



# Article Controlling Factors on Petrophysical and Acoustic Properties of Bioturbated Carbonates: (Upper Jurassic, Central Saudi Arabia)

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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Abstract: Many of the world's productive Jurassic reservoirs are intensively bioturbated, including the sediments of the Upper Jurassic Hanifa Formation. Hydrocarbon exploration and production from such reservoirs require a reliable prediction of petrophysical properties (i.e., porosity, permeability, acoustic velocity) by linking and assessment of ichnofabrics and trace fossils and determining their impact on reservoir quality. In this study, we utilized outcrop carbonate samples from the Hanifa Formation to understand the main controlling factors on reservoir quality (porosity and permeability) and acoustic velocity of bioturbated carbonates, by using thin-section petrography, SEM, XRD, CT scan, porosity, permeability, and acoustic velocity measurement. The studied samples are dominated by Thalassinoides burrows that have burrow intensity ranging from ~4% to 27%, with porosity and permeability values ranging from ~1% to 20%, and from 0.002 mD up to 1.9 mD, respectively. Samples with coarse grain-filled burrows have higher porosity (average  $\mu = 14.44\% \pm 3.25\%$ ) and permeability ( $\mu$  = 0.56 mD  $\pm$  0.55) than samples with fine grain-filled burrows ( $\mu$  = 6.56%  $\pm$  3.96%, and 0.07 mD  $\pm$  0.16 mD). The acoustic velocity is controlled by an interplay of porosity, bioturbation, and mineralogy. Samples with relatively high porosity and permeability values (>10% and >0.1 mD) have lower velocities (<5 km/s) compared to tight samples with low porosities and permeabilities (<10% and <0.1 mD). The mineralogy of the analyzed samples is dominated by calcite (~94% of total samples) with some quartz content (~6% of total samples). Samples characterized with higher quartz (>10% quartz content) show lower velocities compared to the samples with lower quartz content. Bioturbation intensity, alone, has no control on velocity, but when combined with burrow fill, it can be easier to discriminate between high and low velocity samples. Fine grain-filled burrows have generally lower porosity and higher velocities ( $\mu = 5.46$  km/s) compared to coarse grain-filled burrows ( $\mu = 4.52 \text{ km/s}$ ). Understanding the main controlling factor on petrophysical properties and acoustic velocity of bioturbated strata can enhance our competency in reservoir quality prediction and modeling for these bioturbated units.

**Keywords:** bioturbation; carbonates; petrophysical properties; acoustic velocity; upper Jurassic; Saudi Arabia

## 1. Introduction

In many parts of the world, Jurassic strata contain extensive bioturbated intervals that encompass significant hydrocarbon reservoirs such as the Fulmar Formation and Brent Group, North Sea, UK [1,2]; the Ile Formation, Norway [3]; the Shaqra Group and the Ghawar Field, Saudi Arabia [4–6]; and the Vaca Muerta Formation, Argentina [7]. Bioturbation is defined as the biogenic (by benthic infauna) transport of sediment particles and pore

water which destroys the sediment stratigraphy. These processes also impact the physical properties of the sediment such as grain size spectrum, porosity, and permeability [8]. Benthic infauna can significantly modify the original sediments while generating new structures through sediment mixing and redistribution of the grains. Such modification may include sediment removal (bioerosion), sorting (biostratification), emplacement (biodeposition), and compaction [9]. Moreover, geochemical signatures of sediments may also be modified by burrowing organisms through a combination of organic matter produced by these organisms [6,10].

Bioturbation can have a significant influence on the petrophysical properties of hydrocarbon reservoirs. Several studies were carried out that demonstrated the impact of bioturbation on improving and decreasing of petrophysical properties of siliciclastics [11–15], as well as of carbonates [5–8]. Some studies demonstrated that bioturbation can enhance the reservoir quality, mainly in permeability, to variable degrees [5,6,12,15–19]. All the aforementioned studies have demonstrated that the impact of bioturbation on reservoir quality is dependent on the bioturbation style and burrow attributes [20,21].

The acoustic velocity is the main controlling factor on seismic reflectivity of different rock units. Seismic reflectivity is the basis for seismic reflection behavior, one of the most important principles in hydrocarbon exploration. The acoustic velocity of carbonate sedimentary strata is largely controlled by (i) the mineralogy, (ii) petrophysical properties, i.e., amount of porosity, pore type, pore distribution, and (iii) diagenetic processes modifying the sediments [22–31]. Bioturbated strata are characterized by a complex distribution of porosity and permeability, as the trace fossils can alter the pore-throat distribution and the bioturbation traces may act as loci for dissolution and cementation processes during early and late diagenesis [32]. These processes consequently influence the acoustic wave propagation through these bioturbated units.

Bioturbation is common throughout the carbonate strata of the Middle-Upper Jurassic of Saudi Arabia (Tuwaiq Mountain, Hanifa, Jubaila, and Arab formations), and they show a significant control on fluid flow properties of these strata [4–6,33]. These studies have shown that *Thalassinoides* burrows have enhanced flow properties of the dolomitic and mud-dominated units of the strata of these formations, and contributed significantly to the fluid flow properties of the Super-K Zone in the Ghawar field of Saudi Arabia [6].

The previous studies aimed at understanding the impact of bioturbation and ichnofabrics on reservoir quality, and specifically, permeability. However, the impact of bioturbation on carbonate acoustic velocities was not reported in the literature so far. This study aims to determine the main factors that control the reservoir quality (porosity and permeability) and acoustic velocities of the Upper Jurassic bioturbated strata of the Hanifa Formation in Central Saudi Arabia.

To determine the factors influencing the petrophysical properties and acoustic velocities of bioturbated strata, a series of outcrops along the Riyadh-Mecca road in the Darma quadrangle (Figure 1) in Central Saudi Arabia were studied, sampled, and analyzed in detail. Analyses include the characterization of all intrinsic and extrinsic features such as mineralogical composition, texture, porosity and pore types, and permeability. Additionally, sample plugs were scanned using the computer tomography (CT scan) technique to precisely estimate the bioturbation intensity of the strata studied. Finally, the acoustic velocity was measured for all plugs under variable effective pressures (5–40 MPa) and compared to the aforementioned intrinsic and extrinsic properties (porosity, permeability, mineralogy, bioturbation intensity, and burrow infill).



**Figure 1.** Geological sketch map showing the outcrop belts of Tuwaiq Mountain, Hanifa, and Jubaila formations in Central Saudi Arabia. The measured section is highlighted by the yellow star to the west of Riyadh modified after [34].

## 2. Geological Setting

The Neotethys opened in the Late Permian following major extensional stresses that affected the eastern part of the Arabian-Nubian Shield [35]. A series of rift basins evolved that were infilled by shallow marine siliciclastics and carbonates [36].

Throughout the Phanerozoic, the Arabian Plate was moving in different directions with different rates [37]. By the beginning of the Jurassic, the Arabian Plate approached the tropical latitudes [38,39], and witnessed a major marine transgression that caused the deposition of extensive shallow marine carbonates called "the Shaqra Group" over the Triassic mixed system [40,41].

The Hanifa Formation is mainly of Oxfordian–Kimmeridgian age [42–46], and is subdivided into two members; the basal Hawtah and the upper Ulayya member [47]. The strata of the Hanifa Formation were deposited in an open intrashelf basin, where the organic-rich fine limestones that were deposited represent one of the major source rock intervals in the Arabian Platform petroleum system [48,49]. The occurrence of the source rock interval (equivalent to the lower Hawtah member mudstone) synchronizes with a major transgressive event that separated the Hanifa Formation from the underlying Tuwaiq Mountain Formation [49,50]. The upper, Ulayya member is grainier than the Hawtah member, and represents the equivalent strata to a major hydrocarbon reservoir in the Middle East. The Ulayya member is overlain by the muddy limestones of the Jubaila Formation that make the main seal [51].

## 3. Materials and Methods

## 3.1. Field Work

Field work was carried out in the Riyadh area and incorporated geological characterization of the Hanifa strata including color, thickness, sedimentary structures, bedding planes, and morphology. Twenty-eight samples were collected from the Riyadh-Mecca road outcrop of the Upper Jurassic Hanifa Formation within the Darma Quadrangle at 24°51′43.8″ N 46°26′17.4″ E. The studied outcrop is located in the Ar-Riyadh area (Figure 1). This location was selected because it shows a complete exposure of the sediments of the Hanifa Formation at this locality, where all the strata, including the muddy intervals (which are covered in other localities such as Wadi Nisah), are well exposed.

#### 3.2. Thin-Section Petrography

Thin-sections of all samples were prepared to identify the texture, pore types, and diagenetic features. Samples were impregnated with blue epoxy to define the pores and highlight the geometry of the pore spaces. Alizarin Red S was used for partial stain of the thin-section to differentiate between calcite and dolomite [52]. The depositional textures were classified based on the Dunham [53] classification, modified by Embry and Klovan [54]. Photomicrographs of the studied thin-sections were obtained using BX53M Olympus petrographic microscopy with an Olympus Camera. In addition, pore types were classified using the Choquette and Pray [55] classification scheme.

## 3.3. X-ray Diffraction Analysis (XRD)

Twenty-seven samples were crushed and ground to examine the mineralogy of the studied samples using XRD analysis. The percentages of different minerals (calcite, dolomite, quartz, and clays) were determined using the X'Pert<sup>3</sup> system of Malvern Pananalytical. The database used in this analysis is ICDD PDF-4 2021, with Cu- anode and measurement voltage of 45 kv. Each sample was placed in a sample holder with a 20  $\mu$ m square capacity. In order to cover a wide range of minerals, the scan range (2 theta) was fixed from 10 to 90 degrees.

#### 3.4. Scanning Electron Microscopy

A JEOL JSM-7900F scanning electron microscopy (SEM) with 20 kv accelerating voltage was used on seven representative samples (covering a wide range of porosity and permeability values), to determine microstructural features such as micro-porosity, pore geometries and distribution, grain contacts and shapes, cementing material and texture, and matrix. Fresh broken surfaces of selected samples were utilized to perform the SEM analysis. Gold coating was applied on fresh surfaces of the samples to avoid sample charging [56].

#### 3.5. Porosity and Permeability

Porosity and permeability were measured for all samples to determine the air porosity and permeability. Samples were obtained perpendicular to the bedding planes. A 1.5-inch diameter, water-cooled, diamond drill bit was used to cut the plugs. Plugs were leveled at the top and bottom to within 0.001 inch. To dry the samples, all plugs were placed in an oven at 60  $^{\circ}$ C for 72 h. Porosity and permeability were measured, at 500-psi pressure, for all the plugs using a pressure decay technique utilizing the AP-608 Automated Permeameter-Porosimeter of Coretest System INC. Based on the sample dimensions and measured porosity, bulk and grain densities were calculated for all samples.

## 3.6. Acoustic Velocity Measurement

Twenty-seven dry samples were used for acoustic velocity measurement (compressional and shear velocity) using a NER 500 machine. The measurement was carried out at four different confining pressures: 5, 10, 20, and 40 MPa. The NER 500 contains one P-wave transducer and receiver and two orthogonal S-wave transducers and receivers. Confining pressure is built through a connected oil reservoir that can provide pressure up to 100 MPa. A computer and oscilloscope are attached to the NER 500 machine to translate the signal to digital data that can be used to calculate the P- and S-wave velocities (V<sub>P</sub> and V<sub>S</sub>, respectively).

## 3.7. Computed Tomography

All the plugs were scanned using X-ray computer-aided tomography (CT scan) to visualize the internal structure of the plugs and to estimate the bioturbation intensity in each sample (Figure 2). All scans were conducted using a Toshiba Alexion TSX-032A Medical CT scanner (spatial resolution = 1 mm). PerGeos software (FEI-ThermoFisher, Hillsboro, OR, USA) was used to analyze the CT tomograms. Filtering and segmentation were performed on the images to label the bioturbation structures and surrounding grains based on the threshold. The segmented data were used to quantify the bioturbated volume of each sample as well as the 2D and 3D visualization of the structures.



**Figure 2.** Bioturbation estimation using CT scan. (**A**) Plug photo showing the *Thalassinoides* burrow highlighted by a dotted red line. (**B**) 3D CT scan view of the studied sample showing the bioturbation network within the plug.

## 4. Results

## 4.1. Texture and Lithofacies

The Hanifa Formation in the study area mainly consists of mudstone and bioclastic wacke- to packstone in the lower part (Hawtah member), and pack-to grainstone units with some coral reef fragments in the upper part (Ulayya member). A detailed description of lithofacies and the depositional environment of the Hanifa Formation can be found in [57]. In this study, we tried to use the texture mainly to differentiate between lithofacies. Hence, five lithofacies were identified:

- 1. Mudstone. Massive and thickly bedded, light grey to brown, burrowed mudstone. Skeletal grains are common and in most cases are dominated by scattered sponge spicules and scattered benthic foraminifera, and bivalve and brachiopod fragments (Figure 3A).
- 2. Wackestone. White to beige massive beds with fine texture and high level of hardness. The sediments of this facies are well distributed throughout the studied stratigraphic section. The wackestones are rich in sponge spicules and in a few cases, show jasper chert nodules. It also contains scattered fragments of bivalves, echinoderms, brachiopods, and agglutinated foraminifera (especially the species *Kurnubia palastiniensis*) (Figure 3B). However, in general, it is similar to the mudstone lithofacies but with a higher abundance of skeletal grains, and the sediments show a higher bioturbation intensity with abundant *Thalassinoides* burrows. Mudstones and wackestones are more dominant in the lower part of the formation.
- 3. Packstone. Massive beige beds mainly comprising skeletal grains of foraminifera, bivalves and sponge spicules, quartz grains, oncoids and peloids (Figure 3C). The

percentage of each skeletal and non-skeletal grain type varies considerably based on the associated lithofacies. The packstone lithofacies occur together with the sponge spiculitic skeletal wackstones, the peloidal grainstones, and the reefal lithofacies.

- 4. Grainstone. This facies caps the sedimentary cycles in both the upper and lower parts of the studied succession. However, their abundance is more frequent within the upper cycles. The grainstone beds are massive, horizontally laminated and show trough cross-bedding; and at times, the beds have an erosive base. The sediments are brownish in color and mainly composed of peloids, combined with angular fine quartz grains and scattered skeletal grains, mainly bivalves (Figure 3D).
- 5. Reefal lithofacies. The main reef builders found in the Oxfordian Hanifa succession are scleractinian corals in addition to demosponges, especially, stromatoporoids (Figure 3E). These reef builders are found either in association forming a mixed coral/stromatoporoid framestone, rudstone (Figure 3F), or do occur independently, forming their own buildups. Both coral and stromatoporoid fragments are found scattered in a floatstone texture, with a skeletal wackestone/packstone matrix. The reefal limestone sometimes shows interbedding with the peloidal grainstone lithofacies.



Figure 3. Lithofacies of Hanifa Formation: (A) Massive carbonate mudstone with scattered monaxon

sponge spicules and agglutinated foraminifera (*Kurnubia palastineinsis*). (**B**) Wackestone facies composed of monaxon and triaxon sponge spiculitic wackestone. Associating biocomponents are echinoderm spines (**E**), and agglutinated foraminifera (**F**), and scattered fragments of sponge spicules (S). (**C**) Packstone lithofacies dominated by skeletal grains (mainly bivalves), sub-rounded poorly-sorted quartz grains and fine peloids. (**D**) Grainstone lithofacies composed of peloids with scattered quartz grains, cortoids, and grapestones. (**E**) Polished slab of a highly cemented scleractinian coral head, which is the main reef builder in the studied succession. (**F**) Oncoidal rudstone beds associating the reefal limestone. Scale bar at bottom right.

## 4.2. Mineralogy

Based on XRD analysis, calcite is the dominant mineral in the studied samples (~94% of total samples), with some quartz (~6% of total samples) that may reach up to 25% in some samples (Appendix A). In addition to XRD, quartz abundance can also be observed from thin-section (Figure 4). Dolomite is also present but in minor amounts of less than 1%.



**Figure 4.** Quartz-rich peloidal packstone with some skeletal fragments (yellow arrows). Quartz grains range in size between 30 to 200 microns. Scale bar at bottom right.

#### 4.3. Pore Types

Using Choquette and Pray's (1970) [55] classification, four pore types were identified in the studied samples (Figure 5): inter-particle, intra-particle, fracture, and moldic pores. In addition, we used the Cantrell and Hagerty [58] definition of microporosity (pores that have a size of 10 micron or less) to describe and quantify the microporosity. Microporosity is the most common pore type, as dissolution pores (moldic and vugs) are not frequent. Other pore types such as interparticle pores are only found in grain-dominated samples (Figure 5A). Moreover, dissolution-related pores (molds) are very rare in the studied samples, with only two samples showing moldic pores resulting from the dissolution of skeletal grains such as dasycladacean algae. Only one sample displays vugs as the dominant pore type, which are partially filled with coarse-grained sediments, e.g., ooids and peloids (Figure 5D).



**Figure 5.** Pore types of the Hanifa Formation: (**A**) Inter-particle pores. (**B**) Fracture pores. (**C**) Microporosity. (**D**) Vugs on plug (red rectangle) and thin-section (arrow).

## 4.4. Bioturbation

Bioturbation by marine fauna is abundant throughout the Hanifa Formation (Figure 6), especially in the Ulayyah member (upper part of the formation). All trace fossils belong to the *Cruziana* ichnofacies [34]. The most common trace fossils are *Thalassinoides* burrow networks penetrating a firm ground of mud-dominated carbonate strata [33,34] (Figure 6). These burrows show different infill and either contain fine or coarse grains. At outcrop scale, some of the burrows are still partially or completely open, and form connected or non-connected vugs or tubes with a diameter varying between 0.4 and 3.0 cm (Figure 6B). However, the majority of our collected samples are either filled by coarse, or fine sediments. Moreover, burrows filled with fine sediments (fine-filled burrows) are more frequent in grain-dominated units (Figure 6C), but are also present in mud-dominated units. Similarly, burrows filled with coarse grains (coarse-filled burrows) are more frequent in mud-dominated units (Figure 6D), but also occur in grain-dominated units. The filling in the coarse-filled burrows is composed of peloids, ooids, oncoids, and skeletal fragments (Figure 7).



**Figure 6.** *Thalassinoides* burrows of the Hanifa Formation. Outcrop photos showing burrows filled with coarser materials than matrix (**A**), or partially to completely unfilled burrows (**B**). Pen (**A**) and hammer for scale (**B**). Scan of two of the studied samples showing burrows filled with (**C**) fine material in grain-dominated matrix highlighted by red dotted lines, and (**D**) coarse fill in mud-dominated matrix. Scale bar in cm in (**C**,**D**).

The bioturbation intensity (BI), which is the total volume of the sample that is occupied by burrows or trace fossils, in the studied samples was measured using a CT scan (see Section 3.7). The bioturbation intensity shows a very weak correlation, R2 < 0.2, with both porosity and permeability (Figure 8A,B). However, the burrow filling material seems to have a significant control on porosity and permeability values, with the coarse-filled burrows having higher values ( $\mu$  = 14.44% and 0.56 mD) than fine-filled burrows ( $\mu$  = 6.56% and 0.07 mD) (Figure 8C,D).



**Figure 7.** Filling material of burrows. Thin-section photomicrographs showing the outline of the burrows, yellow dashed line. Main component of filling material in (**A**) a fine-filled burrow in coarse-grained material and (**B**) a coarse-filled burrow with coarse grains including oncoids, peloids (p), and skeletal fragments (s).



**Figure 8.** Bioturbation impact on porosity (**A**) and permeability (**B**) values, with weak relation between bioturbation and both porosity and permeability. (**C**,**D**) Burrow fill impact on porosity and permeability. Samples with coarse-filled burrows have higher porosity and permeability values.

## 4.5. Porosity and Permeability

The porosity values of the studied samples (n = 27) range from ~1 to 20% with an average  $\mu$  of ~11%  $\pm$  5.3%. The samples are tight in terms of permeability with values ranging from 0.002 to 1.9 mD; an average of ~0.3 mD  $\pm$  0.5. The porosity–permeability relationship of the studied samples is shown in Figure 9A, with the data points being classified based on their textural variations. Mud-supported samples (mudstone and wackestone) have higher porosity (5.33–19.72%,  $\mu = 13.74\% \pm 4.31\%$ ) and permeability values (0.0035–1.91 mD,  $\mu = 0.55$  mD  $\pm 0.54$  mD) relative to grain-supported samples (packstone, grainstone) (5.05–16.33%,  $\mu = 9.99\% \pm 4.2\%$  for porosity, and 0.003–1.09 mD,  $\mu = 0.24$  mD  $\pm 0.32$  mD for permeability). Reefal lithofacies samples (rudstone and framestone) possess the lowest porosity values (0.077–5.77%,  $\mu = 2.89\% \pm 2.58\%$ ) combined with very low permeability values (0.003–0.004 mD,  $\mu = 0.004$  mD  $\pm 0.0003$  mD) (Figure 9A). In



addition, and as mentioned in the last part (Section 4.4), the coarse-filled burrows have higher porosities and permeabilities than fine-filled burrows (Figure 9B).

**Figure 9.** (**A**) Porosity–permeability relation with texture superimposed. The mud-supported samples show higher poroperm values relative to grain-supported samples. (**B**) Porosity–permeability data with burrow filling material superimposed. Samples with coarse-filled material have higher porosity–permeability values.

## 4.6. Factors Controlling Acoustic Velocity

## 4.6.1. Porosity, Permeability, Texture, and Mineralogy

The compressional acoustic velocities ( $V_P$ ) of the measured samples range from 3 to 6.5 km/s (Appendix A). The velocities display an inverse relation with both porosity and permeability (Figure 10). However, a wide scatter of velocities at the comparable porosity and permeability values can be observed (i.e., at 15% porosity, and at 0.6 mD permeability). Samples with mud-dominated texture (mudstone and wackestone) show higher porosity

and permeability values (Section 4.5), and thus, lower velocity values ( $\mu = 4.58 \pm 0.77$  km/s) than samples with grain-dominated texture (packstone and grainstone) ( $\mu = 5.02 \pm 0.62$  km/s), as shown in Figure 11A. However, some samples with grain-dominated texture have high porosity and permeability values (up to ~16.3% and 1.1 mD), and low velocities (Figure 11A).



**Figure 10.** (**A**) Porosity and (**B**) Permeability inverse relation with compressional velocity ( $V_P$ ). Velocity is more controlled by porosity (R2 = 0.7) than permeability (R2 = 0.5).



**Figure 11.** (**A**)  $V_P$ -porosity relation with depositional texture superimposed. Majority of the mud-dominated samples (mudstone and wackestone) have higher porosity and permeability values with relatively lower velocities (below 5 km/s). (**B**)  $V_P$ -porosity relation with quartz content superimposed. Quartz-rich samples have lower velocities than quartz-poor samples.

Based on XRD data (Section 4.2), the majority of the samples are dominated by calcite. However, quartz is common throughout the studied section. In this study, the 10% quartz content limit is used to differentiate between quartz-rich and quartz-poor samples. Quartzrich samples have lower velocity values relative to quartz-poor samples at any given porosity (Figure 11B).

4.6.2. Pore Types

Based on thin-section petrography, microporosity is the most common pore type in the studied samples of the Hanifa Formation. The velocity–porosity cross-plot of Figure 12

displays that samples dominated by microporosity follow a tight velocity–porosity trajectory. The only one sample that is dominated by vugs has the highest velocity, relative to the other pore types with the same porosity. Samples characterized by fractures and interparticle pores possess the lowest velocities.



**Figure 12.** Pore types impact on the compressional velocity (Vp). Samples dominated with fractures and interparticle pores have the lowest velocities, while samples dominated by vug pores (open burrows) have the highest velocity.

4.6.3. Bioturbation Intensity and Burrow Infill

Based on CT scan, bioturbation intensities in the studied samples range between 3 and 27%. The bioturbation intensity shows a very weak relation with the compressional velocity (VP) (Figure 13A) with correlation coefficient R2 < 0.1. However, fine-filled burrows display higher velocities than coarse-filled burrows (Figure 14B).

Similarly, the velocity–porosity cross plot (Figure 14) shows that the bioturbation intensity (BI) has no major control on velocity, where samples with higher bioturbation intensities (15–30%) have a wide range of porosities (5–20%) and about 1 km/s velocity difference at the same porosity (at 5.5% porosity in Figure 14A). Similarly, samples with medium BI (10–15%) have a wide scatter of velocity at the same porosity; compare velocities at about 15% porosity in Figure 14A. Likewise, samples with low bioturbation intensities (BI < 10%) show similar velocities although they have 10% porosity difference; compare values at about 5.5 km/s Vp in Figure 14A. Nevertheless, when adding the burrow filling material parameter, the results show that fine-filled burrows have lower porosity and permeability values ( $\mu = 6.56\%$ , 0.66 mD), and higher velocity values ( $\mu = 5.46$  km/s), relative to the coarse-filled burrows ( $\mu = 14.44\%$ , 0.56 mD, and 4.52 km/s) (Figure 14B).



**Figure 13.** (**A**) Compressional velocity ( $V_P$ )-bioturbation intensity cross plot showing the weak relation. (**B**)  $V_P$ -bioturbation intensity relation with burrow filling material superimposed, and showing that fine-filled burrows have higher velocities than coarse-filled burrows.



**Figure 14.** (**A**) Compressional velocity ( $V_P$ )–porosity cross plot with bioturbation intensity superimposed. Bubble size indicates the bioturbation intensity. A wide scatter of velocities for samples with the same bioturbation intensities (at 5% and 14% porosity). (**B**) Compressional velocity ( $V_P$ )–porosity cross plot with burrow filling superimposed. Samples with coarse-filled burrows have lower velocities relative to samples with fine-filled burrows.

## 5. Discussion

Bioturbation can enhance or destroy the reservoir quality based on the trace fossil type, size, sediment infill, and connectivity [14,17,59,60]. The positive impact of bioturbation on reservoir quality was widely documented in recent studies [12,61].

As mentioned before, bioturbation can play a major role in controlling the petrophysical properties of carbonate strata (porosity and permeability). Hence, other properties that are controlled by porosity (i.e., acoustic velocity) or permeability (flow properties) will also be influenced by bioturbation. Bioturbated strata of the Hanifa Formation were used to investigate the bioturbation impact on the petrophysics and acoustic velocities. Bioturbation intensity and burrow fill impact on porosity and permeability will be discussed in the following context. Moreover, in addition to the influence of porosity, permeability, mineralogy, and texture on acoustic velocity, the impact of bioturbation and burrow fill will also be discussed.

## 5.1. Bioturbation and Burrow Fill Impact on Porosity and Permeability

The studied samples show a weak relationship between bioturbation and both porosity and permeability, with an R2 < 0.2 (Figure 8A,B). However, when burrow fill is added, it becomes evident that the coarse-filled burrows have higher porosity and permeability values than the fine-filled burrows (compare Figure 8C,D). This means that burrow filling material has a significant control on the porosity–permeability values (Figure 9B). The positive relationship of porosity and bioturbation is well documented in literature discussing the enhancement of porosity and permeability of an otherwise impermeable matrix through the passive infill of burrows by coarse material [8,14,32,59–62]. In addition, the burrow networks can act as fluid conduits and may form loci for preferential dissolution by meteoric water and these processes may modify the vertical and lateral flow properties [4,14]. Open and coarse-filled burrows provide preferred, permeable flow conduits in otherwise less permeable intervals [61].

Eltom et al. [61] in their study of the Upper Hanifa Formation (Ulayyah member), demonstrated that coarse material infilling the burrows in mud-dominated units indicate that the filling material was deposited in a high-energy environment, unlike the host material which was deposited under a low-energy depositional environment. Because of the coarse-grained infill, the burrows are characterized by higher porosity and permeability values than the host muddy units. Our data agree with their findings for the muddy units (Figure 9B). However, [61] did not discuss the impact of bioturbation on the grain-dominated units and subsequent infill with fine-grained sediments.

In grain-dominated units, bioturbation has a negative impact on porosity and permeability as most of these units possess lower porosity and permeability values, compared to mud-dominated units. This was attributed to cementation of inter-particle pore spaces, and filling of burrows by fine-grained sediments, which act as baffles or barriers within an otherwise porous and permeable zone [61]. Golab et al. [14] in their study of the influence of bioturbation on the fluid flow system of the Lower Cretaceous Glen Rose limestone, demonstrated that grainstone units have low ichnofabric indices (ii1 to ii2) and restrict the fluid flow due to their low permeabilities. This restriction was attributed to cementation of interparticle pores by sparry calcite cement. Likewise, [63] in his study on ichnofabric impact on reservoir quality of the Permian-Triassic Khuff Formation, demonstrated that some bioturbation burrows (dwelling burrows) may occur in grainy units with considerable amounts of mud. As result, these burrows reduce porosity and permeability and act as barriers for fluid flow through these units. Our data agree with these findings [14,63]; the grain-dominated samples show both scenarios of extensive cementation (Figure 3D,E) and burrow fill by muddy material (Figure 6C).

The microstructure of the micrite plays another significant role in controlling the porosity, permeability, and acoustic velocity. Some mud-dominated samples are characterized by a subhedral porous micritic texture, leading to higher porosity, permeability, and low velocity values (Figure 15A). In contrast, the burrow mud-fill of the grain-dominated samples show a compact coalescent micritic texture (Figure 15B) associated with lower porosity, permeability, and high acoustic velocity values. The coarse-filled burrows of the mud-dominated units might have enhanced the fluid flow that resulted in micrite dissolution by meteoric water, resulting in a porous and permeable micritic structure [4,59,62]. Conversely, the absence of flow pathways for meteoric water within the grain-dominated units, in addition to extensive cementation, resulted in the tight compact micritic texture discussed above.



**Figure 15.** Micrite microstructure impact on petrophysical and acoustic properties. (**A**) SEM photomicrograph of porous, subhedral micrite of a mud-dominated sample. (**B**) SEM photomicrograph of tight, compact micrite of a grain-dominated sample.

#### 5.2. Controlling Factors on Acoustic Velocity

Similar to the majority of sedimentary rocks [22,64,65], our data show V<sub>P</sub>–Porosity and V<sub>P</sub>–Permeability inverse relations (Figure 10). However, a wide scatter of velocities at comparable porosity and permeability values can be observed (i.e., at 15% porosity, and at 0.6 mD permeability). This scatter probably reflects the impact of other sediment-inherent factors on the V<sub>P</sub>–Porosity and V<sub>P</sub>–Permeability relations, which include mineralogy and bioturbation. The indirect relation between permeability and velocity is also discussed.

#### 5.2.1. Mineralogy and Compressional Velocity

Although our data show a dominance of calcite, many samples are quartz-rich (>10% quartz). As quartz has a lower mineral-acoustic moduli than calcite, the quartz-rich samples do show lower velocities (Figure 11B). Similar results are documented in literature from mixed carbonate-clastic systems [26,27,65,66], which all showed that for similar porosity values, samples with higher quartz content have lower velocities relative to samples with lower quartz content.

#### 5.2.2. Bioturbation Impact on Acoustic Velocity

The impact of bioturbation on the acoustic wave velocities is not widely documented in literature. However, earlier studies discussed the relationship between bioturbation and sediment acoustic and geotechnical properties [67–70]. Those studies demonstrated, based on recent sea-bottom derived box cores, that different bioturbation activities (i.e., dwelling, grazing, feeding, etc.) have a different impact on the acoustic behavior of sediments, where the individual processes can either increase or decrease the acoustic velocity. Our data show a weak relationship between compressional wave velocity ( $V_P$ ) and bioturbation intensity (Figure 13). Therefore, bioturbation intensity alone does not explain the velocity variation, but the combination with the type of burrow filling material may explain the variation in the petrophysical properties (porosity and permeability) as well as the acoustic velocity.

However, the grain-dominated samples in our case show higher velocities ( $\mu = 5.02$  km/s  $\pm 0.62$  km/s) and lower porosity ( $\mu = 9.99\% \pm 4.2\%$ ) and permeability values ( $\mu = 0.24$  md  $\pm 0.32$  md). Such observations can be attributed to the burrow infill of the grain-dominated samples, by fine material in addition to the extensive calcite cementation of the host matrix. In addition, samples that have open burrows (vugs) have higher velocities relative to the samples with filled burrows (Figure 12). These results agree well with the findings of [22,24,29,64,71] who demonstrated that carbonates with vuggy pores have higher velocities relative to the other pore types.

The mud-dominated samples (coarse-filled burrows) show lower compressional velocities relative to those with fine-filled burrows (Figures 11A and 14B). This is mainly attributed to the higher porosity of coarse-grained infill of the burrows within muddominated units, and dissolution of micrite, resulting in a porous subhedral micrite texture (Figure 15). These results agree to some extent with findings of [68], who reported an inverse relationship between rigidity and bioturbation intensity of A. marina and *C. arenarium* trace fossils (open burrows), in sandy sediments of the coast of North Wales. Our data also agree with the study of [69] for the Venezuela basin carbonate sediments, who documented that an increase of *Mulinia lateralis* decreased the compressional velocity significantly. On the other hand, ref. [69] attributed the increase of bulk modulus and Lame's constant in sediments dominated with *Heteromaslus filiformis* to the dewatering process by bioturbation, which increased sediment compaction.

#### 5.2.3. Permeability, Bioturbation, and Compressional Velocity

A series of studies investigated the relationship between acoustic velocity and permeability and tried to define the factors controlling acoustic velocity and permeability in carbonates [64,71–75], and found that pore structure, size, connectivity, and distribution are the main factors controlling acoustic velocity and permeability. The majority of these studies have shown an inverse relation between permeability and acoustic velocity, either as direct or indirect relation. The aforementioned studies demonstrated that large pores with a simple pore structure will have higher velocities and lower permeabilities compared to small pores with a complex pore structure with lower velocities and higher permeabilities.

Similarly, our data show an inverse relationship between velocity and permeability, where the samples with relatively higher permeability (>0.1 mD) have lower velocities compared to samples with lower permeability values (<0.1 mD) (Figure 16). Our results agree with findings of the aforementioned studies and the inverse relation between velocity and permeability is evident in Figure 10B. However, the data discussed for this study are different as bioturbation is controlling permeability and thus plays a significant role in permeability enhancement of mud-dominated samples. In other words, bioturbation burrows (empty or coarse-filled) act as fractures [32] by enhancing permeability and reducing the acoustic velocity [71,76].



**Figure 16.** Velocity–porosity relationship with permeability values superimposed. Most of the samples with higher permeabilities (>0.1 mD) lie below the line of 5 km/s velocity.

Likewise, and as discussed in Section 5.1, the *Thalassinoides* burrows enhance permeability of the mud-dominated units. Hence, it can be concluded from the inverse relation between velocity and permeability that bioturbation will increase permeability while decreasing the velocity of bioturbated muddy strata that are dominated by *Thalassinoides* burrows and filled by coarse grain material.

## 6. Conclusions

Outcrop samples of the Upper Jurassic Hanifa Formation were studied to understand the main controlling factors on the petrophysical properties and acoustic velocity of bioturbated carbonate strata. Our findings can be summarized as follows:

- The Upper Jurassic Hanifa Formation is composed of slightly to intensely bioturbated strata that were deposited within an intra-shelf basin on a shallow-marine carbonate platform.
- Porosity and permeability are controlled by bioturbation and burrow filling material, where mud-dominated strata with coarse-filled burrows have higher porosity and permeability values relative to the grain-dominated strata with fine-filled burrows.
- Acoustic velocity of Hanifa Formation sediments is controlled by the interplay between porosity, permeability, mineralogy, bioturbation, and burrow filling material and texture.
- Porosity and permeability are inversely related with acoustic velocity, where samples
  with higher porosity and permeability values have lower acoustic velocities than
  samples with low porosity and permeability.
- Mineralogy has a main control on acoustic velocity, with quartz-rich samples showing lower velocities than quartz-poor samples.
- Burrow filling material and texture seem to have a significant control on petrophysical
  properties (porosity and permeability) and acoustic velocity. Coarse-filled burrows
  have higher porosity and permeabilities, and lower velocities compared to the finefilled burrows.

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## Appendix A

| ID      | Porosity<br>(%) | Permeability<br>(mD) | Density<br>(gm/cc) | Texture | BI (%) | Burrow<br>Fill | Mineralogy (%) |          |        | Compressional Velocity |       |       |       | Shear Velocity |       |       |       |
|---------|-----------------|----------------------|--------------------|---------|--------|----------------|----------------|----------|--------|------------------------|-------|-------|-------|----------------|-------|-------|-------|
|         |                 |                      |                    |         |        |                | Calcite        | Dolomite | Quartz | Vp 5                   | Vp 10 | Vp 20 | Vp 40 | Vs 5           | Vs 10 | Vs 20 | Vs 40 |
| H2-2.2  | 5.33            | 0.0035               | 2.56               | W       | 15.30  | F              | 96.1           | 0.1      | 3.7    | 5.89                   | 5.93  | 6.07  | 6.07  | 2.96           | 3.16  | 3.21  | 3.23  |
| H2-4.6  | 15.29           | 1.91                 | 2.28               | W       | 8.44   | С              | 99.8           | 0.1      | 0.1    | 5.22                   | 5.26  | 5.29  | 5.32  | 2.61           | 2.60  | 2.70  | 2.71  |
| H2-9.5  | 13.83           | 0.3362               | 2.34               | М       | 11.56  | С              | 98.6           | 0.1      | 1.3    | 4.96                   | 5.07  | 5.02  | 5.02  | 2.47           | 2.52  | 2.58  | 2.71  |
| H2-10.4 | 3.51            | 0.0019               | 2.60               | Р       | 8.01   | F              | 80.7           | 0.2      | 19.1   | 5.84                   | 5.91  | 6.02  | 6.05  | 3.24           | 3.26  | 3.26  | 3.26  |
| H2-17   | 9.27            | 0.0098               | 2.41               | W       | 6.54   | F              | 98.5           | 0.1      | 1.1    | 4.08                   | 4.10  | 4.15  | 4.28  | 2.29           | 2.32  | 2.36  | 2.40  |
| H2-18   | 6.27            | 0.0064               | 2.51               | М       | 9.73   | F              | 98.7           | 0        | 1.3    | 5.24                   | 5.31  | 5.35  | 5.42  | 2.81           | 2.88  | 2.93  | 2.94  |
| H2-29   | 14.28           | 0.12                 | 2.25               | М       | 12.88  | С              | 87.6           | 0        | 12.4   | 2.85                   | 2.94  | 3.03  | 3.19  | 1.72           | 1.75  | 1.79  | 1.84  |
| H2-36   | 5.39            | 0.0031               | 2.57               | Р       | 7.19   | F              | 96.6           |          | 3.4    | 5.42                   | 5.44  | 5.44  | 5.52  | 2.92           | 2.95  | 2.96  | 2.98  |
| H2-37   | 11.91           | 0.1456               | 2.39               | Р       | 16.87  | С              | 95.8           | 0        | 4.1    | 4.80                   | 4.80  | 4.83  | 4.88  | 2.58           | 2.62  | 2.64  | 2.67  |
| H2-40   | 12.23           | 0.0281               | 2.37               | G       | 12.50  | С              | 95.6           | 0        | 4.1    | 4.51                   | 4.59  | 4.59  | 4.70  | 2.46           | 2.50  | 2.54  | 2.55  |
| H2-41.8 | 9.13            | 0.0724               | 2.46               | G       | 14.85  | F              | 96.4           | 0.1      | 3.5    | 5.56                   | 5.56  | 5.53  | 5.47  | 2.95           | 2.98  | 3.00  | 3.00  |
| H2-44.4 | 17.95           | 0.6715               | 2.18               | W       | 17.22  | С              | 89.8           | 0        | 10.2   | 3.50                   | 3.52  | 3.57  | 3.65  | 2.05           | 2.08  | 2.10  | 2.13  |
| H2-47.9 | 5.27            | 0.0057               | 2.54               | G       | 15.58  | F              | 98             | 0        | 2      | 5.01                   | 5.04  | 5.09  | 5.20  | 2.71           | 2.74  | 2.79  | 2.83  |
| H2-49   | 14.77           | 0.5988               | 2.28               | W       | 10.24  | F              | 87.3           | 0        | 12.7   | 4.04                   | 4.07  | 4.11  | 4.20  | 2.30           | 2.34  | 2.36  | 2.37  |
| H2-54.4 | 12.64           | 0.1475               | 2.33               | Р       | 6.31   | F              | 86.5           | 0        | 13.5   | 4.23                   | 4.24  | 4.31  | 4.27  | 2.46           | 2.50  | 2.51  | 2.52  |
| H2-58.7 | 5.05            | 0.0035               | 2.56               | G       | 6.98   | F              | 96.6           | 0.1      | 3.2    | 5.85                   | 5.93  | 5.98  | 5.98  | 3.04           | 3.08  | 3.12  | 3.15  |
| H2-62   | 17.28           | 0.5302               | 2.25               | W       | 7.42   | С              | 98.8           | 0.1      | 1      | 4.48                   | 4.48  | 4.58  | 4.58  | 2.51           | 2.56  | 2.58  | 2.60  |
| H2-64   | 14.86           | 0.4857               | 2.34               | W       | 12.44  | С              | 99.3           | 0.2      | 0.5    | 4.78                   | 4.78  | 4.81  | 4.83  | 2.59           | 2.63  | 2.66  | 2.68  |
| H2-64.6 | 5.77            | 0.0041               | 2.54               | R       | 3.63   | F              | 97.5           | 0.1      | 2.3    | 5.04                   | 5.17  | 5.27  | 5.42  | 2.77           | 2.84  | 2.89  | 2.92  |
| H2-68   | 12.35           | 0.0884               | 2.38               | Р       | 8.10   | С              | 81.4           | 0        | 18.6   | 4.25                   | 4.25  | 4.29  | 4.36  | 2.70           | 2.73  | 2.81  | 2.85  |

**Table A1.** Porosity, permeability, texture, bioturbation intensity (BI) in %, burrow fill, mineralogy, compressional and shear wave velocity of the studied samples. Texture; (M = Mudstone, W = Wackestone, P = Packstone, G = Grainstone, F = Framestone, R = Rudstone). Burrow Fill (F = Fine Fill, C = Coarse Fill).

| ID          | Porosity<br>(%) | Permeability<br>(mD) | Density<br>(gm/cc) | Texture | BI (%) | Burrow<br>Fill | Mineralogy (%) |          |        | Compressional Velocity |       |       |       | Shear Velocity |       |       |       |
|-------------|-----------------|----------------------|--------------------|---------|--------|----------------|----------------|----------|--------|------------------------|-------|-------|-------|----------------|-------|-------|-------|
|             |                 |                      |                    |         |        |                | Calcite        | Dolomite | Quartz | Vp 5                   | Vp 10 | Vp 20 | Vp 40 | Vs 5           | Vs 10 | Vs 20 | Vs 40 |
| H2_94.1     | 16              | 0.5988               | 2.29               | W       | 9.29   | С              | 97.7           | 0.1      | 2.1    | 4.33                   | 4.39  | 4.42  | 4.56  | 2.53           | 2.54  | 2.55  | 2.61  |
| H2-95.6     | 16.33           | 1.0905               | 2.67               | Р       | 10.94  | С              | 98.7           | 0        | 1.1    | 4.34                   | 4.38  | 4.44  | 4.50  | 2.43           | 2.46  | 2.48  | 2.50  |
| H2-97       | 13.73           | 0.5532               | 2.33               | М       | 13.98  | С              | 98.1           | 0        | 1.9    | 4.34                   | 4.36  | 4.41  | 4.44  | 2.64           | 2.65  | 2.68  | 2.66  |
| H2-99.6     | 19.72           | 1.3002               | 2.18               | W       | 27.03  | С              | 97.8           | 0        | 2      | 3.99                   | 3.95  | 4.04  | 4.03  | 2.18           | 2.21  | 2.24  | 2.32  |
| H2-102.8    | 0.77            | 0.0036               | 2.68               | F       | 10.00  | F              | 89.2           | 0.3      | 10.5   | 6.54                   | 6.60  | 6.54  | 6.61  | 3.19           | 3.27  | 3.31  | 3.34  |
| H2-103-Head | 2.14            | 0.0035               | 2.62               | F       | 14.03  | F              | 98.2           | 0.1      | 1.7    | 6.24                   | 6.35  | 6.44  | 6.51  | 3.23           | 3.33  | 3.36  | 3.39  |
| H2-109.4    | 6.34            | 0.0108               | 2.69               | G       | 7.94   | С              | 75.1           | 0.1      | 24.7   | 5.21                   | 5.24  | 5.27  | 5.24  | 2.83           | 2.91  | 2.94  | 2.95  |

Table A1. Cont.

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