Evidence for Isolated Platform Development in the Cenomanian on the Passive Margin of Neotethys, Southwest Iran

Mersad Moeini, Hossain Rahimpour-Bonab and Vahid Tavakoli *

School of Geology, College of Science, University of Tehran, Tehran 1417935840, Iran
* Correspondence: vtavakoli@ut.ac.ir; Tel.: +98-219-127-035-242

Abstract: In the Cenomanian, the southern passive margin of the Neotethys Ocean was dominated by a giant carbonate factory. This succession is known as Sarvak Formation, a significant reservoir in Iran. This study focuses on a detailed analysis of facies variations and paleoenvironmental reconstruction, including the interpretation of the platform types, during this time interval. Based on field observations and petrographical studies, 12 facies have been recognized and ascribed to six facies belts on a carbonate ramp. Sub-environments include the outer ramp and basin (distal open marine), talus and channel (mid-ramp) and lagoon and shoal (inner-ramp). The frequency of the facies and isochore maps indicate the paleoenvironmental conditions and their spatial variations in the study area. Based on all data and analyses, the suggested conceptual model for the Sarvak Formation in the Lurestan Zone is an isolated platform surrounded by two ramps. The upwind and downwind parts of these ramps were located in the central and northern sub-zones of the Lurestan Zone. This model can be used as a template for isolated platforms worldwide.

Keywords: carbonate factory; isolated platform; Cenomanian carbonate ramp; upwind-downwind facies; Neotethys

1. Introduction

A carbonate platform is defined as a sedimentary body possessing topographic relief and consisting of in-situ carbonate constituents [1]. For any systematic reservoir characterization and evaluation of essential reservoir parameters, the profile of the platform and paleoenvironmental conditions must be known. Because of variability in reservoir quality and facies patterns, it is necessary to discriminate different platform types (with diverse characteristics) to evaluate hydrocarbon-bearing units. Reservoir geometry is mainly controlled by platform type, while reservoir quality is determined by environmental conditions of various facies [2,3] and later diagenetic impacts. In turn, platform geometry and type, along with the facies successions and patterns, control depositional facies and sequence stratigraphic framework [2–5].

An isolated carbonate platform is identified as a carbonate factory composed of shallow marine constituents surrounded by deeper water [6]. A marginal reef or sand body may exist, separating shallow carbonates from deep water deposits. This high-energy margin shows the highest rates of carbonate production. The production rate is reduced in the center of the platform, and a lagoonal setting can be established [3,6,7].

Generally, isolated platforms are constructed in offshore settings on oceanic islands. These islands have different origins, including volcanos, grabens, different subsidence or uplift rates, faulting, etc. [8–12]. Sedimentary facies distribution, geometry, and characteristics of these platforms are mainly controlled by the energy of the carbonate factory and wind direction. Reef and talus facies of isolated platforms may be important due to their higher reservoir quality [13,14]. In turn, leeward facies are mainly mud-dominated, reflecting lower energy conditions, and having lower reservoir quality [14,15]. A modern
example of this unattached platform is the Florida-Bahamas region formed in the subsid-
ing passive margin basin, where the basement is characterized by different subsidence
rates [16].

Isolate platform models for Carboniferous and Cretaceous carbonates have been
studied in NW and S Spain. An isolated carbonate platform was created in the Aptian-
Albian in southern Spain (South Iberian Continental Margin, northwestern margin of
the Tethys) under the influence of an extensional phase of the Central Atlantic. It was
associated with changes in subsidence and uplift of the basin floor, relative sea-level fall,
and a depression (creation of graben) on the sedimentary carbonate platform. Results are
based on the studies of the carbonates of the Seguili and Sacaras formations [17].

An isolated sedimentary model has been proposed in NW Spain in the Cantabrian
Mountains (Valdediezma Formation) based on facies and tectonic studies on Carboniferous
carbonates (Mississippian–Lower Pennsylvanian). Changes in subsidence and uplift of the
basin floor, relative sea-level changes, and an increase in the rate of carbonate deposition
in the deep parts of the sedimentary basin has resulted in the creation of an isolated
platform [18,19].

The Cretaceous Sarvak Formation with Late Albian to mid-Turonian age is one of the
most important reservoir units in SW Iran. Using facies analysis, the ratio of benthic to
pelagic fauna, and well-drilling data, Sharland et al. [20] identified four cycles of the third-
order sequences for this time interval in the Arabian Plate. These cycles include two systems
tracts. Highstand systems tract (HST) and transgressive systems tract (TST) are separated
by type 2 sequence boundary (SB2) and maximum flooding surface (MFS). The depositional
environment of this formation in Lurestan has been the center of considerable debate.
Hence, our goal is to characterize this carbonate platform by analyzing its sedimentary
facies distribution and properties in an extensive area of the Lurestan Zone, both in surface
and subsurface sections. In other words, our main target is to systematically introduce an
isolated platform conceptual model for the Middle Cretaceous carbonates of the Arabian
Plate passive continental margin.

2. Materials and Methods

This study is based on data obtained from two outcrops (Kuh-Sultan and Behesht
Reza) and ten boreholes in the Maleh-Kuh, Sarkan, Halush, Gaver, and Veyzenhar oil fields
from the central and northern subzones of the Lurestan Zone (Figure 1). The classification
of [21,22] were used to determine the texture and microfacies. Most sedimentological
features such as lithology, textures, sedimentary structures, rock facies, biofacies, visual
porosity, pore types, rock color, grain size, allochems, stylolites, and fractures have been
studied using a polarizing microscope and during the core description. A depositional
conceptual model was proposed by combining available data from outcrops, core samples,
cuttings, and thin sections (Table 1). Facies types and depositional settings were interpreted
based on matrix and grain content, compositional and textural fabrics, fossil content, sedi-
mentary characteristics, and a comparison with modern and ancient environments [1,3,6,23].
Lithofacies of the Sarvak Formation have been determined based on field observations and
core analysis. All results were integrated, and isochore and the relative frequency maps
were prepared for various facies. A Gamma-ray log has been used in subsurface sections to
better characterize the microfacies.
Table 1. The number of thin sections from the core, cutting and hand specimens in boreholes and surface sections. The thickness of the Sarvak Formation is also evident in each case.

<table>
<thead>
<tr>
<th>Section</th>
<th>Borehole</th>
<th>Thickness (m)</th>
<th>No. of Thin Sections</th>
<th>Core</th>
<th>Cutting</th>
<th>Outcrop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarkan</td>
<td>Sk 1</td>
<td>491</td>
<td>340</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Sk 2</td>
<td>408</td>
<td>651</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Sk 3</td>
<td>226</td>
<td>250</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Sk 4</td>
<td>460</td>
<td>303</td>
<td>−</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Mal-e- Kuh</td>
<td>Mk 1</td>
<td>260</td>
<td>161</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Mk 2</td>
<td>165</td>
<td>95</td>
<td>+</td>
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</tr>
<tr>
<td></td>
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<td>102</td>
<td>83</td>
<td>−</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Halush</td>
<td>Hh 1</td>
<td>118</td>
<td>127</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Gavar</td>
<td>Gr 1</td>
<td>391</td>
<td>260</td>
<td>−</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Vizenhar</td>
<td>Vr 1</td>
<td>359</td>
<td>187</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Kuh Soltan</td>
<td>—</td>
<td>108</td>
<td>140</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Behesht Reza</td>
<td>—</td>
<td>943.5</td>
<td>550</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
</tbody>
</table>

Figure 1. The location map of the studied area includes oilfields and subsurface sections in the Central and Northern subzones parts of the Lurestan Zone. The Sarkan, Maleh-Kuh, Halush, Gaver, and Veyzenhar oil fields and Kuh-Sultan surface section are located in the central subzone of the Lurestan. The Behesht Reza surface section is located in the Northern subzone.
3. Geological Setting

The Zagros Mountains contain 8.6% of the oil and 15% of the gas of the world’s proven reserves [24–27]. The NW/SE trending Zagros fold-and-thrust belt extends ~1800 km from Taurus Mountain to the Anatolian fault. The N/S trending Oman Line separates the Zagros belt from the Makran accretionary prism [27,28]. Southern Iran is located in S.W. of the Neotethys suture zone and consists of the High Zagros and the Zagros Folded Belt. This region is subdivided into Lurestan, Khuzestan, and Fars zones [27,28] (Figures 1 and 2). The Albian-Campanian Bangestan Group hosts some of the most prolific reservoirs of the Arabian Platform and the Zagros fold-and-thrust belt hydrocarbon provinces. The most important interval of the Bangestan Group regarding reservoir quality includes neritic carbonates of the Sarvak and llam formations [29]. Thus, the Sarvak Formation and its equivalents comprise significant reservoir intervals in the S and S.W. of Iran (including the Lurestan Zone) and throughout the Middle East [25,30–36] (Figure 2).

![Detailed stratigraphy of the Cretaceous successions in different parts of Iran, including the Sarvak Formation of the Bangestan Group.](image)

Facies distribution and reservoir characteristics of the Sarvak Formation vary significantly in different regions of the Zagros due to the influence of several geological factors [37–39]. So far, many studies have been carried out in the Dezful Embayment, Izeh, Fars, and the Persian Gulf area (Figure 1). These studies have shown a simple ramp or shelf profile for Sarvak depositional environment [40–43]. In the Lurestan Zone, the Late Albian–mid-Turonian, Sarvak carbonate factories were dominated by deeper platform environments and some special climatic conditions that led to different facies characteristics compared with other parts of the Zagros area [26] (Figures 1 and 2). Deeper water conditions and resulting mud-dominated carbonate facies led to its relatively lower reservoir quality [39].

3.1. Palaeogeography and Tectonic Events

Development of the Zagros area began in the Late Cretaceous due to the foredeep subsidence of the continental closure along the Zagros Suture [44,45]. The late Cretaceous was also a period of global sea-level highstand [46,47]. Paleogeographic studies suggest that in the mid-Cretaceous, a carbonate ramp prevailed in this area which gradually surrounded most of the Middle East in response to eustatic sea-level rise [48,49]. Meanwhile, during the Cenomanian–Turonian, sedimentation rates varied considerably. This variability is evident from the total thickness of formations and the absence or scarcity of some microfacies, especially the open-marine microfacies in the Lower Sarvak Formation in southern Iran and the Persian Gulf region [32,33]. These variable thicknesses are evident from the isopach maps of the middle Cretaceous for this
sedi\ntary basin [26]. Such variations suggest a period of instability characterized by the reactivation of basement block faults in Dezful Embayment and active salt tectonism in the Persian Gulf. Thickness differences within the Sarvak Formation could also be ascribed to erosion at the disconformable surfaces (discussed in this study) or variable subsidence rates in different parts of the depositional environment [27] (Figure 2).

3.2. Lurestan Zone

The Lurestan Zone has a long hydrocarbon exploration and production history, but relatively few successful boreholes have been drilled in this zone. Nevertheless, both high-quality source rocks and regional seals are present. The Cenomanian Sarvak Formation carbonates form the major reservoir unit [26]. Permeabilities of the samples in the Sarvak Formation vary significantly due to variations in depositional facies and diagenetic overprints.

During Early Cretaceous, a sedimentary basin extended in the passive margin of the NE-N of the Arabian Plate, covering the whole present Zagros fold belt, Persian Gulf, and the Arabian Platform [27]. The center of this basin was situated in the Lurestan Zone and Eastern Iraq. From Iran to the southwest of the Arabian Plate, carbonate facies are replaced by clastic facies, which indicates a shallowing upward trend of the sedimentary basin [50] (Figures 2 and 3). The Lower Cretaceous in the Lurestan Zone consists of dark gray to black radiolarian bearing shale and argillaceous limestone belonging to a deep marine environment (Garau Formation) (Figure 2). This stratigraphic unit is overlying the Gutnia Formation (evaporite deposits) (Figure 2). The latest Albian–Cenomanian transgression led to the deposition of shallow marine limestone (Sarvak Formation) in the Zagros Basin. Towards the end of the Cenomanian, regional uplift caused significant subaerial exposure and erosion in the upper part of this limestone unit (in most parts of the Zagros) [50]. However, because of the deeper settings in the Lurestan Zone, deposition continued without significant unconformities [51] (Figures 2 and 3). In the central Lurestan Zone, deeper marine conditions led to the deposition of shale and argillaceous limestone of the Surgah Formation [52]. In Lurestan, this unit overlies the Sarvak Formation and, in turn, is overlain by the argillaceous limestone of the Ilam Formation [52] (Figure 2).

Figure 3. (A) Generalized stratigraphy of the Sarvak Formation in the type section located in the Zagros region (SW Iran). (B) Stratigraphic column of the Sarvak Formation in Sarkan Field situated in the central subzone.
3.3. Stratigraphy

In the S.W. parts of Iran, the Sarvak Formation has two significant facies: neritic and pelagic [21] (Figure 3A). The unit is bounded at the top by a significant disconformity in the Khuzestan and Fars Provinces that is less apparent in the Lurestan Zone, where it shows deeper facies of Albian–The Turonian age [53]. In this area, the upper part of the succession, which underlies the Surgah Formation with a disconformity surface, shows deep marine pelagic facies. However, the lower parts are shallow marine or neritic facies. In the Lurestan Zone, the lower boundary of the Sarvak has been developed in two forms. In some places, there is a transition zone between Garau and pelagic argillaceous limestone of the Sarvak Formation. In other areas, a massive neritic limestone sharply overlies the Garau Formation [26,50] (Figure 3B). Radiolarian limy mudstones dominate the Sarkan, Maleh-Kuh, Halush, Gaver, Veyzenhar fields and Kuh-Sultan sections in the central Lurestan Zone (Figure 1). They were deposited during Albian and early Cenomanian (Lower Sarvak Formation) [50]. These facies change into calcispheres mudstone towards the shelf edge.

3.4. Study Area

The objective of this study was to evaluate the paleoenvironmental conditions of the Sarvak Formation in the Lurestan Zone. Accordingly, data from the Sarkan (four boreholes), Maleh-Kuh (three boreholes), Halush (one borehole), Veyzenhar (one borehole), and Gawar (one borehole) fields have been used. Outcrop sections, including Behesht-Reza and Kuh-Sultan, were also studied, and used to achieve this aim (Figure 1). The Maleh-Kuh and Sarkan fields are located 70 and 55 km to the S.W. of Khorramabad city, respectively, and are ~10 km apart. The Kuh-Sultan Anticline is between the two fields and is ~50 km long and 4 km wide (Figure 1). The Maleh-Kuh Field is an elongated anticline ~35 km long and up to 5 km wide. The Halush Field is located south of the Maleh-Kuh structure. The first borehole in the Maleh-Kuh Field (MK-1) was drilled on the eastern nose of the structure in 1967. Gas and oil have been found in the Ilam Formation and the Sarvak Formation. So far, three boreholes have been drilled in the Maleh-Kuh Field (MK-1, MK-2, and MK-3) (Figure 1).

The Sarkan Field is located north of the Maleh-Kuh Field. This field is an elongated anticline ~25 km long and up to 5 km wide. The structure can be recognized at the surface. The boreholes drilled in the Bangestan Group (Ilam and Sarvak formations) contain gas and oil. So far, four boreholes have been drilled in the Sarkan structure (SK-1, SK-2, SK-3, and SK-4) (Figure 1).

The Veyzenhar Field is a small asymmetrical anticline 17 km long and 3 km wide. The S.W. flank of the structure is steeper, and its measured dip is up to 60° while the flank varies between 15°–30°. The Gawar Field is located in N.W. of the Veyzenhar Field and N.W. of Lurestan. The Behesht Reza surface section is located west of Khoram Abad city at the Sefid Kuh Anticline (Figure 1).

4. Results

4.1. Facies Analysis

Using the mentioned methods and considering the field observations and laboratory data, 12 microfacies have been recognized in the Sarvak Formation in all seven studied sections. These facies can be ascribed to the distal open marine (outer ramp and basin), patch reef talus and channel (mid-ramp, proximal open marine or fore reef), and lagoon and shoal (inner-ramp) facies belts of a carbonate ramp.

4.1.1. Distal Open Marine (Outer Ramp and Basin)

Altogether, five microfacies were documented for this facies belt, including planktonic/sponge spicule wackestone to packstone (MF1), calcispheres mudstone to packstone (MF2), grey to dark grey planktonic fauna wackestone to packstone (MF3), peloidal skeletal wackestone to packstone with planktonic fauna (MF4), and thin layers of skeletal peloidal
packstone and grainstone (MF5) (Figures 4 and 5). This facies belt shows the most diverse microfacies of the Sarvak Formation in the studied area.

Figure 4. Photomicrographs (PPL) of microfacies of distal open marine and outer ramp. (A) MF1, planktonic/sponge spicule wackestone to packstone. (B,C) MF2 calcispheres mudstone to packstone. (D,E) MF3, grey to dark grey planktonic fauna wackestone to packstone. (F,G) MF4, peloidal skeletal wackestone to packstone with planktonic fauna. (H) MF5, thin layers of skeletal peloidal packstone and grainstone. um: microns.

Figure 5. The lithology of the distal open marine and outer ramp microfacies: (A) Argillaceous limestone with planktonic fossils. (B) Calcareous shale. (C) Argillaceous limestone with fine lamination and bioturbation. (D) Argillaceous limestone with planktonic fossils (Globotruncanidae), bioturbation and pyrite crystals. (E) Argillaceous limestone with planktonic fossils, echinoderm debris, lamination, pyrite mineral, and bioturbation. (F) Argillaceous limestone with peloidal, planktonic fossils, sponge spicule, and boring. (G) Limestone to argillaceous limestone with peloidal planktonic fossils. (H) Argillaceous limestone with skeletal peloidal grainstone, planktonic fossils, echinoderm debris, fishbone debris, fine lamination, and bioturbation.
Bioclasts of all microfacies in this facies belt include planktonic sponge spicule, calcispheres, pelagic fauna, silt-sized bioclasts, planktonic bivalve debris, planktonic foraminifera such as *Heterohelix* sp., *Favusella washitensis*, *Macroglenes bentonensis*, *M. ultramicrus*, *Macroglenes* sp., *Muriochedbergella delrioensis*, *M. planispirea*, *M. ricshi*, *M. simplex*, *Muriochedbergella* sp., *Whiteinella praehelvetica*, *Whiteinella* sp., *Biticinella breggiensis*, *Ticinella praeticinensis*, *T. primula*, *Ticinella* sp., and *T. roberti*.

Other less frequent constituents are fine echinoderm fragments, fishbone debris, bivalves, rudist debris, and peloids. This facies belt has different characteristics, including pyrite crystals, deep marine fauna, small grain size, high amounts of organic matter, and local siliceous cement. The abundance of these microfacies is higher in the Sarkan, Veyzenhar, Gaver, and Behesht-Reza areas compared to Male-Kuh and Kuh-Sultan. Table 2 presents the microfacies characteristics of the studied sections.

4.1.2. Talus and Channel (Mid-Ramp)

Channel facies is composed of 2 microfacies, including rudist debris floatstone/wackestone (MF6) (Figure 6A,B) and intraclast skeletal grainstone (rudist rudstone) (MF7) (Figure 6C,D). The microfacies number 6 comprise rudist debris of variable sizes, peloids, small benthic foraminifera, and echinoderms fragments. These facies are composed of intraclasts and rudist debris floating in the mud-rich matrix and also show textural inversion (high-energy allochems such as crushed and coarse bioclasts in a low-energy/mud-dominated matrix). The intraclasts comprise some bioclasts such as echinoderms debris, green algae, gastropods, and benthic foraminifera that indicate the shallower environments such as lagoon and proximal mid-ramp. The rudist’s debris originated from the destruction of rudist patch reefs in the mid-ramp environment. The depositional setting of these facies can be attributed to channels located in the proximal to middle parts of the mid-ramp setting near a high-energy fair weather wave base (FWWB). The gamma-ray of the interval is 20 to 40 GAPI. Its lithology is mostly argillaceous limestone.

Microfacies number 7 consist of medium to coarse-grained skeletal debris, such as echinoderms and rudist debris, frequently observed in these microfacies. The peloids are mainly accompanied by micritized bioclasts and small benthic foraminifera originating from the peloidal bioclastic shoals and re-deposited in low-energy settings. Considering the variations in size and type of bioclasts, textural inversion, and the mixture of the planktic and benthic fauna associated with stormy fabric, these facies could be ascribed to the channels developed from proximal parts of the mid-ramp to outer-ramp settings. These microfacies exhibit a light color on the outcrop. It was mainly recognized in the Sarvak Formation of Maleh Kuh and Behesht Reza. The average gamma-ray is lower than 10 GAPI in the wells and about 20 GAPI in the outcrops. Its lithology is limestone [54,55].

Talus facies consist of three distinct microfacies, including peloidal skeletal grainstone (MF8) (Figure 6E,F), skeletal packstone to grainstone (MF9) (Figure 6G), and crystallized skeletal grainstone (MF10) (Figure 6H).

The microfacies number 8 are mainly composed of echinoderm and rudist debris. However, planktonic fossils in a few samples may indicate relative sea-level rise or storm deposition. This evidence clearly shows fore-reef or rudist patch reefs talus that was extended to the middle parts of the mid-ramp. They have been mixed with mid-ramp bioclasts. The value of gamma ray is between 10 to 40 GAPI. The main lithology is argillaceous limestone to limestone.

The microfacies number 9 are formed of medium to coarse-grained echinoderm and rudist debris along with a few dispersed planktonic fossils. The presence of such faunas indicates deposition in the reef to fore-reef (and occasionally as a patch reef) setting. Most bioclast debris is micritized and rounded to sub-rounded. The gamma-ray often shows a value lower than 10 GAPI but occasionally reaches 30 GAPI. The main lithologies are limestone and argillaceous limestone [55].
Table 2. Microfacies and facies associations (MF1–MF12) of Sarvak carbonates in the studied sections. Main facies properties are also presented.

<table>
<thead>
<tr>
<th>Facies Code</th>
<th>Facies Name</th>
<th>Lithofacies</th>
<th>Main Components</th>
<th>Grain Properties</th>
<th>Energy Level</th>
<th>Depositional Environment</th>
<th>Gamm-ray (GAPI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>planktonic sponge spicule wackestone to packstone</td>
<td>grey to dark grey limestone to argillaceous limestone</td>
<td>planktonic fossils, sponge spicule</td>
<td>peloid</td>
<td>very fine</td>
<td>poor</td>
<td>very low</td>
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<tr>
<td>F2</td>
<td>calcispheres mudstone to packstone</td>
<td>limestone to calcareous shale with fine laminations, bioturbation and fissility</td>
<td>calcispheres, radiolarian, echinoder, sponge spicule, fish bone, rudist debris</td>
<td>—</td>
<td>very fine</td>
<td>poor</td>
<td>very low</td>
</tr>
<tr>
<td>F3</td>
<td>grey to dark grey planktonic fauna, wackestone to packstone</td>
<td>grey to dark grey limestone to argillaceous limestone</td>
<td>planktonic fauna, echinoderm, fish bone, rudist debris</td>
<td>—</td>
<td>very fine</td>
<td>poor</td>
<td>very low</td>
</tr>
<tr>
<td>F4</td>
<td>peloidal skeletal wackestone to packstone with planktonic fauna</td>
<td>limestone to argillaceous limestone</td>
<td>echinoderm, fish bone, sponge spicule, rudist debris, planktonic fossil (minor)</td>
<td>peloid</td>
<td>fine to medium</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>F5</td>
<td>thin layers of peloidal skeletal grainstone to packstone and grainstone</td>
<td>argillaceous limestone</td>
<td>echinoder, fish bone, sponge spicule, rudist debris</td>
<td>peloid</td>
<td>fine</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>F6</td>
<td>rudist debris floatstone/wackestone</td>
<td>foraminiferal and bivalve well-bedded argillaceous floatstone/limestone</td>
<td>rudist debris, small bentic and planktonic foraminifera, echinoderm</td>
<td>peloid</td>
<td>very coarse to very fine (diverse size)</td>
<td>poor</td>
<td>low to high</td>
</tr>
<tr>
<td>F7</td>
<td>intraclast skeletal grainstone (rudist rudstone)</td>
<td>grey foraminiferous, bivalve, rudist and shell fragmental well-bedded floatstone/limestone</td>
<td>echinoder, rudist debris, benthic foraminifera and pelagic fauna</td>
<td>intraclast, peloid</td>
<td>coarse to fine (diverse sizes)</td>
<td>poor</td>
<td>low to high</td>
</tr>
<tr>
<td>Facies Code</td>
<td>Facies Name</td>
<td>Lithofacies</td>
<td>Main Components</td>
<td>Grain Properties</td>
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<td>Depositional Environment</td>
<td>Gamm-ray (GAPI)</td>
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<td>F8</td>
<td>peloidal skeletal grainstone</td>
<td>foraminiferous, shell fragmental dolomitized well-bedded grainstone/limestone</td>
<td>rudist debris, echinoderm, benthic foraminifera</td>
<td>peloid, intraclast (minor)</td>
<td>moderate to coarse</td>
<td>moderately</td>
<td>10–40</td>
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<td>F9</td>
<td>skeletal packstone to grainstone</td>
<td>shell and rudist fragmental, bioturbated well-bedded argillaceous packstone to grainstone/limestone</td>
<td>rudist debris, echinoderm, fish bone</td>
<td>—</td>
<td>medium to coarse</td>
<td>moderately</td>
<td>&gt;25</td>
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<tr>
<td>F10</td>
<td>crystallized skeletal grainstone</td>
<td>grey rudist fragmental well-bedded grainstone/limestone</td>
<td>echinoderm, fish bone, rudist debris</td>
<td>—</td>
<td>coarse</td>
<td>moderately</td>
<td>10–30</td>
</tr>
<tr>
<td>F11</td>
<td>skeletal peloidal packstone to grainstone</td>
<td>foraminiferous shell fragmental peloidal well-bedded argillaceous packstone to grainstone/limestone</td>
<td>echinoderm and rudist debris, planktonic fossils</td>
<td>intraclast, peloid (minor)</td>
<td>medium</td>
<td>well</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>rudist debris, echinoderm, benthic foraminifera</td>
<td>peloid, intraclast</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F12</td>
<td>skeletal wackestone to packstone with large benthic foraminifera</td>
<td>foraminiferal shell fragmental well-bedded argillaceous wackestone to packstone/limestone</td>
<td>large benthic foraminifera, <em>Dicycina</em>, <em>Miliolidae</em>, <em>Rotula</em>, gastropod, echinoderms rudist, bivalve, ostracod, green algae debris</td>
<td>peloid, intraclast</td>
<td>medium to very fine</td>
<td>poor</td>
<td>low to high</td>
</tr>
</tbody>
</table>
The microfacies number 10 comprise echinoderm and bivalve (rudist) debris. The presence of such faunas indicates deposition in fore-reef or channels located in proximal parts of the mid-ramp. These microfacies have been observed in the Sarvak in Sarkan and Maleh Kuh Fields. The gamma ray shows a value lower than 25 GAPI. Its main lithology is limestone to argillaceous limestone.

Mid-ramp microfacies have been observed in all studied sections but are most abundant in the Sarkan, Maleh-Kuh, and Halush fields (Table 2).
4.1.3. Lagoon

Two microfacies of the lagoon setting are skeletal peloidal packstone to grainstone (MF11) (Figure 7A–D) and skeletal wackestone to packstone with large benthic foraminifera (MF12) (Figure 7E–H). Allochems include peloids and benthic foraminifera such as Ammodiscus sp., Glomospira sp., Murreina apula, Nezzazata conica, N. gyra, N. simplex, N. sp., Nezzazatinella picardi, Trochospira avnimelechi, Moncharmontia apenninica, Fleuryana adriatica, Bolivinopsis sp., Gaudryina sp., Arenobulimina sp., Pseudohastulina sp., Pseudotextulariella sp., Pseudolituonella reicheli, Dictyoconus sp., Orbitolina sp., Chrysadina sp., Marssonella sp., gastropods, green algae. Other observed allochems are echinoderm debris, rudists, coral debris, and intraclasts. The bioclast diversity, a mixture of planktonic and benthic fauna, textural inversion, presence of large benthic foraminifera, and a mud-dominated fabric all indicate that these microfacies have been deposited in a lagoon environment near an open-marine setting (channel) \[4,56\]. The lagoonal microfacies were only observed in the Sarvak Formation of Kuh-Sultan and some layers of the Behesht Reza section.

![Figure 7. Photomicrograph of microfacies of inner ramp (shoal and lagoonal facies). (A–D) MF11, Skeletal peloidal packstone to grainstone (A,B leeward shoal–C,D seaward shoal). (E–H) MF12, skeletal wackestone to packstone with sizeable benthic foraminifera, rudist, ostracod, green algae, echinoderm, and debris.](image)

The microfacies number 11 are divided into two groups. The first group consists of echinoderm debris (up to 30%) with overgrowth cement and rudist fragments (up to 5%), along with a minor amount of intraclasts. Based on field observations, these intraclasts are fine-grained and seem to be red algae debris, but they are not recognizable under the microscope due to micritization. Valvulamina picardi and Valvulamina sp. were also observed. Based on the petrographic study, the above microfacies were deposited in the seaward shoal.

The second group consists of rudist debris (30%), echinoderm, and some benthic foraminifera with minor amounts of peloids (up to 20%). Considering the petrographic studies, these microfacies have been deposited in a leeward shoal environment. The grain-dominated fabric and a relatively good sorting of grains are related to higher energy and
turbulence during deposition. Therefore, these facies have been formed in a shoal’s seaward and leeward parts. The microfacies were only observed in Behesht Reza Section. These microfacies have a light color and massive appearance. The gamma-ray ranges between 20 to 30 GAPI. The main lithology is limestone to argillaceous limestone.

The microfacies number 12 are characterized by skeletal wackestone to packstone with large benthic foraminifera. The lagoonal fossils, such as gastropods and green algae, are predominant. However, a few rudists, echinoderms, and coral debris would also be observed. The bioclast’s diversity, large benthic foraminifera, and mud-dominated fabric indicates a lagoon environment near an open-marine setting (channel). These facies are observed in the Sarvak Formation of Kuh Sultan and Behesht Reza sections. They show a light color and massive texture. The gamma-ray ranges from 20 to 70 GAPI, and its main lithology is limestone to argillaceous limestone.

4.2. Frequency of Facies Associations

The frequencies of the recognized facies throughout the study area and each studied section have been calculated (Figure 8). According to these calculations, the distal open marine sub-environment microfacies show the highest frequency, while the lagoon is less frequent than other facies. The percentage of lagoonal microfacies decreases from southeast to north-northwest in the central subzone of the Lurestan Zone. All evidence indicates that the lagoon sub-environment was prevailed in the Kuh Sultan area in the Central subzone. In addition, these microfacies are present in the Behesht Reza section in the northern subzone (Figure 9A). Open marine facies vary considerably in the Sarvak Formation of the studied area (Figure 8), indicating that the main body of fore-reef sediments was deposited in the Maleh-Kuh and Halush areas (high energy level, windward side) (Figure 9B). The frequency of fore-reef microfacies in the Sarvak Formation shows a decreasing trend from southwest to east-northeast (Figure 9B).

The frequency of open marine microfacies (proximal and distal open marine) (MF1–MF8) shows an increasing trend from S.W. to the north-northeast in the central subzone of Lurestan Zone (Figure 9C). This indicates the domination of deep basin conditions towards the N-NE. In addition, the main body of open marine facies was deposited in the Sarkan, Veyzenhar, and Gaver areas. However, moving northeast to the northern subzone and Behesht Reza outcrop, the frequency of talus facies decreases while inner-ramp facies (particularly shoal facies) increase. According to isochore maps of the Sarvak Formation, an increasing thickness from southeast to N-NW could be observed, indicating a deepening...
trend in this direction (low energy level, leeward) (Figure 9D). Sedimentological columns of Behesht-Reza, Kuh-Soltan, Male-Kuh and Sarkan wells and outcrops are illustrated in Figures 10–13.

**Figure 9.** (A) Isochore map of lagoonal microfacies (open marine lagoon and shoal) frequencies in the Sarvak Formation in the studied area. The frequency of these microfacies decreases from the southeast to the north-northwest in the central subzone of the Lurestan Zone. (B) Isochore map of fore-reef microfacies (channel and Talus located mid-ramp) frequencies in Sarvak Formation in the studied area. The frequency of these microfacies decreases from S.W. to the east-northeast. (C) Isochore map of frequency of open marine microfacies (proximal and distal open marine) in Sarvak Formation in the studied area. The frequency of these microfacies increases from S.W. to the north-northeast. (D) Isochore of the Sarvak Formation thickness in the studied area (central subzone). The thickness of this formation increases from south-southeast to north (according to the meter scale).
Figure 10. The sedimentological column of the Sarvak Formation in the Behesht-Reza outcrop in the northern subzone shows thickness, gamma-ray, lithology, texture, biozone and sequence framework.
Figure 11. Sedimentological column of the Sarvak Formation in the Kuh-Soltan and Beheshte-Reza outcrops. Thickness, gamma-ray, lithology, rock type, zonation, and sequences of the Sarvak Formation are shown. Equivalent MFS have been recognized in different parts of the Middle East [20]. The main sequence stratigraphic surfaces (maximum flooding surfaces and sequence boundaries) have been determined based on facies (microfacies) properties, log data (gamma-ray logs), and paleontological evidence (ratio of planktonic to benthic foraminifera).

4.2.1. Sequence Stratigraphy

The sequence stratigraphical analysis has been carried out using petrophysical data, facies, and fossil contents. A total of 4 depositional sequences (third order) were distinguished using the available data [56–58].

Sequence No. 1

Sequence 1 comprises the TST and HST intervals characterized by transgressive and regressive cycles (Early Cenomanian age). The TST interval is characterized by fine-grain skeletal wackestone to packstone, followed by planktonic facies (Oligosteginitidae facies). A significant retrogradational parasequence can be observed in this transgressive interval (associated with the high-gamma radiation). The TST interval is bounded at the top by the MFS, characterized by a thick interval of the planktonic facies and bioturbation. The HST interval has been deposited above the MFS and is composed of a significant assemblage of Rudist debris (Rudist skeletal grainstone). Regarding lithology, the HST comprises dolomite with low gamma radiation (SK-1). The HST interval is bounded at the top by
a type 2 sequence boundary distinguished based on an abrupt marine flooding event (Figures 10–13).

Figure 12. Sedimentological column of the Sarvak Formation in the two wells of the Male-Kuh Field. Depth, rock type, zonation, and sequences of the Sarvak Formation are shown. Equivalent MFS have been recognized in different parts of the Middle East [20]. The main sequence stratigraphic surfaces (maximum flooding surfaces and sequence boundaries) have been determined based on facies (microfacies) properties, log data (gamma-ray logs), and paleontological evidence (ratio of planktonic to benthic foraminifera).
Figure 13. Sedimentological column of the Sarvak Formation in three wells of the Sarkan Field. Depth, gamma-ray, lithology, rock type, zonation, and sequences of the Sarvak Formation are evident. Equivalent MFS in different parts of the Middle East can be find in [20]. Maximum flooding surfaces and sequence boundaries have been recognized based on facies (microfacies) variations, gamma-ray logs and paleontological studies (ratio of planktonic to benthic foraminifera).

Sequence No. 2

Sequence no. 2 consists of TST and HST intervals, characterized by limestone to argillaceous lithologies (Cenomanian age). The TST interval is composed of an alternation between peloids packstone/grainstone and rudist packstone. Deepening upward cycles with retrogradational stacking patterns are dominated in the TST interval. This interval is bounded at the top by the MFS, which is marked by a large community of planktonic facies (Oligosteginidae packstone). The MFS key bed also represents high radiation of gamma-ray. The HST interval is dominated by an alternation between planktonic packstone/wackestone and peloidal skeletal packstone/grainstone, representing a gradual progradational stacking pattern. Regarding lithology, the HST interval mainly comprises limestone to argillaceous limestone. This interval is bounded at the top by a type 2 sequence boundary (Figures 10–13).

Sequence No. 3

Sequence no. 3 consists of TST and HST systems tracts. This depositional sequence is dominated by limestone and argillaceous limestone lithologies (Late Cenomanian to Turonian age). The TST interval is mainly composed of the planktonic facies (mostly Oligosteginidae assemblages) with a few layers of rudist skeletal packstone. The TST interval also corresponds to the retrogradational parasequences, accompanied by a considerably high gamma ray. The TST interval is bounded at the top by the MFS key bed, characterized by the concentration of Oligosteginidae microfauna (corresponds to the highest gamma radiation). The HST interval represents an alternation between planktonic facies (Oligosteginidae wackestone/packstone) and rudist skeletal packstone to grainstone (equivalents to the progradational stacking pattern). The HST interval is capped by a thick interval of intraclast grainstone adjacent to the overlaying sequence boundary type 2. As a result, the
HST interval reveals a shallowing upward cycle terminated at the next abrupt flooding surface (sequence boundary type 2/transgressive surface) (Figures 10–13).

Sequence No. 4

Sequence 4 comprises the outer shelf facies (Late Turonian to Early Santonian age). The TST interval shows a deepening upward cycle characterized by planktonic facies (wackestone/packstone). The TST interval begins with intraclast skeletal wackestone as an indicator of abrupt marine flooding and is followed by a thick succession of Globotruncanidae microfauna, including Globotruncana skeletal wackestone/packstone. The main lithology is argillaceous limestone with few limestone interlayers. The TST interval is bounded at the top by the MFS assigned to the maximum increase of planktonic microfauna and glauconite debris. It is noted that MFS indicates an increase in gamma radiation. The HST interval is mainly characterized by alternating Globotruncana skeletal wackestone and Globotruncana skeletal packstone. The HST interval is capped by a type 2 sequence boundary or abrupt marine flooding surface (transgressive surface) (Figures 10–13).

5. Discussion

5.1. Cenomanian Palaeoheight

In the Zagros, three unconformities have been identified in middle Cretaceous deposits [40,53,57,58]. The lower unconformity (Mid-Cenomanian) has been observed at the base of this interval in the southern part of the Fars area and Bandar Abbas. Another unconformity (Late Cenomanian–Early Turonian) is traced throughout the Zagros area, except in the Lurestan. The last unconformity is seen after Mid Turonian throughout the Zagros area, and its effects are sometimes recognized in the Lurestan Zone [27]. In most subzones, these events have paved the way for exposure and erosion [32,33,59]. However, in the Lurestan Zone, in contrast to the other areas of the Zagros, deep marine conditions were dominated, which prevented the emergence of the Sarvak platform (except for the past-mid-Turonian event, which is documented in some parts of the Lurestan Zone) [60].

In the Cenomanian, two significant unconformities have been introduced. The first one (middle Cenomanian) has a eustatic nature. The second one (the Late Cenomanian) occurred due to local palaeoheight, as indicated by faulting, basement block uplift, and halokinetic movements [60]. These unconformities are readily traced and correlated on a regional scale in the Arabian Plate and Zagros region [61–66]. However, they gradually disappear towards the N.W. of the Zagros (i.e., the Lurestan Zone), reflecting the predominance of deeper marine conditions during Cenomanian. Then, the tectonic regime changed from extensional (passive margin) to compressional (active margin). Thus, the Lurestan Zone, on the distal part of this changing platform, experienced deeper marine conditions. Therefore, these unconformities (an active compressional regime) gradually disappear toward the Lurestan Zone. However, the driving force was active, resulting in basement uplifts, leading to the development of some shallower realms in the Sarvak platform suitable for isolated platform establishment. Thus, compressional tectonic paved the way for basement uplift and shaping platforms with optimum conditions for carbonate production (carbonate factory).

Favourable conditions for the generation of Palaeoheights in Cenomanian of the Lurestan Zone were like NW Spain during the Carboniferous period in the Cantabrian Mountains. Both were identical regarding tectonic activities and location in the sedimentary basin. The generation of palaeoheights in both places was influenced by a compressional tectonic regime in a deep sedimentary basin. With the basement uplift of the basin and their emplacement in optimum depth, it was possible to create a carbonate factory [17–19]. In S Spain during the Aptian-Albian transition, an isolated sedimentary platform was formed after an extensional tectonic regime. Thick layers have been deposited during sea-level fall [17]. After basement uplifts in the Lurestan Zone to the optimum depth (euphotic zone), rudist-bearing patch reefs formed at the windward side. Bioclastic shoals were created on the opposite side (leeward). Therefore, the isolated platforms in the Lurestan were
shaped by the same forces creating the two Cenomanian unconformities in other areas of the Zagros. Later, these isolated platforms were also affected by the basin-scale relative sea-level fall after the mid-Turonian that led to their exposure (carbonate factory shut down). The middle Turonian unconformity originates from the ophiolite obduction on the north-western margin of the Arabian Plate [27,50]. This resulted in the development of an isolated platform in the east-south-eastern sections adjacent to the palaeoheight (Figures 14 and 15).

The nearest sections to palaeoheights (Behesht Reza and Kuh-Soltan) are the only ones having lagoon facies, implying that they are located at the central parts of the platform.

The creation of the atoll in the Aptian-Albian isolate platform in southern Spain started with creating a graben on the platform. With the higher sedimentation rate and sea-level fall, the atoll divided the platform into two parts. The presence of continental sediments, organic matter, soil horizon, and carbonate sediments indicate the formation of a barrier island near the coast. With the rising sea level and the drowning of the barrier island, the isolated platform has been shut down [17].

Unlike the southern platform of Spain, isolated platforms in the Lurestan Zone and NW Spain (Mississippian–Lower Pennsylvanian isolated carbonate platform), atolls have been created under the influence of tectonic activities and basement uplift in deep sedimentary basins far from land. The absence of continental sediments in the identified facies indicates this issue. In both platforms, carbonate facies of the shallow environment are surrounded by facies of the deep basin. One of the main differences between the Cenomanian platform in the Lurestan Zone and the Mississippian–Lower Pennsylvanian platform in NW Spain is the profiles of the platforms. In the Lurestan Zone, the atoll has been surrounded by two ramp profiles, while in the NW Spain platform, the atoll has been surrounded by two shelf profiles. This can be inferred from the difference in the type of reef-builder organisms. In the Lurestan Zone, three-dimensional rudist reefs were not present, and it was not possible to create a shelf profile, while in the Carboniferous period in NW Spain, reef-builder organisms were able to create three-dimensional structures, and subsequently, there were atoll shelf profiles [17–19].

Figure 14. Proposed ramp carbonate platform conceptual depositional model for the Sarvak Formation in the Central and Northern subzones of the Lurestan Zone. Schematic microfacies illustrations for the main facies’ belts are shown. Based on the frequencies of various facies associations, the approximate locations of each section in the conceptual depositional model were also determined.
Figure 14. Proposed ramp carbonate platform conceptual depositional model for the Sarvak Formation in the Central and Northern subzones of the Lurestan Zone. Schematic microfacies illustrations for the main facies’ belts are shown. Based on the frequencies of various facies associations, the approximate locations of each section in the conceptual depositional model were also determined.

Figure 15. Reconstruction of the location of the study sections on the isopach map of the Cenomanian interval in the Lurestan Zone, based on logged surface sections together with fieldwork and borehole data [67](up). Three considerable palaeoheights have been caused by these tectonic movements that resulted in an isolated platform (down).

Far from palaeoheights, Sarkan, Male Kuh, and Halush sections were located at the edge of the platform, and they contain frequent talus and rudist facies. The Visenhar and Gaver sections were in the open marine setting of the proposed isolated platform. In addition, the Kabir Kuh and Samand sections (located in the southern part of the Lurestan Basin) were influenced by two palaeoheights in east-southeastern and south-southwestern areas. Therefore, they were placed at the platform’s edge (Figure 15).

5.2. Conceptual Depositional Model

Significant features of this isolated platform include its controls over the facies distribution expressed by the windward or leeward orientations or tide-or-storm-dominated conditions. Outer high and low energy belts in the platform have been occupied by the rudist reefs along with the channel and shoal facies. The isochore map shows that the platform’s general pattern of facies distribution was almost circular in the studied area (Figure 14). In addition, the gradual changes of facies and low diversity and type of facies throughout this platform are other indicators of its isolated platform model.

6. Conclusions

Reconstruction of depositional palaeoenvironments by combining the results of various data indicates an isolated platform with two ramp profiles for the passive margin of Neotethys. According to the textural properties of the facies and their distribution, the ramp profile located in the central subzone was windward-oriented and had a relatively high energy level (significant development of rudist reefs). The ramp profile in the northern...
subzone was leeward-oriented, and its lower energy led to the replacement of the rudist reefs by bioclastic shoal bodies. The lagoonal facies were only observed in the Kuh-Sultan and Behesht-Reza sections. Therefore, the shallower part of the platform was in these areas.

Based on the frequencies of various facies associations, the approximate location of each section in the conceptual sedimentary model was determined. Accordingly, the lower and upper successions have been deposited in open marine (distal and proximal) environments. However, in the central zone, in the Kuh-Sultan section, lagoonal environments and an open marine lagoon (back-reef) are visible in the upper part of this unit. It could have been caused by erosion at the Sarvak Formation’s top. In the Sarkan and Maleh-Kuh fields, the middle part of the Sarvak Formation was deposited in channel and talus (fore-reef) environments, but in the Kuh-Sultan area, it shows lagoonal environments. The talus and channel facies were primarily observed in the Maleh-Kuh area. In other words, most of the open marine facies were deposited in the Sarkan area, while lagoonal facies were dominant in the Kuh-Sultan. However, in the northern subzone at the Behesht Reza section, all mentioned facies belts are present. Shoal facies were dominant in the Behesht Reza section.

The Sarvak Formation in the Lurestan Zone, including most of its reservoir interval, has been formed as an isolated platform (Albian–Early-Turonian). In this time interval, the high-energy settings of the ramp profiles were dominated by high-energy shoals and rudist patch reefs. While the entire studied carbonate successions have been formed in the carbonate factory of an isolated platform, the overall anatomy was shaped by local and regional tectonic movements.

The Sarvak Formation have been analysed regarding sequence stratigraphy in the study area. Altogether, four distinct depositional sequences were distinguished (corresponding to the third order cycles). The relevant depositional sequences comprise the TST and HST intervals formed by frequent and gradual relative sea-level fluctuations in the basin.

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