Masirah Graben, Oman: A Hidden Cretaceous Rift Basin?[1]

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ABSTRACT

Reflection seismic data, well data, geochemical data, and surface geology suggest that a Cretaceous rift basin exists beneath the thrusted allochthonous sedimentary sequence of the Masirah graben, Oman. The Masirah graben is located east of the Huqf uplift, parallel to the southern coast of Oman. The eastern side of the northeast-trending Huqf anticlinorium is bounded by an extensional fault system that is downthrown to the southeast, forming the western edge of the Masirah graben. This graben is limited to the east by a large wedge of sea floor sediments and oceanic crust, that is stacked as imbricate thrusts. These sediments/ophiolites were obducted onto the southern margin of the Arabian plate during the collision of the Indian/Afghan plates at the end of the Cretaceous. Most of the Masirah graben is covered by an allochthonous sedimentary sequence, which is complexly folded and deformed above a detachment. This complexly deformed sequence contrasts sharply with what is believed to be a rift sequence below the ophiolites. The sedimentary sequence in the Masirah graben was stable until further rifting of the Arabian Sea/Gulf of Aden in the late Tertiary, resulting in reactivation of earlier rift-associated faults. Wells drilled in the Masirah graben in the south penetrated reservoir quality rocks in the Lower Cretaceous Natih and Shuaiba carbonates. Analyses of oil extracted from Infracambrian sedimentary rocks penetrated by these wells suggest an origin from a Mesozoic source rock.

INTRODUCTION

During the Mesozoic and Cenozoic, the Arabian Peninsula, northeast Africa, and northwest India were broken up by several generations of rifts prior to the final fragmentation of Gondwana. Several of the rifts are linked to failed arms of the Neo-Tethys or to the present-day Indian Ocean. Dating the rifts and their infill is vital for understanding plate kinematics and restorations of Gondwanan fragments. Many of the rift structures and synrift sedimentary rocks are hidden by younger allochthonous strata, hence seismic data are required for the study of Mesozoic tectonics along the current plate margins of Oman. The Masirah graben is believed to be part of a Mesozoic rift system associated with the Neo-Tethys along the southern margin of Oman and the Arabian plate (Figure 1).

The sedimentary sequence in the Masirah graben has seen limited penetration by wells, and the northern part of the Masirah graben has no direct well ties to existing seismic data. The northern part of the Masirah graben is covered by an allochthonous sedimentary sequence (Batain melange, Shackleton et al., 1990), which is complexly folded and deformed above a detachment. The Batain melange is composed of a variety of associated deep-marine rocks, such as pillow basalts, marls, porcellanites, radiolarian cherts, and serpentinites. These ophiolitic rocks range from Permian to Upper Cretaceous, and were emplaced during the Late Cretaceous (Maastrichtian) to early Tertiary (Paleocene) (Figure 2). The Batain melange is deformed by north-northwest–verging, low-angle thrusts and complex folding (Shackleton et al., 1990). A marked difference exists in tectonic styles between the complexly deformed allochthonous sedimentary sequence, which crops out at the surface in the Masirah graben, and the less deformed sequence of sedimentary rocks observed on seismic reflection data beneath the thrusted ophiolites. Many of the seismic profiles

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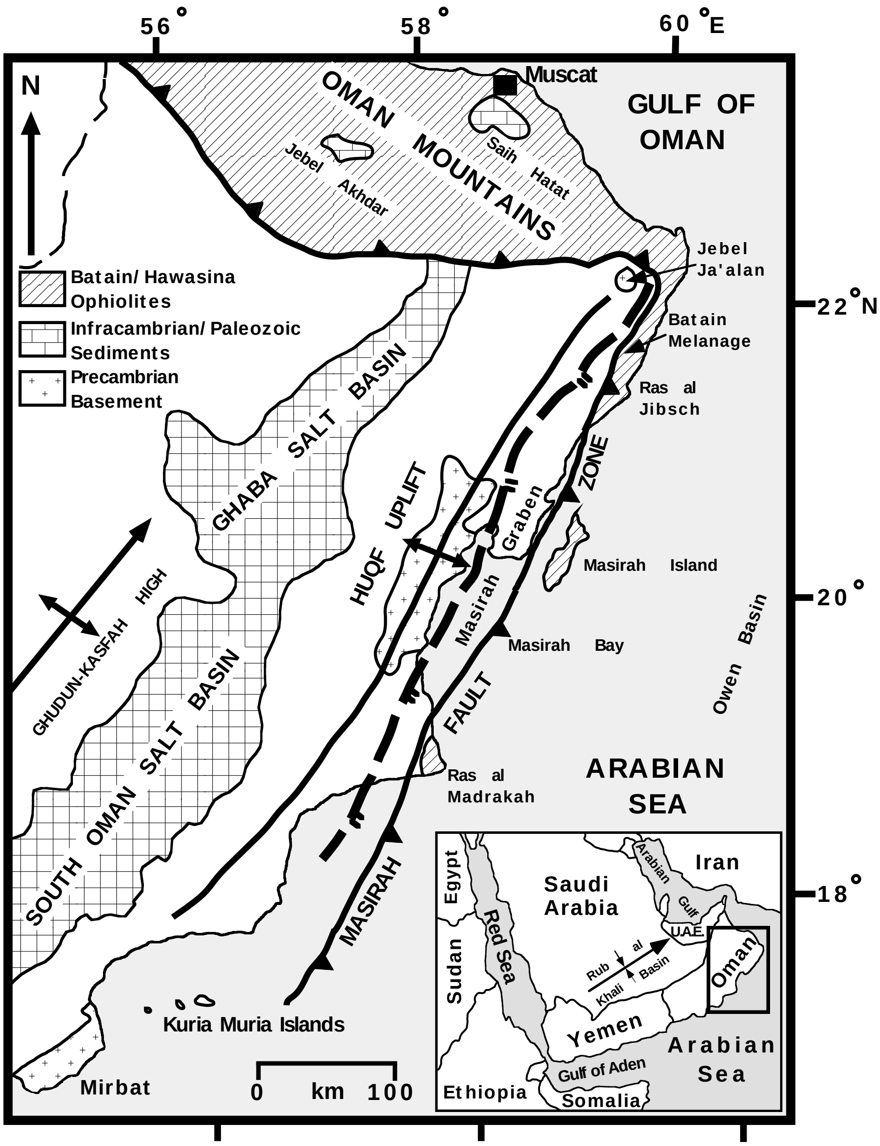

Figure 1—Map of eastern Oman illustrating principal tectonic features (modified from Ries and Shackleton, 1990).

used in this study illustrate large extensional horst-and-graben structures beneath the thrusted ophiolites, which crop out in the graben. The presence of the complex allochthonous sequence has probably resulted in a lack of exploration in the Masirah graben.

The purpose of this study was to map the extent of these large pre-allochthonous structures, identify the age of the sedimentary rocks composing the pre-allochthonous sequence, and evaluate the overall exploration potential in the Masirah graben. Several phases of sedimentation and tectonic activity have resulted in complex stratigraphic relationships that can be addressed using the existing data available in the Masirah graben (Figure 2). The geological relationships observed on seismic reflection data indicate several phases of deformation in the history of the Masirah graben. The western margin of the Masirah graben is bounded by a major normal fault system that has controlled sedimentation in the Masirah graben possibly since the Cambrian (Figure 1). Mapping of seismic sequences in the Masirah graben using existing seismic reflection profiles indicates the presence of significant untested structures with possible exploration objectives below the allochthonous sediments.

GEOLOGICAL SETTING

Tectonically, the area of interest is bounded by the Huqf uplift to the west and the Masirah fault

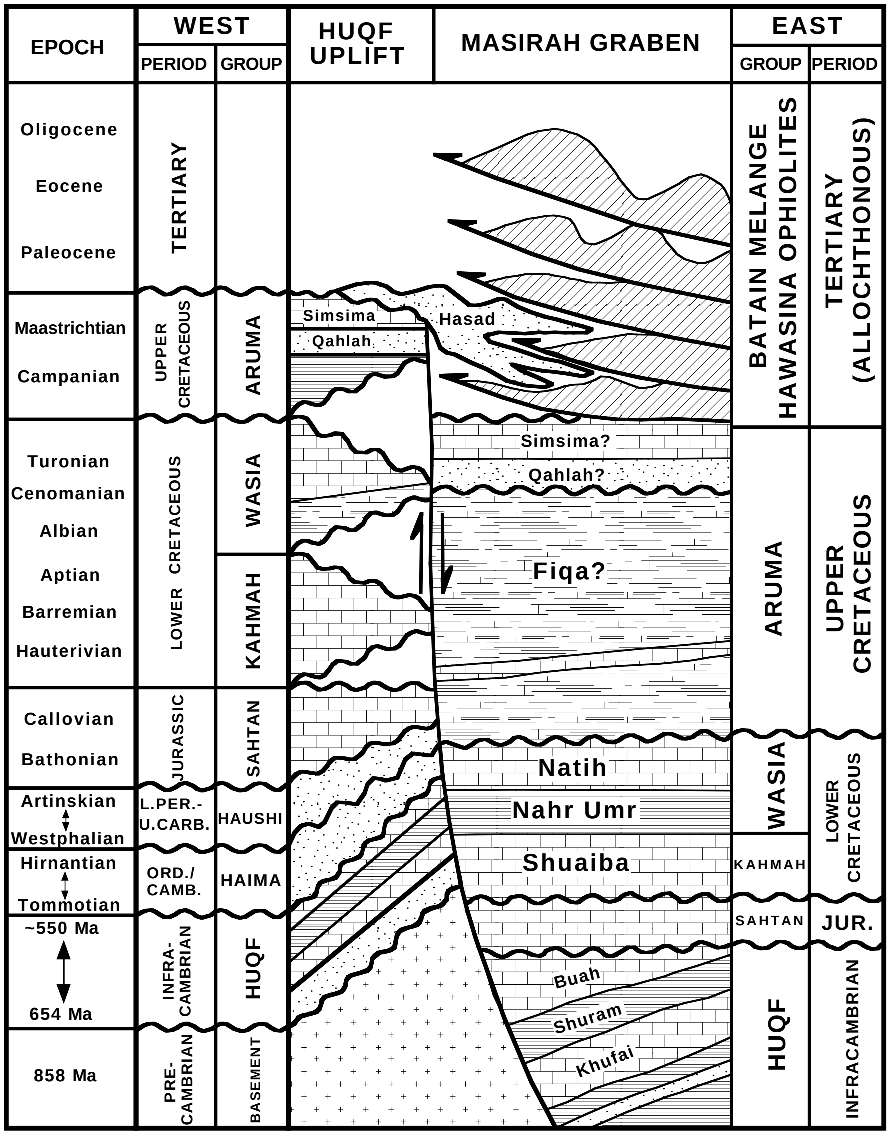

Figure 2—Stratigraphy of the Masirah graben and Jebel Ja'alan/Huqf uplift, based on the stratigraphy of the SMPA 1 and SMPB 1 wells. Data from wells drilled in the southern Masirah graben were used to infer possible stratigraphic relationships that might exist beneath unexplored regions of the Masirah graben.

zone to the east (Figure 1). The Huqf uplift is a broad anticlinorium that trends north-northeast–south-southwest, approximately parallel to the southeastern coast of Oman (Filbrandt et al., 1990). The Huqf uplift was probably initiated during a period of late Precambrian extensional tectonics, which led to the development of a number of Infracambrian–Cambrian salt basins in the Middle East and Pakistan (Grantham et al., 1987; Husseini, 1988). In Jebel Ja'alan, the Mirbat area, and Kuria Muria Islands, Precambrian crystalline rocks are exposed (Figure 1). Similarly, in the central region of the Huqf uplift, Infracambrian to Tertiary sediments are exposed (Figure 3), although there are a number of stratigraphic breaks and unconformities (Gorin et al., 1982). These sediments extend offshore into Masirah Bay where, according to Gorin et al. (1982), the sequence reaches 4 km of thickness in the Masirah graben. The eastern limit to the Masirah graben is marked by the emplacement of allochthonous deep-marine sediments, which on seismic data appear as a wedge of chaotic folding and thrusts. This wedge separates oceanic crust of the Owen basin to the east from continental crust to the west (Ries and Shackleton, 1990). Oceanic rocks, which lie east of the Masirah fault zone, are exposed onshore at Masirah Island, Ras al Madrakah, and Ras al Jibsch (Figure 1). The Batain area of northeast Oman is characterized by outcrops of the Upper Cretaceous Batain melange; in places, the underlying Hawasina Formation is exposed (Shackleton et al., 1990). The melange contains sedimentary clasts ranging in age from Permian to Cretaceous.

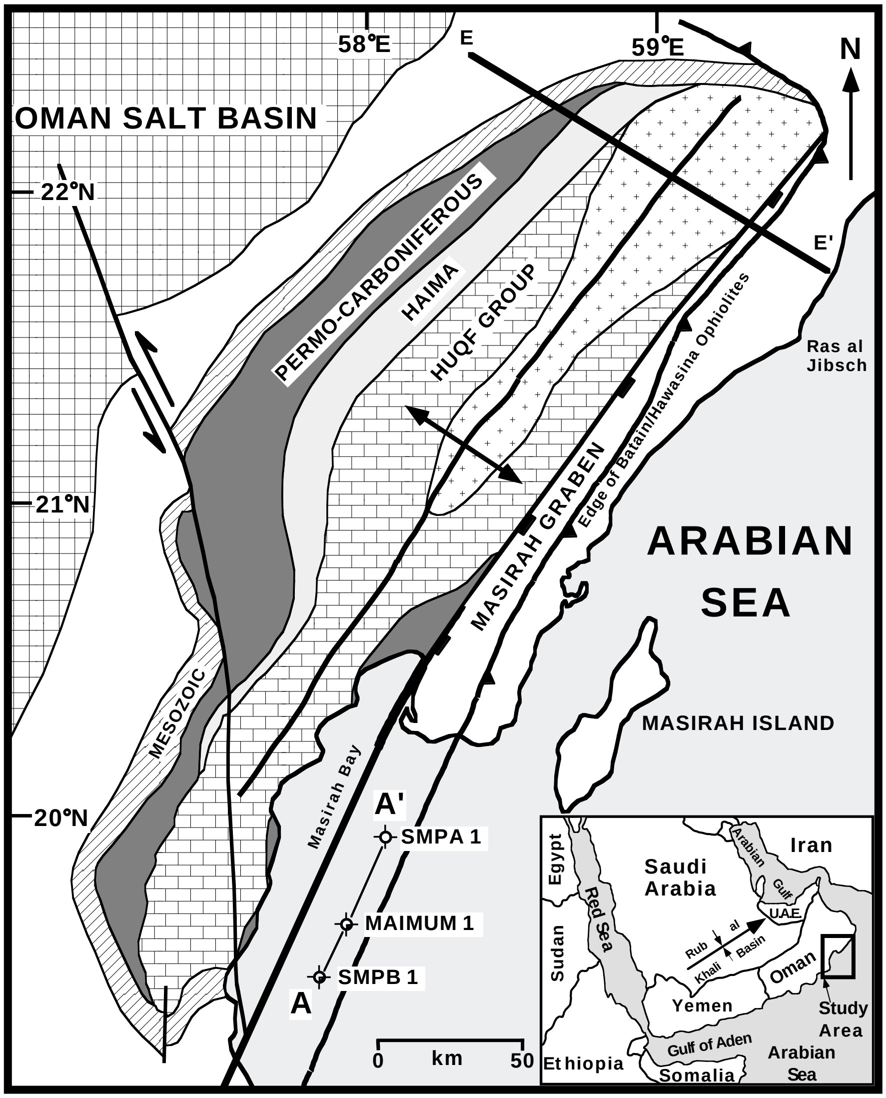

Figure 3—The Masirah graben and a simplified subcrop/outcrop map of the Huqf uplift. Location of composite geoseismic section EE′ (line IUL 87 is the northwestern part of EE′; line IUL 122 is the southeastern part of EE′ shown in Figure 6).

The allochthonous sediments emplaced along the southeastern limb of the Huqf uplift were stable until the rifting of the Arabian Sea/Gulf of Aden in the late Tertiary. The southeastern limb of the Huqf uplift was deformed into a trough or graben in which large horst-and-graben structures were formed. These horst blocks can be clearly identified on seismic beneath the chaotic seismic character of the emplaced oceanic sediments. We propose that late-stage rifting (Miocene) reactivated earlier formed Cretaceous rift faults, some of which extend upward-faulting thrusts upon which the ophiolites were transported.

The sedimentary rock sequence began in Oman as early as the Infracambrian, with the presence of the Huqf Group. Extensional tectonics were active from as early as 645 Ma, where the Abu Mahara sandstones of the Huqf Group have been mapped overlying dated volcanic rocks (Husseini, 1989). The Oman salt basin west of the Masirah graben developed into a restricted basin at the end of the late Infracambrian–Early Cambrian. One of the major features bounding this basin is the Huqf uplift along the southeastern margin of Oman (Figure 1). The northwestern side of the Oman basin was restricted by the Khasfah-Ghudun high, separating the Oman basin from the Rub Al Khali basin of Saudi Arabia. The Oman basin was enhanced by subsidence upon the deposition of a thick sequence of Ordovician clastics, activating the underlying Infracambrian–Cambrian salt to form pillows and diapirs. Oman was subjected to glaciation as a part of Gondwana. The Upper Ordovician and overlying Permian–Carboniferous sediments were glacially deposited (Levell et al., 1988). The Upper Permian–Tertiary is dominated

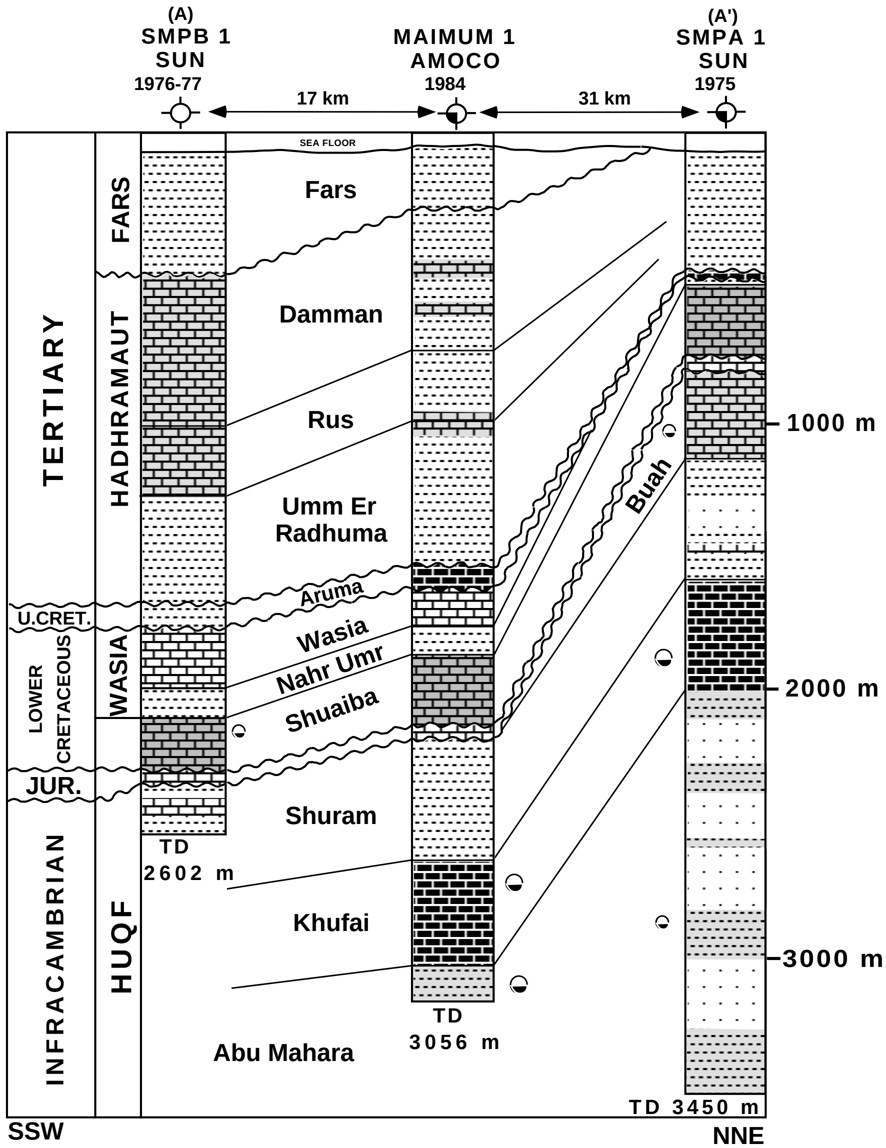

Figure 4—Cross section through wells drilled in the Masirah Graben (well and line locations are shown on Figure 3).

by carbonates, with the Mesozoic and Cenozoic thickening northwestward into the Rub Al Khali basin. We suggest that rifting was active to the east in the Masirah graben during the Cretaceous, or as early as the Jurassic. This Cretaceous synrift sequence is presently hidden by younger allochthonous sediments.

In eastern Oman, the rift kinematics forming the edge of the Arabian Sea are hidden by the obducted Batain ophiolitic melange and the underlying Upper Cretaceous Hawasina Formation (Shackleton et al., 1990). The melange is probably equivalent to the Semail ophiolite sheet in northeastern Oman (Ries and Shackleton, 1990), and was thrust over the northeastern margin of the Arabian plate during the Late Cretaceous, with further thrust movements during the Tertiary. The rocks underlying the Batain melange and the Hawasina Formation are not observable in the field in northeastern Oman.

PREVIOUS EXPLORATION

Wells drilled in the southern part of the Masirah graben have not encountered sedimentary rocks of Cambrian–Triassic age (Figure 4). Cambrian–Triassic sedimentary rocks were either not deposited or eroded after deposition. The Sun SMPA 1 well, drilled in the southern Masirah graben in 1975, penetrated one of the thickest sections of Infracambrian sediments drilled in Oman (2539 m). This thick section of Huqf Group may indicate the presence of another Infracambrian basin east of the Huqf uplift, or of a general thickening eastward.

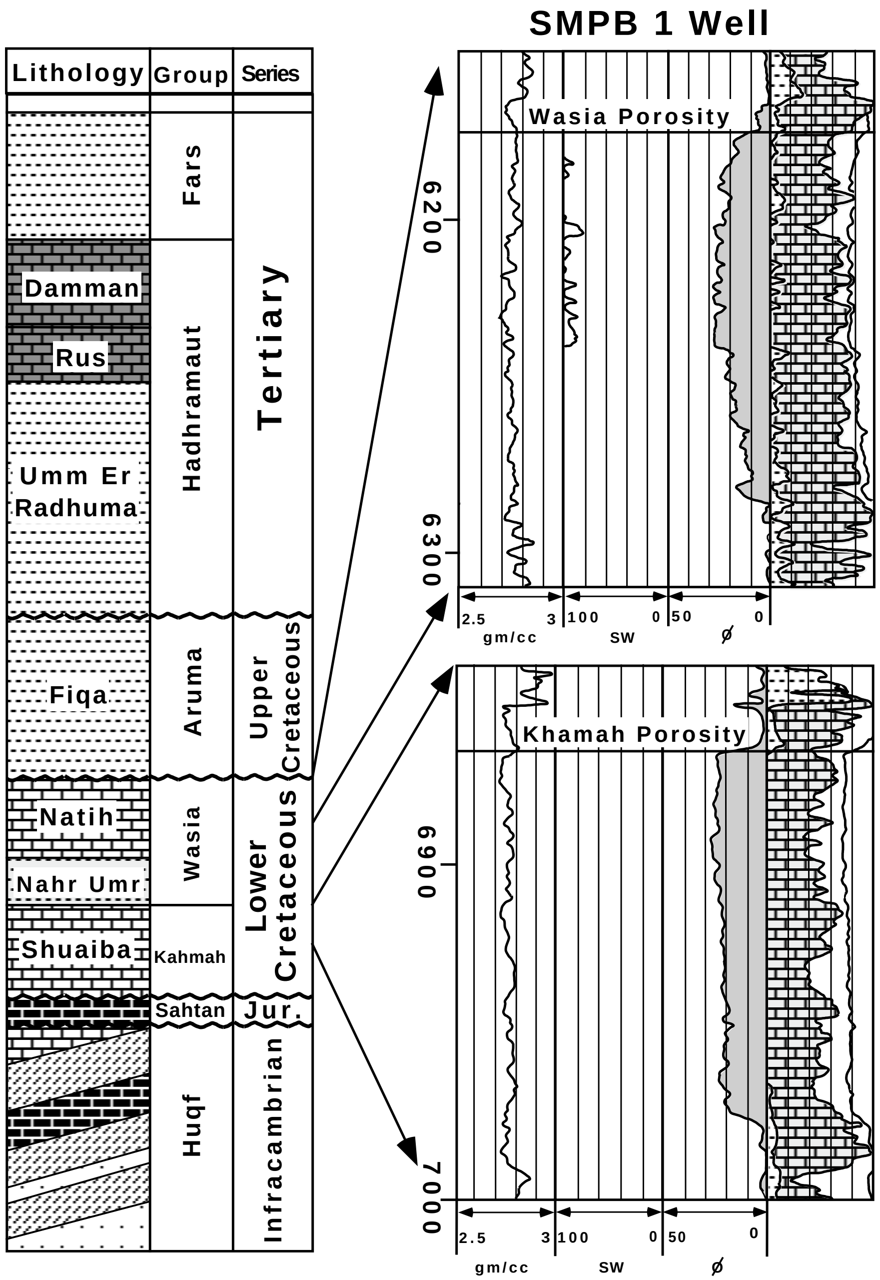

Figure 5—Petrophysical interpretation of the Lower Cretaceous Wasia Group, Natih Formation, and the Lower Cretaceous Kahmah Group, Shuaiba Formation.

These Infracambrian sediments were separated unconformably by 884 m of Jurassic, Cretaceous, and Tertiary sediments, thickening southward toward the Sun SMPB 1 well. Based on the data from the SMPA 1 and SMPB 1 wells (Oman Sun Oil Company), the sedimentary section east of the Huqf uplift is at least 4572 m thick beneath the cover of allochthonous sediments (Figure 4).

The SMPB 1 well penetrated over 2286 m of Mesozoic–Cenozoic sediments, reaching total depth in the Infracambrian Huqf. The SMPB 1 penetrated carbonates of the Lower Cretaceous Wasia Group/Natih Formation, as well as of the Lower Cretaceous Kahmah Group/Shuaiba Formation. These carbonates were found to be water wet, but with well-developed, porous (average 20% porosity), shallow-marine carbonates (Figure 5). These carbonates were oolitic and fossiliferous grainstones-wackestones separated by dense evaporitic mudstones. The porous intervals of the Lower Cretaceous Natih Formation were absent in the SMPA 1 well, having been removed by the Upper Cretaceous unconformity or otherwise not developed. The differences in the thickness of these intervals between the SMPA 1

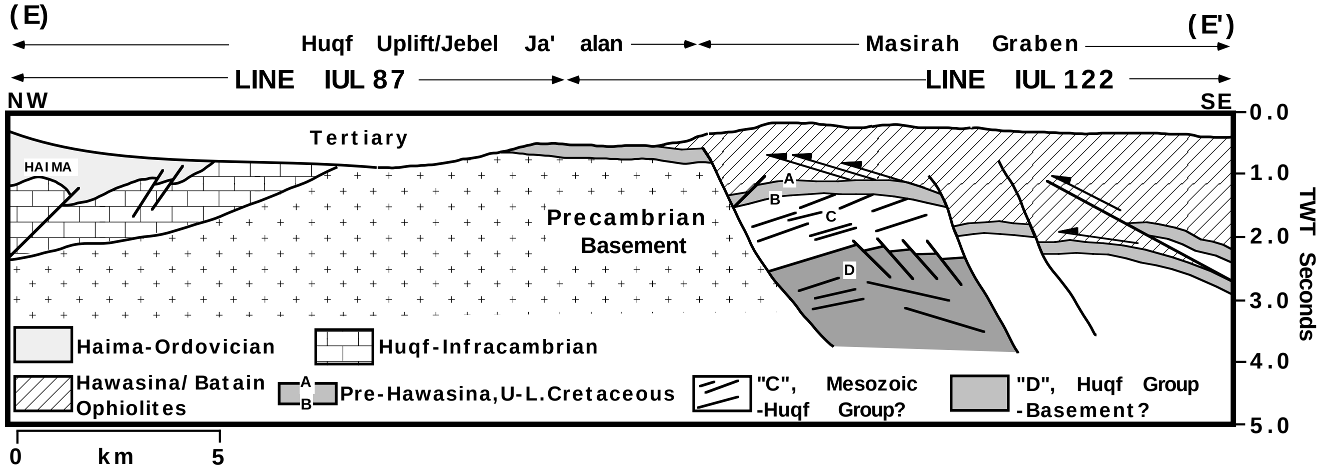

Figure 6—Interpretation of composite seismic sections IUL 87 and 122 (EE′) (locations shown on Figure 3). Line IUL 87 represents the northwestern part of section EE′, and line IUL 122 represents the southeastern part of EE′.

and SMPB 1 may be attributed to varying rates of structural subsidence within the Masirah graben. The shallow-marine Lower Cretaceous Kahmah Group is separated from the Lower Cretaceous Wasia Group by the characteristic regional flooding represented by the deposition of the Nahr Umr calcareous shales. This sequence is similar to those recognized elsewhere in Oman and the United Arab Emirates (Pratt and Smewing, 1993).

The Jurassic sedimentary rocks penetrated in the SMPA 1 and SMPB 1 wells ranged from Bathonian to Callovian in age based on biostratigraphy. The Jurassic was composed of dolomites consisting of micritic mudstones. The Jurassic carbonates were not reservoir quality in the SMPA 1 or SMPB 1 wells.

The SMPA 1 and the SMPB 1 wells had oil shows in cuttings and drill-stem tests from the carbonates of the Khufai Formation and the sandstones of the Abu Mahara in the SMPA 1 well. The shows in both formations were in poor-quality reservoir rocks. Drill-stem tests over intervals of the Khufai and Abu Mahara formations indicated low permeabilities and resulted in minor traces of oil associated with the acid water and cushion recovered. Although no reservoir-quality rocks were encountered in the Huqf Group in either well, the carbonates of the Buah and the Khufai, as well as the sandstones of the Abu Mahara Formation, may be of reservoir quality elsewhere in the Masirah graben. These same-age (Infracambrian) rocks are proven reservoirs in the southern Oman salt basin west of the Huqf uplift (Figure 1).

DATA ANALYSIS AND INTERPRETATION

The thrusts upon which the ophiolites were transported do not appear to cut the older Cretaceous(?) rift sequence, which can be identified on seismic reflection sections as a high-amplitude package beneath the thrusts (Figure 6). The high-amplitude seismic packages identified beneath the thrusts may represent the Lower Cretaceous Natih or Shuaiba carbonates (Figure 2), or they could indicate rock units as young as Maastrichtian–Paleocene in age (Nolan et al., 1990). The high-amplitude package was evident on most of the seismic data mapped in the Masirah graben, and offers a consistent horizon for mapping of the pre-Hawasina structure. This high-amplitude package (termed A-B) is interpreted as a Cretaceous horizon below a decollement upon which the allochthonous sediments were emplaced. This relationship provides possible evidence for early Tertiary–Late Cretaceous thrusting.

The Jebel Ja'alan uplift (Figure 3) is a tilted extensional fault block related to the eastern margin of the Huqf uplift. Fault scarp sediments (the Hasad beds) of Paleocene age occur along the southeastern margin of the block, whereas the western dip of the block is draped by Maastrichtian carbonates (Figure 2). The northeastern and southwestern edges of the block are formed by post–lower Eocene normal/strike-slip faults reactivated during the late Paleogene or Neogene to produce folds and thrusts in the Eocene Rus, Damman, and Qahwan formations.

The structure of the Jebel Ja'alan/Huqf uplift of the western Masirah graben is illustrated on a composite cross section (Figure 6), which is based on seismic lines IUL 87 and IUL 122. Seismic line IUL 122 is shown in Figure 7. Southeast of Jebel Ja'alan, the Upper Cretaceous Batain/Hawasina ophiolites are thrust over the Hasad fault scarp sediments. On seismic lines, the ophiolites are deformed into a series of west-northwestward–directed thrusts

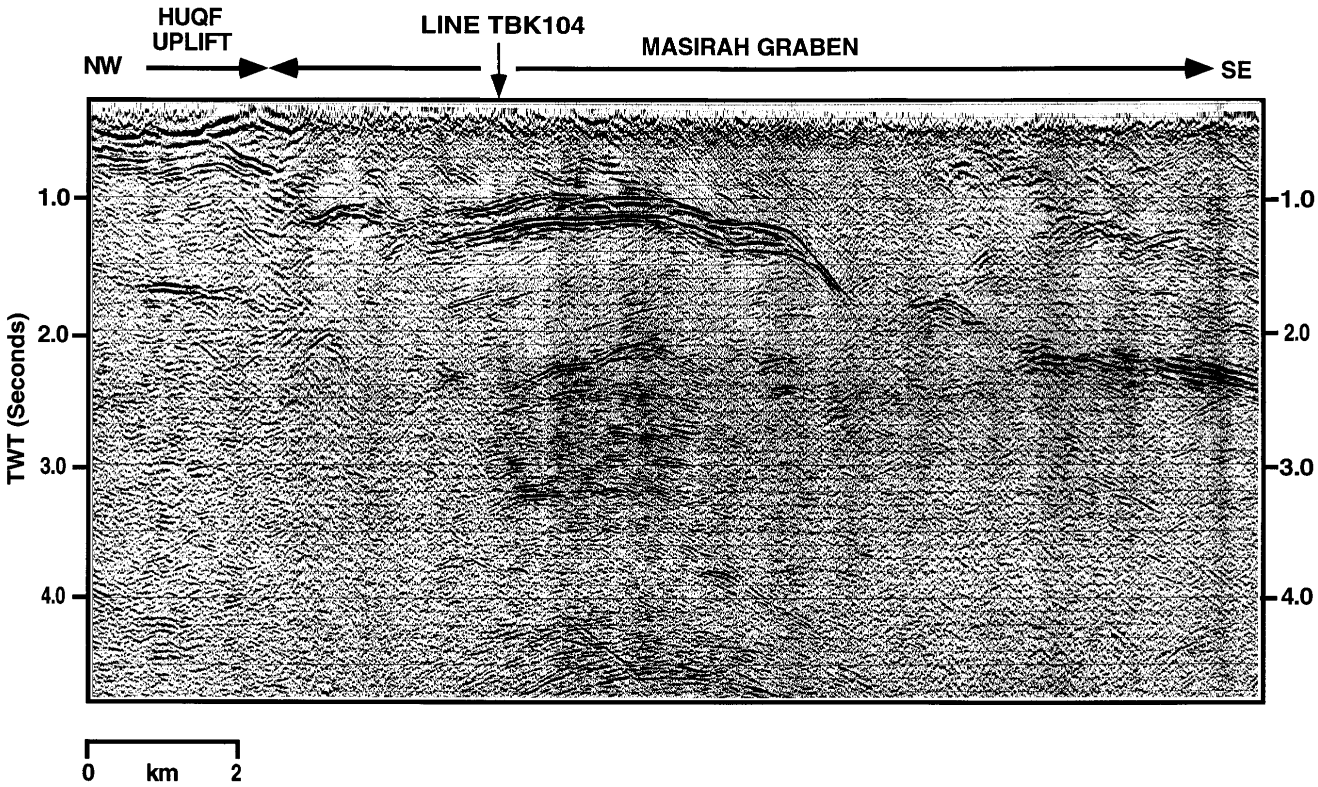

Figure 7—Seismic line IUL 122 extends northwest-southeast from the Huqf–Haushi uplift eastward into the Masirah graben (location of section is approximately along the eastern one-third of EE′ shown on Figure 3).

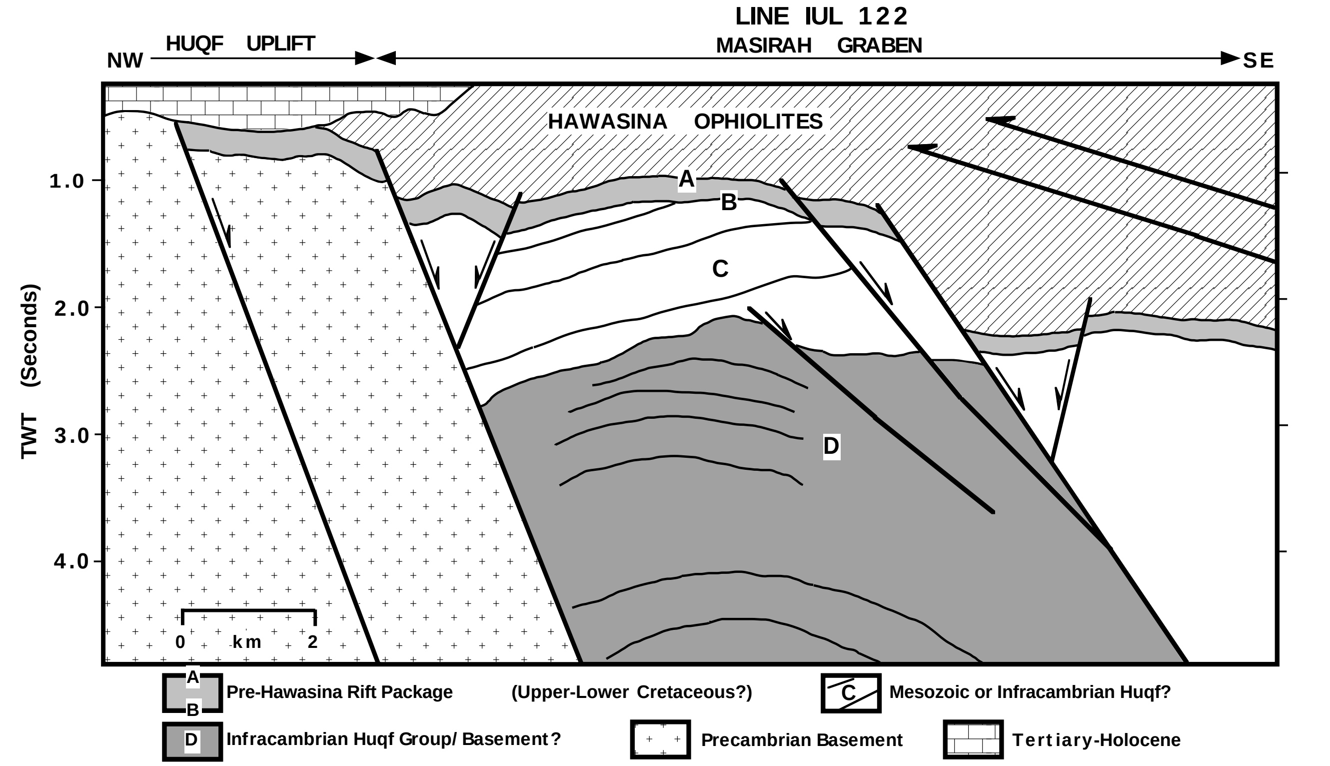

Figure 8—Interpretation of seismic profile IUL 122 (dip line). Extensional fault bounded horsts are present on the left of the line, with the thrusted ophiolite section on the right, upper part of the section (location of section is the southeastern part of EE′ shown on Figure 3).

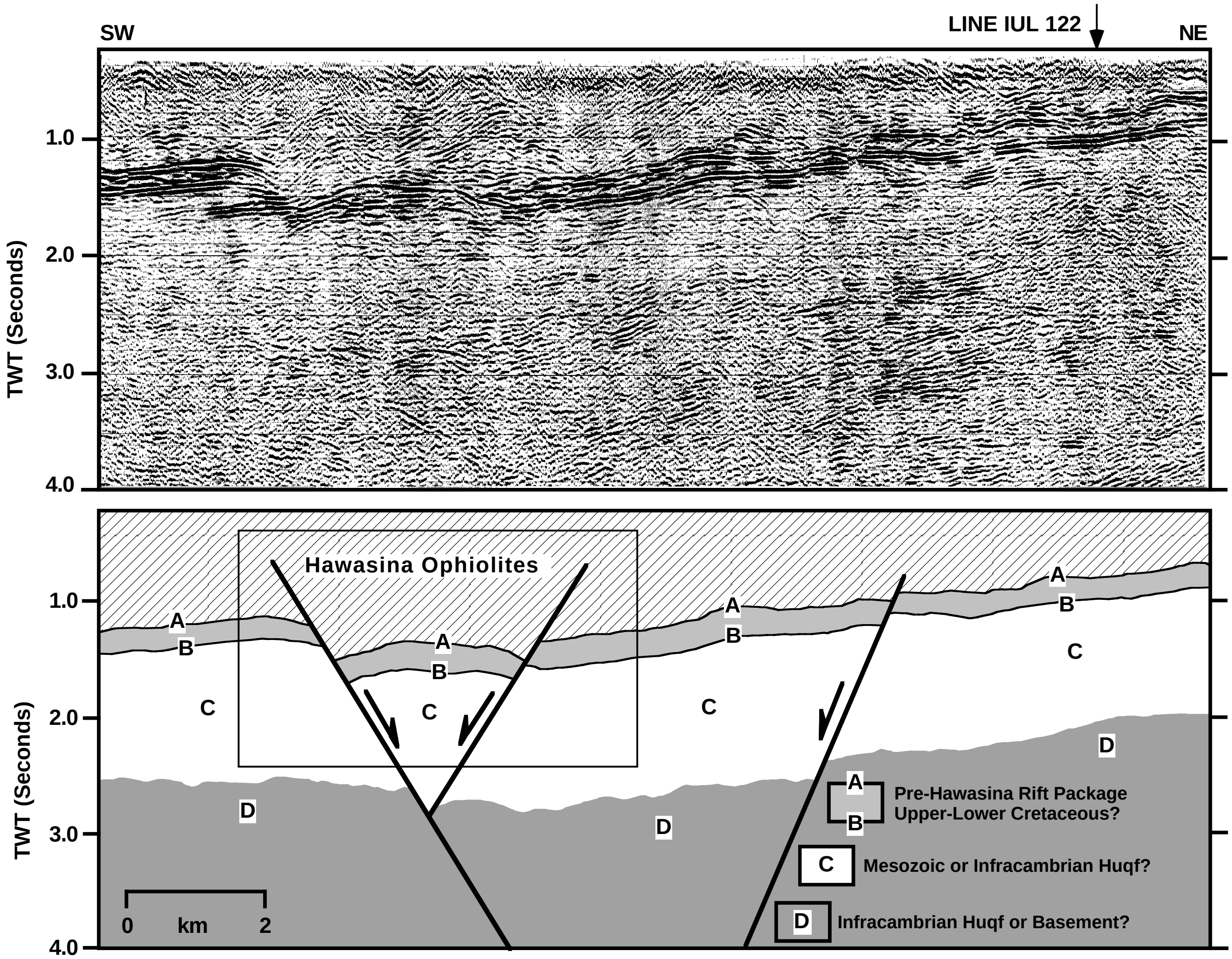

Figure 9—A seismic profile TBK 104 (strike line) and interpretation of pre-Hawasina/Batain allochthonous sequence.

(Shackleton et al., 1990) and the basal detachment now lies above two prominent packages of reflectors (termed reflectors A and B, Figure 6). The age of these reflectors is unknown; they underlie the Tertiary Qahwan Formation and may be age equivalent or older than the Paleocene Qahlah Formation and Maastrichtian Simsima Formation. The upper reflectors (A, Figure 6) are slightly imbricated, suggesting a detachment horizon between A and B (Figure 7). Beneath reflector B (Figure 6), a westward-dipping package of reflectors (C, Figure 6) is bounded to the west by an eastward-dipping normal fault (Jebel Ja'alan/Huqf fault) (Figure 8). These sediments do not occur west of the normal fault in the Jebel Ja'alan area. Reflector B truncates the C reflectors in this lower package, suggesting the sediments were tilted before deposition of B and may represent the base Cretaceous unconformity. To the east, the basal reflection of package D is offset down to the east by several small normal faults. The overall picture is one of a large half graben bounded and cut by eastward-dipping normal faults. Reflector D unconformably overlies gently folded reflectors that may represent basement structures or an unconformity within the Infracambrian. The normal faults that cut reflector D are asymptotic to the fabric in the basement at depth. The western-bounding fault of this large half graben lies along the southeastern side of Jebel Ja'alan, and can be traced southwestward along the flanks of the Huqf uplift and Masirah graben.

The general structural style present in the Masirah graben is illustrated on seismic line IUL 122, and in our interpretation of this line, we propose the presence of a pre-Hawasina/Batain rift

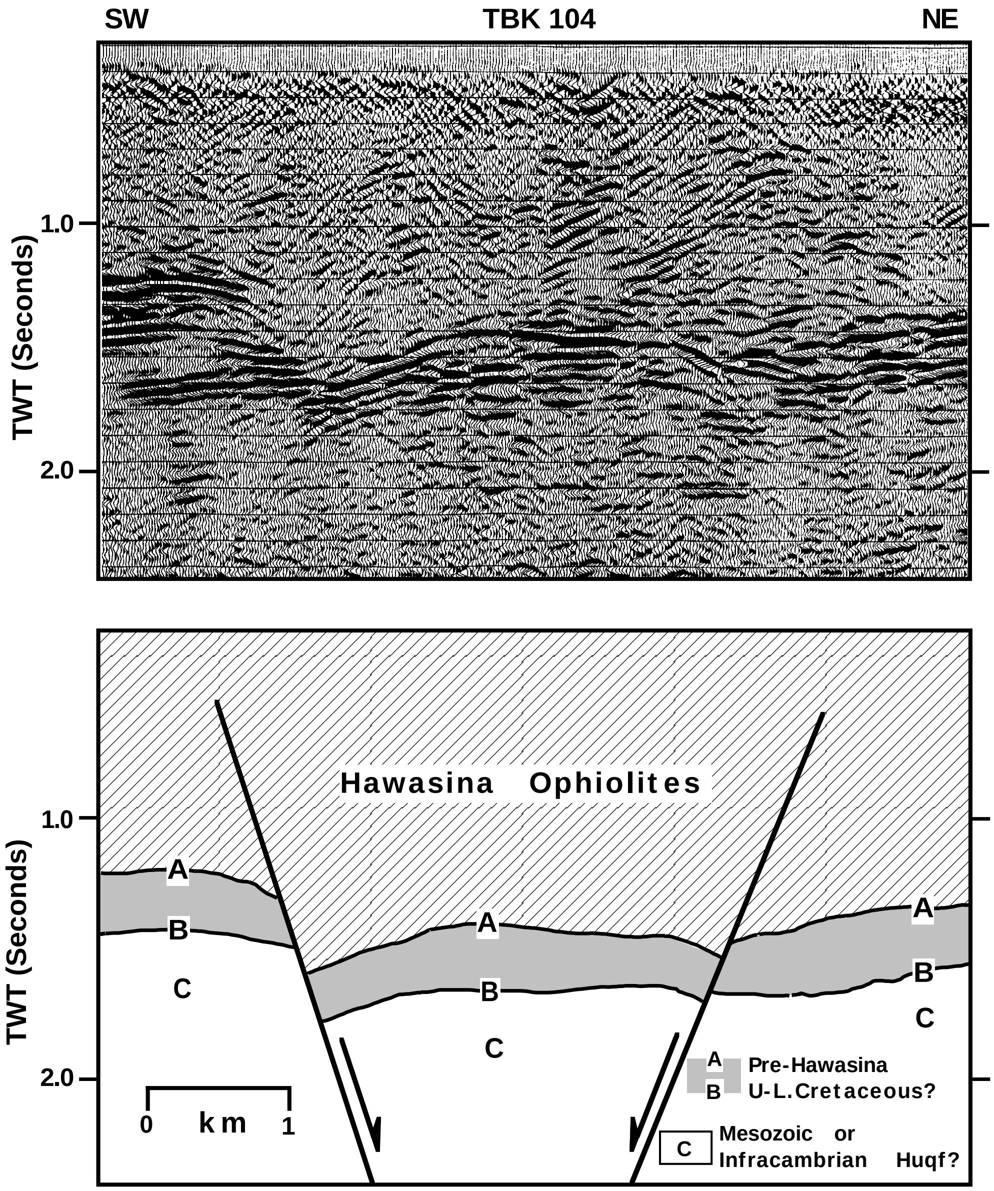

Figure 10—Detailed area of seismic profile TBK 104. Highly reflective autochthonous sequence (A-B) is relatively undeformed compared to the tightly folded allochthonous sequence above the basal detachment on top of reflector A. Normal Miocene faulting cuts the proposed rift sequence as well as the overlying ophiolites. (See Figure 11 for location of line.)

sequence (Figure 8). The autochthonous rocks beneath the ophiolites can be seen on seismic line TBK-104, which is a strike line trending northeast-southwest tying line IUL 122 (Figures 9, 10). The prominent package of reflectors (A-B) can be seen dipping to the southwest, disrupted by normal faults that postdate the obduction of the allochthonous Hawasina/Batain units. The detailed relationships of the Miocene normal faults and the highly deformed/folded allochthonous sequence are shown on a detailed portion of line TBK 104 (Figure 10). Both lines IUL 122 (dip line) and TBK 104 (strike line) were used along with other seismic data in the northern region of the Masirah graben (Figure 11) to map the pre-allochthonous structure of the Masirah graben based on the reflective package (A-B). The seismic data in the northern region of the Masirah graben have no direct ties to the well data and seismic data in the southern region of the Masirah graben. It is evident from the pattern and style of faulting present beneath the allochthonous sequence that a late phase of extension related to the opening of the Arabian Sea in the Miocene deformed the allochthonous sequence emplaced during the earlier convergence between the Arabian and Indian plates (Figure 11). The underlying extensional fault system is not evident from the surface exposures of the Hawasina/Batain units and younger rock units, and is apparent only when using seismic reflection profiles.

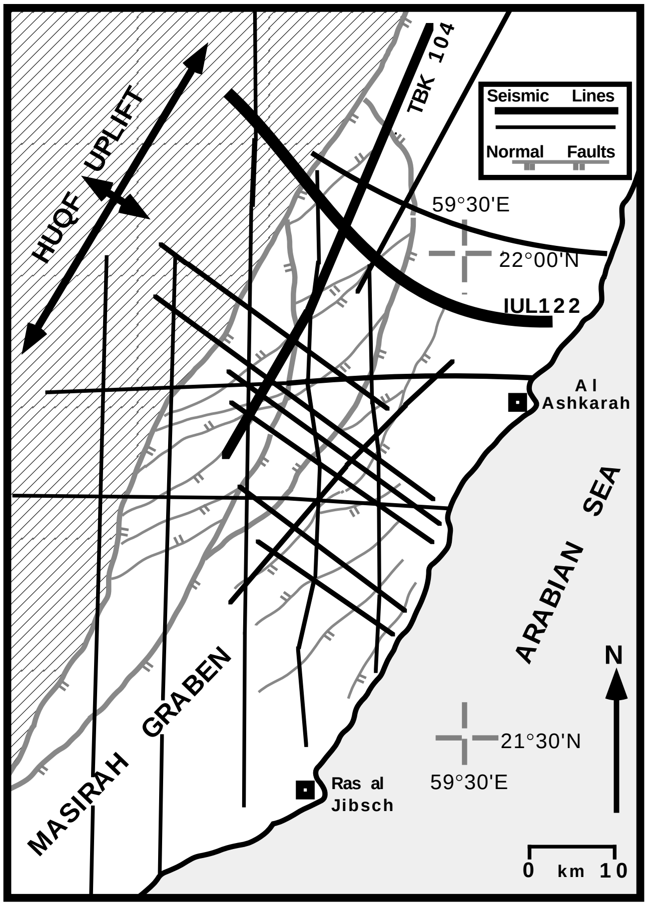

Figure 11—Fault-trace map of extensional faults in the Masirah graben and the location of seismic lines IUL 122, TBK 104, and additional seismic data.

TECTONIC HISTORY

The tectonic history of Oman extends from the late Precambrian, when the Arabian plate underwent accretion and collision (720–620 Ma), and was followed by an extensional phase of deformation (620–540 Ma) (Husseini, 1989). The Huqf anticlinorium has been a large-scale regional feature that has controlled the sedimentation of most rock units since the late Paleozoic (Hughes Clarke, 1988). The Huqf anticlinorium probably separated the Oman salt basin (Infracambrian–Cambrian) to the northwest of the Huqf uplift from what is now the salt ranges of Pakistan (Grantham et al., 1987). The western flank of the Huqf uplift contains outcrops of Permian–Carboniferous tillites and striations in older rock units resulting from glaciation (Levell et al., 1988). The Huqf uplift may have also acted as a barrier to the deposition of upper Paleozoic sediments to the southeast of the arch, because wells drilled east of the uplift have not penetrated rock units between the ages of Infracambrian to Jurassic.

Triassic faulting and spreading occurred along Tethyan and African rift systems; this faulting and spreading then resulted in the deposition of Jurassic and Lower Cretaceous shelf carbonates over Oman. This phase is represented by the Jurassic Sahtan Group and Kahmah Group penetrated by wells in the Masirah graben (Figure 4). These rocks are similar in age to the Upper Jurassic Shuqra-Sabatayn formations of Yemen, and the Upper Jurassic Arab-Hith formations of central Arabia (Beydoun, 1988).

From the Aptian to the Cenomanian, the African and Arabian plates drifted northward toward the equator, and regions of Oman and the Middle East were affected by flooding, which resulted in the deposition of the Nahr Umr Formation shale unit (Hughes Clarke, 1988). The Nahr Umr Formation and the Lower Cretaceous Wasia Group were penetrated by wells in the Masirah graben. During the Late Cretaceous, the Hawasina/Batain allochthonous sequence was obducted onto the southern Arabian continental margin. The direction of transport was from the northeast to the southwest, with estimates of several hundred kilometers of displacement (Shackleton et al., 1990). The previous continental margin of the Arabian continent is now hidden beneath the obducted allochthonous sediments.

The tectonic history of the Masirah graben and adjacent Huqf uplift is illustrated in a series of cross sections (Figure 12).

(1) The Huqf Group was folded and thrusted, possibly by thin-skinned deformation or by reactivation of earlier normal faults. Ordovician sediments were deposited in a growth basin at this time by compression-related folds. Regional studies suggest the Huqf uplift was initiated at this time, possibly as a large compressional structure. The Huqf uplift formed the eastern margin of the Oman salt basins.

(2) There is no evidence for sedimentation in the Masirah area until extension and deposition in the basin/graben east of the Huqf uplift. The age of the sediments is unknown, with several possible alternatives. Three of these alternatives are as follows. The first alternative is based on the fact that reflectors A and B can be traced across the main fault to the southern edge of Huqf uplift, possibly correlative with Maastrichtian Qalah and Simsima formations. If this correlation is valid then the sediments in the Masirah graben must be older than Maastrichtian.

The second alternative has the sediments in the half graben as a synsedimentary package, which can be correlated with the Hasad fault scarp sediments on the eastern flank of the Huqf

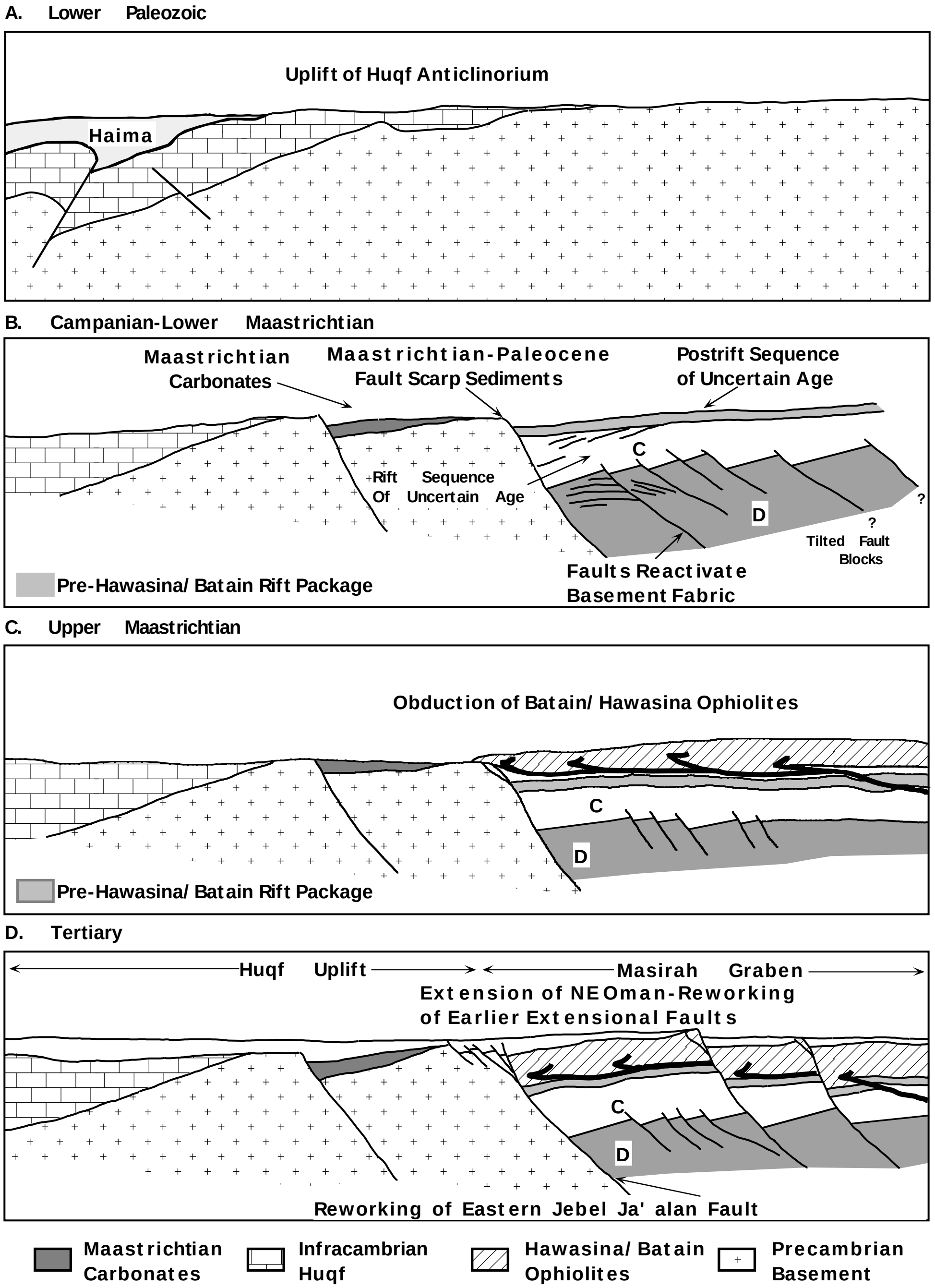

Figure 12—Tectonic history of the Masirah graben. Sections located along the same line of section EE′ (see Figure 3 for location).

uplift. Reflectors A and B, in this case, would be uppermost Maastrichtian–Paleocene sediments not recognized from surface data.

The third alternative states that reflectors A–C may be part of a pre-Maastrichtian package deposited in an extensional basin that was reworked at the end of the Cretaceous. These sediments could be as old as Infracambrian, or could be part of a later extensional basin not yet recognized in this part of Oman.

The presence of Permian–Cretaceous blocks in the Batain melange suggests that Mesozoic sediments were present in northeastern Oman. Basement granite blocks in the ophiolites suggest basement was eroded from beneath the Permian. The Late Cretaceous age for the formation of the ophiolites points to an active transtensional margin. The simplest model is for sediments A-B to be of Upper Cretaceous age, related to a late Mesozoic opening of the Indian ocean.

(3) The Batain/Hawasina ophiolites were obducted in a large thrust sheet overlying reflector A. The overthrust direction was to the west-northwest, and involved imbricates branching from a basal detachment above reflector A.

(4) Extensional faults formed during the Eocene in the eastern part of the Huqf uplift. The faults were reactivated and the footwall of the Huqf/Jebel Ja'alan block was further uplifted and tilted. The Cretaceous–Tertiary component of the Huqf uplift formed in the footwall of these extensional faults, probably related to isostatic forces at the edge of the rift. The extension direction during the Upper Cretaceous–Tertiary was west-northwest–east-southeast, and was the extension direction of the graben throughout its history.

(5) During the later Paleogene or Neogene, there was subsequent inversion of the faults surrounding the Jebel Ja'alan/Huqf uplift, folding of the Tertiary sediments, and overthrusting of the ophiolites. The transport direction was to the northwest, so the main Jebel Ja'alan/Huqf fault zone was reactivated as an oblique-slip fault with a left-lateral and reverse sense of motion. The original fault system was of a normal sense of motion and formed the western margin of the Masirah graben.

GEOCHEMICAL EVALUATION

Detailed geochemical analyses have been reported on a wide range of oils and source rocks in Oman. Most of the data available in the public domain originate from the Shell Oil Company. Most of the data are of biological marker distributions, which are the most useful in oil-source correlations. The earliest publication (Grantham, 1986) described the analysis of 85 oils from southern and central Oman. Two different sets of characteristics were found to be present, termed "A" and "B," respectively, by Grantham (1986). The A set was found to constitute 74 oils of the 85, and are those present in southern Oman. These oils were correlated to a Huqf Formation, Infracambrian source. The B set of 11 oils was found to be restricted mostly to southern central Oman, and no source was suggested. Further publications (Grantham et al., 1987; Grantham and Wakefield, 1988) termed this second set of oils the "Q" crudes, and this name has been adopted into wider use. Common properties of the Q and Huqf oils, and regional geological reasoning have indicated that the Q oils are also sourced from the Infracambrian, but probably from areas older than the Huqf Formation. Grantham et al. (1987) expanded their geochemical study to oils and source rocks from all over Oman. They were able to correlate oils from close to the Saudi Arabian border with the Silurian Safiq Formation, oils from northern Oman to the Cretaceous Natih Formation, and oils from the Jurassic Diyab Formation were also suspected.

With this excellent background data set, we analyzed oil stains from the SMPA 1 well. The stains were found at two levels in the Infracambrian. They were analyzed geochemically to produce data comparable to published data. Oils from the two zones, 1811–1905 m depth and 1985–2042 m depth, were found to have identical properties. These geochemical characteristics were that alkanes were present between nC^{15} and nC^{36}, lighter hydrocarbons being absent, and the isoprenoid alkanes pristane and phytane were present with phytane greater than pristane, indicating a reducing environment. Resolved and unresolved compounds were present between C^{22} and C^{29}, indicating the presence of the biological markers. Notable by their absence was a series of branched alkane compounds, referred to as the "X" series by Grantham et al. (1987); these alkane compounds are between C^{19} and C^{24}, and are found in both sets of Infracambrian oils from Oman and in Precambrian oils from Siberia (Moldowan et al., 1985; Fowler and Douglas, 1987). The absence of these compounds, even at this level of investigation, suggested that the SMPA 1 oils were not sourced from the Infracambrian. This view was confirmed by the biological marker traces, which showed no similarities to the Infracambrian oils of Grantham's work. The oils appear to be normal salinity marine and clastic sourced from a relatively aerobic depositional environment of non-Infracambrian age and based on sterane, rearranged sterane, and triterpane distributions. The absence of diagnostic biological marker environmental indicators, as well as the presence of those mentioned, support this source environment. Unfortunately, the oils did not appear to correlate with any of the published biological marker signatures, although they bore the closest resemblance to the Jurassic Diyab oils. On the basis of data from Grantham and Wakefield (1988), the age of the oils appears to be most likely Mesozoic. Oil recovered from the SMPA 1 well in the Infracambrian sediments is believed to have been sourced from Mesozoic source rocks, unlike the oils generated from Infracambrian source rocks in the Oman salt basins. This might also imply the existence of a precollision Cretaceous rift basin because such a basin would have been necessary to generate a Mesozoic oil for migration into existing structures in the Masirah graben.

Source rock studies were performed on the Infracambrian interval from 1795 to 2018 m in the SMPA 1 well. The interval was believed to contain intrusive volcanics near the well location, so special efforts were made to establish maturation levels. Unfortunately, vitrinite reflectance values studies cannot be performed on older Paleozoic

Table 1. Organic Carbon and Rock-Eval Pyrolysis Data from Sun Oil Company SMPA 1 Well, Haqf Group–Khufai Formation, Oman

			Pyrolysis							
Depth (m)	Sample Type	TOC (wt.% rock)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	T_{max} (mg/g)	HI (°C)	OI	PI	S_2/S_3
1954–1957	Cuttings	0.38	0.17	0.22	0.50	58	–	132	0.43	0.44
1966–1970	Cuttings	0.58	0.44	0.51	0.54	420	88	93	0.46	0.94
1976–1979	Cuttings	0.67	0.73	0.71	0.42	431	106	63	0.50	1.69
2006–2009	Cuttings	0.56	0.36	0.37	0.56	426	66	100	0.49	0.66
2012–2015	Cuttings	0.53	0.59	0.44	0.43	430	83	81	0.57	1.02
2015–2018	Cuttings	0.55	0.45	0.37	0.45	431	67	82	0.54	.082

*TOC = total organic carbon, HI = hydrogen index, OI = oxygen index, PI = production index.

rocks because land plants, the source of the vitrinite, had not yet evolved. Spore color and TAI (thermal alteration index) analyses were performed, but the section was found to be devoid of indigenous polymorphs. TAI studies indicated that the section was late mature, although a wider than normal spread of values was found, consistent with the section being intruded with volcanics. Source-quality data from TOC (total organic carbon) and Rock-Eval were determined (Table 1). TOC values were less than 0.67%, indicating no true source rocks were present. Hydrogen indices indicated that there was no remaining oil potential, although because maturity levels were high this was not surprising. T_{max} values, which indicate immaturity, are unreliable in rocks with low organic content; these values should be disregarded. Although any oil potential that this rock sequence ever had would now be spent, the low TOC values indicate that it is very unlikely that they were ever source rocks.

Two zones (1811–1905 and 1985–2042 m) contained heavy oil staining. The extracts from this interval were fractionated and the saturate fractions examined by gas chromatography (Figure 13) and gas chromatography–mass spectrometry (GC–MS). The two extracts were identical, and had several diagnostic features:

- Normal alkanes from C^{15} to C^{36} were present.
- Phytane dominated over pristane.
- Unresolved compounds were abundant in the C^{18} to C^{30} region of the trace.
- Resolved branched and cyclic alkanes were present between the normal alkane peaks from C^{22} to C^{28}, in the region of biological markers.
- Compounds to C^{18} were weathered, probably by storage.

These features would indicate that the oil is sourced from a reducing, possibly carbonate environment. On the basis of published data from Oman (Grantham et al., 1987), the oil stain more closely resembles Huqf rather than the unpenetrated Q source rocks. However, the published data are from tested oil samples, and they look quite different from this oil stain. The only absolute method of determining that the source is from biological distributions was by GC–MS. The GC–MS data indicated that the oil is probably from a marine, clastic source rock. The sterane distributions do not resemble either the Huqf or Q oils, thus the source is not believed to be Infracambrian. The GC–MS also confirmed the absence of branched alkanes, called X compounds by Grantham et al. (1987). The abundance of rearranged steranes, present in amounts similar to regular steranes, is yet another dissimilar feature to the Infracambrian oils of other parts of Oman. The most similar sourced oils described elsewhere in Oman are those attributed to the regionally known Jurassic Sahtan Group (Diyab Formation). This Jurassic source was not present in the wells of the Masirah trough, but was inferred by correlation of oil types from northwestern Oman, United Arab Emirates, and Qatar. These oils also have some affiliations to the Silurian Safiq sourced oils, but the correlation is better with the Jurassic source.

The oil analyzed in the SMPA 1 well is mature on the basis of biological marker ratios, probably from a peak to late-mature source. Although the exact source cannot be determined, it is most likely not an Infracambrian or Q source rock. This points to a younger sedimentary section as a source (Mesozoic–Jurassic), presently off structure from the area of the SMPA 1 well.

SEAL

The shales of the Infracambrian Shuram Formation, as well as intraformational shales within the Abu Mahara Formation, would form excellent

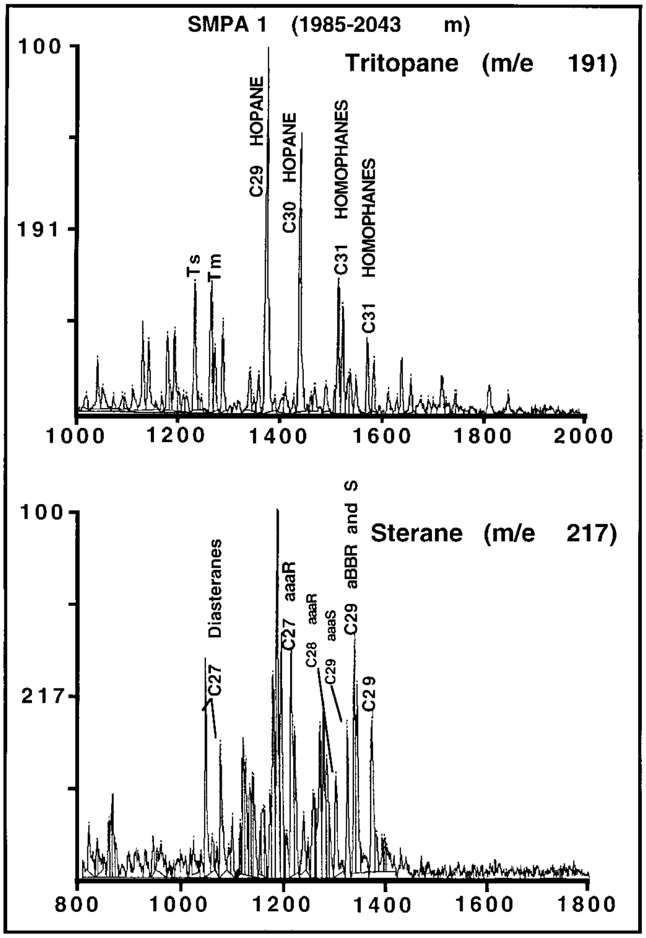

Figure 13—Tritopane (m/e 191) and sterane (m/e 217) traces from the oil extracted and analyzed from the Khufai Formation (1985–2043 m) in the SMPA 1 well. The results of these data indicate a normal-marine mature clastic-sourced oil. The age of this oil is most likely Mesozoic (Jurassic?) or possibly Silurian.

top and cross-fault seals for the Abu Mahara sandstones and the Khufai carbonates. Potential Mesozoic source rocks, which are juxtaposed against the Huqf Group by synrift normal faults, might also provide sourcing for the Huqf. Oil extracted from the Huqf in the SMPA 1 and SMPB 1 wells indicates that this relationship is possible. Structures having sufficient throw on synrift faults to place Mesozoic source rocks against the Huqf Group would also place Tertiary shales (Umm Er Radhuma, Rus, and Damman formations) on the footwall of the faults, providing an excellent cross-fault seal for the Lower Cretaceous reservoirs on the hanging walls of structures. The thrusted allochthonous sequence overlying the synrift/postrift sequence would also provide excellent top and cross-fault seals.

CONCLUSIONS

The Masirah graben is thought to represent a Mesozoic rift basin overlain by allochthonous sediments. Rifting during the Mesozoic resulted in the deposition of Lower Cretaceous carbonates similar in character to those found elsewhere in Oman. Further infilling of the graben took place in the Late Cretaceous with the deposition of the Aruma Group. During the Tertiary, the evidence of rifting in the Masirah graben was hidden by the thrusting of the Upper Cretaceous Batain/Hawasina ophiolites and sediments.

Previous exploration activity in the Masirah graben has proven that there are good-quality Cretaceous reservoir rocks and potential Infracambrian Huqf reservoirs, and that seal potential is good. Reflectors beneath the allochthonous sediments most likely represent either Lower Cretaceous carbonates or younger Maastrichtian–Paleocene carbonates. Seismic data have indicated large undrilled structures in the Masirah graben beneath the complexly deformed and thrusted Hawasina sedimentary rocks and Batain melange. Oil recovered from the Huqf Group in Sun's SMPA 1 well indicates the presence of mature marine Mesozoic (Jurassic?) source rocks in the Masirah graben.

The sedimentary sequence interpreted on seismic data beneath the allochthonous sediments/ophiolites of the Masirah graben is most likely the same as that penetrated by wells south of the Masirah graben. Despite the lack of a direct well tie, seismic character and stratigraphic relationships infer such an interpretation. Evidence from this area indicates further exploration potential in the Masirah graben and in similar settings along the southern margin of the Arabian plate.

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