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Stratigraphic Evolution of the Midyan Basin and its Hydrocarbon Potential (NW Saudi Arabia)

Midyan Havzası'nın Stratigrafik Evrimi ve Hidrokarbon Potansiyeli (KB Suudi Arabistan)

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Abstract: The hydrocarbon-producing Midyan Basin is located in northwestern Saudi Arabia and is surrounded by the Proterozoic igneous basement of the Arabian Shield. It includes thick hydrocarbon-producing sedimentary sequences deposited in half-grabens that formed during rifting of the Red Sea and the gulfs of Suez and Aqaba in the Early Miocene (23.3 Ma). The early syn-rift succession consists of arid alluvial fan sediments and playa evaporates, followed by shallow marine carbonates. The late syn-rift sequences consist of progradational deep sea turbidites and Alpine-type glacial deposits indicating strong vertical uplift during the climax of the rifting (19 Ma). The post-rift succession overlies the late syn-rift successions and consist of shallow marine marls and evaporites. The aim of this study is to examine the hydrocarbon potential of the turbidite sandstones and the formation of various types of glacial deposits in the Burqan Formation. This study also encompasses the importance of various geologic processes in order to understand their significant influence on the geometry, continuity and reservoir quality of oil and gas producing genetically different sandstones in the subsurface of the Burqan Formation in the Midyan Basin. The Alpine-type glacial deposits provide an excellent opportunity to study the presence of continuous vertical and lateral facies variations between true glacial, glacio-fluvial and glacio-marine deposits in the direction of sediment transportation. Unsorted moraines deposited in the deep and U-shaped glacial valleys occupy the northwestern part of the basin. They pass gradually into glacio-fluvial sandstones that contain large polished and striated boulders. In the southeastern part of the deep basin, the glacio-marine deposits are associated with deep sea turbidites and pelagic shales. Many stratigraphic and sedimentologic sections were measured from well-exposed outcrops in every part of the basin to establish various depositional environments. A large number of sandstone samples was collected to examine their reservoir quality.

Keywords: Glacio-fluvial, glacio-marine, Gulf of Aqaba, Gulf of Suez, Midyan Peninsula, Sinai Peninsula, true glacial

Öz: *Önemli miktarlarda hidrokarbon üretiminin yapıldığı Midyan Havzası, Suudi Arabistan'nın kuzeybatısında yer alır ve Arap Kalkanı olarak bilinen Proterozoyik yaşlı kristalin temel tarafından çevrilmiştir. Bu havza, Erken Miyosende (23,03 My) Kızıldeniz, Süveyş ve Akabe Körfezleri'nin açılması ile oluşmuş yarı-grabenlerde çökelmiş petrol ve doğal gaz potansiyelleri yüksek kalın sedimanter istifler içerir. Açılmanın erken aşamasında çökelen istifler, karasal alüvyon yelpazesi çökelleri, playa evaporitleri ve bunların üzerine gelen bol fosilli sığ deniz karbonatlarından oluşur. Midyan Havzası'nın Erken Burdigaliyen zamanında derinleşmesi nedeniyle, sığ deniz karbonatları üzerine uyumlu olarak Burqan Formasyonu'nun derin deniz yelpazeleri içindeki hidrokarbon üretiminin yapıldığı klasik türbidit istifleri gelir. Kızıldeniz, Süveyş ve Akabe Körfezleri açılmasının en etkili oduğu zirve döneminde (yaklaşık, 19 My) Sina Yarımadası düşey yönde 4 kilometreden daha fazla yükselmiş ve yüksek dağ zirvelerinde Alp-tipi buzul*

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çökelleri oluşmuştur. Açılmanın geç ve son aşamasını temsil eden istifler sığ deniz ortamında çökelmiş marnlar ve evaporitlerle temsil edilir. Bu çalışmanın amacı, Burqan Formasyonu içindeki türbidit istiflerinin hidrokarbon potansiyellerini ortaya çıkarmak ve değişen iklim koşullarını temsil eden buzul çökellerinin farklı fasiyeslerini incelemektir. Arazide ölçülmüş sedimantolojik kesitler yardımıyla farklı jeolojik süreçlerin, Burqan Formasyonu içindeki petrol ve gaz rezervuarını oluşturan kökensel yönden farklı kumtaşlarının geometrileri, devamlılıkları ve rezervuar kaliteleri üzerindeki etkileri araştırılmıştır. Sina Yarımadası üzerinde oluşan Alp-tipi buzul çökelleri, gerçek buzul (moren), buzul-fluviyal ve buzul-denizel çökeller arasındaki düşey ve akış yönündeki yanal değişimleri anlamak için önemli bir olanak sağlar. Masif, boylanmamış morenler havzanın kuzeyindeki derin, U-şeklindeki buzul vadilerinin içinde çökelmiştir. Bu çökeller vadilerin akışı yönünde içinde cilalanmış ve çizilmiş bloklar içeren buzul-fluvial çökellere geçer. Havzanın en derin olduğu güneydoğu bölgesinde buzul-denizel çökeller pelajik şeyller ve türbiditlerle birlikte çökelmiştir. Midyan Havzası'nın, stratigrafik evrimini anlamak, çökelme ortamlarını yorumlamak ve hidrokarbon potansiyelini ortaya çıkarmak için istiflerin devamlı olduğu bölgelerde çok sayıda kesit ölçülmüş ve kumtaşlarının rezervuar özelliklerini ortaya koymak için örnekler alınmıştır.

***Anahtar Kelimeler:** Aqaba Körfezi, denizel buzul, fluviyal buzul, gerçek buzul, Midyan Yarımadası, Sina Yarımadası, Süveyş Körfezi*

INTRODUCTION

The Midyan Peninsula is located east of the Gulf of Aqaba in the northwestern corner of the Arabian Peninsula. It is bounded by high mountains of Neoproterozoic crystalline basement rocks, the Gulf of Aqaba, and the Red Sea (Figures 1A and 1B). The peninsula is dissected by east-west normal faults and north-south oriented strike-slip faults. The crystalline basement rocks are at least 40-45 km thick and consist mainly of ultramafic, metavolcanic, metasedimentary rocks and granitic plutons which have been intruded by basalt, rhyolite and dolerite dikes (Figures 2A and 2B) that have been dated to about 600-700 (Ma), likely associated with the breakup of Rodinia (Gardner et al., 1996). The surface of the Arabian-Nubian Shield has been uplifted several times. The Red Sea and Gulf of Aqaba rifting started in the Early Miocene (about 23.3 Ma) and resulted in the formation of the Midyan Basin (Stern and Johnson, 2010; Rasul and Stewart, 2018). The region is severely dissected by NW-SE and NE-SW trending fault and joint systems (Figure 3A). The Midyan Basin forms a large part of the Midyan Peninsula and contains thick and continuous pre-rift, syn-rift and post-rift-related sedimentary successions deposited in a series of deep half-grabens.

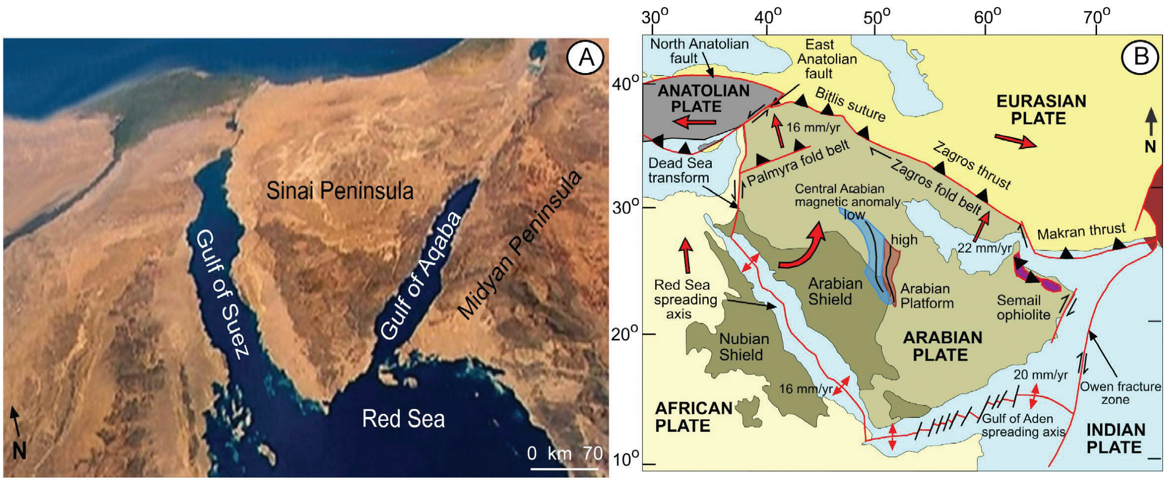

Figure 1. A) The Midyan Peninsula is located north of the Red Sea and east of the Gulf of Aqaba (NW Saudi Arabia). The dark areas represent the Neoproterozoic crystalline basement. High mountain ranges are located in the Sinai

Peninsula between the Gulf of Suez and Gulf of Aqaba. **B)** Simplified tectonic map of the Arabian and East African plates. The map shows the plate margins, rift and subduction boundaries and other important tectonic features. Arrows indicate plate movements of the Proterozoic Arabian and Nubian shields and Anatolian Plate (Stern and Johnson, 2010).

Şekil 1. ***A)*** *Midyan Yarımadası Kızıldeniz'in kuzeyinde ve Akabe Körfezi'nin (Suudi Arabistan) doğusunda yer alır. Koyu renkli alanlar Neoproterozoyik kristalin temeli temsil eder. Sina Yarımadası'ndaki yüksek dağ silsilesi Süveys ve Akabe Körfezleri arasındadır.* ***B)*** *Arap ve Doğu Afrika levhalarının basitleştirilmiş tektonik haritası. Bu harita levha sınırlarını, açılma ve dalma-batma zonlarını ve diğer önemli tektonik özellikleri gösterir. Ok işaretleri Proterozoyik yaşlı Arap ve Nubiyan Kalkanları'nın ve Anadolu Levhası'nın hareket yönlerini gösterir (Stern ve Johnson, 2010).*

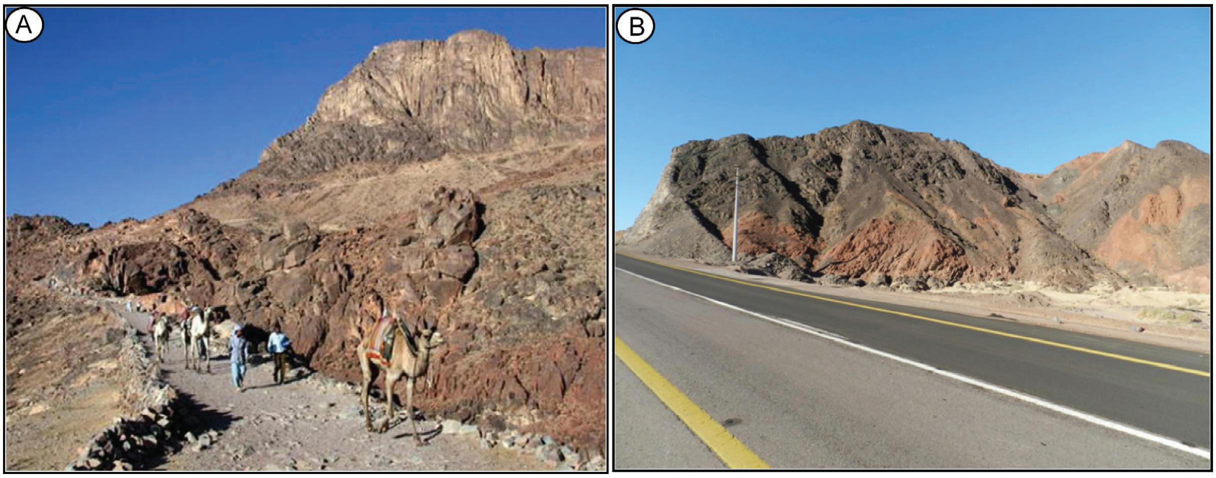

Figure 2. A) Photograph showing Neoproterozoic crystalline basement rocks in Sinai Peninsula which lies along the NE flank of the Red Sea with two long prongs extending NW and SE for a total of 1,800 km. This Neoproterozoic crystalline basement dated to 600-700 Ma (Gardner et al., 1996) is made up of ultramafic, metavolcanic, metasedimentary rocks and granitic plutons, which in turn are intruded by a variety of dyke swarms (including basaltic, rhyolitic, and doloritic). It is considered to have been formed along an accreting Proterozoic volcanic arc and has been uplifted periodically along the Red Sea and Gulf of Aqaba rifting during Early Miocene, which resulted in formation of the Midyan Basin (Stern and Johnson, 2010). The Sinai Peninsula was vertically uplifted more than 4 km during the Early Miocene Red Sea and Gulf of Aqaba rifting (Garfunkel and Bartov, 1977). Thick Alpine-glaciers formed in the Sinai Peninsula above the permanent snow line of this uplifted Neoproterozoic crystalline basement (Şenalp, 2016). **B)** The Neoproterozoic Arabian Shield is most exposed on both sides of the Al Bad'-Magna highway in the Midyan Area. Magna is a coastal town located on the south coast of the Gulf of Aqaba in NW Saudi Arabia.

Şekil 2. A) *Sina Yarımadası'ndaki Neoproterozoyik kristalin temel kayaçlarını gösterir fotoğraf. Bu bölge Kızıldeniz'in kuzey kanadı boyunca iki uçlu sivri kollar şeklinde kuzeybatı ve güneydoğu yönlerinde uzanır ve toplam uzunluğu 1.800 km dir. Bu Neoproterozoyik kristalin temel 600-700 milyon yıl önce, (Gardner vd., 1996) ultramafik, metavolkanik, metasedimanter kayaçlardan, granitik plütonlardan, riyolitik ve doleritik dayk sistemlerinden oluşur. Bu farklı kökenli kayaçlar Proterozoyik ada yayının büyümesi sonucu ortaya çıkmışlardır ve Erken Miyosen zamanında Kızıldeniz, Süveyş ve Akabe Körfezleri'nin açılma sırasında sürekli fakat periyodik olarak yükselmişlerdir. Bu açılma ile ilişkili olarak Midyan Havzası ortaya çıkmıştır (Stern ve Johnson, 2010). Erken Miyosen sırasında ve açılmanın en etkin olduğu dönemde Sina Yarımadası tektonik olarak 4 km den fazla yükselmiş (Garfunkel ve Bartov, 1977) ve Neoproterozoyik kristali temelin yüksek dağ zirvelerinde daimi-buzul çizgisinin üzerinde Alp-tipi buzullar oluşmuştur (Şenalp, 2016).* ***B)*** *Neoproterozoyik Arap Kalkanı'nın en güzel mostraları Midyan bölgesi'nin Al Bad-Magna karayolu üzerinde görülebilir. Magna, KB Arabistan'da Akabe Körfezi'nin güneyinde yer alan bir kıyı kasabasıdır.*

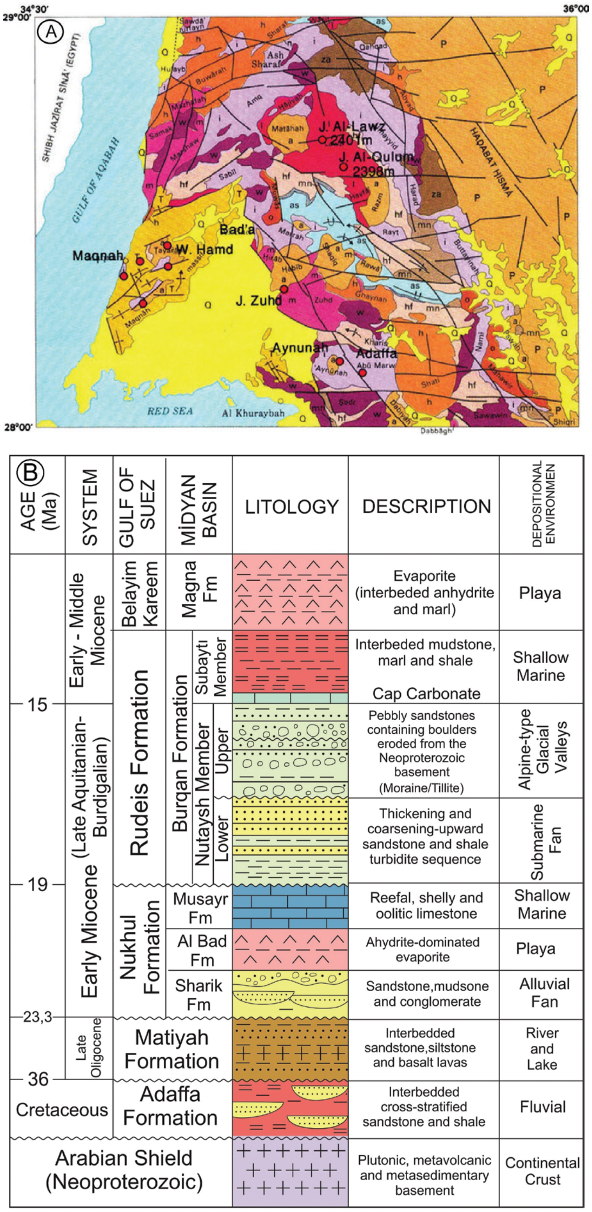

Figure 3. A) Simplified geologic map of the Midyan Peninsula (modified after Clark, 1986). The Midyan Basin occupies the southwest of the Midyan Peninsula and is surrounded by the Gulf of Aqaba and Red Sea. The region is severly dissected by a NW-SE and NE-SW trending fault and joint system. **B)** Stratigraphic succession shows the pre-rift (Adaffa and Matiyah formations), early syn-rift (Sharik, Al Bad, and Musayr formations), late syn-rift (Lower and Upper Nutaysh members of the Burqan Formation), and post-rift (Subayti Member of Burqan Formation and Magna Formation).

Şekil 3. ***A)*** *Midyan Yarımadası'nın sadeleştirilmiş jeolojik haritası (Clark, 1986). Midyan Havzası bu yarımadanın güneyinde yer alır. Kızıldeniz ve Akabe Körfezi ile çevrilmiştir. Bu bölge KB-GD gidişli faylar ve eklem sistemleri ile şiddetli bir şekilde kesilmiştir.* ***B)*** *Stratigrafik istif havza içindeki açılma-öncesi (Adaffa ve Matiyah Formasyonları), erken-açılma (Sharik, Al Bad ve Musayr formasyonları), geç-açılma (Burqan Formasyonu'nun Aşağı ve Yukarı Nutaysh Üyeleri) ve açılma-sonrası (Burqan Formasyonu'nun Subayti Üyesi ve Magna Formasyonu) birimlerle temsil edilmiştir.*

The proven hydrocarbon potential of the sandstones and carbonates in the Midyan Basin has attracted the interest of various oil companies and Saudi universities. Many stratigraphic and sedimentologic sections have been measured in almost every part of the Midyan Peninsula as a sunbstantive framework for hydrocarbon explorations (Alsharhan and Nairn, 1997; Hughes and Johnson, 2005; Al-Ramadan et al., 2013; Al-Laboun et al., 2014; Şenalp, 2016). These hydrocarbon-bearing successions present an excellent opportunity to identify the influence of severe tectonic uplifting of the source areas on paleoclimates and the evolution of water depths, resulting depositional systems and basin filling as rifting progressed. However, these aspects have not yet been addressed in detail.

This paper provides a case study of the role of tectonics, rifting and regional uplift in promoting regional climatic cooling and the resulting glaciogenic sedimentation recorded by the recently-identified Early Miocene (*c.* 19 Ma) Upper Nutaysh Member of the Burqan Formation within the Midyan Basin. The Alpine-type glacial deposits provide an excellent opportunity to study the presence of continuous vertical and lateral facies variations between true glacial, glaciofluvial and glaciomarine deposits in the direction of sediment transportation. The paper also comments on the hydrocarbon prospectivity of the shallow marine carbonates of the Musayr

Formation and sand-dominated deep sea turbidite fans of the Lower Nutaysh Member and glacially-influenced strata, principally glacio-fluvial and deep water turbidite sandstones, of the Upper Nutaysh Member of the Burqan Formation.

STRATIGRAPHIC SUCCESSIONS OF THE MIDYAN BASIN

The Midyan Peninsula is part of the northern Red Sea Basin and consists of a thick sequence of siliciclastic and carbonate rocks deposited from Late Cretaceous to Late Miocene (Figure 3B). The geology and depositional environments of the succession is strongly affected by the complex tectonic and structural history associated with the Early Tertiary opening of the Red sea and Gulf of Suez, and the Late Tertiary transform faulting of the Gulf of Aqaba and Dead Sea. The stratigraphic succession in the Midyan Peninsula includes the Adaffa, Sharik, Musayr, Burqan (Lower and Upper Nutaysh and Subayti members) and Magna Formations and can be easily subdivided into pre-rift, syn-rift, and post-rift successions (Şenalp, 2016). The nomenclature of the stratigraphic units was based on the outcrop locations, which can be visited and studied easily by geologists (Figure 3B).

Sedimentary successions of the pre-rift period

Adaffa Formation

The Late Cretaceous pre-rift Adaffa Formation directly overlies the Neoproterozoic crystalline basement rocks of the Arabian-Nubian Shield (Clark, 1986). It is unconformably overlain by the Sharik Formation formed during the early syn-rift period of Early Miocene (23.3 Ma). The Adaffa Formation is a 90 m thick meandering fluvial sequence, consisting of yellow to reddish-brown, cross-bedded, well-sorted, friable quartz arenitic sandstones with basal conglomerates in the lower parts, and thin marl, siltstone, and fine-grained sandstone and gray-green shale layers in its upper parts. The basal conglomerate contains granite pebbles and cobbles, phosphatic nodules, dinosaur and turtle bones, and petrified wood fragments in the thin beds of limonitic sandstones at the top of the sandstone succession. Şenalp (2016) reported that the bone fragments were identified as those of a sauropod, (possibly titanosaurid) dinosaur and turtle plates, which indicates Late Cretaceous (Albian-Maastrichtian) age.

Sedimentary successions of the syn-rift period and post-rift periods

The Midyan Basin includes thick syn-rift and post-rift sedimentary sequences deposited in a series of deep half grabens formed during the opening of the Red Sea, Gulf of Suez and Gulf of Aqaba between the early Early Miocene (about 23.3 Ma) and Early Middle Miocene (about 11 Ma) periods (Hughes and Filatoff, 1995; Hughes and Johnson, 2005). Based on the type of depositional environment and depth of water, the thick syn-rift successions were subdivided into early syn-rift and late syn-rift sequences (Figure 3B).

Sedimentary successions of the early syn-rift period

The sedimentary successions were deposited during the early syn-rift period of the Red Sea, Gulf of Suez and Gulf of Aqaba tectonic-rifting. These Early Miocene (between 23.3-19 Ma) successions consist of the Sharik, Al-Bad' and Musayr formations (Figure 3B). They are conformable, genetically related and represent well-defined transgressive system tracts. The stratigraphic succession, ranging from arid alluvial fan siliciclastic sediments (Sharik Formation) to coastal playa evaporites (Al-Bad' Formation) and finally into tide-dominated shallow marine carbonates (Musayr Formation), clearly indicates a gradual change in depositional regime resulting from the progressive regional increase of marine influences. Şenalp (2016) interpreted these formations to have been deposited contemporaneously within the same systems tract, and due to the rising base level (sea level), they were stacked vertically.

At the type locality, the Early Miocene (23.3 Ma) Sharik Formation overlies the irregular topographic surface of the igneous Neoproterozoic Basement of the Arabian Shield and represents the oldest sedimentary succession of the early syn-rift period. This red-colored, arid continental siliciclastic sequence is conformably overlain by the genetically-related playa evaporites of the Al-Bad' Formation. However, in the absence of Al-Bad' evaporites (beyond the depositional margin of the playa), the shallow marine carbonates of the Musayr Formation sit directly on the Sharik Formation. The lower part of the Sharik Formation comprises poorly-sorted conglomerates consisting of large pebbles and boulders of chert and igneous basement rocks, representing deposition in the uppermost parts of an alluvial fan environment (Figure 4A). Red-colored, thick-bedded, cross-stratified, well-sorted channel-filled sandstones overlie these coarse-grained deposits. This section is also incised frequently by large gullies and several tens of meters-deep channels, representing the canyons and their tributaries that formed on the apex of the alluvial fans deposited at the base of the uplifted Sinai Peninsula. In the centre of the Midyan Basin, these channel-filled sandstones are medium- to fine-grained, better-sorted and have significant reservoir potential for hydrocarbon accumulation (Figure 4B).

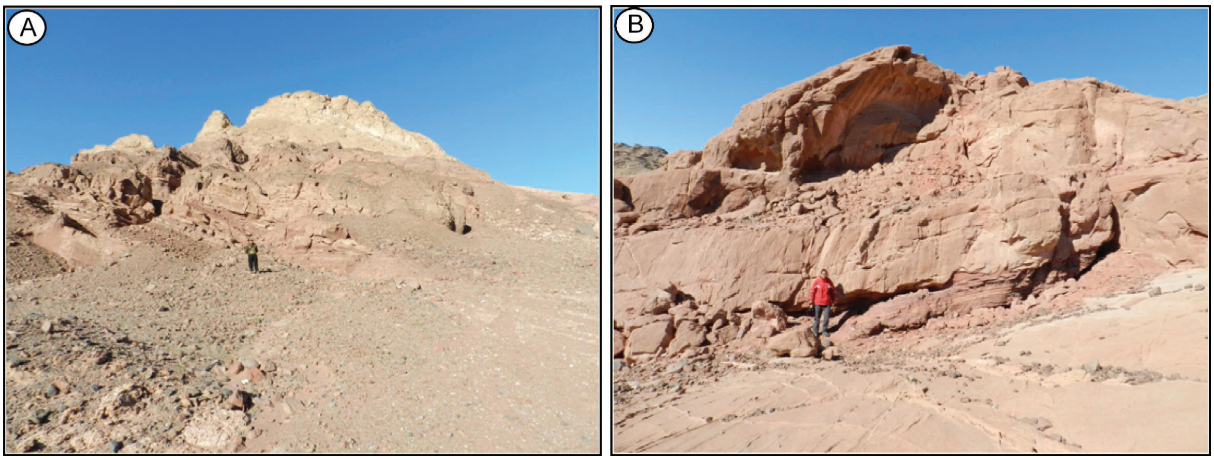

Figure 4. A) Coarsening- and thickening upward progradational alluvial fan environment formed during deposition of the early syn-rift Sharik Formation. The uppermost part is cut deeply by the canyon and filled with poorly-sorted conglomerates (Location: 28°27'49.6"N/34°51'30.5"E). These alluvial fan sediments are overlain by genetically-related playa evaporites of the Al Bad Formation. **B)** Red-colored, medium- to coarse-grained, trough cross-bedded, well-sorted and friable sandstones deposited in the braided stream system in middle parts of the alluvial fan environment. Sandstones are the major aquifer in the Midyan area (Location: 28°27'49.6"N/34°51'30.5"E).

Şekil 4. A) *Erken-açılma sırasında Sharik Formasyonu içinde çökelmiş alüvyon yelpazesi ortamının, havzanın daha derin kısımlarına doğru ilerlemesi sonucu ortaya çıkan tabaka kalınlığının ve tane-boyunun üste-doğru arttığı sedimanter istif. Bu istifin en üst kısmı kötü-boylanmış konglomeralarla doldurulmuş kanyon tarafından derince kazılmıştır (Lokasyon: 28°27'49,6"K/34°51'30,5"D). Alüvyon yelpazesi çökelleri genetik-ilişkili oldukları playa evaporitleriyle örtülmüştür.* ***B)*** *Kırmızı renkli, orta-iri taneli, tekne-şekilli çapraz-tabakalanmalı ve kırılgan özellikteki kumtaşları alüvyon yelpazelerinin orta ve aşağı kısımlardaki örgülü nehirler tarafından çökeltilmiştir (Lokasyon: 28°27'49,6"K/34°51'30,5"D).*

The Al-Bad' Formation consists of white-colored, massive-looking evaporites (mainly anhydrite and gypsum) and occurs between the arid alluvial fan deposits of the Sharik Formation and the shallow marine carbonates of the Musayr Formation, forming distinct lithofacies in the middle of the transgressive sequence (Figures 5A and 5B). On outcrops, halite is not present; however, in the subsurface the same section consists of halite, anhydrite and a minor amount of shale (Hughes and Johnson, 2005). The thickness of the Al-Bad' Formation ranges from 0 (zero) to about 50 m at the outcrop, depending on the depositional site of the evaporites. Its localized geographic distribution and relationships between lateral and vertical facies suggest its precipitation in a hypersaline water body. All the evidence indicates that these evaporites were deposited in a playa (coastal sabkha) environment situated between the outer alluvial fan and the shallow sea, and were subjected to occasional marine flooding.

The Musayr Formation consists of shallow marine carbonates and represents the first regional marine transgression into the Midyan Basin during Early Miocene (Burdigalian) and forms the uppermost part of the early-rift transgressive system tract. At the type locality, the carbonates conformably overlie the playa evaporites of the Al-Bad' Formation (Figures 6A and 6B). However, in some places, beyond the limit of the playa environment (coastal sabkha) where the evaporites are missing, the Musayr carbonates directly and disconformably overlie the continental red bed deposits of the Sharik Formation. In this case, the boundary between these two formations indicates a significant time gap.

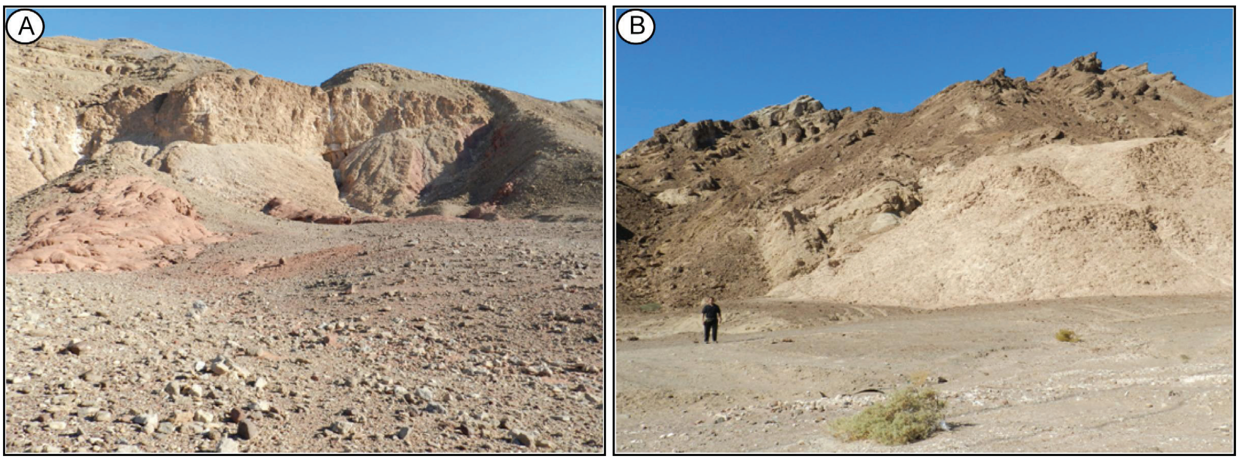

Figure 5. A) White-colored, massive playa evaporites of the Al Bad' Formation directly overlying fluvial sandstones of the Sharik Formation (Şenalp, 2016). **B)** These playa type evaporites (mainy anhidrite) are overlain by light brown-colored, fossiliferous transgressive shallow marine carbonates of the Musayr Formation (Location: 28°28'07"N/34°51'41.16"E).

Şekil 5. A) *Al Bad' Formasyonu'nun beyaz renkli, masif playa evaporitleri Sharik Formasyonu'nun flüviyal kumtaşları üzerine doğrudan oturur (Şenalp, 2016).* ***B)*** *Bu playa evaporitleri (başlıca anhidrit) Musayr Formasyonu'nun açık kahve renkli, bol fosilli sığ deniz ortamının karbonatları ile örtülmüştür (Lokasyon: 28°28'07"K/34°51'41,16"D).*

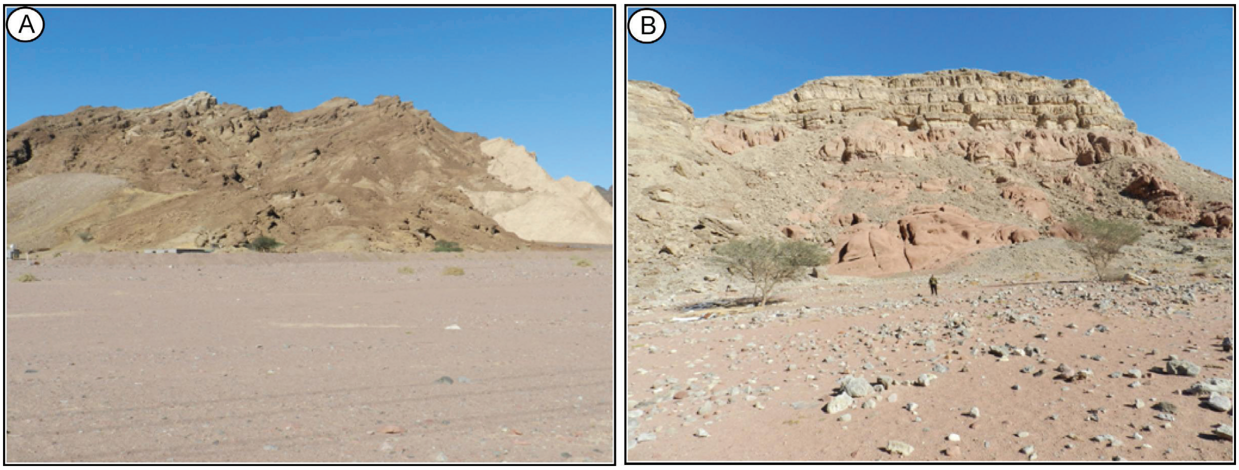

Figure 6. A) Shallow marine carbonates of the Musayr Formation conformably overlie the playa evaporites of the Al Bad' Formation (28°28'11.0″N/34°51'01.4″E). This indicates the first open marine transgression into the Midyan Basin (Şenalp, 2016). **B)** However, beyond the limit of playa environment (coastal sabkha), where the evaporites are missing, the Musayr carbonates directly and disconformably overlie the red bed Sharik Formation. The boundary between these two formations indicates a significant time gap.

Şekil 6. A) *Musayr Formasyonu'nun sığ deniz ortamında çökelmiş karbonatları Al Bad' Formasyonu'nun playa evaporitleri üzerine uyumlu olarak oturur (28°28'11,0″K/34°51'01,4″D). Karbonat fasiyesi, Midyan Havzası içindeki ilk denizel çökellerdir (Şenalp, 2016).* ***B)*** *Buna karşın, playa ortamını sınırlarının ötesinde, evaporitlerin çökelmediği bölgelerde, Musayr Formasyonu Sharik Formasyonu'nun kırmızı flüvial kumtaşları üzerine uyumsuz olarak oturur ve aradaki bu uyumsuzluk yüzeyi önemli bir zaman boşluğunu temsil eder.*

The upper boundary of the formation with overlying deep sea turbidites of the Lower Nutaysh Member of the Burqan Formation is very sharp. This indicates a strong vertical tectonic uplifting of the Sinai Peninsula and also significant rapid rifting on the Musayr carbonates and formation of deep, half-graben type basins. At some time during the deposition of the Burqan Formation, the Musayr Formation was uplifted in different parts of the Midyan Basin, and brought sediment into the basin. At the outcrop, the Musayr Formation is 66 m thick and consists of cream-colored, medium- to thickly-bedded, various genetically-related carbonate lithofacies. The most common lithofacies types are skeletal grainstone, oolitic grainstone, packstone and wackestone, including abundant coral heads, large oyster shells and clams. Large blocks of the same coral heads were also transported into the basin during the deposition of the turbidites in the Burqan Formation. The oyster beds, corals, and miogypsinid assemblages in the carbonate rocks indicate a warm, shallow marine environment, such as a shallow marine carbonate platform. The stratigraphic position of the carbonate succession sitting directly on the thick evaporite unit supports this interpretation. It is more likely that the shallow marine carbonate platform was situated next to the playa environment where the evaporites were deposited. Due to a rising sea level, the carbonates gradually transgressed on top of the evaporites, forming a transgressive sequence.

Sedimentary successions of the most active syn-rift period

The sedimentary successions deposited during the most active (climax) syn-rift period of the Red Sea, Gulf of Suez and Gulf of Aqaba rifting is defined as the Burqan Formation after the exploration well Burqan-3, which was drilled in the offshore Midyan area of the Saudi Arabian part of the Red Sea. Stratigraphically, it is located between the shallow marine carbonates of the Burdigalian Musayr Formation at the base, and the anhydrite-dominated evaporites of the Late Middle Miocene Magna Formation at the top. The Burqan Formation correlates with the hydrocarbon producing Rudeis Formation in Egypt and the Gulf of Suez. These two formations include the key reservoir and source rock units in Egypt and the Gulf of Suez regions, including fields on the Midyan Peninsula and immediately offshore. As in the case of other similar syn-rift sedimentary successions, the Burqan Formation is highly variable in its thickness, lithofacies assemblages and depositional environment, indicating the presence of small fault-controlled depositional sites within the entire Midyan Basin and Gulf of Suez. All these variations are related to the depth of the Midyan Basin and the effects of periodic uplifting in the Sinai Peninsula, which accounts for the bulk of sediments in the basin. The Late Early Miocene (19-15 Ma) Burqan Formation consists of three wells defined as distinctly different members, namely: 1) Lower Nutaysh (submarine fan turbidites), 2) Upper Nutaysh (Alpine-type glacial sediments), and 3) Subayti (shallow marine marls, mudstone and evaporites) (Figure 3B).

Lower Nutaysh Member

The hydrocarbon-producing Lower Nutaysh Member of the Burqan Formation consists of thick, generally sandstone-dominated, vertically- and laterally- stacked coarsening-and thickening-upward classical turbidite sequences which were deposited in a progradational deep sea submarine fan system (Figures 7A and 7B). The open marine pelagic shales and distal turbidites directly overlie the shallow marine carbonates of the Musayr Formation, indicating rapid subsidence of the basin during the climax of the syn-rift period (Figure 8A). During deposition in the Burqan Formation, the basin topography was very irregular, and in some places, this carbonate platform was a uplifted area and the limestone blocks were eroded and transported into the deep sea turbidites. Therefore, the thickness and type of lithofacies of the Lower Nutaysh Member change from place to place in the basin, controlled directly by the underlying horst-graben system created by repeated syn-rifting tectonic events. In many places, the upper part of the turbidite succession is cut and severely eroded by the glacial unconformity surface formed at the base of the Upper Nutaysh Member (Figure 8B). This unconformity surface is directly overlain by massive, unsorted conglomerate and conglomeratic sandstones, and includes many polished and striated granitic boulders transported from the Neoproterozoic igneous basement of the Sinai Peninsula, where the Alpine glaciers were formed during the Late Early Burdigalian (19 Ma). Measured paleocurrent directions from the axis of submarine canyons, pebble imbrications and flute casts indicate that the sediments forming the Lower Nutaysh Member were derived from several sources.

In most of the measured stratigraphic and sedimentologic sections, the three genetically-related but distinctly different distal, intermediate and proximal turbidites, including submarine canyons forming the uppermost part of the section, have been well-preserved and are easily recognized in the centre of the Midyan Basin (Figure 8A). These three depositional facies are stacked vertically and laterally, separated by massive open marine shales indicating periodic subsidence of the basin and progradation of a new submarine fan system. Şenalp (2016) reported that proximal turbidites and deep submarine canyons occupy the northwestern part of the basin. Their bedding thickness and the grain size of the sandstones gradually decrease in a southeast direction and change into distal fan turbidites and basin floor sediments. However, in other parts of the basin, the same sections have been cut and eroded by the west-east running, deep and narrow U-shaped glacial valleys of the Upper Nutaysh Member.

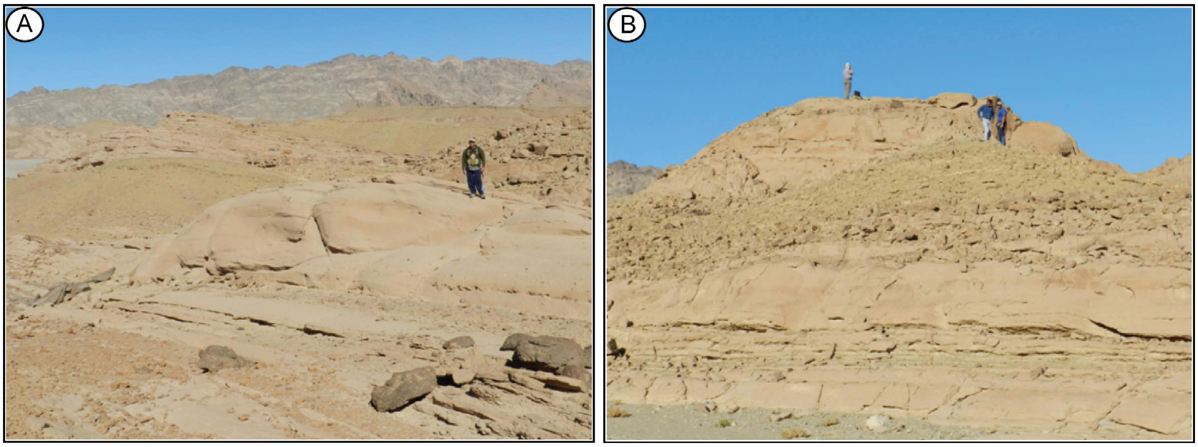

Figure 7. A) Laterally- and vertically-stacked, sand-dominated hydrocarbon-producing turbidite sequences of the Lower Nutaysh Member of the Burqan Formation were deposited in a progradational deep sea fan environment during the climax of the syn-rift period of the Midyan Basin (Şenalp, 2016). **B)** A large number of sandstone samples was collected at outcrops from the upper parts of submarine fans for petrographic examination of their composition and diagenetic changes.

Şekil 7. A) *Burqan Formasyonu'nun Alt Nutaysh Üyesini temsil eden yatay-ve düşey yönde-istiflenmiş, kum-ağırlıklı, önemli miktarda hidrokarbon üretimi yapılan türbidit istifleri Midyan Havzası'nın açılımın zirvesi döneminde denizaltı yelpazeleri içinde çökelmiştir (Şenalp, 2016).* ***B)*** *Çatıyı oluşturan minerallerin ilişkisi için petrografik çalışmalar yapmak, diyajenetik değişimleri anlamak amacına yönelik olarak arazide çok sayıda kumtaşı örnekleri alınmıştır.*

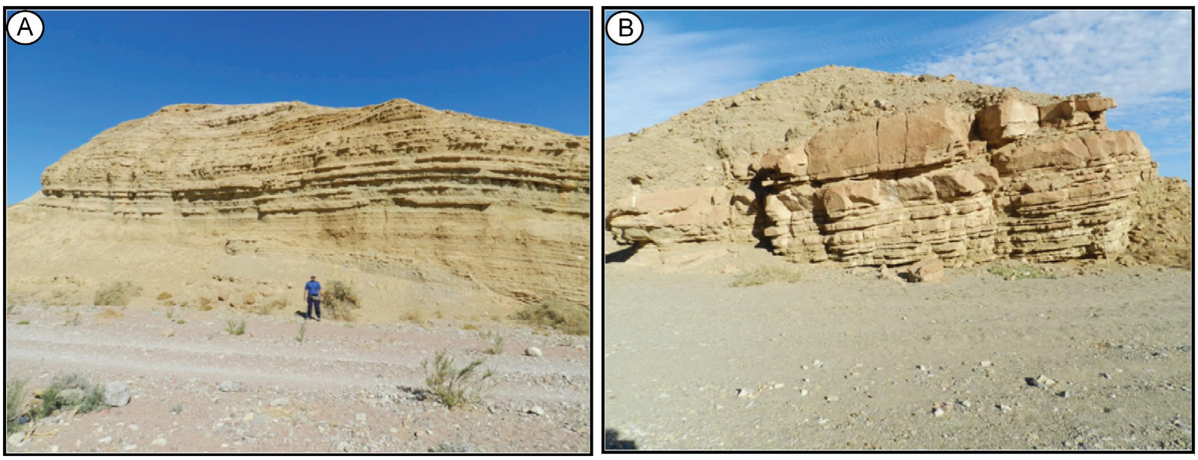

Figure 8. A) Regularly interbedded shale and sandstones of distal and medial (classical) turbidites from the coarsening- and thickening-upwards turbidites sequence of Lower Nutaysh Member of the Burqan Formation. Medial turbidite sandstones are sharp-based, graded-bedded and heavily bioturbated by Ophiomorpha burrows. **B)** The medial turbidite sandstones of the Lower Nutaysh Member are separated from the Upper Nutaysh Member by a strong glacially-formed erosional unconformity surface. This erosional surface is directly overlain by true glacial deposits (moraine) and includes large boulders of polished and striated granite and other types of igneous rocks transported from the glaciated Neoproterozoic crystalline basement located in the Sinai Peninsula.

Şekil 8. A) *Burqan Formasyonu'nun Alt Nutaysh Üyesi'nin önemli bir bölümünü oluşturan normal türbidit istifleri, düzenli olarak ardalanma gösteren kumtaşı ve şeylden yapılmış olup tabaka kalınlıkları ve çökellerin tane-boyu üste* *doğru artar. Kumtaşları keskin tabanlı, derecelenmeli olup biyotürbasyon (Ophiomorpha) yapıları gösterir.* ***B)*** *Alt Nutaysh Üyesi'nin klasik türbidit istifleri Üst Nutaysh Üyesi'nin tabanını temsil eden buzul-kökenli önemli bir aşınma yüzeyi tarafından aşındırılmış ve derince kesilmiştir. Bu aşınma yüzeyinin üzerine gerçek buzul (moren) çökelleri gelir. Buzul çökellerinin içinde Sina Yarımadası'ndan taşınmış yüzeyleri cilalanmış ve çizilmiş çok bol miktarda granitik çakıllar ve bloklar bulunur.*

Three distinct lithofacies, mentioned above, can easily be identified in each laterally- and vertically stacked, coarsening- and thickening-upward progradational turbidite parasequence sets. The lower part of each parasequence is composed of dark gray, massive fissile shale and includes very thin-bedded, very fine-grained, poorly-sorted, and current rippled sandstones. The shales contain pelagic fossils. Total organic carbon (TOC) content of the shales at the very base of the succession is around 3% but this value gradually decreases upward. The middle part of the succession conformably overlies the distal turbidites and consists of regular alternations of shales and sandstones. The sandstones are sharp-based, thin- to medium- bedded, and medium-to fine-grained and pass gradually into the overlying silty shale. The most common sedimentary structures are sole marks, graded-bedding, current-ripples, horizontal and vertical bioturbation - all indicating deposition from turbidity currents. These coarsening- and thickening upward typical medial turbidites of the mid-fan region range in thickness from 6.5 to 18.2 meters. The uppermost part of the coarsening- and thickening upward classical turbidite succession consists of thick, well-bedded, medium- to coarse-grained, well-sorted and friable sandstone. These hydrocarbon-producing reservoir sandstones form the most significant part of the Lower Nutaysh Member. They were deposited in the upper parts of the submarine fan and within the well-defined deep submarine canyons. The total thickness of one of the fully preserved submarine canyons is 34.4 m. In some cases, the base of the canyon has deeply eroded the underlying organically-rich massive distal turbidites and open marine pelagic shales (Figure 9A). In some canyons, less than 0.5 m thick lenses of conglomerates occupy the deepest part of the canyon. There are erratic boulders of basement rocks and coral limestones eroded from the uplifted Sinai Peninsula. Paleocurrent directions of the channel axis indicate N40°W, N30°E and N50°E, coming from the Sinai Peninsula and flowing to the south of the Midyan Basin.

The potential hydrocarbon reservoir sandstone facies may cut directly into the source rock shale facies. The pelagic shales of the next overlying coarsening- and thickening-upward turbidite sequence also overlie the reservoir sandstones. In this case, the reservoir sandstones are completely surrounded by these open marine shales. In this respect, the hydrocarbons generated in the pelagic shales migrate directly into the good quality reservoir sandstones deposited in the submarine canyons. These sandstones are the main and the most prolific hydrocarbon-producing reservoirs in the Midyan Basin and Gulf of Suez. A large number of hand specimens was collected from the sandstones at the outcrop to study their composition, textural parameters and diagenetic changes to understand and predict their reservoir quality in offshore and onshore exploration wells. The best reservoir sandstones, having high porosity and permeability values, were deposited in the lowermost part of the submarine canyons just above the erosional surface, where the depositional energy was high due to the steep depositional slope (Figure 9B).

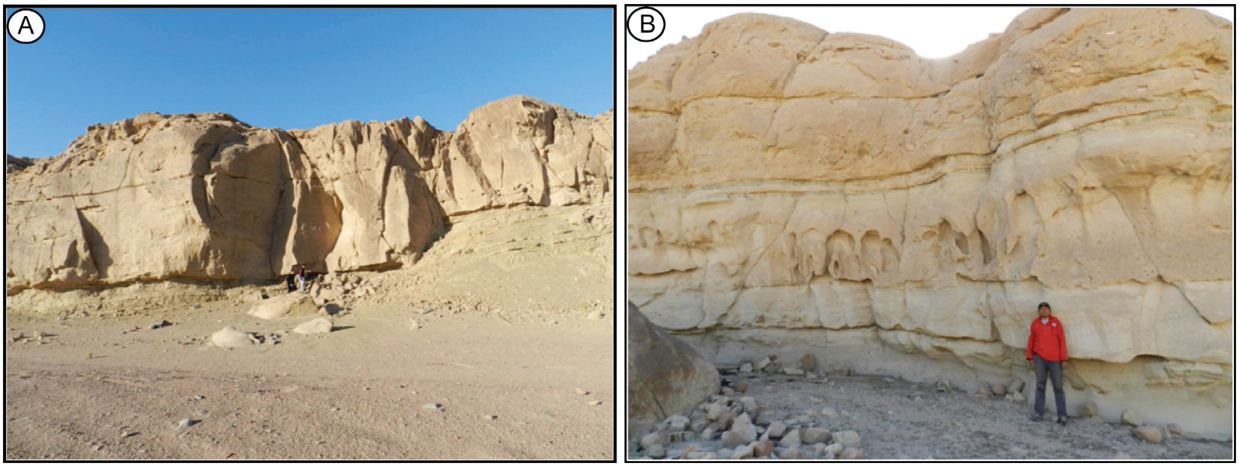

Figure 9. A) Steep-sided submarine canyons formed in the upper part of the Lower Nutaysh Member of the Burqan Formation cut into either regularly interbedded sandstone and mudstone of classical turbidites (medial turbidites) or much deeper into shale-dominated distal turbidites. **B)** Thick-bedded, medium- to coarse-grained, well-sorted, friable, porous and permeable sandstones forming the uppermost part of coarsening- and thickening-upward turbidite parasequences are especially important in the Midyan Peninsula.

Şekil 9. A) *Burqan Formasyonu'nun Alt Nutaysh Üyesi'nin üst kısımlarında bulunan dik-yamaçlı denizaltı kanyonları klasik normal türbiditler veya istifin daha alt kısımlarındaki pelajik şeyller ve ıraksak türbiditler içine kazınmıştır.* ***B)*** *Kalın-tabakalı, orta-iri taneli, iyi-boylanmış, gözenekli ve geçirimli kumtaşları türbidit istiflerinin en üst kısımlarını oluşturur ve ayrıca denizaltı kanyonlar içinde çökelmiştir.*

Upper Nutaysh Member and Formation of Alpine-Glaciation

This newly-defined Upper Nutaysh Member of the Burqan Formation (Şenalp, 2016) consists of various genetically-related glaciogenic deposits, depending on their depositional site in the entire system and on the climatic and tectonic conditions during their deposition. There are continuous lateral and vertical facies changes between them. In many respects, the newly- defined Upper Nutaysh Member is distinctly different from the underlying deep sea turbidite fans of the Lower Nutaysh Member. The glaciogenic deposits were broadly classified as: 1) true glacial deposits (massive unsorted moraine, stratified diamictite), 2) glacio-fluvial deposits (stratified, poorly cross-bedded sandstone containing ice-rafted basement boulders), and 3) glacio-marine deposits (deep sea turbidites and pelagic shales with dropstones of the basement blocks). The true glacial deposits form the most important part of the Upper Nutaysh Member. They fill the deep and narrow U-shaped valleys. The directional geometry of these valleys and the composition, sedimentary structures and textures of the boulders and cobbles indicate an important glacial event occurred in the tectonically-uplifted Sinai Peninsula during Late Early Miocene.

The glacially-formed unconformity surface at the base of the Upper Nutaysh Member cuts deeply into the underlying turbidite sequences of the Lower Nutaysh Member and carbonates of the Musayr Formation. In the southern end of the Midyan Basin, the entire turbidite section has been completely eroded and the glacio-fluvial deposits directly overlie fluvial deposits of the Late Cretaceous pre-rift Adaffa Formation. In many places, this glacially-formed unconformity surface has been severely faulted after its formation.

Al-Laboun (2012) recognized the evidence of glaciation in the Midyan Basin and identified glacially-formed sedimentary structures, polished and striated boulders. He considered them as the products of Pleistocene continental glaciation and informally called them the Midyan Formation. Şenalp (2016) fully agreed that the spectacular polished and striated boulders were deposited by glacial processes, but he differs from Al-Laboun (2012) in respect to their stratigraphic position, type of glaciation and Pleistocene age.

Based on intensive geologic and geophysical studies carried out in northwestern Saudi Arabia, East Africa, Sinai Peninsula, Red Sea, Egypt, and Middle East regions, the presence of a close relationship between the breakup and rifting of the Neoproterozoic Arabian-Nubian Shield and formation of the Midyan Basin was fully understood. Every single stage of this breakup and vertical uplifting along the Red Sea, Gulf of Suez and Gulf of Aqaba rifting has been recorded by well-defined tectono-stratigraphic successions deposited in marine rift-basins, including the Midyan Basin in NW Saudi Arabia (Stern and Johnson, 2010). Garfunkel and Bartov (1977) reported that in the Late Early Miocene (about 19 Ma), the Sinai Peninsula was tectonically uplifted more than 4 km above the sea level. This climax in the rifting period is informally called the "mid-Rudeis event" in Egypt. This very valuable data was a major breakthrough in understanding the location, formation and age of the Alpine-type glaciation in northwest Saudi Arabia. During this time, the Neoproterozoic crystalline basement, early syn-rift Sharik Formation and the carbonates of the Musayr Formation were elevated and formed a high mountain range located to the west and northwest of the Midyan Peninsula. The uplifted topographic elevation was at least a few kilometers (about 1.5 to 2 km) above the permanent snow line. Based on the present-day topographic height and the thickness of the eroded material added to it, the height of the mountains in the Sinai Peninsula is expected to have been at least more than 5,000 meters above sea level when this mountain range was tectonically uplifted during the most severe period (or climax) of rifting. Based on recent stratigraphic and sedimentologic investigations, it is well established that typical Alpine-glaciers were formed in the above-mentioned tectonically uplifted Sinai Peninsula during the deposition of the Late Early Miocene Burqan Formation.

The thick snow cover in the deep depressions on the crests of high mountain ranges above the permanent snow line turned into glaciers and the glacial valleys extended towards the adjacent Midyan Basin and deeply incised the underlying sequences during cold periods. The schematic picture (Figure 10) shows the main geomorphic features of Alpine-type glaciation and terrestrial glacial facies (after Molnia, 2004). However, during warm seasons (interglacial periods), all the glacially-deposited sediments were carried by meltwater further into the deeper parts of the basin. The depositional slope was high and the continental shelf area on the rift shoulders was very narrow.

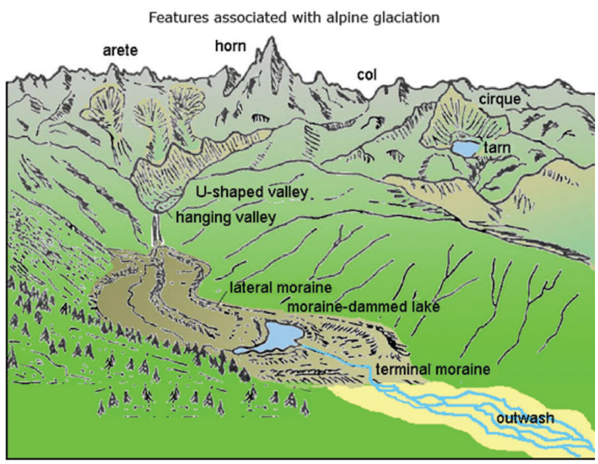

Figure 10. Schematic illustration showing the main geomorphic features of Alpine-type glaciation and terrestrial glacial facies (after Molnia, 2004).

Şekil 10. *Alp-tipi buzullaşmasının jeomorfolojik özelliklerini ve karasal ortamda çökelmiş buzul fasiyeslerini gösterir şematik resim (Molnia, 2004'den alınmıştır).*

Şenalp (2016) used the “zipper-rift tectonic model” to explain many aspects of the depositional systems of this true Alpine-type glaciation and their genetically related glacio-fluvial and glacio-marine sequences in the Upper Nutaysh Member. The zipper-rift tectonic model was developed by Eyles (1993, 2004, 2006) and Eyles et al. (1985) and re-utilized by Eyles and Januzscak (2004a, 2004b, 2007) to support their interpretations to explain the probable diachronism of Neoproterozoic glaciations as the super continent Rodania began to fragment. The same model is perfectly applicable to explain the formation of Alpine-type glaciers on the tectonically-active mountain ranges of the Sinai Peninsula.

The uplifted Neoproterozoic crystalline basement and carbonates of the Musayr Formation forming high mountain ranges in the Sinai Peninsula have been severely dissected by E-W trending faults and N-S trending joint systems, which greatly helped the lifting and removal of basement blocks from their locations. The cubical shape of many erratic blocks supports this structural setting and also the presence of steep slopes and the short distance of transportation between the Sinai Peninsula and Midyan Basin.

GLACIAL AND GLACIOGENIC DEPOSITS IN THE MIDYAN PENINSULA

The presence of Alpine-type glaciation in the Upper Nutaysh Member of the Late Early Miocene Burqan Formation was first recognized and documented by Şenalp (2016). His interpretation was based on many measured stratigraphic and sedimantologic sections in every part of the Midyan Peninsula to understand the sequence of stratigraphy, nature of the contacts between various lithofacies, depositional model, type of glaciation and its age. Şenalp (2016) tried to interpret the source, transportation mechanism and depositional processes of the genetically-related different glacial deposits in the Upper Nutaysh Member. High energy environments in the Midyan Basin are typically dominated by the strong and periodic vertical uplifting of the high mountain range in the Sinai Peninsula, providing necessary conditions for the formation of thick glaciers and also increasing the gradient of the slope. Today, remnants of the typical steep-sided, U-shaped glacial valleys extending towards the Midyan Basin are common and well-preserved at the holy places of Jebel Musa (Touri Sina Mountain). One of the direct manifestations of glacier advancement is the deposition of moraines (terminal and lateral) within the well-defined, straight, narrow, steep-sided, U-shaped valleys (Figure 11). The three-dimensional geometry, trend of these glacial valleys, and lateral facies changes in these glacial deposits indicate clearly that these glacial valleys originated and were eroded in the Sinai Peninsula in the west and were transported to the Midyan Basin in the east.

Figure 11. Photograph showing remnants of the well-defined, narrow, deep and steep-sided, symmetrical U-shaped glacial valley that cuts into the Neoproterozoic crystalline basement at the holy place of Jebel Musa (Touri Sina) in Sinai Peninsula. There are many polished and striated boulders at the bottom of the valley.

Şekil 11. *Sina Yarımadası'nın kutsal Musa Tepesi'nin bulunduğu bölgede Neoproterozoyik kristalin temel içine kazılmış, çok iyi korunmuş, simetrik, U-şeklinde buzul vadilerin kalıntıları bulunur. Bu vadilerin tabanında çok miktarda yüzeyleri cilalı ve çizikli bloklar yer alır.*

Various true glacial and glaciogenic (glacio-fluvial and glacio-marine) facies and facies associations observed in the Midyan Peninsula are very complex; therefore, it is difficult to interpret the exact depositional processes and depositional medium. There are all sorts of variations and lateral/vertical transitions between these facies. This complexity reflects the presence of a large variety of sedimentary processes and depositional environments during the development of the Midyan Basin. of course, these complexities are associated with periodic tectonic uplifting, changes in the thickness of the ice mass and gradient of the slope of the Sinai Peninsula, number of glacier expansions, stadial conditions or withdrawal/ retreating during interglacial periods and the relative rise in sea level, as suggested by Le Heron et al. (2009, 2010).

The natural fluctuations of both ice sheets and Alpine glaciations during glacial periods cause multiple phases of ice advance and retreat on the margins of the ice sheets (Şenalp and Al-Laboun, 2000; Şenalp, 2006a, 2006b; Hirst et al., 2002; van der Vegt et al., 2012; Şenalp, 2016; Şenalp et al., 2018). These fluctuations are often associated with significant erosion and reworking of previously-deposited sediments interspersed with depositional phases, leading to often complex and spatially very heterogeneous facies associations (Şenalp, 2016). A large number of shale samples was collected from the underlying Lower Nutaysh Member and the overlying Subayti Member to define the age and duration of the glacial period. The Paleontologic data of the shale samples provided by Hughes and Filatoff (1995) indicate that the glaciation lasted about five million years in Late Early Miocene (19-15 Ma).

In the measured sections at least five cycles of glacial advances and retreats (interglacial) were recorded. Each glacial cycle lasted about one million years and was separated by the strong glacially-formed unconformity surface formed at the base of the glacial valleys, which are directly overlain by moraines. In the measured sections the total thickness of each cycle ranges between 21.6 m and 203.27 m. The oldest unconformity surface cuts directly into the classical turbidites and represents the boundary between the Lower Nutaysh and the Upper Nutaysh members. The younger three glacially-formed unconformity surfaces cut into the thick-bedded glacio-fluvial sandstones which were deposited during the deglacial period and are also overlain by massive, unsorted true glacial moraines, without any sign of reworking. Several measured sections indicated that the spectacular deep U-shaped glacial valleys cut deeply into the classical turbidite sequences of the Lower Nutaysh Member in the west; towards the east they cut progressively into the early syn-rift Musayr and Sharik formations. Şenalp (2006a) also reported the presence of distal moraines unconformably overlying the Late Cretaceous pre-rift Adaffa Formation.

In connection with the periodic uplift of the Sinai Peninsula, the depth of the Midyan Basin has increased periodically causing slumping and sliding, thereby transporting the previously-deposited glacial deposits from shelf areas into deeper parts of the basin. Glacial deposits transported from the Sinai Peninsula consist of erosional products of the Neoproterozoic igneous basement complex and carbonates of the Musayr Formation mixed with mudstones of the Sharik Formation. The glacial deposits observed in the Midyan Peninsula range from true glacial (moraines or tillites) facies to meltwater streams (glacio-fluvial) and glacio-marine (diamictites, dropstones and turbidites) facies (Şenalp, 2016). It is also true that under less colder conditions (interglacial periods), some of these true glacial deposits (mainly erratic boulders) were reworked and transported by slides, slumps and gravity flows into the Midyan Basin, and were then deposited within the thick-bedded and coarse-grained sandstones of proximal turbidites of the submarine fan system. It is well-established that there is a continuous transition from true glacial deposits to glacio-fluvial and glacio-marine deposits. In this respect, there are no well-defined and clear cut boundaries between different processes and different depositional systems because tectonics and climate have a significant impact on these processes. The geologic definitions and general characteristics of these various glacial and glaciogenic deposits will be discussed in the following sections.

Moraines (Tillites)

In the Midyan Peninsula moraines were deposited in 80-100 m deep and about 3.4-5 km wide U-shaped valleys and are exposed on west-east extending ridges with sharp edges; they contain evidence of both direct glacial derivation and gravitational reworking at the ice margin. They originate from the vertically-uplifted Sinai Peninsula; therefore, the distance of transportation was short and the moraines were not reworked. Their original depositional characteristics and the textural features of the blocks and large boulders indicate that their glacial features are well-preserved along the western flank of Wadi Al Hamd between Al-Bad' and Magna towns. The thickest and most impressive moraines were deposited and are fully-preserved within the deep and narrow U-shaped glacial valleys located in the northern part of Midyan Peninsula close to the Sinai Peninsula. They are formed from debris previously carried along by a glacier from the vertically-uplifted Sinai Peninsula.

Moraines consist of massive, unsorted debris ranging in size from blocks, large boulders and pebbles to silt-sized glacial flour. They consist predominantly of pink granite and dark gray-to-black igneous basement rocks of the Neoproterozoic basement and blocks of Musayr limestone; showing significant variations in roundness ranging from well-rounded to angular. Their size ranges from small pebbles and large boulders to huge blocks exceeding 2.5 m in diameter. In general, most the well-rounded boulders are polished and striated. The matrix between the large boulders is typically characterized by fine-grained sediments (clay to silt) eroded from the underlying deep sea turbidites of the Lower Nutaysh Member (Şenalp, 2016). Some blocks have been split along the joint system. The glacial valleys extend in a west-east direction. Their depth gradually decreases in this direction and their U-shaped geometry is lost, because the valley becomes wider and shallower. The thickness and grain size of the boulders of moraines decrease significantly. The moraine facies laterally change into the polymictic conglomerate facies deposited in glacio-fluvial and finally glacio-marine environments. In the proximal parts of the glacial valleys, typical moraines include huge basement blocks transported from the tectonically-uplifted Sinai Peninsula (Figures 12A and 12B).

One prominent glacial valley, located on the coastal highway 8.5 km south of Magna town, is exposed in its transverse section and displays the rather narrow, steep-sided U-shaped cross-sectional geometry incised into turbidites of the Lower Nutaysh Member. It is 3.4 km wide (extending between 28°20′45.7″ N; 34°43′23.1″ E and 28°19′16.7″ N; 34°42′27.4″ E) and about 98 m high (deep), as measured from the road. The valley is completely filled with massive, unsorted moraines including large polished and striated erratic boulders and blocks of various basement rocks up to 2.5 m in diameter. The matrix is typically reworked clay to silt derived from the underlying deep sea turbidites of the Lower Nutaysh Member (Şenalp, 2016). These basal and pushed moraines, including erratic boulders, were deposited in the more proximal parts of the valleys during the low stand ice sheet expansion during cold climate periods and show no sign of evidence of reworking. In some cycles, lateral facies changes are present between the true glacial deposits occupying the deepest part of the glacial valley and the sides of the valley.

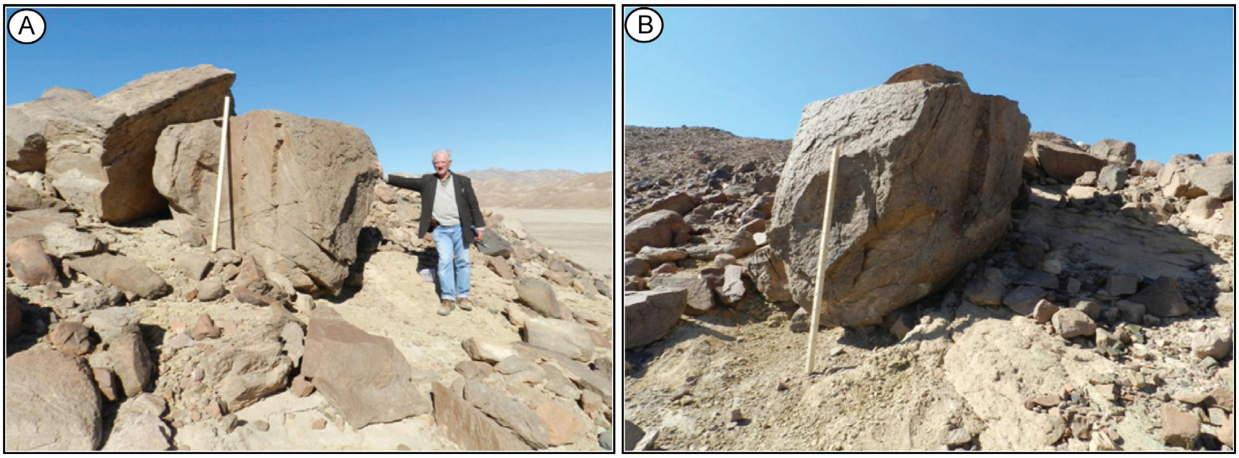

Figure 12. A) and **B)** In proximal parts of the glacial valleys, typical moraines include huge basement blocks transported from the tectonically-uplifted Sinai Peninsula. Some blocks have split along the joint system and green shale has been eroded from the deeply-eroded turbidites of the Lower Nutaysh Member.

***Şekil 12. A)** ve **B)** Buzul vadilerinin en yukarı kısımlarında, gerçek buzul çökelleri (tipik morenler) tektonik olarak yükselmiş Sina Yarımadası'ndan taşınmış çok büyük boylarda bloklar içerir. Bu bloklar buzullaşma olayı ile faylanmış ve eklemlenmiş Neoproterozoyik kristalin temelden kolayca kaldırılıp buzulların tabanında taşınmış ve buzulların erimesi sonucu çökeltilmiştir.*

Some glacially-transported boulders have been pushed and injected into the underlying non-glacial graded bedded sandstones through strong internal dynamic forces and subglacial glaciotectonic pressure exerted by the moving ice mass during the maximum glaciation period (Figures 13A and 13B). This relationship gives a wrong impression, as if the boulders are part of the sandstones of turbidites and were deposited at the same time. However, the top surfaces of some of these blocks have been faceted, polished and striated, clear indications of their glacial origin (Figures 13C and 13D).

Polymictic conglomerates

Polymictic conglomerates of glacial origin are composed of thickly-bedded to massive heterogenic sediments, consisting of a large amount of poorly-sorted conglomerates, pebbly sandstones and clean cross-bedded sandstones with small amounts of siltstones and mudstone matrix. The blocks and boulders consist mainly of igneous basement rocks sometimes exceeding 2 m in diameter. There are also large boulders of red-colored coral head limestones, eroded and transported from the faulted and vertically-uplifted Musayr Formation in the Sinai Peninsula. The sandstones are thickly-bedded (ranging between 0.5 and 2 m) and are laterally continuous for long distances. They are generally very coarse to fine-grained and show well-developed graded bedding, indicating that they were deposited by high density turbidity currents.

Glacio-fluvial and outwash plain sediments

In the Midyan Peninsula, there are several glacial paleovalleys where well-defined and continuous lateral facies change from true glacial deposits to glacio-fluvial and glacio-marine deposits. The glacial valleys, exposed between Al-'Bad and Magna towns, form well-defined linear ridges about 80-100 m above ground level and extend in a west-east direction, suggesting that

Figure 13. A) and **B)** Many large polished and striated boulders and blocks (outsized clasts) of igneous basement rocks protrude from the sandstones of proximal turbidites. They were injected into the sandstones from the slowly moving ice mass. **C)** and **D)** Large blocks of igneous rocks transported from the Sinai Peninsula were injected deeply into thickly-bedded sandstones of the proximal turbidites due to strong internal dynamic forces exerted by the moving ice mass. Their top surfaces were faceted, polished and striated during transportation.

Şekil 13. A) *ve* ***B)*** *Çok sayıdaki cilalanmış ve çizilmiş çok büyük boylardaki kristalin temel bloklar buzullarla yavaşça taşınarak yakınsak türbidit kumtaşları içine sokulmuştur.* ***C)*** *ve* ***D)*** *Sina Yarımadası'ndan buzullarla taşınan aşırı büyüklükteki Neoproterozoyik kristalin bloklar üzerinde hareket ettikleri yakınsak türbidit kumtaşları içine buzulların etkili olduğu dinamik kuvvetlerle sokulmuştur. Bu buzul kökenli blokların en üst yüzeyleri cilalanmış ve çiziklenmiştir.*

they originated in the Sinai Peninsula to the west of Midyan Peninsula. The most important lateral facies changes occur along the long axis of the glacial valleys. The nature of the sedimentary sequence within the glacio-fluvial successions displays important facies variations; from proximal parts in the west of the Midyan Basin to distal parts in the east. The proximal parts consist of medium- to thick-bedded and coarse to very coarse-grained sandstone, including large boulders (Figures 14A and 14B). Sedimentary structures include poorly-developed cross-bedding and current ripple marks. There is a large amount of polished and striated boulders and blocks which are still deeply embedded in the sandstones of the proximal glacio-fluvial deposits (Figures 14C and 14D). The depth of glacial valleys becomes distinctly shallower from west to east and the size of the faceted, polished and striated boulders in the moraines becomes much smaller.

The distal glacio-fluvial succession in the eastern part of the Midyan Basin consists of well-stratified, medium- to thickly-bedded, medium- to fine-grained, well-sorted and strongly trough cross-bedded sandstones with high reservoir potential in the basin. This distal glacio-fluvial facies is also characterized by the presence of polished and striated boulders, randomly distributed in the succession.

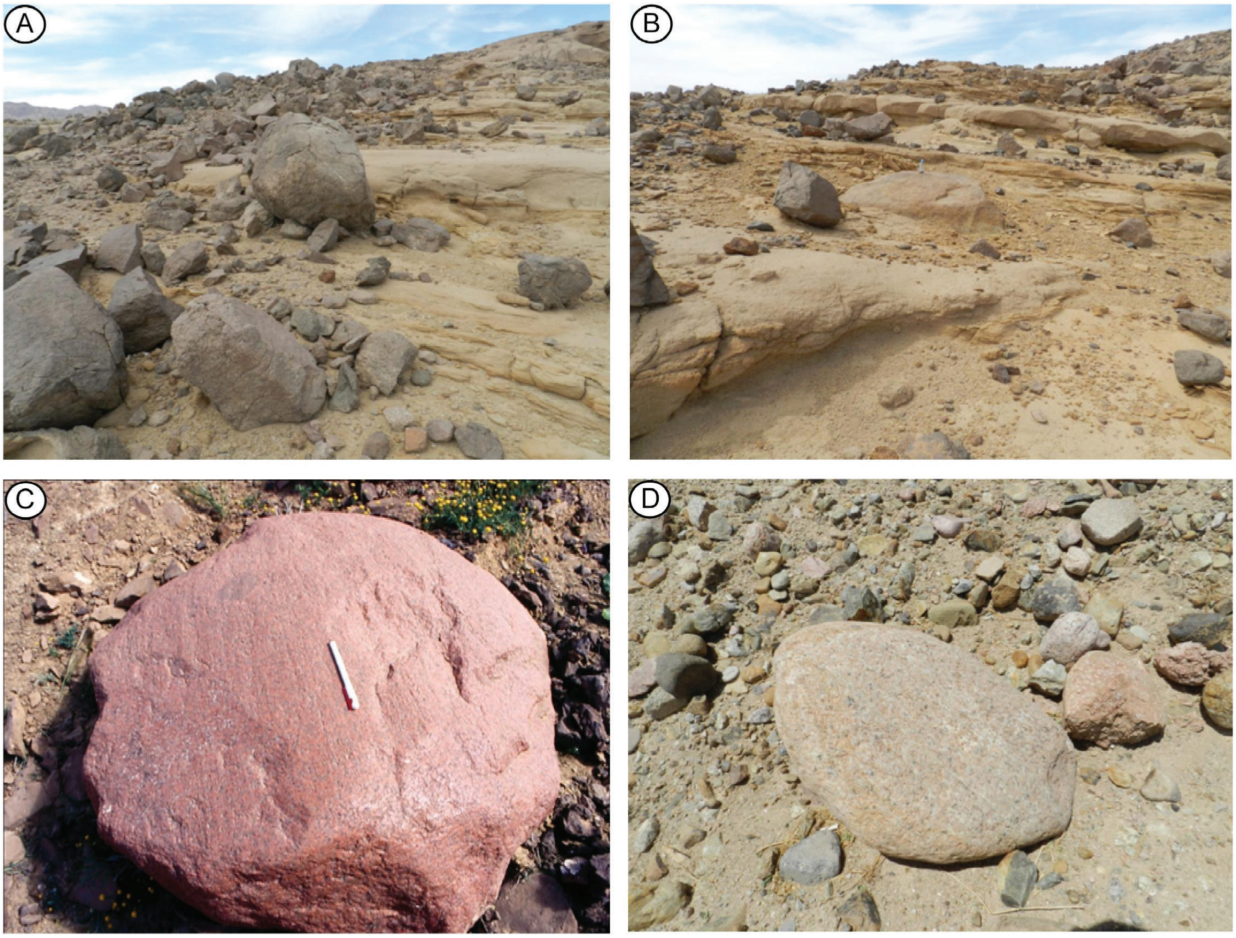

Figure 14. A) and **B)** A proximal glacio-fluvial succession deposited in the western part of the Midyan Basin. Outsize, polished and striated granite blocks are deeply embedded in the sandstones. **C)** and **D)** Faceted, polished and striated pink-to-red boulders of granite and various other basement rocks in the moraines filling glacial valleys cutting into the Upper Cretaceous Adaffa Formation, observed in Wadi Aynunah. These boulders are located on the north side of the highway between Al Khuraybah and Wadi Aynunah.

Şekil 14. A) *ve* ***B)*** *Midyan Havzası'nın batı kısmında çökelmiş buzul-flüviyal istif. Bu istif içinde aşırı büyüklükte cilalanmış ve çiziklenmiş granit blokları kumtaşlarının içine gömülmüştür.* ***C)*** *ve* ***D)*** *Yüzeylenmiş, cilalanmış ve çizilmiş pembe renkli granit bloğu ve kristalin temelden türemiş bloklar Aynunah Vadisi'nde, Üst Kretase yaşlı Adaffa Formasyonu'nu kesen buzul vadilerini dolduran morenler içinde gözlemlenmiştir. Bu mostra Al Khuraybah ile Aynunah Vadisi arasında uzanan karayolunun kuzeyinde bulunur.*

Glacial erratics

The term erratic is used in this study to refer to erratic blocks, described as: large masses of rock, often as big as a car (Figures 15A and 15B). They have been transported by glacier ice and lodged in a prominent position in the glacier valleys or scattered over hills and plains. Erratics are formed by glacial ice, resulting from the movement of ice during periods of glacial advances. Glaciers erode any kind of bedrock by multiple processes, such as 1) abrasion, 2) scouring, 3) plucking, and 4) ice thrusting. Examination of their mineralogical character leads to identification of their sources and short distance of transportation. Şenalp (2016) reported that the huge glacial erratics in Midyan Peninsula originated from the vertically-uplifted Sinai Peninsula and transported in west-east orientated glacial valleys. They were carried mainly by ice rafting and floatation during the multiple periods of glacial advance. The big blocks or large boulders of the igneous basement rocks and some coral limestone of the Musayr Formation appear to have floated onto the present day topographic surface over a very large area north of Al ‘Bad town. They are the erosional products of the underlying glacial deposits and are found jutting out of the glacio-fluvial sandstones. Huge blocks of the igneous rocks are completely embedded in the sandstone and shale sequences (Şenalp, 2016). The large erratic blocks were transported by glacial valleys onto the continental shelf and later they were further carried periodically into the Midyan Basin through slumping and sliding during the deposition of the turbidite facies. The composition and the texture of the boulders in the glacio-marine deposits are the same as those found in the moraines filling U-shaped valleys. In general, most of the boulders are rounded, faceted, polished, striated and even slightly grooved. The polymictic conglomerates are very significant, because they show the continuous lateral facies variation between all the glacial and glaciogenic depositional environments and also the geological processes responsible for their deposition.

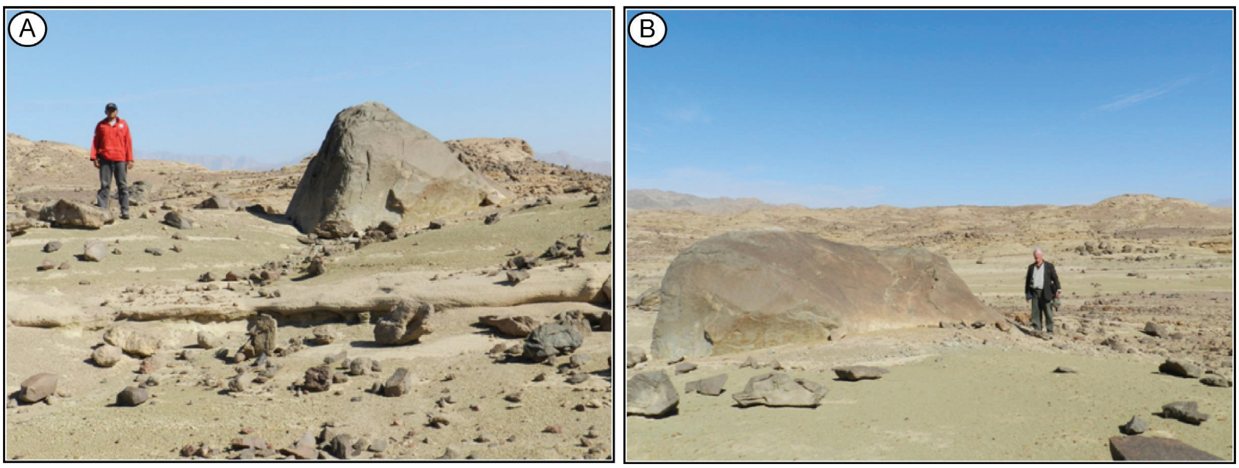

Figure 15. A) and **B)** Huge glacial erratic blocks and various sizes of igneous basement rocks are completely embedded in the interbedded sandstone and shale sequences of the open marine environment.

***Şekil 15. A)** ve **B)** Çok büyük boylarda ve düzensiz olarak dağılmış magmatik kayaç blokları, Burqan Formasyonu’nun Üst Nutaysh Üyesini oluşturan denizel ortama buzullar tarafından taşınmış ve aratabakalı olarak çökelmiş kumtaşı ve şeyl istifi içine derince gömülmüşlerdir.*

Glacio-marine sediments

Towards the distal parts of the glacial paleovalleys, the true glacial deposits change gradually into glacio-fluvial polymictic conglomerates and finally into glacio-marine sediments where the ice-rafted dropstones (Matthew et al., 1996) are found. Deglaciation sequences are formed during ice retreat phases, caused by melting of the ice due to climatic change. They were laid down during a sea-level rise and ice margin retreat with the volume of meltwater and the amount of sediment input depending on temporary still stands of the ice margin during the retreat phase (Şenalp and Al-Laboun, 2000). The glacio-marine deposits were deposited by high density turbidity currents most likely issuing from an ice margin located at the head of the valley and are thus interpreted as subaqueously-deposited ice-proximal outwash facies deposited on an ice-fed submarine fan. The absence of any wave-formed facies indicates that deposition occurred below the wave base, possibly reflecting the steepness of the basin margin. Subaqueous glaciogenic facies contain numerous ice-rafted boulders of red-colored coral head limestones, eroded and transported from the faulted and vertically-uplifted Musayr Formation in the Sinai Peninsula together with crystalline basement-derived lithologies.

Glacio-marine sediments in the measured sections have provided valuable records suggesting five stages of glacial advance and retreat of the ice sheet fluctuations beyond the limit of glacial erosion in the Midyan Peninsula. The presence of four or possibly five glacial advances is best recorded in the shallower part of the sea where the thick marine and turbidite sandstones were cut from their tops by glacially-formed unconformities and overlain by typical unsorted moraines representing the next period of glacial advance. The accumulation of ice and sediments in relation to eustatic changes were reported by (Schack Pedersen, 2012, Figure 16). As result of frequently occurring tectonic uplifting in the Sinai Peninsula and the faulted rift margins of the Midyan, these glacially formed deposits were periodically remobilized from their original positions and were then transported through mass movements (sliding and slumping), debris flow, grain flow, and high density turbidity currents and deposited in the deeper parts of the basin. Spectacular polished and striated blocks and boulders of igneous basement rocks were deposited interstratified with the shallow marine sandstones and proximal turbidites of the Upper Nutaysh Member. In the thick sections of proximal turbidites, large polished and striated igneous boulders are embedded in the coarse- to very coarse-grained, graded-bedded and poorly cross-bedded sandstones (Figures 17A and 17B).

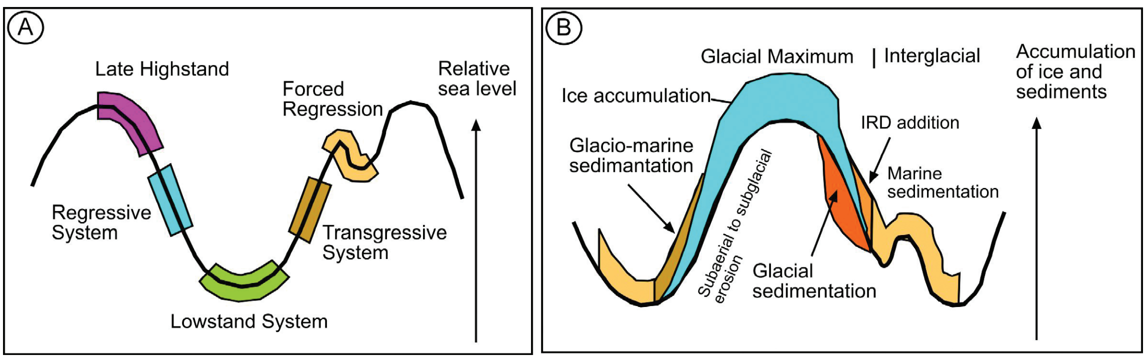

Figure 16. Glaciodynamic sequence stratigraphy: accumulation of ice and sediments in relation to eustatic changes (adapted from Schack Pedersen, 2012).

Şekil 16. *Buzul-dinamik sekans stratigrafisi: deniz seviyesi değişimleri ile ilişkili olarak biriken buzul ve sedimanter çökeller (Schack Pedersen, 2012'den alınmıştır).*

Figure 17. A) Thick-bedded, proximal turbidite sandstones deposited during deglacial periods were cut by glacially-cut unconformity surfaces during periods of glacial advance during cold periods. **B)** Glacially-formed unconformity surfaces cutting into proximal turbidites are directly overlain by massive, unsorted small boulder and pebble conglomerates of moraines deposited during glacial advance. They are thought to record subglacial erosion and glacio-tectonism in ice-contact environments and represent direct glacial derivation during the period of glacial advances.

Şekil 17. A) *Buzulların eridiği dönemlerde çökelen kalın-tabakalı yakınsak türbidit kumtaşları soğuk iklim koşulları döneminde oluşan buzulların büyüyüp yamaç aşağı hareket etmeleri sırasında oluşan aşınma yüzeyleri tarafından derince kesilmiştir.* ***B)*** *Yakınsak türbidit kumtaşlarını kesen, buzulların oluşturduğu aşınma yüzeyleri üzerine masif, buzulların ilerlemesi sırasında çökelen hiç boylanma geçirmemiş ve içlerinde küçük çakıldan büyük blok boyuna kadar değişen malzeme bulunan morenler tarafından örtülmüştür.*

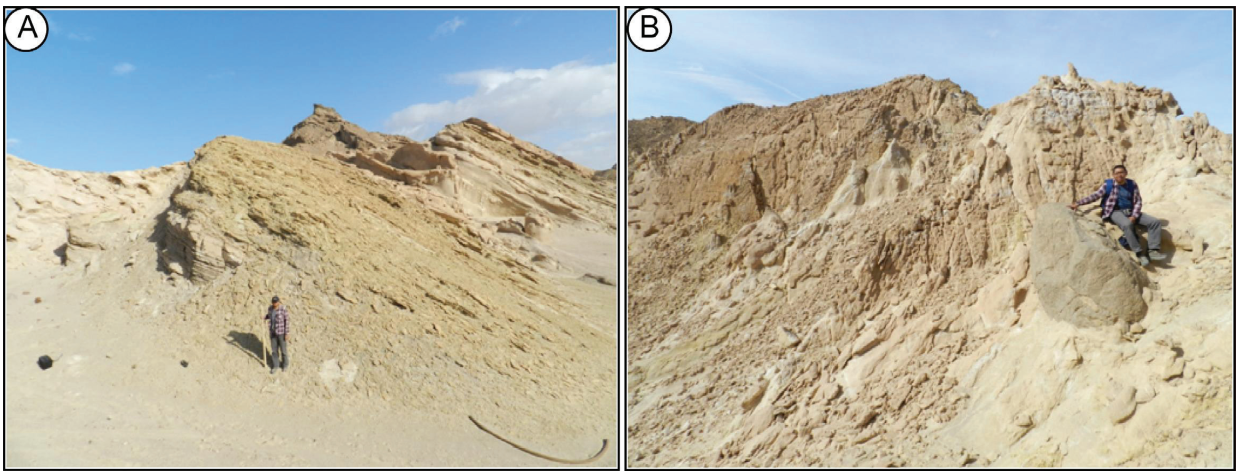

Figure 18. A) Glacial dropstones are very common in the thick, coarsening- and thickening-upward classical turbidite sequences of the glaciogenetic Upper Nutaysh Member of the Burqan Formation, deposited during long-lasting interglacial periods (about 5 million years). **B)** Large, polished and striated granitic boulders also dropped onto the sea bed from the floating ice mass and were deposited together with classical (medial) and distal turbidites (Location: 28°21′09.15″N/34°42′55.4″E).

Şekil 18. A) *Açık deniz ortamında sürüklenen buzul kütlelerinin erimesi sonucu buzulların taşıdığı büyük boy granit ve diğer magmatik kökenli bloklar Burqan Formasyonu'nun Üst Nutaysh Üyesi'nin yakınsak türbidit fasiyesinin* *kalın-tabakalı kumtaşları içine düşmüştür. Bu kesit 5 milyon yıl süren buzullaşma olayının buzul-arası dönemlerde çökelmiştir.* ***B)*** *Cilalanmış ve çizilmiş yüzeylere sahip büyük boy granit blokları deniz ortamında gemiler gibi yüzen buzul kütlelerinin erimesi sonucu derin deniz ortamında çökelen klasik türbidit ve ıraksak türbidit istifleri içine düşmüşlerdir (Lokasyon: 28°21'09,15"K/34°42'55,14"D).*

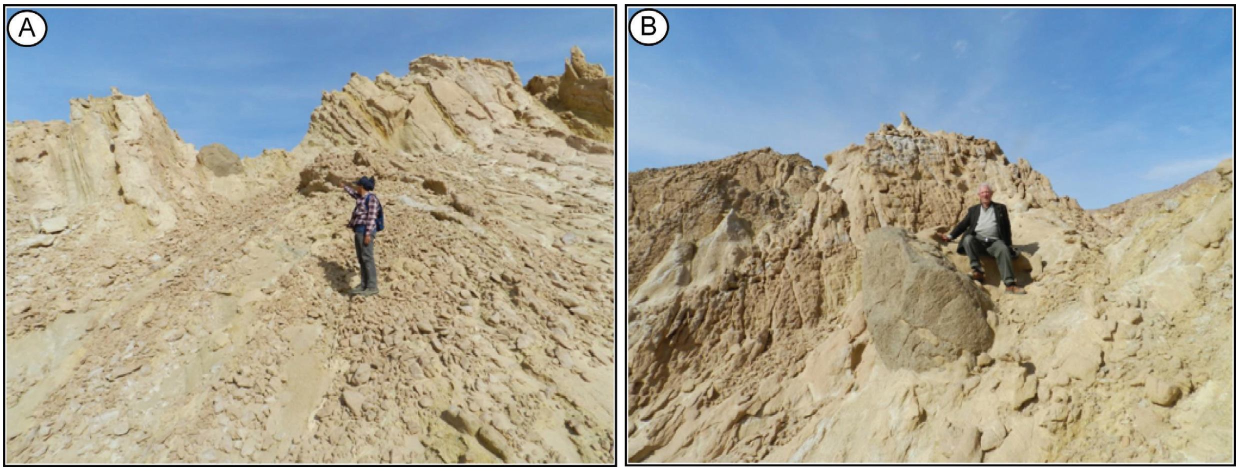

Figure 19. A) Two stacked coarsening- and thickening-upward turbidite sequences separated by deep marine shale facies. This shale facies includes numbers of large, polished and striated granite boulders. **B)** This polished and striated granite boulder dropped onto the sea bottom from an iceberg floating in the deep open ocean. The impact of the granite boulder on the pelagic shale was considerable and formed a shallow depression (Location: 28°21′10.9″N/34°43′54.4″E).

Şekil 19. A) *Düşey yönde istiflenmiş iki üste-doğru kabalaşan ve kalınlaşan istifler derin deniz şeyl fasiyesi ile birbirinden ayrılmıştır. Bu derin deniz şeyl fasiyesi içinde çok sayıda açık deniz ortamında yüzen buzul kütlelerinden düşmüş büyük cilalanmış ve çizilmiş granit blokları bulunur.* ***B)*** *Düşen granit blokları, içine düştükleri henüz taşlaşmamış derin deniz şeyl fasiyesinin üzerinde büyük etki yapmış ve onları deforme ederek çukurluklar oluşturmuştur (Lokasyon: 28°21'10,9"N/34°43'54,4"E).*

Almost at the final melting phase of the ice mass, the above-mentioned facies pass distally into well-bedded graded turbidite sandstones and open marine pelagic shales. There are numerous polished and striated igneous ice-rafted blocks that dropped from the floating ice mass (or iceberg) into the fine-grained distal turbidites and massive pelagic shales during their deposition and greatly impacted these sediments (Figures 18A and 18B; Figures 19A and 19B).

Glacial dropstones

In the measured sections, the dropstones of the granite blocks and boulders occur in the thinly-bedded distal turbidites and massive deep pelagic shales, indicating clearly that glaciation occurred during the Early Miocene (19-15 Ma) in the Midyan Peninsula. This is good evidence to suggest that glaciers reached sea level during their advance during a five million years-long glacial period. The critical evidence is the vertical positions of the blocks and presence of impact depressions beneath the polished and striated granitic dropstones. These indicate that the pelagic soft mud had been squeezed up around the edges of the falling igneous rock block (Figures 18A and 18B; Figures 19A and 19B). A depositional model of the glacio-marine facies deposited in the Upper Nutaysh Member of the Burqan Formation is presented by Şenalp (2006a) in Figure 20.

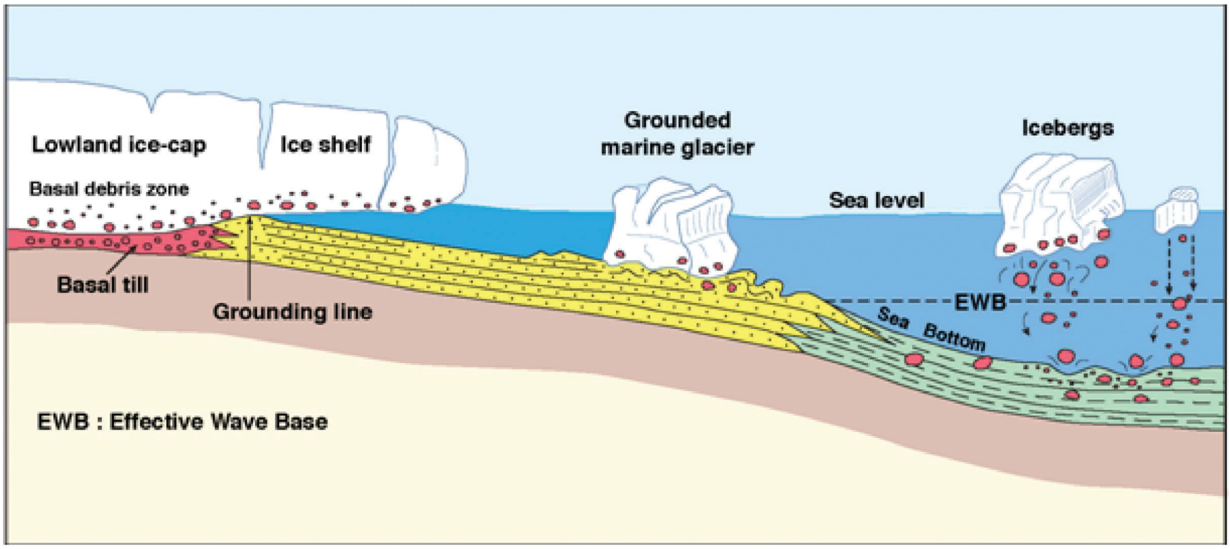

Figure 20. Interpreted depositional model of glacio-marine facies deposited in the Upper Nutaysh Member of Burqan Formation. This model is based on the sedimentologically studied and measured sections at outcrops in every part of the Midyan Peninsula (Şenalp, 2006a).

Şekil 20. *Burqan Formasyonu'nun Üst Nutaysh Üyesi içinde çökelmiş olan buzul-denizel fasiyeslerinin çökelme ortamının yorumlanması. Bu model Midyan Havzası'nın her bir bölgesinde mostra veren stratigrafik istiflerde ölçülen sedimantolojik kesitlere dayandırılmıştır (Şenalp, 2006a).*

MEASURED SEDIMENTOLOGIC SECTIONS IN THE MIDYAN BASIN

Several stratigraphic and sedimentologic sections of the Midyan Basin were measured with a 1.5 m long wooden Jacob staff to understand the lithofacies types for each of the five periods of glacial advance and retreat during the long-lasting (about 5 million years) Alpine glaciation. This fieldwork forms the most important part of this paper. Each glacial advance is represented by deeply-cut erosional surfaces which may be called the Type-1 sequence boundary. The section was measured both in the transverse and longitudinal sections of U-shaped glacial valleys. Continuous lithofacies changes from true glacial deposits to glacio-fluvial and glacio-marine deposits were clearly recognized in the basin. In many cases, the glacio-fluvial sandstone deposits, including large boulders of polished and striated granite, conformably overlie the true glacial deposits. On the other hand, many large ice-rafted granitic boulders dropped from the icebergs into the distal turbidites and deep marine pelagic shales. These glacial and glaciogenic deposits are described in the following sections and each distinct lithofacies unit is numbered.

Section 1: true glacial and glacio-fluvial successions

The first measured section from the interstratified true glacial (moraines) and glacio-fluvial deposits is located south of Magna town east of the coastal highway. The base of the measured section starts in a narrow valley, located at 28°20′54.4″ N., 34°43′56.3″ E. In this section, four periods of glacial advances were recorded in a glacially cut unconformity surface overlain by thick, massive and unsorted moraines. Thickly-bedded sandstones represent the glacio-fluvial successions (Figures 21A and 21B) .

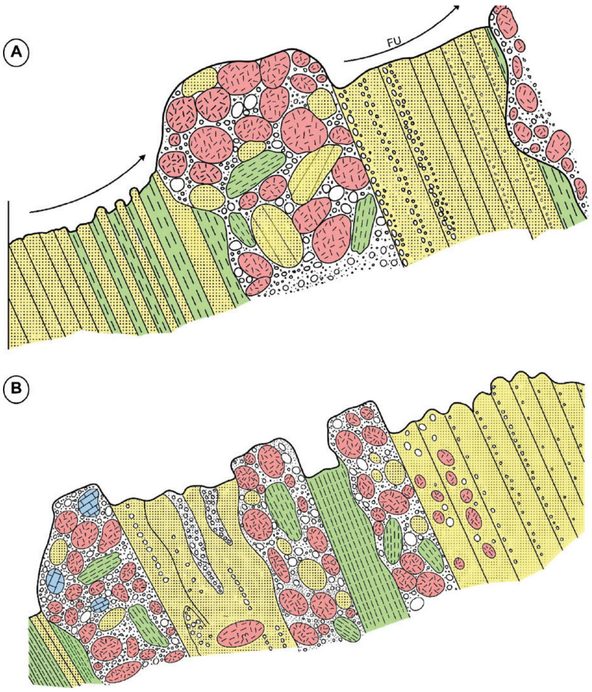

Figure 21. Section 1 represents true glacial and genetically-related glacio-fluvial successions. A) This cross section shows the lowermost part of measured Section 1 in the Midyan Basin (located at 28°20′54.4″N/ 34°43′56.3″E) representing the close relationship between true glacial deposits (moraine) and glacio-fluvial sandstones, which are strongly dominated by glacial processes. The base of the moraine represents the first glacial advance cut deeply into the turbidite sequence. It is overlain by conglomeratic sandstones of glacio-fluvial origin. This figure includes Unit 1 (distal turbidites deposited before Alpine glaciation formed) and Unit 2 (base of the glacial valley, thick tillite and overlying glacio-fluvial deposits). B) This is a continuation of the previous section and represents the middle and upper part of measured Section 1. The base of this section is located at 28°20′51.15″N/34°43′57.1″E and includes units 3, 4, 5, and 6. It represents several stages of glacial advance (moraines) deposited during a cold climate period. The base of each moraine deposit represents a significant glacially-formed unconformity surface. At least five stages of glacial advance and retreat were recorded in the Midyan Basin.

Şekil 21. *Kesit 1 gerçek buzul ve kökensel ilişkili buzul-flüviyal istifleri gösterir. A) Bu enine-kesit Midyan Havzası'nda ölçülmüş Kesit-1 in en tabanını temsil eder (lokasyon: 28°20'54,14"K/34°43'56,13"D). Bu kesit, gerçek buzul çökelleri (moren) ile buzulların erimesi sonucu ortaya çıkan flüviyal sistemin oluşturduğu ve bloklar içeren kumtaşları ile temsil edilmiştir. Moren çökellerinin tabanındaki aşınma yüzeyi havzaya gelen ilk buzul dönemini temsil eder. Bu aşınma yüzeyi Alt Nutaysh Üyesi'nin buzullaşma döneminden önce çökelmiş olan klasik türbiditlerin (Birim-1) içine derince kazılmıştır. Birim-2, buzul vadisinin tabanını, üzerine gelen kalın moren istifini ve onun üzerine uyumlu olarak gelen buzul-flüviyal bloklu kumtaşları ile temsil edilmiştir. B) Bu kesit, alttaki kesitin devamıdır ve Kesit-1 in orta ve üst kısımlarını temsil eder (lokasyon: 28°20'51,15"K/34°43'57,1"D) ve Birim- 3, 4, 5 ve 6'yı içerir. Bu kesit, iklimin soğuması sonucu genişleyen ve kalınlaşan buzulların Midyan Havzası'na doğru ilerlemesi sonucu ortaya çıkan buzul-kökenli aşınma yüzeyleri ve bu yüzeyler üzerine çökelen moren çökellerini temsil eder. Havzanın bu kısmında beş buzul ilerlemesi ve geri çekilme aşamaları gözlemlenmiştir.*

Unit 1: This lowermost unit is only 20 m thick and is partly preserved, because its upper part is deeply cut and eroded by the overlying glacially-formed unconformity surface overlain by thick moraine deposits. This unit consists of regularly interbedded shale and a sandstone section of typical classical turbidite; representing the Lower Nutaysh Member of the Burqan Formation.

Unit 2: This unit is 51.5 m thick and extends between two glacially-formed erosional surfaces. It consists of two distinct, but genetically-related depositional facies. This erosional surface represents the first glacial advance into the Midyan Basin. The lower interval, directly overlying the erosional surface, is 32 m thick and represents the best example of a moraine. It is massive (unstratified), unsorted and the size of the material ranges from small pebbles to large boulders. There is a small amount of sand matrix but no evidence of reworking of these true glacial deposits. The conformably overlying section of this unit 2 is 19.5 m thick and distinctly different from the true glacial (moraine) deposits. This section consists of well-stratified, planar bedded sandstones which are very coarse- to coarse-grained in the lower parts and medium-grained in the upper parts. Pebbles of granite and other igneous basement rocks are completely absent in this unit. Some thick sandstone beds show normal grading. The upper section of this unit is interpreted as glacio-fluvial deposits.

Unit 3: The sharp, irregular erosional lower boundary of this unit represents the second period of glacial advance (Figures 22A and 22B). The upper contact is also marked by the third period of glacial advance. The base of the unit is best exposed at location 28°20′51.5″N, 34°43′57.1″E. Total thickness of this unit was measured as 115 m; however, distinctly different subunits were identified. The lower subunit is 37 m thick, massive, matrix-supported and unsorted moraine. The material consists of angular and subrounded pebbles and boulders of mainly granite and other igneous rocks. Some granite boulders reach up to 50 cm in diameter. The upper subunit conformably overlies the lower subunit and consists of thickly-bedded, coarse- to very coarse-grained sandstone deposited by the fluvial system when the ice mass started melting.

Unit 4: This unit is 21.6 m thick and extends between two glacially formed erosional surfaces. It consists of 17.6 m of identical moraine facies overlying the very irregular erosional surface of the third glacial advance (Figures 23A and 23B). The overlying 4 m thick interval is massive bedded, friable pebbly sandstone. The overlying second subunit is 78 m thick and has very heterogeneous lithofacies, indicating both glacial and glacio-fluvial deposition during the deglacial period. This interval is massive- to thickly-bedded with cut and fill structures. There are lenses of conglomeratic horizons and diffused pebbles in the gray to buff-colored very coarse-grained and poorly-sorted sandstone. Also, there are a few granite boulders about 1.2 m in diameter. This subunit was deposited by both debris flows and normal melt water fluvial flow.

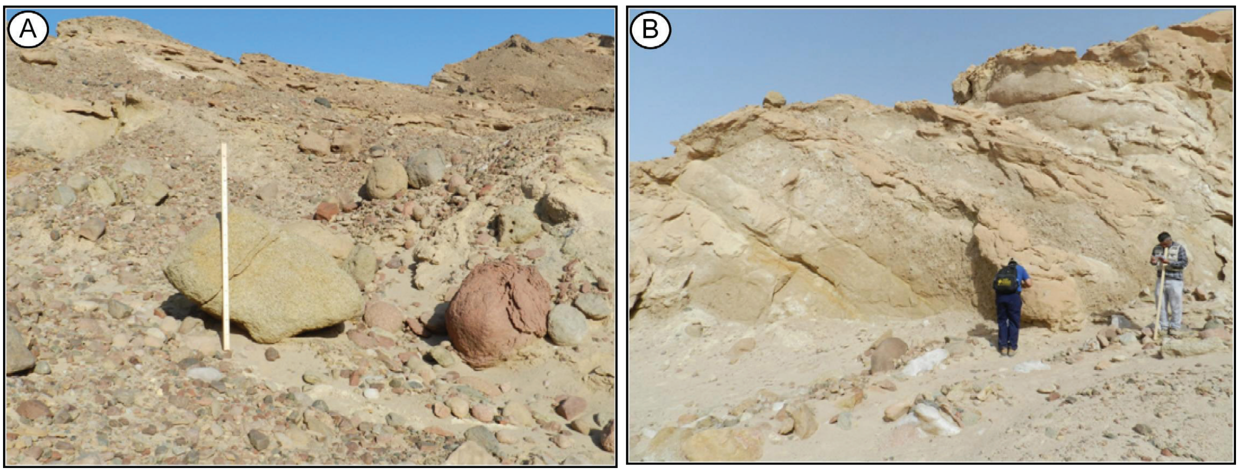

Figure 22. True glacial and genetically-related glacio-fluvial deposits observed in measured Section 1. **A)** The massive unsorted moraines were deposited during the second glacial advance. **B)** The glacio-fluvial sandstones were deposited during a later deglaciation period.

Şekil 22. *Ölçülmüş Kesit-1 de gözlemlenmiş gerçek-buzul (moren) ve genetik ilişkili buzul-flüviyal çökelleri.* ***A)*** *Masif, boylanmasız morenler, buzulların ikinci periyodunun ilerleme aşamasında çökelmiştir.* ***B)*** *Buzulların erimesi sonucu ortaya çıkan ve gerçek buzul çökelleri ile genetik ilişkili olan büyük bloklar içeren buzul-flüviyal çökeller.*

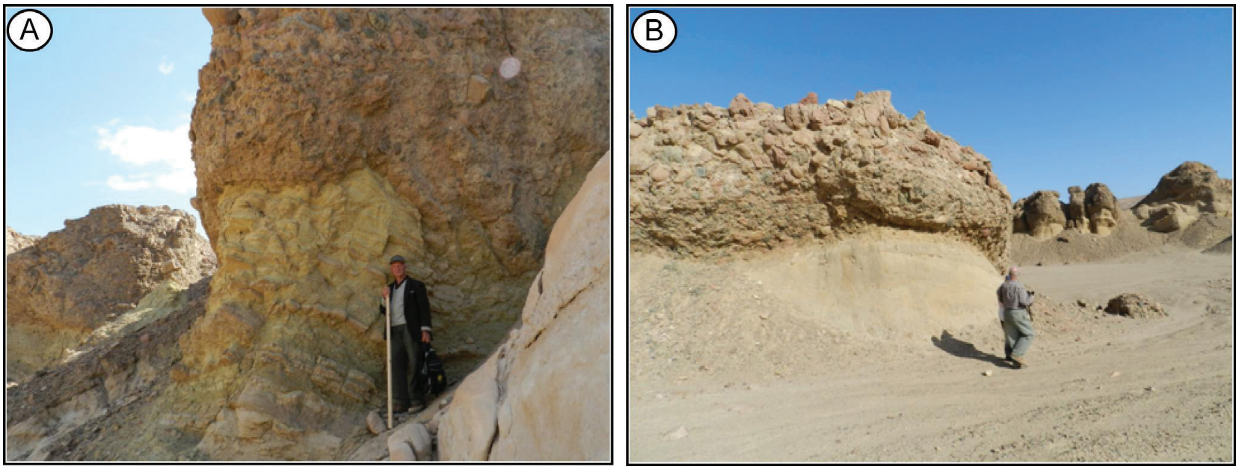

Figure 23. Glacially-formed unconformity surfaces recognized in measured Section 1. **A)** A sharp and irregular unconformity surface was formed at the base of the third glacial advance and overlain by a massive and unsorted moraine. **B)** A similar glacially-formed erosional unconformity surface was formed at the base of the fourth glacial advance which cuts into the distal parts of the glacio-fluvial deposits. The overlying unsorted moraine is 3.25 m thick (Şenalp, 2016).

Şekil 23. *Ölçülmüş Kesit-1 de tanımlanan buzul-kökenli aşınma yüzeyleri.* ***A)*** *Keskin, düzensiz buzullaşmanın üçüncü döneminde buzulların tabanında ortaya çıkan aşınma yüzeyi. Bu yüzey de diğer aşınma yüzeylerinde olduğu gibi masif, tabakalanmasız ve boylanma geçirmemiş moren çökelleri ile örtülmüştür.* ***B)*** *Daha önceki buzul-kökenli aşınma yüzeylerinde olduğu gibi buzullaşmanın dördüncü döneminde oluşan aşınma yüzeyi de aynı özellikleri gösterir. Bu aşınma yüzeyi alttaki buzul-flüviyal kumtaşlarının içine kazılmıştır. Bu yüzeyin üzerine doğrudan gelen tipik boylanmasız moren çökellerinin kalınlığı 3,25 metre olarak ölçülmüştür (Şenalp, 2016).*

Unit 5: This 203.25 m thick unit represents the final stage of glacial advance recorded in this section. The lower 3.25 m thick interval just above the fourth glacially-formed erosional surface is a typical massive, unsorted moraine with no evidence of reworking (Location: 28°20′51.7″N, 34°54′058″E). The overlying 200 m thick section is very poorly stratified coarse- to very coarse-grained pebbly sandstone. There are large and small granite and igneous basement boulders. Poor grading (upward fining) in the pebble size represents a typical glacio-fluvial environment. The type of stratification and size of the boulders clearly indicate that the depositional site of this glacio-fluvial system is much closer to true glacial deposits. Debris flow may be the dominant transporting process.

Unit 6: This is the last unit of the measured section. There is no evidence of glacial influence in the deposition of this unit. It is 57 m thick and consists of three subunits. The lower subunit is 29 m thick and consists of interstratified thin-bedded, fine- to very fine-grained sandstone and gray shale intervals. It represents a flood plain environment. The 23 m thick middle subunit is a continuous fining-upward channel fill sequence. The lower erosional boundary represents a channel base, but the upper boundary is transitional with overlying interbedded shale and very thin-bedded sandstones. The lower 10 m interval is coarse- to medium-grained and includes small pebbles along the scoured surfaces. The 13 m thick remainder of the unit consists of medium- to thin-bedded, fine- to very fine-grained sandstone. The 4 meter thick third subunit is shale-dominated with a minor number of thin sandstone beds.

Section 2: glacio-marine successions

The second sedimentologic section was measured from the fully-preserved Upper Nutaysh Member which represents mainly the glacio-marine succession. It consists of classical coarsening- and thickening-upward turbidite sequences overlain by fining- and thinning-upward submarine canyon deposits. Ten distinctly different but genetically-related units were identified in the measured section. Evidence of glaciation is indicated by the common occurrence of faceted, polished and striated ice-rafted (dropstones) granite and other igneous crystalline boulders in various intervals of the fully marine succession. The measured section is exposed on the south side of the coastal highway located 5.6 km south of Magna town. The base of the section is located at 28°21′00.4″N, 34°43′37.9″E. It is 636 m thick and consists of a coarsening- and thickening-upward classical turbidite parasequence of the Lower Nutaysh Member in the lower part and laterally- and vertically-stacked fining- and thinning-upward glacio-fluvial and glacio-marine parasequences of the Upper Nutaysh Member. These two genetically-different depositional facies were separated by the glacially-formed unconformity surface. The lower contact of the section with the Musayr Formation is not exposed but its transitional upper contact with the post-rift Subayti Member is well-exposed.

Unit 1: This 50 m thick unit is a coarsening- and thickening-upward progradational turbidite sequence deposited in the deep sea submarine fan environment. The lower 28 m is greenish gray, massive shale but there are some (less than 5%) thin-bedded, very fine-grained and bioturbated sandstone beds in the upper parts. The overlying unit consists of regularly interbedded, thin-bedded, medium- to fine-grained, graded bedded, and bioturbated sandstone (60%) and green fissile shale (40%). This interbedded lithofacies is gradually overlain by classical turbidite facies. The sandstones (80-90%) are medium- to thick-bedded, coarse- to fine-grained (mostly medium-grained), graded bedded, well-sorted and bioturbated. The shales occur as thin beds between the sandstone beds.

Unit 2: This unit is also another coarsening- and thickening-upward parasequence but is not fully preserved. Its upper part is cut and eroded by the submarine channel forming the base of the first fining- and thinning-upward sequence. This contact is defined as a type-1 sequence boundary, indicating a sharp drop in sea level and migration of the upper or inner-fan part of the submarine fan environment. Total thickness of this parasequence is 155 m. The lower 101 m is greenish gray massive shale without any sandstone beds. It was deposited in a deep sea basin. The upper 54 m consists of regularly-interbedded sandstone and shale of typical turbidite facies of the lower mid-fan region. The sandstones are thin- to medium-bedded, fine- to very fine-grained, graded bedded, and bioturbated. Ice-rafted (glacial dropstones) boulders of polished and striated granite and other igneous rocks cover the outcrop.

Unit 3: This is the first fining- and thinning-upward parasequence (Figure 24A). It is 66 m thick and starts with a strong erosional surface. Its lower 24 m is composed of massive- to thickly-bedded, coarse- to very coarse-grained pebbly sandstone, friable and showing multiple graded-bedding. There are also polished and striated granitic boulders. This facies was deposited in the deepest part of the channel of the submarine fan environment. Striated granitic boulders have a definite glacial origin. They were reworked, re-mobilized and transported from the previously-deposited moraines, and were then re-deposited in the submarine canyons. There is 4 m thick, planar-bedded, coarse- to medium-grained sandstone conformably overlying the underlying channel-fill deposits which are transitional with the upper 42 m thick section of this unit. This uppermost unit consists of an interbedded shale (80%) and sandstone (20%) sequence of typical classical turbidite facies. The shale beds are greenish gray to green-colored and range in thickness from 5 to 10 cm. Individual sandstone beds are 10-32 cm thick and display flute and groove casts at their base and horizontal burrows on their top surfaces. The thick beds are very coarse-grained (with some granule-size igneous pebbles) in the lower parts and fine upward into medium- to fine-grained sandstone. The thin sandstone beds are strongly bioturbated. All the sedimentary structures indicate their deposition through well-developed turbidity currents.

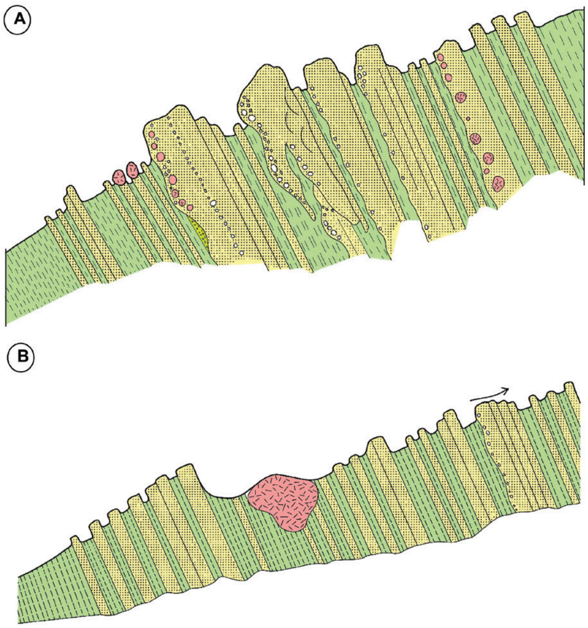

Figure 24. Sedimentologic cross-section of measured Stratigraphic Section 2 in the Midyan Basin. **A)** The base of the section is located at 28 21 004 N/34 43 37.9 E. This shows in detail the glacio-fluvial and glacio-marine (turbidite) succession and indicates a continuity between glacial, fluvial and marine processes. This section includes all the sedimentary facies between Unit 1 and Unit 8. The thickly-bedded sandstones, including large igneous boulders, show graded bedding representing proximal turbidite facies of the deep submarine fan environment. **B)** This figure represents the upper part of the measured sedimentologic cross-section. The base of the section is located at 28 21 09.5 N/34 43 55.9 E. This shows the glacio-marine (dropstones) and classical turbidite succession, and deep sea sediments. This figure relates to units 9 and 10. Huge granitic boulders (dropstones) are very common and completely embedded in the deep sea turbidites representing the final depositional site of the Alpine-type glaciation.

Şekil 24. *Midyan Havzası içinde ölçülmüş Kesit-2 sedimantolojik kesitini gösterir.* ***A)*** *Bu ölçülmüş kesit gerçek buzul, buzul-flüviyal ve buzul-denizel (türbidit) çökelme fasiyeslerinin önemli özelliklerini ve aralarındaki yanal fasiyes değişimlerini açıklamaktadır. Ölçülmüş kesit alttan üste doğru Birim- 1 den Birim- 8 olarak tanımlanmış tüm çökelme fasiyeslerini içerir. İçinde büyük boyda magmatik kayaç blokları içeren, kalın-tabakalı, dereceli-tabakalanma gösteren kumtaşları yakınsak türbidit fasiyesini temsil eder.* ***B)*** *Bu şekil ölçülmüş kesitin üst kısımlarını temsil eder ve Birim- 9 ve Birim- 10 içinde temsil edilmiş buzul-denizel, ıraksak türbidit fasiyeslerini ve derin deniz çökellerini temsil eder. Çok büyük boy granit blokları eriyen buzullardan deniz tabanına düşerek pelajik şeyllerin içine gömülmüşler ve düştükleri yerde çukur oluşturmuştur.*

Unit 4: This unit is 45.72 m thick and forms the second fining- and thinning-upward sequence. The base of the sequence represents a submarine canyon which cuts deeply into an interbedded shale and sandstone sequence of classical turbidites. The lower 39.70 m thick section consists of laterally- and vertically-staked fining upward multiple channels. Conglomerates and conglomeratic sandstones, with occasional boulders, overlie the base of each channel (Figure 24A). Most of the pebbles and boulders are polished and striated, indicating their glacial origin. The sandstones overlying the conglomerates are light brown, massive- to thick-bedded and show normal graded bedding from coarse- to medium sand. Thin green shales are partly-preserved between channels. Conformably overlying this section is 6.2 m thick regularly interbedded shale and a graded bedded, current rippled sandstone section representing medial turbidities.

Unit 5: This 32.40 m thick unit represents another fining- and thinning-upward parasequence. It starts with a strongly erosional channel base, cutting into the thin-bedded turbidite section. The lower 22.40 m section is a single channel-fill sequence consisting of medium- to thin-bedded, fine- to very fine-grained, well-sorted and friable sandstone and includes a few small igneous pebbles. The overlying 10 m is composed of regularly interbedded sandstone and shale representing classical (medial) turbidite facies.

Unit 6: This 27 m thick unit is the fourth fining- and thinning-upward parasequence. Its erosional base is located at 28°21′10.9″N, 34°43′54.4″E. The lower 20 m is a massive- to thickly-bedded, very coarse- to coarse-grained, strongly fractured pebbly sandstone facies and shows short cycles of multiple-graded bedding. It is gradually overlain by 7 m thick planar bedded, medium- to fine-grained sandstone. The common sedimentary structures, such as the complete graded bedding and well-developed current ripples in the uppermost part of the section, suggest final deposition. The sediments filling the canyon are mostly reworked glaciogenic sediments transported by slumps, slides and turbidity currents from the narrow continental shelf areas and are called glaciogenic diamictite.

Unit 7: This 18 m thick unit conformably overlies the underlying fining-upward channel-fill sequence and consists of interbedded sandstone and a shale sequence of classical turbidite facies representing the lower and middle parts of the submarine fan environment.

Unit 8: This 60 m thick unit represents another fining- and thinning-upward turbidite parasequence. The lower 10 m thick section consists of 6 m of coarse- to very coarse-grained, unsorted pebbly sandstone of debris flow deposits. There are small boulders of granite and other igneous rocks (Figure 24A). It is overlain by 4 m thick medium-bedded, coarse -to medium-grained, graded-bedded, well-sorted, friable and good reservoir sandstone covered with thin lenses of shale. The upper 50 m thick section consists of vertically- and laterally- stacked channel-filled sandstones. There are erosional remnants of shale beds between the channels. This interval is very thickly bedded, coarse- to medium-grained and well-sorted; showing well-developed multiple graded-bedding.

Unit 9: This unit consists of two genetically related, vertically-stacked, well-developed classical coarsening- and thickening-upward turbidite parasequences and represents the best examples of genetically related glaciogenic deposits and deep sea turbidites (Figure 24A). The lower 50 m thick parasequence starts with 10.5 m thick, light gray to green-colored massive shale and includes lenses of the conglomerates, including granite and basement rocks, enclosed in the shales (Figure 24B). The upper parasequence is 30 m thick and includes one single and isolated granite block embedded in the shale (location: 28°21′10.9″N., 34°43′54.4″E.). The heavy weight of the polished and striated granitic block made a significant impact on the underlying pelagic shale and opened a depression. This important observation on the well-exposed outcrops in the deeper parts of the basin indicates dropstone origin of the granitic block from a floating ice-mass (iceberg) in the open sea. It is suggested that the thick ice-mass advanced into the shallower parts of the sea during the long-lasting (about 5 million years) glaciation.

This glacio-marine pelagic shale facies is gradually overlain by 16 m thick, thin- to medium-bedded, fine- to medium-grained, graded bedded sandstone with thin beds of shale, representing classical turbidite facies. The upper part of this turbidite parasequence is 23.5 m thick, consisting of light brown, very thickly-bedded, coarse- to very coarse-grained conglomeratic sandstone, also including a number of striated granitic boulders. The thick sandstone beds show multiple graded bedding. This facies was transported from rift margins and was deposited by high density turbidity currents. The upper coarsening- and thickening-upward progradational turbidite parasequence of this unit is 38.5 m thick. Its lower part is 8 m of massive, gray-green shale and indicates a marine flooding surface. Its upper part is 30.5 m thick and consists of thin-bedded, fine- to very fine-grained bioturbated sandstone.

Unit 10: This uppermost unit is 49 m thick and consists of alternating sandstone and shale sequences. The thickness of green, massive shale sequences ranges from 4-10 m. The thickness of the sandstone sequences ranges from 1.5 m to 4.5 m. The 4.5 m thick sandstone unit shows a fining- and thinning-upward sequence deposited in a small turbidite channel. The uppermost fining-upward parasequence is 7 m thick. Its lower 5 m section consists of massive- to thickly bedded, coarse- to very coarse-grained, well-sorted and friable sandstone with very good reservoir quality. The middle part is medium-grained, trough cross-bedded and shows multiple graded bedding, indicating frequent fluctuations in the current regime. The overlying 2 m thick interval is composed of regularly interbedded green shale and thin-bedded, very fine-grained, bioturbated sandstone. The uppermost part of the unit is 14 m thick and consists of 2.5 m of massive green shale overlain by 11.5 m of mostly green shale interbedded with thin-bedded, fine- to very fine-grained and bioturbated sandstone. One 2.5 m thick lenticular sandstone body was deposited in a small channel in the distal part of the submarine fan. Based on the measured outcrop sections, a structural and depositional model of the Midyan Basin is shown in Figure 25.

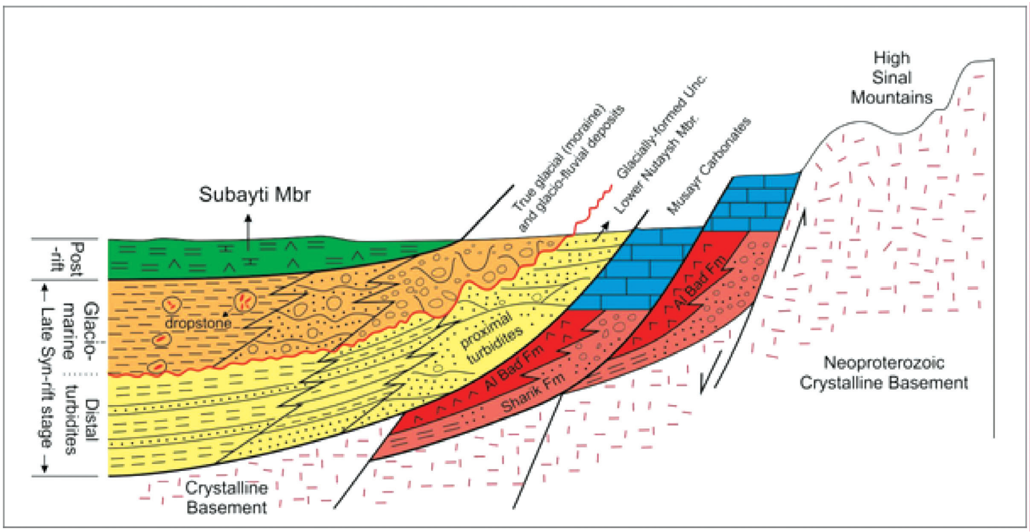

Figure 25. Interpreted geologic model illustrating the genetic relation between the uplifted Sinai Peninsula and the stratigraphy and sedimentology of the successions deposited during the Early Miocene syn-rift (early and late) periods in the Midyan Basin. (Mbr: Member, Fm: Formation, Unc: Unconformity).

Şekil 25. *Sina Yarımadası'nın tektonik olaylarla yükselmesi ile yakın ilişkili olarak Midyan Havzası içinde Erken Miyosen zamanında açılma sırasında (erken ve geç açılma) ortaya çıkan istifin stratigrafik ve sedimantolojik modeli.*

POST-RIFT SUCCESSIONS IN THE MIDYAN BASIN

The sedimentary successions, representing the post-rift stage (between 14 and 11.6 million years ago) of the Red Sea, Gulf of Suez and Gulf of Aqaba were fully-preserved on outcrops and in the subsurface (Figure 3B). They were deposited in very shallow marine and playa environments under warm climatic conditions representing post-glacial facies. These mainly evaporitic successions include the Subayti Member of the Burqan Formation and the Magna Group (Figures 26A and 26B). The Magna Group consists of two evaporite-bearing formations: (1) the Lower to Middle Miocene Jabal Kibrit Formation; and (2) the Middle Miocene Kial Formation (Hughes and Johnson, 2005). In the Midyan area, the Magna Group forms an extensive blanket of gypsum and anhydrite that covers much of the central part of the basin.

Subayti Member

The Subayti Member overlies the underlying glaciogenic Upper Nutaysh Member and forms the youngest member of the Burqan Formation; it is conformably overlain by the massive evaporites of the Magna Formation (Şenalp, 2016). This is one of the most important cap rock facies in the Midyan Basin, Red Sea, Gulf of Suez and Egypt (Şenalp, 2016). The best outcrop is located along the coastal highway south of Magna. The section consists of interbedded light gray to cream-colored, massive shale, siltstone, marl, evaporitic

Figure 26. Post-rift depositions exposed in the Midyan Basin of NW Saudi Arabia. **A)** Outcrop of the Subayti Member located on the coastal highway south of Magna town. It consists of light grey, massive shale, mudstone, calcareous mudstone (marl) and evaporitic mudstone, interbedded with siltstone and a minor amount of thin-bedded sandstone. **B)** The type locality of Magna Formation near the town of Magna, located on the east coast of the Gulf of Aqaba. These thick massive evaporites form a significant cap rock on the sandstone reservoirs of the Burqan Formation.

Şekil 26. *Kuzeybatı Suudi Arabistan'ın Midyan Havzası içinde açılma-sonrası ortaya çıkan sedimanter istifler.* ***A)*** *Magna köyünün güneyinde Akabe körfezinin kıyısında mostra veren Burqan Formasyonu'nun Subayti Üyesinin fotoğrafı. Bu mostra, açık gri renkli, masif şeyl, çamurtaşı, kalkerli çamurtaşı (marn) ve bu ince-taneli çökeller ile aratabakalı olan ince-tabakalı kumtaşları ve miltaşları ile temsil edilmiştir.* ***B)*** *Akabe Körfezi'nin doğu kıyısı üzerinde yer alan Magna köyü yakınında mostra veren Magna Formasyonu'nun tipik yeri. Bu kalın ve masif evaporitler Burqan Formasyonu'nun hidrokarbon üretimi yapılan rezervuar fasiyesleri üzerinde çok önemli ve geçirimsiz bir örtü kaya fasiyesi oluşturur.*

mudstone, and thin-bedded gypsum-cemented sandstone (Figure 26A). Hughes and Johnson (2005) reported the presence of a minor amount of limestone in the subsurface. The thickness of the section is 150 m at the outcrop and 3.680 ft (1.122 m) in the Burqan-3 (BRQN-3) well. The succession shows a shallowing-upward regressive sequence. The lower parts of the member are deposited in the shallow marine environment on the continental shelf. This environment gradually became restricted and turned into evaporitic basins. The Early Middle Miocene age (Langhian) of the member was determined from the subsurface palynologic data (Hughes and Filatoff, 1995).

Magna Formation

The evaporite-dominated Magna Formation is best exposed in the town of Magna and forms the uppermost part of the succession that was deposited after the rifting event was completed in the Midyan Peninsula. The massive evaporitic sequence of anhydrite and gypsum deposits covers much of the central part of the Midyan Basin (Figure 26B). Large-scale slump structures in the evaporites of the Magna Formation can easily be observed in almost every part of the outcrop. The thickness of the formation ranges from 150 m thick at the outcrop (Motti et al., 1982) and 300 m in exploration wells drilled in the Red Sea and offshore Midyan Peninsula (Dullo et al., 1983). Based on the presence of age-diagnostic planktonic foraminifera and calcareous nannofossils collected from the surface and subsurface samples of the Magna Group, it was dated as Early to Middle Miocene (Hughes and Filatoff, 1995).

HYDROCARBON POTENTIAL OF THE MIDYAN BASIN

The Midyan Peninsula has great potential for hydrocarbon exploration and for production of oil and sweet gas in the onshore and offshore Midyan Basin and the Red Sea (Figure 27). Intensive fieldwork at outcrops and subsurface and laboratory studies carried out by different departments of Saudi Aramco and Saudi universities indicated that the shallow marine carbonates of the Musayr Formation and the thick sandstone-dominated turbidite successions of the Lower Nutaysh Member of the Burqan Formation have potential source rock and reservoir rock facies in the Burqan field area of the Midyan Basin (Hughes and Johnson, 2005). This has been confirmed in the exploration well AI-Wajh South-1 (AWSO-1) at a depth of 2875-3819 m, making it a 944 m thick oil producing reservoir interval (Hughes and Johnson, 2005). The transgressive open marine shales overlaying the fossiliferous carbonates of the Musayr Formation are rather rich in organic matter (about 3-5% TOC) and provide a good potential source rock to generate hydrocarbon and migrate upward into the sand-dominated proximal turbidites and submarine canyons.

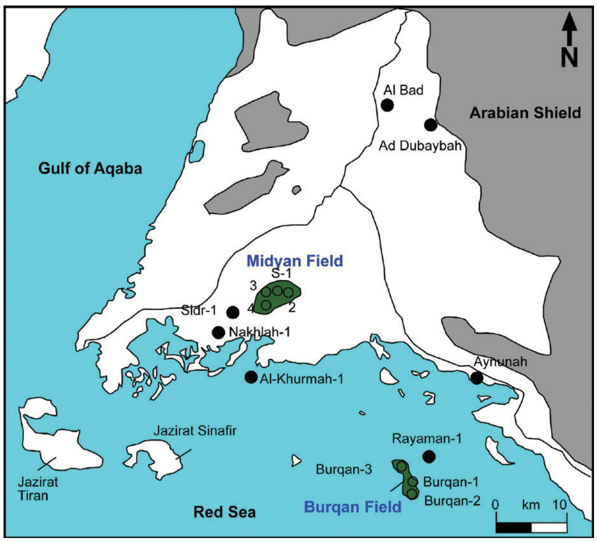

Figure 27. Map showing locations of all hydrocarbon-producing fields and exploration wells drilled in the offshore and onshore fields of the Midyan Peninsula (Hughes and Johnson, 2005).

Şekil 27. *Midyan Yarımadası'ndaki deniz ve kıyı alanlarındaki tüm hidrokarbon üretim alanlarının ve arama kuyularının konumlarını gösterir harita (Hughes ve Johnson, 2005).*

In this study, a large number of shale and sandstone samples was collected from various facies of the turbidite sequences. However, it was obvious that the thick bedded, medium- to coarse-grained, friable- to weakly-cemented sandstones deposited in the submarine canyons form the best reservoir facies. It was very important to understand their trend in the subsurface and recognize them on seismic lines. Therefore, paleocurrent directions were collected from the bottom structures (flute and groove casts) and cross-bedding formed in the lower parts of the vertically-stacked channels. These studies provided an important source of data to correlate them with oil producing reservoir facies in exploration wells in the Red Sea, Gulf of Suez and Midyan Basin (Alsharhan, 2003). They also greatly assisted in understanding the burial history and roles of different diagenetic processes on the reservoir properties, which can in turn be used to predict porosity and permeability of the subsurface reservoirs (Al-Ramadan et al., 2013; Al-Laboun et al., 2014; Şenalp, 2016).

The potential reservoir sandstones deposited in the submarine canyons are medium- to thick-bedded, laterally continuous, medium- to coarse-grained, well-sorted, and friable or weakly cemented, porous and permeable. The essential framework grains of the sandstones consist of quartz (80%), feldspar (9.7%) and rock fragments (10.3%). The porosity of the studied sandstone samples, measured with a helium porosimeter, ranges from 7% to 24% depending on the location of the samples in the measured sections and their grain size. The studied sandstones from the hydrocarbon-producing turbidite sequence of the Lower Member of the Burqan Formation reflect a wide range of permeability values, ranging from 62 to 11,320 millidarcy, with an average value of 2846 millidarcy. The hydrocarbon-producing turbidite sequence of the Burqan Formation is overlain by the thick and massive evaporites of the Magna Formation, forming an efficient tight cap rock.

CONCLUSIONS

Based on long-term outcrop studies and measured sections in the Midyan Peninsula, the stratigraphy and depositional environments of the rift-related stratigraphic successions in the Midyan Basin have led to the following conclusions.

1. The Midyan Basin was formed as result of the Red Sea, Gulf of Suez and Gulf of Aqaba rifting in the Early Miocene (23.3 Ma) and represents the full stratigraphic succession deposited during the pre-rift, syn-rift and post-rift phases of the rifting; thus providing an excellent geological window to understand the tectonic influences on the type of climate and depositional systems in the basin.
2. The early syn-rift sedimentary successions (between 23.3 Ma and 19 Ma) consist of the arid continental alluvial fan and fluvial sediments (Sharik Formation), overlain by the coastal sabkha (playa) evaporites (Al‘Bad Formation), and capped by the shallow marine carbonates (Musayr Formation) representing transgressive system tracts. The later syn-rift sedimentary successions consist of hydrocarbon-producing deep sea turbidites of the Lower Nutaysh Member and Alpine-type glacial, glacio-fluvial and glacio-marine deposits of the Upper Nutaysh Member. There is a glacially-formed unconformity surface between these two members.
3. Alpine-type glaciation was formed when the Sinai Peninsula and the rift shoulders were uplifted vertically more than 4 km above sea level during the climax of rifting during Early Miocene (19Ma). The height of the mountains in the Sinai Peninsula is expected to be at least more than 5,000 meters above sea level and at least a few kilometers above the permanent snow line.
4. The thick snow cover in the deep depressions on the crests of high mountain ranges in the Neoproterozoic Sinai Peninsula turned into glaciers. The depositional slope was high and the continental shelf area on the rift shoulder

was very narrow. The Alpine glaciation lasted about 5 million years and during this glacial period at least five major glacial advances and retreats were recorded in the measured sedimentologic sections. The duration of each glaciation (glacial advance) and deglaciation (glacial retreat) cycle is slightly more than 1 million years.

5. The glacial sediments were eroded and transported through narrow but deep U-shaped glacial valleys from the Sinai Peninsula in the west to the Midyan Peninsula in the east. They were deposited as true glacial, glacio-fluvial and glacio-marine sediments in the Midyan Basin. However, during the less cold seasons (during the melting phase or deglacial period), some of these coarse-grained glacial deposits were reworked and carried further down into deeper parts of the basin by means of gravity slide, slump and high density turbidity currents; whereupon polished and striated igneous blocks dropped from the floating ice (or iceberg) into the fine-grained sediments during their deposition, further indicating their glacial origin. There was a continuous transition and the lateral facies changed from being true glacial deposits (unsorted moraines) to genetically-related reworked moraines, erratics, glacio-fluvial and glacio-marine deposits. Every depositional system has its own convincing characteristics, but it is not easy to draw a sharp boundary between different geologic processes.
6. The sedimentary successions which were deposited during the post-rift period of the Red Sea and Gulf of Aqaba rifting (between 18 Ma and 5 Ma) consist of the conformably overlying Subayti Member of the Burqan Formation and the Magna Formation. The Magna Formation is a thick evaporitic succession, consisting mainly of massive anhydrite interbedded with secondary gypsum and evaporitic mudstone forming a very tight cap rock facies on top of the sandstone reservoirs essential for an effective petroleum system.

ACKNOWLEDGMENTS

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GENİŞLETİLMİŞ ÖZET

Bu çalışmada Erken Miyosen (23,03 My) zamanında başlayan Kızıldeniz, Süveyş ve Akabe Körfezleri'nin tektonik açılmalarıyla ortaya çıkan Midyan Havzası'nın stratigrafik evrimi, çökelme ortamları ve çok farklı fasiyes özelliklerinin ayrıntılı olarak çalışılması sonucunda, bunların havzanın hidrokarbon potansiyelin etkilerinin ortaya konulması amaçlanmıştır. Havzanın hidrokarbon potansiyelinin ortaya konması için ilgili petrol sisteminin unsur ve süreçlerinin çok daha ayrıntılı araştırılması gerekmektedir. Ayrıca, bu çalışmada açılma sırasında Sina Yarımadası'nın düşey yönde önemli miktarlarda yükselmesiyle ortaya çıkan Alp-tipi buzullaşmasının yarı-graben özelliğindeki Midyan Havzası'nın içinde gelişen farklı çökelme ortamlarına nasıl yansıdığı açıklanmıştır. Süveyş Körfezi ve Kızıldeniz'de üretim yapılan 200'den fazla petrol sahasının bulunması ve körfez içindeki sedimanter istiflerin her yönüyle Midyan Havzası'ndaki istiflere benzerlik göstermesi, bu havzanın hidrokarbon potansiyelini önemli derecede artırmıştır. Bu istif, petrol sistemlerinin en önemli unsurları olan kaynak kaya, rezervuar kaya, örtü kaya ve hidrokarbonların kapanlanması için gerekli olan yapısal (antiklinal ve fay) ve stratigrafik özelliklere sahiptir. Midyan Havzası içinde, Oligosen'den *başlayıp Miyosen sonuna kadar uzanan sedimanter istiflerin stratigrafisi, sedimantolojisi ve fasiyes analizlerini içeren bilgiler bu yayının yazarlarından birinin uzun yıllar boyunca Suudi Aramco Petrol Şirketi ve King Fahad Üniversitesi'nde yapmış olduğu arazi çalışmalarının sonuçlarına dayandırılmıştır. Midyan Havzası, Geç Oligosen (Şatiyen)-Erken Miyosen (Akitaniyen, 23,3 My) zamanında açılmaya başlamış ve bu açılma Orta Miyosende sona ermiş ve bunu doğrultu atımlı faylanma olayları takip etmiştir. Kızıldeniz açılmasının toplam yer değiştirmesinin 100 km den daha fazla olduğu bilinmektedir (Garfunkel, 1988). Sina Yarımadası'nın Erken Burdigaliyen (19 My) zamanında 4 km den fazla yükselmesi sonucu gelişen Alp-buzullaşması ile ilişkili olarak havza içinde buzul-kökenli en azından beş aşınma yüzeyleri ve stratigrafik istifte gelişmiş kesiklik düzlemleri tespit edilmiştir. Faylanma ile ortaya çıkan çökme olayları, Miyosendeki deniz seviyesi dalgalanmaları ve açılma sırasındaki tektonik olayların neden olduğu Sina Yarımadası'nın kuvvetli yükselmesi ile ilişkilidir (Evans, 1988; Şenalp, 2016). Midyan Havzası içindeki sedimanter istifleri içinde birbirini takip eden üç açılma evresi tespit etmiştir. Bunlar: 1) açılma-öncesi, 2) açılma-sırası (erken ve geç) ve 3) açılma-sonrası istifler olarak tanımlanmıştır. Açılma-öncesi İstifler Kızıldeniz'in açılmasından önce çökelen Paleozoyik, Mesozoyik ve Erken Tersiyer istifleri yalnızca Tayma-Tabuk ve Sakaka (Al Jawf) havzaları içinde temsil edilmiştir. Bu çalışmanın yapıldığı bölgede sadece Üst Kretase yaşlı Adaffa Formasyonu mostrada korunmuştur. Adaffa Formasyonu Kretase yaşlı olup (Clark, 1986) Midyan bölgesinin güneydoğusunda yer alan Ifal havzasında, açılma-öncesi istifin en alt birimini oluştur ve Arap Kalkanı'nın Neoproterozoyik yaşlı kristalin temel üzerine oturur. Formasyonun üst kısmı Sharik Formasyonu'nun tabanındaki erken-açılma dönemini temsil eden Erken Miyosen yaşlı (23,03 My) bölgesel aşınma yüzeyi ile sınırlandırılmıştır. Ölçülmüş tip kesitte bu istif 90 m, olup alttan üste doğru çakıltaşı, kırmızımsı-kahve renkli, çapraz-tabakalı, iyi boylanmış, gevşek çimentolu kuvars kumtaşlarından oluşmaktadır. İstifin en üstü kesimleri ince-tabakalı marn, miltaşı, ince-taneli kumtaşı ve gri-yeşil renkli şeyl fasiyesleri ile temsil edilen menderesli nehir ortamında çökelmiştir. Şeyller içinde dinozor ve kaplumbağalara ait kemik parçaları ve silisleşmiş ağaç parçaları bulunmaktadır. Dinozor kemik parçalarının Geç Kretase (Albiyen) yaşlı titanosaurid dinozor türü olduğu saptanmıştır (Şenalp, 2016). Kızıldeniz'in açılması sırasında çökelen ve çok önemli hidrokarbon potansiyeline sahip sedimanter istifler, Suudi Arabistan'ın kuzeybatısında yer alan Midyan Havzası içinde hiç kesiksiz olarak korunmuştur. Bu havza, Oligosen sonunda (Şatiyen, 23,03 My) başlayan sürekli ve birbirleri ile bağlantılı olarak gelişen Kızıldeniz, Süveyş ve Akabe Körfezleri'nin açılması ile ilişkili olarak ortaya çıkmıştır. Açılmanın erken aşamasında birbirleriyle bağlantısı olmayan yarı-grabenler oluşmuş, fakat açılma ilerledikçe bu grabenler gittikçe derinleşen geniş çökelme havzalarına dönüşmüş ve içlerinde kalın, açılmanın tüm aşamalarını ve ortaya çıkan farklı çökelme ortamlarını temsil eden istifler çökelmiştir. Açılım sırasında oluşan bu istif erken-açılma ve geç-açılma istifleri olmak üzere iki gruba ayrılmıştır. Erken-açılma istifi, tabanda alüvyon yelpazesi ve flüviyal ortamda çökelmiş Sharik Formasyonu, onun üzerine gelen playa ortamında çökelmiş masif anhidrit fasiyesindeki Al Bad' Formasyonu ve en üstte sığ deniz ortamında çökelmiş karbonatların temsil ettiği Musayr Formasyonu ile temsil edildiği transgresif bir çökelme modelini temsil eder. Musayr Formasyonu'nun çökelmesinin hemen sonrasında Midyan Havzası, bitişik bulunduğu Proterozoyik yaşlı kristalin temelin oluşturduğu Sina Yarımadası'nın tektonik olarak düşey yönde yükselmesiyle ilişkili olarak aşırı bir derinleşme kazanmıştır. Bu olay, açılmanın en şiddetli olduğu ve hatta zirve yaptığı bir dönemi temsil edip ortaya çıkan istifler Burqan Formasyonu (Mısırda Rudeis Formasyonu) olarak tanımlanmış, Alt ve Üst Nutaysh olarak* *adlandırılan iki üyeye bölünmüştür (Şenalp, 2016). Alt Nutaysh Üyesi, Musayr Formasyonu'nun karbonatları üzerine uyumlu olarak gelen deniz altı yelpazeleri içinde çökelmiş klasik türbidit istifleridir. Üst Nutaysh Üyesi, Sina Yarımadası'nın Erken Burdigaliyen (yaklaşık 19 My) zamanında 4 km'den daha fazla yükselmiş olması (Garfunkel ve Bartov, 1977) nedeniyle yüksek dağ zirvelerinde oluşan Alp-tipi buzulların erimesiyle ortaya çıkan derin vadilerin çökeltmiş olduğu farklı buzul fasiyesleriyle temsil edilmiştir. Bu iki farklı üye arasındaki buzul aşındırma yüzeyi Mısır'da Rudeis- ortası olay olarak tanımlanmıştır. İstif içindeki büyük granit bloklarının varlığı, buzulların Sina Yarımadası'ndan aşındırıp taşıdığı malzemeleri denizin içine kadar taşıdığını gösterir (Şenalp, 2016). Neoproterozoyik kristalin temel üzerine oturan, Erken Miyosen (Akitaniyen, 23,03 My) yaşlı Sharik Formasyonu, açılmanın en erken dönemindeki graben ve yarı-grabenler içinde çökelmiştir. Bu formasyon, fosil içermeyen başlıca kumtaşı, çakıltaşı ve çamurtaşından yapılmış olup sıcak ve kurak iklim koşulları altında geniş alüvyon yelpazeleri, ve bu yelpazelerin daha aşağı kısımlarındaki örgülü nehir ve playa ortamına yakın eoliyen kumul ortamlarında çökelmiştir. Midyan Havzasında, Al Bad' Formasyonu başlıca beyaz renkli, masif-görünümlü anhidrit, jips ve az miktarda şeylden yapılmış olup alttaki Sharik Formasyonu'nun karasal çökelleri üzerine uyumlu olarak oturur. Al Bad' Formasyonu'nun Musayr Formasyonu'nun sığ deniz karbonat fasiyesleri ile olan üst sınırı önemli bir transgresyon yüzeyini temsil eder. Formasyonun kalınlığı Yanbu-6 arama kuyusunda 461 ayak (140,5 m) kalınlıkta olup kaya tuzu, anhidrit ve az miktarda şeylden yapılmıştır (Hughes ve Johnson, 2005). Al Bad' Formasyonu'nun playa (geçici göl) adı verilen ve genellikle alüvyon yelpazelerinin aşağı kısımlarında ve grabenlerin en çukur olduğu yerlerdeki sınırlı bölgelerde çökelmiş olduğu anlaşılmıştır (Al-Ramadan vd., 2013). Bu playa ortamı, Tetis Okyanusu'nun Midyan grabeni içine sokulduğunun en kanıtlayıcı göstergesidir. Arama kuyularından alınan karotlardaki örneklerinin stronsiyum izotop çalışmaları bu formasyonun yaşını Erken Miyosen (Akitaniyen, 22-23 My) olarak göstermiştir (Cocker ve Hughes, 1993). Clark (1986) tarafından tanımlanmış ve 66 m kalınlıktaki bir karbonat istifi ile temsil edilmiş olan Musayr Formasyonu Kızıldeniz'in erken açılımının en üst devresinde ortaya çıkan sığ deniz ortamında çökelmiştir. Transgresif istifin tümüyle korunduğu bölgelerde karbonat istifi alttaki Al Bad' Formasyonu'nun playa evaporitleri üzerinde uyumlu, fakat evaporitlerin çökeldiği playa ortamının dışındaki bölgelerde Musayr karbonatları Sharik Formasyonu'nun kırmızı renkli karasal kumtaşı ve çamurtaşları üzerine doğrudan oturur (bak: Şekil 12). Bu dokanak çok önemli bir zaman boşluğunu temsil eder. Musayr Formasyonu ve Burqan Formasyonu'nun Alt Nutaysh Üyesini oluşturan türbidit istifi ile olan üst sınırı çok keskindir ve havzanın çok hızlı bir şekilde derinleşmesini işaret eder. En yaygın olan çökelme ortamı gel-git işlemlerinin egemen olduğu sığ deniz platformudur. Bu seviyenin üzerine kavkılı tanetaşı, oolitik tanetaşı ve mikritik kireçtaşı fasiyesleri gelir. Oolitik kireçtaşı seviyeleri yanal devamlılıkları fazla olmayan mercek şeklindeki gel-git kanalları içinde çökelmiştir. Mikritik kireçtaşları içinde zengin makro-ve mikro fosiller bulunur, özellikle istiridye, mercan ve miogypsinid foraminifer fosilleri bu kireçtaşlarının sıcak ve sığ deniz ortamında çökeldiklerini işaret eder. Bu bentonik foraminifer fosillerinden en yaygın olanı Miogypsinoides ve özellikle Miogypsina tani, Erken Miyosen (Geç Akitaniyen, yaklaşık 20,04 My) yaşını işaret eder (Hughes ve Johnson, 2005). Musayr Formasyonu'nun Süveyş Körfezi içindeki karşılığı olan Nukhul Formasyonu'nun petrol ve gaz üretim sahalarındaki kalınlığı 20 m ile 60 m arasında değişir ve ortalama gözenekliliği %16 olarak ölçülmüştür. Hidrokarbon yönünden çok önemli olan Erken Miyosen (Burdigaliyen, 20,44-15,07 My) yaşlı Burqan Formasyonu Mısır'da, Kızıldeniz ve Süveyş Körfezi'nde Rudeis Formasyonu olarak adlandırılmıştır. Açılmanın en aktif olduğu bir dönemde çökelmiştir ve ilk defa Auxerap/Tenneco petrol şirketinin Suudi*

Arabistan'ın Kızıldeniz içinde açmış olduğu Burqan-3 isimli arama kuyusunda tanımlanmıştır. Sina Yarımadası'nda periyodik olarak ortaya çıkan tektonik yükselmeler ve bununla ilişkili iklim değişiklikleri ve Alp-tipi buzullaşma, Midyan Havzası içindeki çökelme ortamının çeşitliğini etkilemiştir. İstifin bu özellikleri göz önüne alınarak Burqan Formasyonu, Alt Nutaysh, Üst Nutaysh ve Subayti olarak üç ayrı üyeye ayrılmaktadır (Şenalp, 2016). Alt Nutaysh Üyesi, formasyonun sığ deniz karbonat istiflerinin çökelmesinden kısa bir süre sonra Sina Yarımadası'nın yükselmesiyle birlikte Midyan Havzası ansızın derinleşmiş ve tabanı sürekli olarak çökmeye maruz kalmıştır. Derin bir havza içinde ortaya çıkan bu ilk istif, sürekli olarak kıta yamacından açık denize doğru ilerleyen denizaltı yelpazeleri içinde çökelmiş klasik türbidit istifleri ile temsil edilmiştir. Türbidit istiflerinin tabaka kalınlıkları ve kumtaşlarının tane boyları istifin altından üstüne doğru dereceli olarak artar. Bu istifleri derince kesen denizaltı kanyonları içinde çökelmiş ve genellikle kumtaşından yapılmış istifler ise tabaka kalınlıkları ve kumtaşlarının tane boylarının dereceli olarak üste doğru inceldiği petrol ve gaz üretimi için çok önemli bir çökelme modeli sunarlar. İstifin en tabanında çökelmiş pelajik şeyller siyah renkli, organik madde yönünden zengin petrol ve doğal için önemli kaynak kaya oluşturur. İstifin en üst kısmı, denizaltı yelpazelerin en üst kısmını oluşturan ve bu istiflerin çökelmesinden sorumlu olan denizaltı kanyonları tarafından kesilmiştir. Bu kanyonların tabanı, belirgin bir aşınma yüzeyini temsil eder. Kanyonu dolduran çökeller tümüyle, orta-kalın tabakalı, yanal yönde devamlı, orta-iri taneli, çok iyi-boylanmış, kırılgan veya gevşek çimentolu, gözenekli ve geçirimli kumtaşlarından yapılmıştır ve çok verimli rezervuar özelliklerine sahip kumtaşlarıdır. Kumtaşının bileşenlerini oluşturan en önemli mineraller kuvars (%80), feldispat (%9,07) ve kaya parçacıklarıdır (%10,13). Süveyş Körfezi içinde petrol ve gaz üretiminin yapıldığı Rudeis Formasyonu'nun karotlarından alınan tapalarda kumtaşlarının gözenekliği, örneğin alındığı yer, tane boyu ve boylanma derecesine bağlı olarak %7 ile %27 arasında değişir. Burada açılmış AI-Wajh South-1 (AWSO-1) üretim kuyusunda 2875-3819 m derinlikler arasında 944 m kalınlıkta ve petrol üreten rezervuar fasiyesi mevcuttur (Hughes ve Johnson, 2005). Bu kuyuda yapılan ayrıntılı laboratuar çalışmaları, Musayr (Nukhul) karbonatlarının üzerine transgresif olarak gelen ve denizaltı yelpazelerinin tabanını oluşturan pelajik organik madde kapsamının yüksek olduğu (ortalama %3-5 TOC), hidrokarbon üretimi için iyi kaynak kaya potansiyeli olduğu kanıtlanmıştır. Burada ortaya çıkan hidrokarbonlar üste doğru genetik ilişkili olarak çökeldikleri yakınsak türbidit ve denizaltı kanyonu içindeki kalın ve gözenekli kumtaşlarının içine göçtükleri kanıtlanmıştır (Hughes ve Johnson, 2005). Burqan (Rudeis) Formasyonu'nun çok verimli petrol ve gaz üreten kumtaşı rezervuarları Magna Formasyonu'nun kalın ve geçirimsiz evaporitleriyle örtülmüştür. Üst Nutaysh Üyesi, Sina Yarımadası'nın tektonik olaylarla yaklaşık 19 milyon yıl önce, düşey yönde 4 km den fazla yükselmesi (Garfunkel ve Bartov, 1977) sonucu bu yüksek dağ silsilelerinin daimi kar sınırının üzerinde kalan büyük bir bölümünde Alp-tipi buzullar gelişmiştir. Bu dağ buzullarının erimesi sonucu ortaya çıkan, yanal yönde dereceli geçiş gösteren gerçek buzul (moren), buzul-flüviyal ve buzul-denizel fasiyesleri çökelmiştir. Bu üç farklı fakat buzul kökenli fasiyeslerin içinde bol miktarda, yüzleri cilalanmış ve çizilmiş büyük granit blokları bulunur. Bölgede yapılan geniş kapsamlı arazi çalışmaları dar ve U-şeklindeki buzul vadilerinin Sina Yarımadası'ndan kaynaklanıp yamaç aşağı yönde Midyan Havzası'na doğru geldiğini kanıtlamıştır. Havzanın en derin kısmında çökelmiş türbidit fasiyesler içinde deniz tabanına düşmüş büyük granit blokları çok yaygın olarak gözlemlenmiştir. Yemen bölgesinde de buna benzer buzul çökellerinin rapor edilmiş olması onların geniş yayılımlı oldukları tarzında yorumlanmıştır. Midyan bölgesinde yapılan gözlemler morenlerin çökelmesinden sorumlu buzul işlemleri ile türbidit fasiyeslerinin çökelmesinden sorumlu olan moloz ve bulantı akıntıları işlemleri arasında kesiksiz bir *devamlılığın olabileceğini orta koymuştur. Bu üç farklı çökelme ortamlarının yakın ilişkileri tüm ayrıntılarıyla çalışılıp yeni bir model olarak ilk defa Şenalp (2016) tarafından ileri sürülmüştür. Kızıldeniz, Süveyş ve Akabe Körfezleri'nin açılmalarının sonunda ortaya çıkan sedimanter istifler (14-1,6 My) havzanın kuzeybatı kısmında ve yeraltında çok iyi korunmuştur. Bu istifler genellikle sıcak iklim koşulları altında, sığ deniz ve geniş playa ortamlarında çökelmiştir. Bu birimler Burqan Formasyonu'nun Subayti Üyesi ve Magna Formasyonu olarak tanımlanmıştır. Subayti Üyesi, buzullaşmanın sona ermesini takip eden dönemde, sığ kıta sahanlığı üzerinde çökelmiş, 150 m kalınlıkta, ara tabakalı krem renkli masif şeyl, kalkerli çamurtaşı (marn), evaporitik çamurtaşı, miltaşı ve ince tabakalı jips çimentolu kumtaşı fasiyesi ile temsil edilmiştir. Burqan Formasyonu'nun hidrokarbon üretiminin yapıldığı Nutaysh Üyeleri'nin üzerine uyumlu olarak gelir çok önemli geçirimsiz bir örtü kaya fasiyesidir. Süveyş Körfezi'nde açılan arama kuyularından alınan karotlarda bu üyenin yaşı palinolojik çalışmalarla erken Orta-Miyosen (Langiyen) olarak belirlenmiştir (Hughes ve Filatoff, 1995). Magna Formasyonu, 150 m kalınlıktaki tipik kesitin ölçüldüğü Akabe Körfezi'nin kıyısındaki Magna köyünde çok iyi temsil edilmiştir. Tümüyle masif evaporit (anhidrit ve jips) istifi ile temsil edilmiş bu formasyon Midyan Havzası'nın yüzeyde görülen en genç birimidir ve yaşı Orta Miyosen olarak belirlenmiştir (Hughes ve Filatoff, 1995). Kuzeybatı Suudi Arabistan'ın Midyan Yarımadası'nda yürütülen bu çalışmalardan elde edilen deneyim ve bilgi birikimleri Isparta-Antalya arasındaki Aksu Havzası'nın Akdeniz içindeki hidrokarbon potansiyelini anlamak için çok yararlı olmuştur. Aynı yaş aralığı ve aynı fasiyeslerle temsil edilmiş sığ deniz ortamında çökelmiş Akitaniyen karbonat istifleri ve Burdigaliyen yaşlı türbidit istiflerinin kalın potansiyel rezervuar kumtaşları Aksu Nehrine paralel olarak uzanan Isparta-Antalya karayolu üzerinde gözlemlenmiş olup, buna yönelik çalışmalar ayrıca sürdürülmektedir.*

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