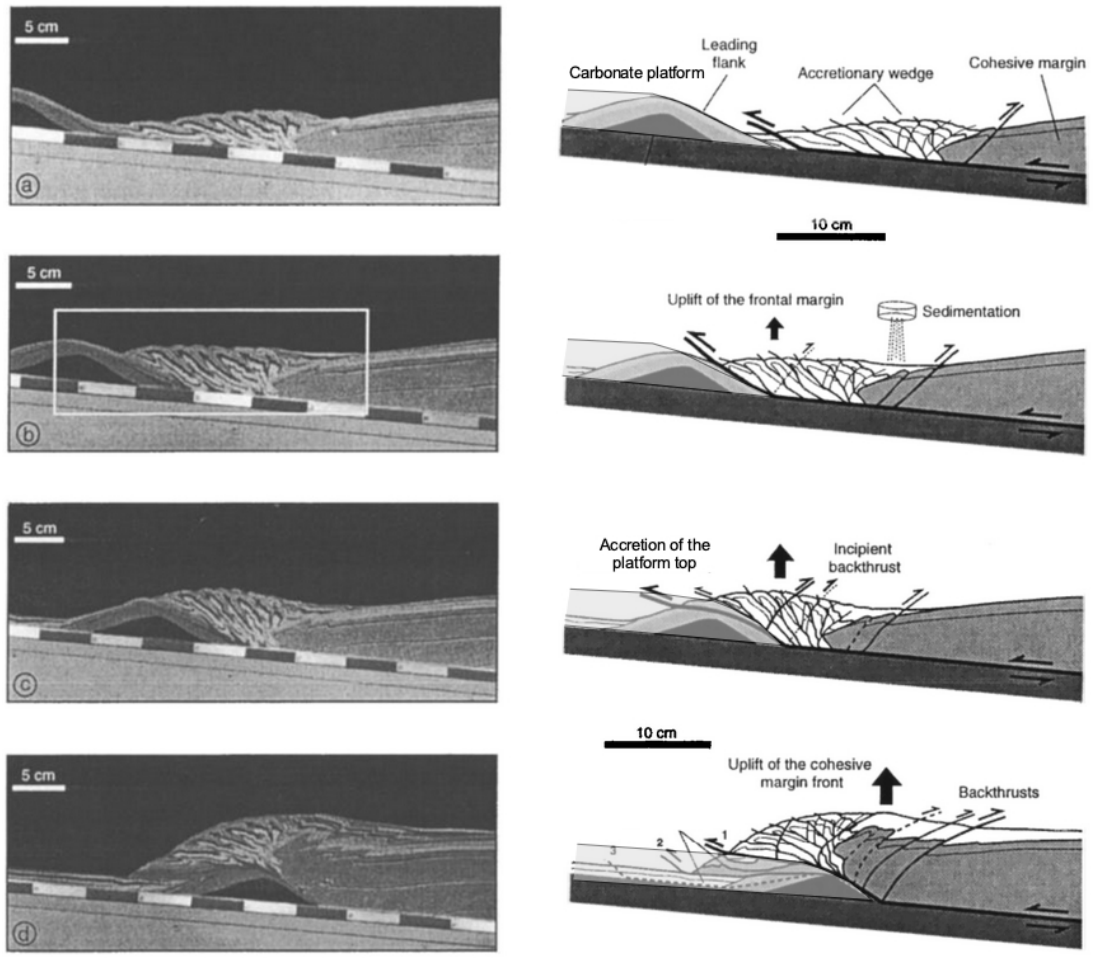


Figure 7-11 Photographs and structural interpretation of a sandbox experiment showing the initial stages of a seamount subduction in cross section. Similar deformation would be expected in the case of a subducting carbonate platform margin, schematically shown on the interpretations. The obstruction causes a slowdown of the thrusting, followed by a renewed thrust pulse, which is reflected in the stratigraphy of the Oman foredeep. Modified from Dominguez et al. (2000).

by a renewed advance (Figure 7-8 and Figure 7-9 D, E). Similar to the modelling results by Sinclair et al. (1991) for the Alpine Foredeep, a thrust pulse following the thickening and slowing down of the orogenic wedge in Oman may have caused migration of the foreland bulge towards the thrust front and progradation of the Halul carbonate ramp and Shargi shelf into the foredeep.

The deformation of the thrust stack as it abuts the shelf margin is likely to be similar to the initial deformation in front of subducting seamounts below an accretionary wedge. Obstructions like seamounts have a major effect on the morphology, structure and vertical motion history of the accretionary complex (Watts et al., 2010). Several studies used sandbox experiments, or numerical modelling, to study the deformation (Dominguez et al., 2000; Ruh et al., 2016; Wang et al., 2021). Figure 7-11 shows the result of a sandbox experiment of a seamount subduction by Dominguez et al. (2000), which could give an indication of the type of deformation that can be expected with shelf margin subduction. An initial uplift of the frontal margin is followed by a shortening and thickening of the accretionary wedge and re-activation of thrusts (Figure 7-11 a, b). With further subduction the top of the seamount is sheared off and accreted to the frontal margin (Figure 7-11 c). In the Oman shelf margin a similar process has been suggested for the Sumeini thrusts with slope deposits (Searle et al., 1990). Backthrusts are initiated and accommodate uplift of the frontal part of the wedge. Further subduction of the mount also starts to uplift the thicker rear part of the wedge, rapidly increasing the load on its leading slope (Figure 7-11d). In the case of a subducting shelf margin, it is expected that, once the uplift reaches sufficient height, the thrust sheets will move further along the platform top.

7.2.3.6 Base Simsima unconformity, Late Cretaceous

The Late Campanian unconformity at the base Simsima is associated with a major incision (Figure 7-9 G). At the same time in the UAE, deposition of the Simsima followed major reactivation of basement and salt related structures (Figure 7-7 F). The Simsima is absent in northeastern Oman by truncation below the base Palaeogene or Neogene unconformities. Lateritic profiles reaching up to 95 m in thickness developed on the ophiolite prior to the Late Maastrichtian transgression (Al-Khirbash, 2015; Al-Khirbash, 2016; Coleman, 1981). Well and seismic data suggest some limited (300 m) erosion of the Fiqa foredeep fill prior to the deposition of the Paleocene Shammar shale (Filbrandt et al., 2006) along the Fahud Fault (see section 5.2.8); this erosion could be pre-Simsima in age.

This structural reactivation – and associated base Simsima unconformity – coincides with the timing of slab-break off and exhumation in Saih Hatat starting after ~77 Ma (Searle et al., 2025). Rebound following complete slab break-off can cause a change from extension due to downbending, to horizontal compression (Di Martire et al., 2015). In the foreland basin NE-SW compression may have caused regional uplift and inversion along the extensional faults formed during the down-bending. The NE-SW trending incision and the tentative NW-SE trending erosional high shown on the Simsima palaeogeographic map in Figure 7.28 can be explained with such an event.

The uplift also coincides with the onset of major sediment shedding from the orogenic wedge into the “Western Gulf of Oman Basin” during the mid-late Campanian and Maastrichtian, resulting in the 2-4 km thick Thaqab Fm. and the Batinah Complex (Levell et al., 2021; Ninkabou et al., 2021). The distribution of detrital sediment between the foreland

(Juweizah Fm.) and hinterland (Thaqab Fm.) basins indicates an asymmetric topography with a drainage divide close to the current mountain front.

Top-to-the-north–northeast extension along shears and normal faults within the platform sequence beneath the nappe complex (Al-Wardi and Butler, 2007; Breton et al., 2004; Duretz et al., 2016; Gomez-Rivas et al., 2014; Grobe et al., 2019) also suggests a tilting of the orogen into the Western Gulf of Oman Basin during exhumation. Post-obduction extension may reflect the resumption of slab-pull forces along a northern subduction zone beneath Eurasia (Agard et al., 2007).

The Late Cretaceous growth of anticlinal structures in the UAE and Saudi Arabia (Figure 7-7 F) is thought to reflect gentle reactivation of N–S-trending basement structures during regional WNW–ESE compression (Johnson et al., 2005; Stewart, 2016).

7.2.3.7 Late Maastrichtian/early Paleocene unconformity at c. 65 Ma

The foreland basin fill is capped by a widespread peneplained surface, which is overlain by middle Paleocene (Selandian) grey calcareous shales and marls of the Shammar Mbr. at the base of the carbonate dominated Umm Er Radhuma Fm. (UeR) (Forbes et al., 2010). In outcrops a low-angle unconformity has been observed along this contact (Skelton et al., 1990). Eroded sediments were likely redeposited into the Palaeogene foredeep remnant (Pabdeh Basin) in NW Oman as the Muthaymimah Formation, comprising shales, marls, and conglomerates with clasts of Simsima limestone, Hawasina chert, and ophiolite (Nolan et al., 1990). This unconformity is likely associated with the emplacement of the Masirah Ophiolite and Batain nappes along the eastern coastline of Oman. These nappes consist of Permian to Cretaceous sediments and volcanic rocks, which have been obducted onto the Arabian Plate

from ESE to the WNW during the late Maastrichtian/early Paleocene, at ca 65 Ma (Immenhauser et al., 1998; Peters, 2000).

7.2.4 The Oman foreland basin model

Seismic sections and the tectonostratigraphic framework indicate that, aside from the reactivation of basement trends, the Oman foreland basin differs significantly from the classical model. In contrast to typical foreland systems, it remained sediment-starved and underfilled until hinterland uplift occurred ~20 Myr after thrusting, as indicated by the Late Coniacian to Late Maastrichtian sedimentary record.

Seismic and well data further show that a key characteristic of the Oman foredeep is the limited supply of orogen-derived detritus. This is reflected in the limited thickness of hemipelagic siliciclastic mudstones and the absence of extensive turbiditic sandstones ("flysch") in the Muti Formation, which is now structurally positioned beneath the thrust complex.

Furthermore, there is no evidence for a significant increase in sediment input into the foredeep following slab break-off and exhumation of the orogenic wedge, which would typically result in late-stage infill by shallow-marine to continental "molasse" facies.

Several factors may have contributed to the restricted sediment input into the foredeep, including:

- limited topographic relief due to the high-density ophiolite load;
- regional tilting and collapse of the orogenic wedge toward the Western Gulf of Oman Basin in the northeast;
- reduced clastic sediment supply from a carbonate-dominated hinterland.

These factors are discussed below.

7.2.4.1 Limited topography due to high density of ophiolite

Commenting on the lack of relief associated with the New Caledonian peridotite nappes in the southwestern Pacific Ocean, Patriat et al. (2018) suggested that any topography generated by overthrusting of peridotite would be attenuated by isostatic compensation, as the densities of obducted peridotite and the underlying mantle are similar. To evaluate this for the Oman ophiolite, simple Airy isostasy calculations were performed using water depth and thickness data derived from this study and from a review of published data summarized below.

Obviously, a 1D approach to isostatic equilibrium is inadequate to explain the formation of the features discussed in this thesis. A detailed analysis is beyond the scope of this study. However, the analysis serves to systematically quantify the parameters required for a full flexural treatment and may provide a basis for future work.

7.2.4.1.1 Input parameters for isostatic calculations

7.2.4.1.1.1 Water depth Hawasina Basin

Based on the reconstruction of the margin discussed in Chapter 3, the water depth at the foot of the Mesozoic escarpment is estimated to have been approximately 1500 m. Deeper water depths in the distal Hawasina Basin during the Middle Cretaceous are indicated by the presence of bedded cherts in the Haybi and Hawasina complexes, which suggest pelagic deep-water deposition below the carbonate compensation depth (CCD). Unfortunately, no information is available on the position of the CCD in the Cretaceous Tethyan Ocean. However, the CCD during the Cretaceous is generally thought to have been much shallower than in the modern oceans, where it lies at about 4.5–5 km depth (Van Andel, 1975).

Average CCD depths during the Cenomanian reported by (Thierstein, 1979), based on DSDP sites, are approximately 1.5 km in the eastern Indian Ocean, 3 km in the Pacific Ocean, 2 km in the South Atlantic, and 3.5 km in the North Atlantic. These estimates suggest that bedded cherts could have been deposited at water depths of only a few kilometres. In the present study, a water depth of approximately 3.5 km is therefore assumed for the distal Hawasina Basin, which is similar to the value used in the reconstruction of (Najafi et al., 2026).

7.2.4.1.1.2 Water depth Aruma foredeep

Ismaiel et al. (2025) estimate the Aruma foredeep in the UAE reached water depths of approximately 3 km. This was based on seismic data and gravity modelling, but no further detail was provided. The distribution of the most distal facies in the Muti Fm. containing bedded radiolarian cherts and fine-grained turbidites suggest bathyal conditions (1-4 km depth) in parts of the foredeep was located below the frontal nappes in the Hamrat ad Duru range (Rabu et al., 1993).

7.2.4.1.1.3 Preserved thickness of the thrust stack.

Thickness of the Hawasina nappe complex penetrated by wells varies from a few hundred metres in the frontal part of the Hamrat ad Duru range up to 3300 m in well located in the UAE foredeep (Ali-2). The thickness variation largely reflect erosion below the Late Cretaceous Neogene unconformity and possible Neogene thrusting of the thrust complex in the UAE. Grobe et al. (2019) suggest 2 km based on maximum present-day thickness of Jebel Misht exotics.

Gravity data for the ophiolite blocks indicate a maximum structural thickness of ~7.5 km and an average thickness of ~5 km (Shelton, 1990). The crustal thickness of the ophiolite

is further discussed by Nicolas et al. (1996). Measured cross-sections suggest an average thickness of ~3.6 km for the gabbroic cumulates in the lower crustal section of the ophiolite.

7.2.4.1.1.4 Thickness of the allochthon constrained by maximum burial indicators

Multiple independent thermal and metamorphic indicators constrain the maximum burial depth of the autochthonous units beneath the allochthonous nappes and ophiolite in the Oman Mountains (Table 1). Metamorphic facies distribution indicates that the autochthonous succession of Jebel Akhdar and the southern part of Saih Hatat lies within the Anchizone (2–4 kbar, <200 °C) and shows a regional trend from Upper Anchizone conditions in the southwest to Deep Anchizone conditions in the northeast for the top of the autochthon (Breton et al., 2004). This pattern suggests an increase in maximum burial depth from approximately 6.6 km to as much as 13 km across the region. Higher-grade metamorphic assemblages corresponding to the pumpellyite/lawsonite–albite–chlorite zone (4–7 kbar, 200–300 °C) occur along the northeastern margin of Jebel Nakhl and in northwestern Saih Hatat (Breton et al., 2004). However, field observations indicate intense shearing, mylonitisation, and the development of sheath folds in these areas, suggesting that these rocks may represent part of an exhumation-related shear complex rather than simple burial metamorphism.

Conodont colour alteration indices (CAI) from the Amdeh-5 Member provide additional thermal constraints. Samples from Wadi Qahza on the northwest flank of Saih Hatat yield CAI values of 4, corresponding to palaeotemperatures exceeding 200 °C (Heward et al., 2018b). Assuming a geothermal gradient of 30 °C/km and a surface temperature of 28 °C, this implies a maximum burial depth of approximately 6–7 km. Given that these strata are overlain by approximately 2 km of Permian to Cretaceous autochthonous sediments, the thickness of the overlying allochthonous units is estimated to have been about 4–5 km at this

location. In contrast, CAI values of 3–4 from Amdeh-5 samples along the southern margin of Saih Hatat (Wadi Dayqah and Hayl al Quwasim) correspond to palaeotemperatures of approximately 150–200 °C (Heward et al., 2018a), suggesting maximum burial depths of about 4–6 km. After accounting for the ~2 km of autochthonous cover, these data indicate only 2–3 km of allochthonous overburden.

Organic-matter thermal maturity data from the Natih B source rock provide somewhat higher burial estimates. Thermal maturities recorded in the Jebel Akhdar area reflect peak temperatures of 226–239 °C, corresponding to maximum burial depths of approximately 7.6–8.2 km, including roughly 6 km of obducted ophiolite (Grobe et al., 2016). Subsequent modelling integrating organic-matter maturity, calcite vein thermochronometry, and basin modelling suggests a maximum sedimentary overburden of about 4 km in the Salakh Arch area located in front of the allochthon (Grobe et al., 2019). Assuming a Hawasina nappe thickness of approximately 2 km, based on the maximum present-day thickness of Jebel Misht exotic blocks, the observed maturity of the Natih B Formation at Jebel Nakhr requires an additional 8–10 km of strongly serpentinised ophiolite. This corresponds to a total maximum overburden thickness of approximately 10–12 km; thicker ophiolite would be required if the section were less serpentinised because of its higher thermal conductivity.

Palaeothermal reconstructions based on clay mineral assemblages provide additional constraints. Clay mineral data from autochthonous and Hawasina units indicate maximum palaeotemperatures of 150–200 °C along the northern limb of the Jabal Akhdar Culmination anticline and 120–150 °C along the southern limb (Aldega et al., 2017). Thermal modelling suggests that the sub-ophiolite rocks of the Jabal Akhdar Culmination were buried beneath approximately 4.5 km of combined Hawasina nappes and Semail Ophiolite, whereas at the

Oman Mountains thrust front burial was more limited, involving about 1.35 km of syn-obduction clastics overlain by roughly 2 km of Hawasina units. Further clay mineral studies of Hawasina and Haybi sediments beneath the ophiolite in the Hawasina Window and Saih Hatat areas indicate burial conditions reaching the deep anchizone (Aldega et al., 2021). Thermal modelling suggests lateral variation in tectonic overburden corresponding to ophiolite thicknesses of approximately 4.1–5.5 km, possibly reflecting variations in the depth of the basal décollement or internal deformation within the ophiolite sequence.

In contrast, redeposited Hawasina- and Haybi-derived sediments preserved on top of the Semail Ophiolite in the Batain area record maximum burial depths of less than about 600 m (Aldega et al., 2021). These deposits are interpreted to result from local back-thrusting of Hawasina and Haybi slices in front of the advancing ophiolite, followed by gravitational mass transport from the frontal thrust complex onto the rear of the ophiolite during exhumation.

Taken together, these datasets indicate that the thickness of the allochthonous overburden varied significantly across the Oman Mountains. Part of the variation in these estimates reflects differences in methodology and in the assumptions used to relate temperature to burial depth. Overall, the available data suggest deeper burial toward the north and a tapering of the orogenic wedge from approximately 2 km in the SW to more than 10 km in the NE. However, kilometre-scale lateral variations in the inferred thickness of the allochthon derived from the same methods indicate that significant internal structural thinning and thickening occurred within the thrust complex.

Thickness estimates derived from geothermal and palaeothermal data indicate that the ophiolite complex was significantly thinner than the ~15 km thickness suggested by

earlier studies based on composite measured outcrop sections (Lippard et al., 1986; Searle and Cox, 2002).

Table 1 Published maximum burial depth estimates of autochthon.

Method	Burial Depths	Remarks	Location	Reference
Metamorphic zones in autochton	13 km	Deep Anchizone	North Jebel Akhdar & SW Saih Hatat	Breton et al. (2004)
Metamorphic zones in autochton	6.6 km	Upper Anchizone	SW jebel Akhdar	Breton et al. (2004)
Natih-b source rock Thermal maturitiy	7.6 – 8.2 km	Suggest 6 km ophiolite	Wadi Nakhr, Jebel Akhdar	Grobe et al. (2016)
Thermal maturity, thermochronometry and basin modelling	10 -12 km	assuming serpentinised ophiolite 8-10 km, Hawasina 2 km	Jebel Akhdar autochthon	Grobe et al. (2019)
Conodont alteration	6-7 km	Includes 2 km Permian to Cretaceous autochthon	Amdeh 5, NW flank Saih Hatat	Heward et al. (2018b)
Conodont alteration	4-6 km	Includes 2 km Permian to Cretaceous autochthon	Amdeh-5 South side Saih Hatat	Heward et al. (2018a)
Thermal modelling clay mineral metamorphism	4.5 km	Autochthonous and Hawasina. Depth autochton	Jebel Akhdar	Aldega et al. (2017)
Thermal modelling clay mineral metamorphism	4100 – 5500 m	Hawasina and Haybi Complex Depth subophiolite	Dibba, Wadi Hawasina, Saih Hatat	Aldega et al. (2021)

7.2.4.1.1.5 Selected parameters

Based on maturity, metamorphic, and thermal modelling studies, an ophiolite thickness of ~5.5 km is assumed. Within this complex, a preserved crustal sequence of ~4 km and a mantle sequence of ~1.5 km is inferred. The thickness of the Hawasina/Haybi Complex, estimated at ~2.5 km, is based on well penetrations. This yields a maximum nappe complex thickness of ~8 km, which lies at the upper end of the range suggested by the maturity data.

7.2.4.1.2 Airy isostatic balance calculations

A first-order estimate of the subsidence resulting from the emplacement of the Oman ophiolite and onto the continental margin has been calculated using Airy isostatic balance.

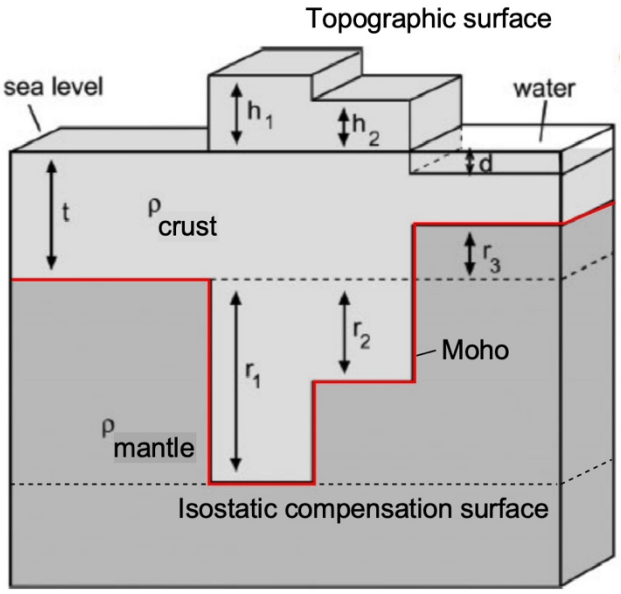


Figure 7-12 Airy isostatic model. The surface topography is calculated by equating masses above an arbitrary compensation depth at the deepest crustal root. Modified from Fowler (2004).

Airy isostasy assumes that topographic heights are accommodated by local isostatic compensation, with crustal blocks floating on a denser, ductile mantle (Watts (2023), see also Figure 7-12). This calculation neglects the flexural response of the lithosphere, which would act to reduce the magnitude of subsidence by distributing the load over a broader region. In addition, the effects of slab pull which acts as an additional downward force increasing subsidence and resulting water depths (Sinclair and Naylor, 2012) are not considered. The calculations below use the parameter values and notation listed in table 2.

Table 2 Parameters and notations used in isostacy calculations

Property/Component	**Value**	**Symbol**
Densities (from (Allen and Allen, 2013)		
Ocean water	1000 kg m^{-3}	ρ_w
Continental crust	2700 kg m^{-3}	ρ_c
Oceanic crust	2950 kg m^{-3}	ρ_{oc}

Mantle	3300 kg m^{-3}	ρ_m
Thicknesses / Depths (This study)		
Water depth Hawasina Basin	3.5 km	$h_{W\ Haw}$
Water depth at foot of Mesozoic escarpment	1.5 km	$h_{W\ esc}$
Thickness Hawasina/Haybi Complex	3.5 km	h_{Haw}
Thickness Ophiolite	5.5 km	h_{Op}
Thickness Ophiolite crust	4 km	h_{Opc}
Thickness Ophiolite mantle	1.5 km	h_{Om}

The subsidence in the Haybi Basin following emplacement of the ophiolite onto the oceanic crust is given by:

$$S = \frac{h_{opc}(\rho_{oc} - \rho_w) + h_{opm}(\rho_m - \rho_w)}{(\rho_m - \rho_w)}$$

Using the parameters outlined above, the total subsidence is estimated at 4.9 km. This places the top of the ophiolite at a water depth of approximately 2.9 km, assuming an initial water depth of 3.5 km ($S + h_{W\ Haw} - h_{Opc} - h_{Om}$).

The subsidence at the foot of the Mesozoic platform escarpment, following emplacement of the ophiolite and associated nappes, is given by:

$$S = \frac{h_{opc} \times (\rho_{oc} - \rho_w) + h_{opm}(\rho_m - \rho_w) + h_{Haw} \times (\rho_{hw} - \rho_w)}{(\rho_m - \rho_w)}$$

This yields an estimated subsidence of approximately 6.7 km, placing the top of the ophiolite at a water depth of ~240 m at the foot of the platform, where the initial water depth is estimated at 1.5 km ($S + h_{W\ esc} - h_{Opc} - h_{Om} - h_{Haw}$). However, the actual depth could be larger due to additional load by slab pull.

Emplacement onto the drowned platform similarly results in approximately 6.7 km of subsidence. Assuming a water depth of 3 km in the Aruma Basin, as suggested by the above

estimates (which would also include loading by slab pull) the top of the nappe complex would lie at a depth of approximately 1.7 km.

Assuming emplacement of the nappe complex as a direct load onto the platform, the total subsidence is given by:

$$S = \frac{h_{opc} \times \rho_{oc} + h_{opm} \times \rho_m + h_{Haw} \times \rho_{hw}}{\rho_m}$$

This results in an estimated subsidence of 7.15 km, leaving approximately 880 m of the nappe complex above sea level. This indicates the potential uplift after slab break-off.

7.2.4.1.3 Conclusions

These calculations suggest that the nappe complex remained largely subaqueous during obduction, explaining the lack of nappe-derived sediments in the Muti Formation. Even during subsequent exhumation, subaerial uplift likely remained below 1 km. This is significantly lower than the 1,500–4,000 m elevations typical of active foreland basins (Vanderhaeghe, 2012). Also lateritic weathering profiles developed on the Oman ophiolite indicate prolonged subaerial exposure under low-relief conditions and low erosion rates (Al-Khirbash, 2016). Notably, the thickness of the mantle section of the ophiolite does not significantly influence surface elevation or water depth, as its density is comparable to that of the underlying mantle it displaces.

7.2.4.2 Regional tilting of the orogenic wedge to the NE

In the foredeep, Late Cretaceous sediments derived from the nappe complex are restricted to the Juweiza Formation, which fringes the margin of the nappe complex and does not fill the foredeep. In contrast, outcrops of the Thaqab Formation on the northeastern side of the orogen indicate that the nappe complex is overlain by a ~1 km thick succession of Late Cretaceous deep-water mudstones, interbedded with lithic sandstones

and conglomerates containing ophiolite and Hawasina/Haybi limestone and chert clasts (Nolan et al., 1990).

Offshore seismic and well data show that this succession thickens into a 2–4 km package of mid- to late Campanian and Maastrichtian deep-water mudstones with mass-transport complexes, deposited in the Western Gulf of Oman Basin (Levell et al., 2021; Ninkabou et al., 2021). This basin formed during the Late Cretaceous along an ENE-dipping extensional fault system and separates the trailing edge of the Semail ophiolite to the southwest from in situ oceanic crust of the Gulf of Oman to the northeast (Levell et al., 2021).

This extensional phase is interpreted to have caused collapse of the orogen, triggered by flexural and isostatic rebound of the continental margin following the release of slab pull and the cessation of subduction (Lippard et al., 1986).

The distribution of detrital sediments between the foreland (Juweiza Formation) and hinterland (Thaqab Formation) basins suggests an asymmetric topography, with a drainage divide located near the present-day mountain front and an overall northeastward tilt of the orogenic wedge. This configuration likely reduced sediment supply to the foredeep.

7.2.4.3 Limited input from hinterland

The hinterland consisted predominantly of carbonates, which resulted in chemical weathering and dissolution. Following the final drowning during the early Santonian, the main sediment input is only from reactivated basement uplifts in the hinterland, hemipelagic carbonates, and some clastic mud derived from the Huqf High.

7.2.4.4 Summary

Figure 7-13 presents a revised model for the evolution of the Oman foreland basin. As in

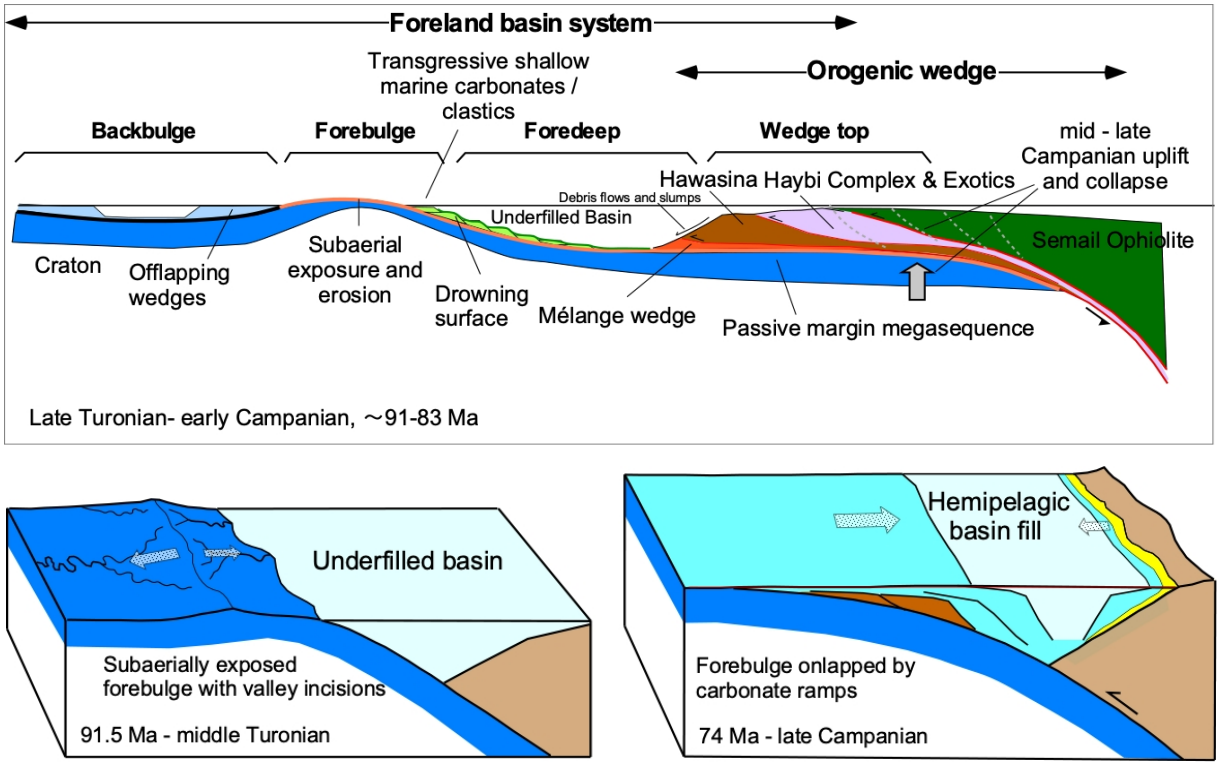


Figure 7-13 Model for the Oman obduction-related foreland basin, based on this study. As opposed to the classical model, there is hardly any sedimentation from the orogenic wedge, as the high-density oceanic crust dominated and the orogenic wedge remained subaqueous. This, together with little shedding from the carbonate platform, left the Oman foreland basin underfilled. Oman's foreland basin was eventually filled with hemipelagic carbonates and carbonate platform progradation. Revised from DeCelles and Giles (1996) and Crampton and Allen (1995).

the classical model, flexural loading of the plate in response to nappe emplacement led to the development of a migrating forebulge. However, the orogenic wedge remained largely subaqueous during emplacement, likely due to the high density of the ophiolite.

Owing to limited sediment input, the characteristic stratigraphic “trinity” of the initial underfilled stage of foreland basin development, as described by Sinclair (1997), is poorly developed. Only the lower transgressive carbonate sequence is well expressed, whereas the overlying deep-water mudstones are relatively thin and the upper turbiditic “flysch” sandstone unit is absent. Likewise, the final-stage infill by shallow-marine to continental “molasse” facies, typically associated with orogenic exhumation following slab break-off is not observed.

Deep-water conditions persisted in the foredeep for approximately 10 Myr after final nappe emplacement, before being replaced by prograding carbonate platforms during the Maastrichtian. In the western foredeep of the UAE, deep-water conditions persisted for at least a further ~10 Myr, extending into the Palaeogene.

Instead, the principal locus of sediment accumulation was in a deep basin located northeast of the orogen. This basin is interpreted to have formed as a result of major extensional collapse of the orogen during the Campanian, associated with flexural and isostatic rebound of the continental margin.

Given the limited post-obduction deformation, the availability of seismic data, and the exceptional preservation of outcrops in Oman, this model provides a useful analogue for ophiolite-related foreland basins now incorporated into mountain belts.

8 SUMMARY AND CONCLUSIONS

This stratigraphic study complements existing studies from the perspectives of the structural geology of the thrust stack (Cooper et al., 2014; Mount et al., 1998; Searle, 2007), metamorphic and geochronological studies on the metamorphic sole of the ophiolite (Rioux

et al., 2021; Searle et al., 2022), as well as the structural deformation of the autochthon (Grobe et al., 2018; Grobe et al., 2019). It is the first comprehensive review of the syn-obduction sediments since the pioneering work of Robertson (1987a; 1987b) and the BRGM (Bureau de Recherches Géologiques et Minières) geological mapping project (Rabu et al., 1993).

It provides a unified understanding of North Oman geology, which has been a challenge because of poorly integrated and inconsistent naming and interpretations between subsurface and outcrop.

The conclusions are summarised below and structured as follows: general points are presented in Sections 8.1–8.3, followed by conclusions relating to the different domains of the foreland basin system in Sections 8.4–8.7.

8.1 The Oman foreland basin model is different from the classic model

- The current study shows that the Oman foreland basin, related to obduction of the Semail ophiolite thrust sheet, requires a different model than the classical one of a foreland basin system (DeCelles and Giles, 1996), which is based on continent-to-continent collision and retro-arc settings. The main difference for the Oman model is that there is no sediment shed from the orogenic belt into the foredeep, because the obducting high-density oceanic plate remained largely subaqueous. Following the final drowning during the early Santonian, the main sediment input is only from reactivated basement uplifts in the hinterland, hemipelagic carbonates, and some clastic mud derived from the Huqf High.
- As there are no modern examples of active ophiolite obduction, Oman can serve as a good analogue - because of limited tectonic deformation after the obduction

event - for the emplacement of other ophiolite complexes now incorporated into mountain belts.

8.2 Impact of pre-existing structures

- Long-lived NE-SW basement terranes and lineaments perpendicular to the obduction front are clearly evident from the stratigraphic record in Oman. The first order difference in geological history between the Jebel Akhdar and Saih Hatat and the presence of Neoproterozoic salt extrusion in the Hawasina window show that these terranes extended below the Late Cretaceous thrust sheets in the mountains.
- The pre-obduction margin was offset in plan view along the same NE-SW lineaments, leading to the promontories and embayments indicated in reconstructions of the Jurassic and Cretaceous shelf edge.
- Prior to obduction there was no major deformation within the Permian to mid-Cretaceous platform. The autochthon behaved as a single block with significant (km scale) tilting down to the west and multiple uplift events along the Huqf axis in the east.
- After a long period with no activity during the Early Cretaceous, reactivation of these structural features occurred again during the Cenomanian. On the epeiric platform significant changes in the palaeogeography are related to the more rigid basement terranes underlying both the Lekhwair area and the Huqf axis. These may record the earliest far-field effects of the processes leading to obduction of the Semail ophiolite ~235 km to the north. The basement re-activation may be related to a change in regional stress that led to the initiation of subduction.

- The patterns of the Base Aruma Unconformity subcrop and isopach maps of the immediately underlying platform carbonates clearly show that the basement features had a major impact on the uplift and erosion preceding the obduction.
- Segmentation of the foredeep into a western and eastern province with a different infill also aligns with the NE-SW trending terranes perpendicular to the obduction front.
- Erosion of up to several hundreds of metres along the BAU, related to reactivation of basement features, is significantly greater than the 150–200 m attributed to forebulge uplift.

8.3 NW-SE compression

- Regional faulting and deformation patterns along basin lineaments show that during the Late Cretaceous the plate was under a NW-SE directed state of compression. This may be related to a counter-clockwise rotation of the Greater Indian plate relative to the Africa/Arabian plate due to the separation of India/Madagascar from Antarctica starting at 133 Myr during the Early Cretaceous.
- The first evidence of this tectonic regime is a phase of inversion in the South Oman Salt Basin during the Aptian, and the development of the base Wasia unconformity.
- The compression becomes apparent during the middle to late Cenomanian with changes in the platform palaeogeography and the development of the Natih-b intra-platform Basin along basement trends.
- The compression continued throughout the Late Cretaceous, as evidenced by syndepositional structural growth of structures over N-S trending basement

lineaments and by salt doming. The obduction of the ophiolite added a NE-SW flexural extension to the NW-SE compressional regime during the Turonian to Campanian.

8.4 The subducting platform margin

- There is no major uplift along the platform margin prior to obduction. The erosional truncation of some 1.5 km along the platform margin suggested in the early studies and which forms a major element in the models of the obduction history in literature is an artefact. This view was based on the miscorrelation of undated slope deposits overlying the Jurassic platform north of the middle Cretaceous margin as a younger, post-unconformity deposit, assigned to the Muti Fm. Not flattening sections along the base of these slope deposits but using instead the unconformity on the top of the platform created the impression of significant truncation of the platform margin.
- The Mesozoic platform margin had its widest extent during the Triassic to Middle Jurassic and shows an overall backstep following Late Jurassic and Late Albian flooding events. As a result, the continental margin, when it was approached by the nappe complex, consisted of three submarine escarpments: Triassic/Jurassic, Lower Cretaceous and middle Cretaceous with a total bathymetric relief of well over 1.2 km.
- The steep platform margin formed a temporary barrier for the advancing nappes. Similar to seamount subduction, this is expected to have slowed down nappe advance, The obstruction caused thickening and steepening of the nappe pile and led to a new thrust pulse once the nappes overrode the platform top. Such a thrust pulse is indicated in the foredeep stratigraphy.

- The preservation of the Cretaceous autochthonous platform margin slope deposits indicates that obduction-related thrusts ramped up very precisely over the then existing topography. Possibly the steep Permo – Jurassic platform escarpment forced a step-up in the basal detachment and incorporation of the slope deposits in a tectonic mélange.

8.5 The forebulge and BAU

- During the Turonian, the infill of the intra-platform basins on the epeiric platform consists of forced-regressive wedges prograding southward, away from the platform margin in the north, which was subaerially exposed and karstified. The relative sea level changes were in the order of several tens of metres and were likely driven by eustacy, as these also occur in other regions. However, the lateral stacking of these wedges toward the south suggests that sea level changes may have been superimposed on an overall uplift to the north of the wedges. This could be evidence of a Turonian back-bulge situation. In which case the forebulge at this time would have been beneath the current mountains: in Oman, Jebel Akhdar.

- The BAU above the Cenomanian platform and the Turonian wedges are associated with regional valley incisions of 100-200 m, in a belt 100-200 km wide, south of the thrust front. These valleys have a NE-SW orientation. The offlapping wedges and the incised valley system point to a migrating forebulge uplift.

- Flattening on the flooding surface within the foredeep infill showed a forebulge-shape topography below the BAU. The bulge separates a region with progradation into the foredeep from a depocentre in the SE with more restricted sedimentation. This bulge is interpreted as the final position of the forebulge and is located 160 – 250

km in front of the frontal thrust. The pinch-out of the Turonian lowstand wedges are now located downdip of the bulge in the foredeep. The foresets were formed in a backbulge setting, when the bulge was located further north. The stratal geometries suggest a migrating forebulge.

8.6 The initial fill of the foredeep: the Muti Formation

- During this study, it became apparent that the Muti Formation - the transgressive unit reflecting the subduction of the continental plate - required re-interpretation and re-mapping.
- The Muti Formation is defined here as comprising all sediments associated with the Late Cretaceous drowning of the epeiric carbonate platform and emplacement of the nappe complex. These deposits are preserved either between the basal Aruma unconformity and the overlying thrust complex or along the toe of the frontal thrust. The Muti Fm. is Turonian to Early Santonian in age.
- A key distinction from previous definitions is that the Muti Formation may incorporate erosional products derived from the allochthon. In addition, the upper part of the formation is interpreted as an underthrust largely sedimentary mélange, separated from the basal unit by a previously unrecognised detachment surfaces.
- Re-evaluation of the outcrops around Southern Jebel Akhdar showed that the Base Aruma Unconformity (BAU) has in the past been mis-picked and what was mapped as the uppermost part of the Natih Fm. is part of the Muti. The BAU is now placed at the top of a weathered and karstified surface that was planed-off by a high energy coastal retreat, to form a ravinement surface at the base of the overlying transgressive Muti Fm.

- The basal Muti Fm. represents a sediment starved transgressive sequence covering the rapidly subducting carbonate platform. It is characterised by slow sedimentation rates, abundant winnowing and erosion, allowing full bioturbation and oxidation. The abundant supply of iron is likely from the reworking of palaeosols that covered the exposed Natih carbonate platform, giving the Muti its distinctive orange-cream, "biscuit" colour. In the east the Muti contains siliciclastics derived from the Huqf uplift. In places these sediments are truncated or completely replaced by debrites.
- The debrites in the Muti Fm. are derived from fault scarps exposed along the sea bottom. Most of these sediments consist of cohesive debris flow deposits, which contain floating angular clasts derived from the Natih and Muti Fms. The onset of faulting is in the Santonian and predates nappe emplacement. The faults are formed by extension during bending of the drowned platform as it entered the foredeep. They show an overall NW-SE strike. The faults and fault-scarp retreat have also been observed on seismic data.
- Some debrites along the western flank of Saih Hatat are polymict conglomeratic megabreccias, which also contain clasts of Permian, Triassic and Jurassic sediments. These deposits are interpreted as fault scarp debris cones. These faults must have throws of many hundreds of metres and may be related to re-activated basement lineaments.
- Detailed outcrop observations in the Oman Mountains indicate that, between the basal transgressive Muti Formation and the overlying thrust wedges, there is a poorly exposed mélange containing both Muti sediments and allochthonous material. This unit is separated from the transgressive carbonates and debrites of the basal Muti by

a sheared zone and ranges in thickness from 0 to several hundred metres. The mélange comprises blocks and rafts derived from the allochthon, mixed with rafts sourced from the underlying Muti and Natih formations.

- This sedimentary mélange is interpreted to have formed at the frontal edge of the thrust stack and was supplied by debris flows, slumps, and slides eroding the leading edge of the thrust complex. These deposits were subsequently overridden and incorporated into the advancing thrust stack. With continued deformation, the sediments evolved into a tectonically sheared mélange, forming a discontinuous sheet along the base of the thrust complex exposed in the Oman Mountains.

8.7 Infill of the foredeep

- The stratigraphy and stratal geometries of the foredeep fill are based on subsurface data. The infill consists of two major progradational cycles: the first cycle is from Santonian to Early Campanian, the second cycle from Campanian to Maastrichtian.
- The sediments filling the foredeep are predominantly derived from the craton; there is little sediment coming from the orogenic wedge.
- The first phase of infill during the Santonian consists of a prograding muddy shelf in the eastern foredeep (Oman) and a carbonate ramp in the western foredeep (UAE). The fine clastics in Oman are sourced from the Huqf axis and transported to the west by alongshore currents.
- The Santonian progradation ends with an erosional surface during which the shelf margin is cut by deep canyons, channels and slump scars. During the early Campanian coarse siliciclastic sediments from the Huqf High enter the eastern foredeep and are

deposited as turbidites. They onlap the shelf margin as well as the front of the nappe complex. They contain some ophiolite debris in the upper part. The stratigraphic relationship suggests that the nappes were in place during the Early Campanian.

- The Santonian progradation can be linked to a thrust pulse following a slowdown and thickening of the frontal thrust as it reaches the steep Triassic to Cretaceous platform margin.
- Following a regional flooding the second phase of infill consists of a prograding Campanian carbonate platform. The infill of the basin centre is by hemipelagic carbonates that onlap the orogenic wedge.
- The platform is truncated by a major late Campanian erosional surface characterised by deep incisions. This surface is interpreted to reflect a regional tectonic event involving reactivation and uplift along basement lineaments. It coincides with the development of the Western Gulf of Oman Basin northeast of the orogenic wedge, which received a substantial influx of orogen-derived sediments, in contrast to the sediment-starved foredeep. The unconformity is overlain by shallow-marine Maastrichtian carbonates, which are preserved only locally due to truncation beneath Palaeogene and younger unconformities.
- The late Campanian uplift and erosion coincides with the timing of slab break-off and exhumation in the Saih Hatat area.
- The new model for the Oman foreland basin shows that, compared to the classic model, the orogenic wedge remained largely subaqueous due to the high density of the ophiolite. As a result, the foreland basin remained sediment-starved, with a poorly developed underfilled stratigraphy lacking both typical “flysch” and later

"molasse" deposits. Deep-water conditions persisted long after nappe emplacement, while most sediment was diverted into a coeval extensional basin northeast of the orogen, formed during Campanian.

Integration of outcrop and subsurface data, zooming out for a regional overview, and researching the pre-obduction geology, were all essential to put everything into context and bring all the pieces of the puzzle together. Yet, our current knowledge of the Late Cretaceous in this area is limited due to lack of data, and the presented model is probably very simplified. In particular the lack of good biostratigraphic data is a key issue. Due to deep burial many samples are recrystallised and not suitable for dating. Also, more fieldwork in the Oman Mountains, especially in the less accessible area in Saih Hatat, perhaps using drones (currently restricted in Oman) could solve some stratigraphic issues on the Aruma subcrop and the tectonic mélange. Availability of the high-quality 3D-seismic data, shot south of the Oman Mountains by the oil and gas industry, would also provide more detail of the foredeep stratigraphy. This study presents the first integrated model of Late Cretaceous foreland basin evolution in Oman, combining both outcrop and subsurface data. It provides a foundational framework for future research and discussion in the region and foreland basin development in obduction settings.

"Knowledge is constantly in motion.
Every answer reveals new questions
and confronts us with what we don't know.
The awareness of not knowing
is precisely what drives science."

From: Poetics of Not Knowing – KU Leuven

9 References

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