An almost-forgotten model for epeiric carbonates: the Irwin concept resurrected — Dhruma Formation in the Sultanate of Oman

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Abstract

Epeiric carbonate systems that are so common in the geological record lack corresponding modern analogues. In this paper, we use data from the Middle Jurassic Dhruma Formation in outcrops and subsurface of Oman to suggest the need for a non-uniformitarian depositional model for some epeiric carbonates.

Main observations for the Dhruma Formation that do not fit popular carbonate ramp models currently in use are (i) vast facies belts extending over 10s to 100s of kilometres, indicated by sheet-like geometries for all observed lithologies and facies, (ii) the absence of a clearly defined shoal-water complex, (iii) the lack of high-relief shoal geometries, (iv) the very rare occurrence of cross-bedding within high-energy facies, and (v) a general dominance of low-angle bedding.

An initial, but almost forgotten, depositional model that corresponds to these observations was described by Irwin (1965): he suggests an extremely wide and shallow ramp with a slope of approximately 0.01°, i.e. less than 20 cm/km, causing a restriction of circulation that creates a threefold zonation in hydrodynamic energy into (i) a low-energy Zone X below wave-base (offshoal equivalent), (ii) a high-energy Zone Y (shoal equivalent), and a (iii) low-energy Zone Z (backshoal equivalent).

To cover the detailed facies description from outcrops, the three proposed Zones X, Y, and Z after Irwin were extended for the Dhruma Formation in Oman to six lithofacies associations, allowing a more detailed differentiation of depositional environments on an epeiric ramp: peritidal, low-energy Zone Z, moderate-energy Zone Y to Z, high-energy Zone Y, moderate-energy Zone X to Y, and low-energy Zone X. This conceptual model has significant implications for hydrocarbon exploration and production, especially regarding prediction of reservoir extent, quality, and distribution, and might have to be considered more widely than it is currently the case.

Key words: Dhruma Formation, Irwin concept, Epeiric carbonate ramp.
Introduction

The Middle Jurassic Dhruma Formation was described in detail by Schlaich and Aigner (2017) in outcrops of Wadi Sahtan in the Oman Mountains (Sultanate of Oman; Fig. 1). A more regional study with correlations between nine outcrop sections and 20 wells over North and Central Oman was carried out by Schlaich and Aigner (in prep.) and will be published in an upcoming paper. It indicates that the Middle Jurassic Dhruma, and most likely also the overlying Tuwaiq Mountain Formation, cannot be interpreted by currently popular and widely used carbonate ramp models.

Ahr (1973) introduced the concept of carbonate ramps to differentiate from steep-sloped and reef-rimmed shelves. He defined ramps as settings with a slope angle of less than 1° and the missing of a distinct slope break. Read (1985) published a comprehensive paper on carbonate platform models over 30 years ago based on his studies and observations from Ahr (1973), Ginsburg and James (1974) and Wilson (1975) where he subdivided ramps further into homoclinal and distally steepened ramps (Read 1982, 1985). Ramps are common in all geological periods and thrive especially when reef-constructing organisms are inhibited or absent. They are often located in cratonic interior basins, passive continental margins, and foreland basins (Leighton and Kolata 1990). A widely used approach to further classify ramps is by referring to the fairweather wave base and storm wave base to divide the depositional ramp system into inner-ramp, mid-ramp, and outer-ramp deposits (Markello and Read 1981; Aigner 1984;

Figure 1: Map of Central and Northern Oman shows the location of investigated outcrop sections (yellow) and wells (green).
An almost-forgotten model for epeiric carbonates: the Irwin concept resurrected—Dhruma Formation in the Sultanate of Oman

Calvet and Tucker 1988; Buxton and Pedley 1989; Burchette and Wright 1992; Somerville and Strogen 1992). According to Burchette and Wright (1992), most ramps are storm-dominated and show only minor tidal influence, causing linear sand ridges in the inner ramp and tempestite deposits and hummocky cross-stratification in the mid-ramp.

Several carbonate ramp deposits have been described for Oman throughout geological times. Starting in the Neoproterozoic, Cozzi, Grotzinger and Allen (2004) described a distally steepened carbonate ramp system (Read 1985) for the Buah Formation where they differentiate between an inner-ramp, tidally influenced oolitic shoal and backshoal lagoon facies and storm-dominated mid-ramp facies. A break in slope separates the mid-ramp from the outer ramp, which is characterised by redeposited carbonates on a gently inclined slope of 1° to 2°. This setting is comparable to a distally steepened ramp described by Sami and James (1993) for the early Proterozoic lower Pethei Group in Canada.

Permian to Triassic times (Obermaier and Aigner 2012) describe a vast and flat epeiric carbonate ramp for the Khuff, Sudair, and Jilh Formation with an extent of over 1500 km in dip direction. On this ramp, supratidal marsh environments with typical karst features and rootlets are followed seaward by peritidal deposits characterised by microbial boundstone, a low-energy backshoal environment with mainly mudstones and wackestones in a protected lagoon with common bioturbation, a moderate-energy backshoal with moderately sorted peloidal or bioclastic-rich pack-grainstones, where wave-ripples occur, to a high-energy shoal environment with dominantly cross-bedded, oolitic grainstones with an erosive base.

In the Cretaceous, several large, restricted basins developed within the Arabian shelf (Murris 1980) leading to the formation of source rocks as well as reservoir rocks. For middle Cretaceous times van Buchem et al. (2002) described for the Natih Formation as a carbonate ramp, bordering an intra-shelf basin, where individual beds can be followed for around 200 km. Van Buchem et al. (2002) separate the succession into an (i) outer ramp, (ii) mid-ramp and (iii) inner ramp. (i) The outer ramp contains organic-rich basal facies with some gastropods. (ii) Mid-ramp deposits contain dominantly wackestones, packstones, and grainstones with abundant rudists and some bioclastic debris, peloids, and benthic foraminifera. High-energy facies consists of well-sorted, fine-to-coarse bioclastic grainstone with normal small-to-medium-scale cross-bedding. (iii) Inner-ramp deposits are dominated by wackestones and packstones with mainly rudists (Philip, Borgomano and Al-Maskiry 1995) and some echinoids, corals, and stromatoporoids, which are organised in up to metre thick shoaling-upward cycles with common Thalassinoides fauna. No unequivocal evidence exists that the paleowater depth was deeper than 10 to 20 m.

During depositional times of the Dhruma Formation, carbonate ramp settings occurred in several places all around the world. One example is the Bajocian Assoul Formation in the High Atlas in Morocco (Christ et al. 2012). Two alternating ramp models were identified: (i) an oolitic ramp, with a sheltered lagoon and shoals acting as barriers, and (ii) an ooid-lean ramp with an overall lower hydrodynamic level and dominant marls, mudstones, and wackestones. Most proximal facies are represented by oncolidal floatstone of the distal inner-ramp to mid-ramp setting. The most distal facies are present in form of marls, which contain some brachiopods and represent the distal mid-ramp to proximal outer ramp.

While all these carbonate deposits contain comparable organisms, the observed sedimentary structures, especially in the high-energy, peloids and ooid-dominated areas, do not fit the observations made for the Dhruma Formation as listed below.

Read (1985) differentiates carbonate ramps based on their profile into homoclinal ramps and distally steepened ramps: homoclinal ramps have a gentle slope of one to a few metres per kilometre (~0.1°). Tidal flat and lagoonal facies turn seaward into a shoal-water complex of banks or ooid-peloidal sand shoals, which turn on a deeper ramp setting into argillaceous lime mudstones and wackestones containing open marine facies. Modern examples for this kind of ramps are the Persian Gulf (Purser and Evans 1973) and Shark Bay (Logan, Read and Davies 1970).
Distally steepened ramps possess characteristics of ramps and rimmed shelves: a shoal-water complex to sub-wave base transition is present well back on the platform, and abundant slumps and breccias occur at the slope (Read 1985). In contrast to a rimmed shelf, the major break in slope occurs many kilometres seaward of the shoal. Read (1985) further distinguishes between low- and high-energy, distally steepened ramps dominated either by widespread mud blankets or broad lime-sand blankets seawards of the shoal-water complex. Examples are the Upper Cambrian-Lower Ordovician sequence of the western United States (Cook and Tylor 1977; Brady and Rowell 1976; Cook 1979).

However, still, an important feature for these ramps is the presence of a shoal-water complex in the form of skeletal banks or shoals (e.g., Petrovic and Aigner 2017) or ooid-pellet sand shoals (e.g., Jahnert et al. 2012), which might be fringing or barrier complexes (Read 1985).

Schlaich and Aigner (2017) document the Dhruma Formation in outcrops of the Oman Mountains and cores and cuttings of North and Central Oman (Schlaich and Aigner in prep.), which indicate that the above-mentioned carbonate ramp models do not allow to explain all observed sedimentological and geometrical features. As the epeiric model by Irwin (1965) seems to best correspond to most observed aspects of the Dhruma Formation, this paper aims to revive and elaborate on his original concept of an epeiric carbonate ramp. In addition, we want to outline the spatial occurrence of reservoir and non-reservoir facies within the Irwin model.

The Dhruma Formation in outcrops and subsurface of Oman

The Middle Jurassic Dhruma Formation in Oman is documented in detail by Schlaich and Aigner (2017) and Schlaich and Aigner (in prep.; Fig. 2). For a complete data documentation, the reader is referred to these papers; the current paper aims to highlight conceptual aspects regarding the most suitable depositional model. The data base comprises nine surface outcrops in the Oman Mountains and, additionally, 20 subsurface wells (Fig. 1), investigated in an integrated approach by combining facies analyses with sequence-, bio-, and chemostratigraphy.

Schlaich and Aigner (2017) report that facies in outcrops and subsurface bear great similarities and cover the same range of depositional environments: mudstones and wackestones were interpreted as low-energy deposits of a lagoonal environment, wackestones to packstones denote moderate-energy, lagoonal deposits and, packstones to grainstones represent high-energy deposits with a more open marine influence. Stratigraphically, argillaceous, muddy facies represent proximal, lagoonal deposits, which typify cycle boundaries, whereas oolitic and peloidal grainstones represent the most distal facies and, thus, the zone of maximum flooding. Components are relatively uniform throughout all textures. Low-energy deposits are richer in bivalves, gastropods, and unidentified skeletal debris and are stronger bioturbated. Moderate-energy deposits are the most diverse, containing the above mentioned, as well as echinoids, brachiopods, oncoids, foraminifera, and peloids. High-energy facies on the other hand are dominated by peloids and ooids.

A pronounced cyclicity was identified on four levels (Fig. 2) and correlated over a distance of more than 60 km in outcrop sections [lithofacies associations (LFAs) modelled with Petrel: Fig. 3] and to the subsurface over more than 300 km in North and Central Oman (Schlaich and Aigner, in prep.; textures: Figs. 4 and 5). A prominent vertical hierarchy of cyclicity (composite sequences, high-frequency sequences, cycle sets, and cycles; after Kerans and Tinker 1997) reflect long periods of almost uniform depositional conditions, largely ruled by eustatic “greenhouse-type” sea-level changes. Correlations of sections from outcrops and subsurface show a thinning of cycles and onlaps within composite sequence 1 (CoSe1; Fig. 2) towards the southeast, indicating an unconformity at the base of the Dhruma Formation. In the following composite sequence CoSe2, cycle thicknesses vary less (Schlaich and Aigner in prep.), and very gradual lateral facies changes can be observed (Figs. 3–5). The extent of facies belts increases from 10 seconds of kilometres in CoSe1 to extremely wide facies belts of 100 seconds of kilometres in
CoSe2. With more proximal, lagoonal deposits towards the east, southeast, and south and a deepening trend in a northwestward direction, an overall facies trend from peritidal to low-energy lagoonal to high-energy “shoal-like” deposits is observed towards the northwest.

Correlations of wells indicate that vastly extensive facies belts are also present in the overlying Tuwaiq Mountain Formation, which is dominated by low-energy facies. High-energy facies and, thus, potential reservoir intervals only occur in the northwestern sections.

The Dhruma Formation represents a remarkable example for epeiric deposits with extremely wide facies belts with an extent of 10 seconds to 100 seconds of kilometres, a distinct vertical hierarchy of cyclicity and very gradual lateral facies changes. Comparable patterns were also described by Poppelreiter and Aigner (2003) in an epeiric succession from the Lower Keuper in Germany.

Principal observations in the Dhruma Formation (Schlaich and Aigner 2017, in prep.) which are not in line with popular carbonate ramp models are the following:

(i) Grainstone beds show sheet geometries and are predominantly massive. When cross-bedding is present, it is always of low angle type.

(ii) All beds, independent of lithology, texture, or facies, show a more or less constant bed thickness over 100 seconds of metres to probably kilometres in outcrops.

(iii) In outcrop sections at the northern flank of the Oman Mountains, where grainstones are most abundant, no high-relief shoal geometries can be observed.

(iv) Cycles, cycle sets, and high-frequency sequences show only minor variations in thickness over a distance of 10 seconds of kilometres in outcrops and 100 seconds of kilometres in Central and North Oman.

(v) An almost homogeneous bio-component distribution over 100 seconds of kilometres indicates only little lateral variation in environmental conditions.

Figure 2: Approximately 238-m-thick section of the Dhruma Formation in Wadi Sahtan at the northern flank of the Oman Mountains (N:2583012, E:531597), including spectral gamma-ray and interpreted cycle levels: “cycles”, cycle sets, HFS: high-frequency sequences, CoSe: composite sequences (Schlaich and Aigner 2017).
Correlations and a regional numerical facies model revealed a width of facies belts of 10 seconds to 100 seconds of kilometres.

The Dhruma Formation and the Irwin concept
Since both homoclinal and distally steepened ramp models predict a significantly smaller width of facies belts and the existence of a distinct shoal-water complex, they are not suitable for the epeiric carbonates of the Dhruma Formation in the Middle Jurassic in Oman.
Figure 4: Regional sequence-stratigraphic correlation of subsurface wells based on investigated cuttings shows that thickness and texture changes over 10 seconds of kilometres in a WNW–ESE direction, indicating laterally extensive facies belts (modelled with Petrel). The header for each well is enlarged in the top right of the figure showing: Dunham texture, lithology, cyclicity, gamma-ray, neutron, and density values.
Figure 5: Regional sequence-stratigraphic correlation of subsurface wells based on investigated cuttings shows thickness and texture changes over 10 seconds of kilometres in a SSW–NNE direction, indicating laterally extensive facies belts (modelled with Petrel). The header for each well is enlarged in the top right of the figure showing: Dunham texture, lithology, cyclicity, gamma-ray, neutron, and density values.
In 1965, Irwin introduced a model on “epeiric clear water sedimentation” that seems suited to match the observations made in the Dhruma Formation in Oman. Irwin (1965) suggests an extremely wide shelf (100 seconds of kilometres) and a very low angle of slope of less than 20 cm/km (≈ 0.01°). The extreme shallowness of the shelf restricts or eliminates circulation and creates a threefold zonation in hydrodynamic energy into the following zones (Fig. 6):

(i) Zone X: low-energy zone with an extent of 100 seconds of kilometres, below wave base; marine currents are the only form of hydraulic energy acting upon the bottom; formation of only little sediment; accumulation of detritus from Zone Y (offshore equivalent).

(ii) Zone Y: high-energy zone with an extent of 10 seconds of kilometres, begins where waves impinge upon the sea floor; extending landward to the limit of tidal action; sediments of biogenic and chemical origin (shoal equivalent).

(iii) Zone Z: low-energy zone with an extent of 10 seconds to 100 seconds of kilometres; extremely shallow (< 1 m); little circulation of water; tides are essentially absent; sometimes storm deposits (backshoal equivalent).

Figure 6: (A) Depositional model (modified after Irwin 1965): 2D and 3D illustration of an epeiric carbonate ramp. The depositional environments for the Dhruma Formation range from peritidal (Zone Z) to high-energy “shoal-like” (Zone Y); (B) schematic 2D illustration of the epeiric carbonate ramp: black bars represent the distribution of lithofacies types (left) along an epeiric carbonate ramp in the hydro-dynamic Zones X, Y, and Z (after Irwin 1965) proposed for the Dhruma Formation and the related lithofacies associations (after Schlaich and Aigner 2017).
According to the Irwin (1965) model, all kinetic energy from tides and waves is dissipated in Zone Y. This causes restriction or even elimination of circulation in Zone Z, creating a low-energy environment comparable to a backshoal environment. The formation of carbonate sands and muds is of biochemical, chemical, and physical nature.

For the Dhruma Formation, carbonate production is dominated by particles like peloids and ooids, as well as skeletal remains. In Zone X and Z, completely preserved components like bivalve or brachiopod shells can be found with increasing distance to high-energy Zone Y. In Zone X, the accumulation of fine-grained detritus is common. In Zone Y, the precipitation of calcium carbonates may occur in turbulent waters, e.g., in form of ooids. Corals may flourish on the seaward side. Peloids can be found in all three zones. Oncoids occur in a moderate- to high-energy environment on the landward side of Zone Y. In Zone Z, beyond the zone of waves and tidal action, algal and microbial laminates, as well as lagoonal organisms, can be found and indicate a water depth of just a few centimetres to metres. Clay input may occur from a landward direction, which allows the formation of marl in a low-energy lagoonal environment in Zone Z. The limited circulation in Zone Z may cause an increased landward salinity and Mg$^{2+}$ concentration, which might stimulate the formation of dolomite in proximal environments.

While Irwin (1965) describes a clear water setting, with no influx of terrigenous clastics, some terrigenous influx occurs in the lower part of the Dhruma Formation, limited to the east and southeast of the study area.

Irwin (1965) used the depositional province of the Great Plains Devonian, which once reached from north of the Arctic Circle in North America, across Canada to at least as far south as South Dakota, as an example of epeiric clear water sedimentation. Several major tectonic basins formed within this vast shelf setting: the Mackenzie, the Alberta, and the Williston. This might be comparable to the formation of the Rub’ Al-Khali intra-shelf basin on the Arabian Peninsula during Middle and Upper Jurassic times in eastern Saudi Arabia and southern UAE as described by Sharland et al. (2001).

Irwin (1965) documents a width of facies belts of 100 seconds of kilometres for the Great Plains Devonian and a slope of ~0.001°, comparable to the Paradox basin in Arizona, New Mexico, Utah, and Colorado. The water depth for present reefs there is assumed to be 15 m or less, leading to an estimated slope angle of ~0.002°, comparable to the calculated slope for the Dhruma Formation in Oman.

**Modification of the model: facies belts of the Dhruma Formation**

Schlaich and Aigner (2017) distinguished 12 lithofacies types (Figs. 7 and 8) in the Dhruma and Tuwaiq Mountain Formation in outcrops of the Oman Mountains and the subsurface of North and Central Oman. To accommodate the detailed facies description from outcrops, Schlaich and Aigner (2017) extended the three proposed Zones X, Y, and Z from Irwin (1965) to six LFAs, allowing a more detailed differentiation of depositional environments across the Dhruma Formation epeiric ramp (Fig. 6):

(i) LFA 1: Peritidal (Zone Z after Irwin 1965)
(ii) LFA 2: low-energy Zone Z (lagoonal; Zone Z after Irwin 1965)
(iii) LFA 3: moderate-energy Zone Y to Z (transition from Zone Y to Z after Irwin 1965)
(iv) LFA 4: high-energy Zone Y (Zone Y after Irwin 1965)
(v) LFA 5: moderate-energy Zone X to Y (transition from Zone X to Y after Irwin 1965)
(vi) LFA 6: low-energy Zone X (offshore; Zone X after Irwin 1965)

According to Schlaich and Aigner (2017), moderate-energy Zone X to Y and low-energy Zone X (Zone X; after Irwin 1965) are not present in the outcrops of the Dhruma Formation in the Oman Mountains.

**Peritidal environment (Zone Z after Irwin 1965)**

The intertidal and supratidal environments together form the peritidal environment (Wright 1984). It is influenced by tidal action and passes seaward into the adjoining lagoonal environment of low-energy
**Figure 7**: Facies atlas for the Dhruma Formation in Oman after Schlaich and Aigner (2017) outcrop and thin section photos of sandstones, mudrocks, microbial boundstone, and dolo-, thinly bedded-, and massive lime-mudstones.
<table>
<thead>
<tr>
<th>LFT</th>
<th>Key Attributes</th>
<th>Outcrop</th>
<th>Specimen</th>
<th>Thin Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wackestone</td>
<td>moderate- to low-energy lagoon or foreshoal; grading might indicate event deposits (influenced by tempestites)</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Wacke-to-Packstone, skeletal</td>
<td>deposition under medium- to high-energy conditions; tempestites; backshoal and foreshoal</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Wacke-to-Packstone, arboideal</td>
<td>moderate- to high-energy conditions; near high-energy shoal-like environment, backshoal</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>Pack-to-Grainstone, massive</td>
<td>moderate- to high-energy conditions; near shoal (spilovers), backshoal and foreshoal; possible tempestites (grading might be lost due to bioturbation)</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>Grainstone, cross-bedded, peloidal</td>
<td>high-energy conditions; shoal-like environment; potential reservoir facies</td>
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<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
<tr>
<td>Grainstone, cross-bedded, calcitic</td>
<td>high-energy conditions; shoal-like environment; potential reservoir facies</td>
<td><img src="image16.png" alt="Image" /></td>
<td><img src="image17.png" alt="Image" /></td>
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**Figure 8:** Facies atlas for the Dhruma Formation in Oman after Schlaich and Aigner (2017) outcrop and thin section photos of wacke-, wackestones to packstones, packstones, and grainstones.
Zone Z (Schlaich and Aigner 2017, Fig. 6). Peritidal deposits are dominated by carbonates, which show dominantly micritic textures and a minor quartz content in outcrops of the Oman Mountains. They are sometimes interbedded with thin sandstone sheets, which indicates a siliciclastic input that was not included in the original Irwin (1965) model. In the Dhruma, the peritidal environment shows a wide spectrum of energy conditions, leading to a diverse sedimentary record ranging from low-energy mudrocks to medium-energy biostromes with microbial laminates and stromatolites, as well as rippled wackestones to packstones. Furthermore, scour fills and occasionally low-angle cross-bedding and hummocky cross-stratification were observed suggesting storm influence. As suggested by Irwin (1965), peritidal facies show a rather low bio-diversity comprising gastropods, bivalves, undefined shell debris, foraminifera, and peloids.

Irwin (1965) considered that, due to the limited circulation of waters in Zone Z, a landward increase in salinity is likely and that a succession from limestone to dolostone, anhydrite, gypsum, and salt may occur. Supratidal indicators, such as evaporites, desiccation cracks, tepee structures, rootlets of mangroves, or saltwater grasses, are, however, absent in deposits of the Dhruma Formation. This is most likely due to the paleoclimatic conditions: in the Dhruma, freshwater and siliciclastic influx from rivers at the coastal area towards the southeast suggest more humid climate preventing the formation of a sabkha environment that would allow the formation of evaporites.

**Low-energy Zone Z (lagoonal; Zone Z after Irwin 1965)**

As suggested by Irwin (1965), the low-energy Zone Z extends over 100 seconds of kilometres (Fig. 6) and contains deposits of a wide, restricted, low-energy, lagoonal setting. Depositional rates are generally low. Zone Z is dominated by lime-stones and dolo-mudstones, occasionally with some clay content. Thin packstone sheets are rare and indicate storm influence (Schlaich and Aigner 2017). Associated facies types are exclusively micritic. With abundant *Thalassinoides* trace fossils, bioturbation is common in Zone Z. Mudstones and wackestones are often bioturbated and contain gastropods, bivalves, echinoderms, or undefined shell debris, as well as abiogenic components, such as peloids and coated grains.

**Moderate-energy Zone Y to Z (transition from Zone Y to Z after Irwin 1965)**

Moderate-energy Zone Y to Z extends over 10 seconds of kilometres (Fig. 6) and represents the transition between high-energy Zone Y and low-energy Zone Z (Schlaich and Aigner 2017) and, thus, comprises the point where wave and tidal actions are largely dissipated by friction. Textures range from wackestones to packstones, which are often bioturbated, e.g., by *Thalassinoides*, and are of a lagoonal to shoal-margin setting. Centimetre- to decimetre-thick, graded layers occasionally contain mud clasts at the base and are interpreted as storm deposits.

Bivalves, peloids, and shell hash with subordinate brachiopods and gastropods or oncoids dominate wackestones to packstones. As oncoids of the Dhruma Formation are usually equidimensional, they were probably formed by continuous rolling above the wave base (Ratcliffe 1988) and indicate a close proximity to Zone Y.

**High-energy Zone Y (Zone Y after Irwin 1965)**

High-energy Zone Y extends over 10 seconds of kilometres (Fig. 6) and is dominated by waves striking the bottom and tidal action. The energy decreases landward towards moderate-energy Zone Y to Z due to friction. Zone Y is dominated by peloidal and oolitic packstones and grainstones, which are occasionally low-angle cross-bedded. In contrast to typical shoal deposits, the observed packstones and grainstones of high-energy Zone Y display consistently uniform bed-thicknesses over many kilometres. Furthermore, low-angle cross-bedding is much more common than high-angle cross-bedding. Thus, deposits in Zone Y are rather sheet-like, as in the depositional model by Irwin (1965), and do not show high-relief shoal geometries.
Low-energy Zone X (Zone X after Irwin 1965)

Zone X deposits of Irwin (1965) were not observed in studied outcrops nor the subsurface in the Dhruma of Oman but would be expected in a northwestward direction of the study area. They should comprise low-energy facies, which were deposited below wave base and extend over 100 seconds of kilometres (Fig. 6).

Hydrocarbon implications for the Irwin model

The sedimentation rate in Zone X is rather low and mainly fine-grained detritus (and organic matter) derived from Zone Y accumulates. Deeper waters seaward of Zone Y can be undersaturated in Ca\(^{2+}\) (Irwin 1965), thus inhibiting the formation of inorganic carbonates. The fallout of plankton in Zone X, in combination with a water depth below the photic zone, which discourages plant (algal) growth (Irwin 1965), and little turbulence at the sea floor, may lead to reducing conditions and allow the formation of source rocks.

The best primary reservoir facies may form in high-energy Zone Y in form of oolitic or peloidal packstones and grainstones, as observed in Oman, or as suggested by Irwin (1965) in the form of reef facies.

In Zone Z, mud-dominated facies dominate. Without freshwater input, a higher salinity with no primary reservoir potential can be expected, and evaporites can form in a sabkha environment in Zone Z. If freshwater influx occurs, either by rain or river water, an environment is created where algae are able to flourish (Irwin 1965). In this scenario, Irwin (1965) suggests that moderate- to high-energy facies of Zone Y transition directly into algal carbonate muds without the presence of evaporites in between. In the Dhruma Formation, these low-energy mudstones and wackestones are dominated by lagoonal facies containing bivalves, gastropods, foraminifera, and the occasional echinoid and brachiopod. Microbial laminates and stromatolites can only be observed in the shallowest deposits. The mudstones or evaporites of Zone Z may act as a baffle or seal. Under restricting conditions with input of organic matter, a minor source rock potential can be assigned to Zone Z.

Consequently, epeiric ramps may form self-contained hydrocarbon factories. The transition from Zone X to Y and Z may reflect a transition from source rock to reservoir and seal facies, which would make a vertical succession created by a seaward shift of facies an ideal vertical succession for a hydrocarbon play concept.

Due to the very low slope angle of the carbonate ramp, minor variations in relative sea level can cause significant lateral shifts of facies belts. This may cause cyclic, vertical alternations of potential reservoir facies of Zone Y and potential baffle or seal units of Zone Z as observed in the Dhruma Formation in Oman (Schlaich and Aigner 2017, in prep.). During times of maximum flooding, especially on the level of composite sequences, the vast lateral extent of high-energy deposits leads to high volumes of potential reservoir facies (Fig. 9), whereas around sequence boundaries, low-energy deposits of Zone Z dominate the Dhruma Formation in Oman and form potential seal intervals over 100 seconds of kilometres in lateral extent.

The width of facies belts is directly linked to the angle of slope: the steeper the slope is, the narrower Zones Y and Z and, thus, the width of potential reservoir facies become. If the slope gets too high, Zone Z might even disappear, and wave and tidal action will reach the shore, leading to the formation of a beach (Irwin 1965).

Regional correlations over 100 seconds of kilometres indicate that the facies transition between Zones X and Y may be complex due to the presence of local paleo-topographic features (Fig. 10). The occurrence of high-energy facies associated with Zone Y is however unlikely in Zone Z, since all hydrodynamic energy is already lost in a seaward direction.
Figure 9: WNW–ESE cross-section in Oman: red and yellow colours represent medium- and high-energy deposits (dominant packstones and grainstones), which can be considered as potential reservoir intervals. Texture maps (A to F) indicate the lateral distribution of the dominating Dunham texture, which is directly linked to the Energy Zones Y, Y to Z, and Z. Due to a deepening trend towards the north and northeast and the development of a westward-oriented deepening trend during depositional times of the Dhruma Formation (A to C), the distribution of the energy zones is more complex than in the idealised model of Fig. 5; HFS: high-frequency sequence.
Detailed sedimentological analyses of outcrop and subsurface sections in the Dhruma Formation of Oman in combination with correlations based on sequence-, bio-, and chemostratigraphy led to the conclusion that popular carbonate ramp depositional models are not suitable for these epeiric carbonates. In this paper, we therefore use the almost-forgotten model by Irwin (1965) for epeiric settings.

Major features that do not fit the conventional carbonate ramp models currently used by many authors are the following:

(i) Sheet-like geometries for all observed facies from mud- to grainstones.
(ii) The lack of a well-defined shoal-water complex.
(iii) All beds of the Dhruma Formation in outcrops, independent of lithology, texture, or facies, show a more or less constant bed thickness over 100 seconds of metres to, probably, kilometres.
(iv) Grainstone beds of the Dhruma Formation show sheet geometries and are predominantly massive. When cross-bedding is present, it is always of the low angle type.
(v) In outcrop sections, no high-relief shoal geometries can be observed.
(vi) Correlations show only minor variations in thickness over a distance of 10 seconds of kilometres in outcrops and 100 seconds of kilometres in Central and North Oman.
(vii) A homogeneous bio-component distribution over 100 seconds of kilometres indicates only little lateral variation in environmental conditions.

According to the Irwin model, the extreme wide extend and shallowness of the shelf leads to a restriction or elimination of circulation and creates a threefold zonation in hydrodynamic energy into a low-energy Zone X below wave-base (offshoal equivalent), a high-energy Zone Y (shoal equivalent), and another low-energy Zone Z (backshoal equivalent).
To cover the detailed facies description from outcrops, the three palaeoenvironmental Zones X, Y, and Z as proposed by Irwin (1965) were extended for the Dhruma Formation in Oman to six lithofacies associations, allowing a more detailed differentiation of depositional environments on an epeiric ramp: peritidal, low-energy Zone Z, moderate-energy Zone Y to Z, high-energy Zone Y, moderate-energy Zone X to Z, and low-energy Zone X.

The Irwin model has significant practical implications for hydrocarbon exploration and production and might be useful for more carbonate deposits than currently recognised.

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References


