Determining the microstructure of soft sediments by automatic analysis of scanning electron microscope images of the Dead Sea fault seismites

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Abstract
The Dead Sea seismites comprise the world's longest record of earthquakes. The seismites appear as deformed layers enclosed between undeformed layers of alternating millimetre-thick laminae with annual pairs of winter detritus and summer evaporitic aragonite. Understanding the physical conditions that govern their formation will promote the recovery of the causative earthquake properties from the deformation character. The first step towards this goal is understanding the microscopic structure of the seismites. To this end, scanning electron microscope images of the Dead Sea Basin sediments were analysed to extract their pore and grain sizes. The implementation of image processing techniques to determine the microscopic-scale physical properties of the deformed and undeformed layers are in general agreement with results from classical labour-intensive instruments. However, the image processing analyses provide more detailed unbiased information. A MATLAB-based code has been developed as a ready-to-use package, which can be easily implemented on any other occurrence of soft sediment outcrops to analyse sediment microscopic-scale physical properties from scanning electron microscope images.

KEYWORDS
Dead Sea Basin, Lisan Formation, microstructures, scanning electron microscope, seismites

1 | INTRODUCTION

Sediments that exhibit earthquake-triggered deformation are called 'seismites' (Seilacher, 1969). Lake deposits within the active Dead Sea Basin (DSB), in particular the Lisan and Ze‘elim formations, contain such seismites in the form of soft-sediment deformation, which were documented in outcrops (Ken-Tor et al., 2001; Marco & Agnon, 1995) and in drill cores (Lu et al., 2020). The seismite sequences of the DSB comprise the world longest palaeoseismic record (Lu et al., 2020).

Soft-sediment deformation structures (SSDS) that are interpreted as earthquake records are common along present and palaeo seismogenic zones (Greb & Archer, 2007; Morsilli et al., 2020; Rodriguez-Pascua et al., 2000; Salomon et al., 2018; Silva et al., 1997; Vanneste et al., 1999).

Understanding the physical rules that govern their formation will aid in the identification of properties of the...
triggering earthquake by characterising the deformation. Although explored with shake tables (Dasgupta, 2008; Moretti et al., 1999), the mechanics of their formation and the physical conditions for their onset and development are not fully understood. One possible mechanism of SSD development, the Kelvin–Helmholtz instability, was proposed in previous studies (Heifetz et al., 2005; Wetzler et al., 2010). These preliminary studies assumed Newtonian behaviour of the sediments, while more recent studies show that soft sediments tend to behave like viscoplastic fluids (Balmforth et al., 2014). Under low stress they behave as solids, however, when the stress load increases and passes the yielding stress, they begin to flow. The location, composition, thickness and shape of yielding surfaces (aka ‘detachment’ or ‘décollement’), across which this transition occurs, depend on the mineralogy, fabric and the microstructural properties of the layers.

Outcrops of the lacustrine Lisan and Ze’elim formations in the DSB include seismitic records in the form of breccia layers and SSD dated to the last 70 kyr (Ken-Tor et al., 2001; Marco et al., 1996). Seismites that occurred over the last 2 kyr are correlated with archaeological and historical earthquake records (Agnon, 2014; Kagan et al., 2011; Ken-Tor et al., 2001; Migowski et al., 2004).

The seismite thickness is up to several decimetres, but in a few places up to 2–3 m. The deformed layers are found between undeformed layers of alternating millimetre-scale laminae with annual pairs of winter detritus and summer evaporitic aragonite. The dark detritus laminae contain silt-size grains of limestone, dolomite, flint and quartz, which are interpreted as winter flood deposits. The white laminae contain aragonite crystals (CaCO₃), that precipitated in the water body when the concentration reached saturation due to increased evaporation during the summer season (Begin et al., 1974; Ben Dor et al., 2018, 2021).

This work examines the microscopic-scale physical properties of the Lisan seismites, aiming to identify some of the seismites’ macroscopic mechanical properties and better understand their formation mechanism. To quantify the sediment microscopic-scale physical properties, scanning electron microscope (SEM) images were analysed, including undeformed layers, deformed layers of detachment surfaces, folded aragonite and detritus and a small fault in the aragonite, all sampled from the Lisan Formation (Figure 1). The microscopic-scale physical properties were obtained by calculating the correlation functions of the SEM images. Some of the calculated microscopic-scale physical properties show similar values to previously reported analyses of

FIGURE 1  Research location. (A) Google earth image of the Dead Sea basin area. The two black rectangles represent the study area from which samples of the sediments were collected. (B) Peratzim Valley (rectangle no. 1 in A) demonstrating the abundance of canyons that expose the Lisan Formation. The black rectangle shows the location of the first group of samples (Peratzim sample, waypoint: 31.08194N, 35.35028E). (C) Masada area (rectangle no. 2 in A). The study area is to the north (black rectangle) where the second group of samples were collected (Masada sample, waypoint 31.31407N, 35.37411E). (D) Outcrop of Lisan Formation (marked by a black rectangle in B). In the lower part, the alternation of aragonite and detritus laminae is evident, where the uppermost part of the section is composed of conglomerates. A fault with a moderate slope (0–20 apparent dip) and a slip distance of 3.95 m can be seen in the middle of the section and is defined in this work as the detachment surface. (E) Close-up of the detachment surface. Sampling of deformed (detachment surface) and undeformed (aragonite and detritus laminae) layers.
the Lisan Formation sediments (Arkin & Starinsky, 1982; Haliva-Cohen et al., 2012).

2 | SAMPLE PREPARATION AND SEM ANALYSIS

2.1 | Fieldwork

Three samples of the Lisan Formation sediments were collected from two outcrops in the south-western part of the DSB (Figure 1A): One sample was collected from the Peratzim Valley (Figure 1B) and two samples were collected from the Masada area (Figure 1C). Undeformed layers and deformed layers (Figure 1D and E) were sampled in the Peratzim Valley, and an outcrop of undeformed laminae crossed by a normal fault was sampled in the Masada area.

2.2 | Sample preparation

Two types of sample were prepared for the SEM analyses: (1) Fragments of laminae – four fragments from the sample collected in the Peratzim Valley were placed (Figure 1B) on SEM specimen stubs, with the samples attached to the stubs by double-sided conductive carbon tape. The samples were placed in a vacuum chamber and were coated by carbon to improve surface electrical conductivity. Figure 2A and B shows two examples of laminae fragments prepared for the SEM analyses. (2) Two thin sections of a standard thickness of 30 μm were prepared from samples that were hardened by soaking in a mixture of epoxy resin and acetone (Appendix S1). Figure 2C and D shows examples of the thin sections.

2.3 | SEM analysis

The analysis was conducted using a SEM, model FEI Quanta 450 at the Geological Survey of Israel. A number of SEM images with different resolutions were obtained under similar beam conditions for each lamina fragment or thin section. Examples of images obtained for samples of aragonite, detritus, folded aragonite, folded detritus, and from the detachment surface and a fault in the aragonite are shown in Figure 2E through M.

3 | IMAGE PROCESSING

Image processing procedures were implemented, using MATLAB™ and ImageJ™ software (Appendix S2), to calculate the 2D physical properties including porosity, specific surface area, mean grain size, hydraulic diameter, mean pore size and permeability (Figure 3). The image sizes for the different samples ranged between 185×185 pixels to 885×885 pixels.

3.1 | Binarization

The SEM produces digital images which are collections of individual elements or pixels with distinct greyscale intensities, indicating the solid and pore phases of the examined material. In contrast to analogue images, digital images enable quantitative analyses (Garboczi et al., 1999). The greyscale typically contains 256 shades of grey with values ranging from 0 (black) to 255 (white), for example, Figure 4A. Each image was transformed to a binary one of black (0) and white (1), so that the black indicates the material grains and white the pores in between (Figure 4C). The frequency of each greyscale value in a SEM image is represented by a histogram (Figure 4B). In general, a histogram provides most of the information required to choose a threshold value for generating the binary image (Berryman, 1985). In this work, for each image, the threshold value was selected as the one corresponding to the mean value of the histogram with a manual subjective refinement for each image to get the best binarization.

3.2 | Image modification

Binary images contain “noise” (for example, Figure 4C). In order to filter the noise out, several filters were applied (‘bwareaopen’, ‘bwdist’, ‘medfilt2’ and ‘bwmorph’ commands in Image Processing Toolbox in MATLAB; Figure 4D; Table 1).

3.3 | Spatial correlation functions from a 2-dimensional image

3.3.1 | One and two-point correlation functions

From the binary image, it is possible to derive correlation functions in order to calculate the physical properties of the material. In the 2D case, an image of a binary porous material may be represented by means of an indicator function, \( f(i,j) \), where \((i,j)\) indicate the position of any pixel in an \(M\times N\) size image \(i = 1,...,M\) and \(j = 1,...,N\). The definition of the indicator function is as follows:

\[
f(i,j) = \begin{cases} 
1 & \text{if } (i,j) \in \text{Pore space} \\
0 & \text{if } (i,j) \in \text{Grain space}
\end{cases}
\]
Hence, the integral of $f$ over the image area provides an estimate of the 2D porosity, $\Phi$ (Blair et al., 1996). According to this measure, the porosity is the one-point correlation function, $S_1$, that is, the probability of a selected point to be in the pore space:

$$S_1 = \langle f(i,j) \rangle = \frac{1}{M \cdot N} \sum_{i=1}^{M} \sum_{j=1}^{N} f_{ij} = \Phi$$  \hspace{1cm} (2)$$

where $\langle \rangle$ indicates areal averaging.

The two-point correlation function $S_2$ is defined as the probability that two points separated by a vector $(x, y)$ both lie in the pore space of the material (Blair et al., 1996). In pixel units of $(x, y)$:

$$S_2(x,y) = \langle f(i,j) f(i+x,j+y) \rangle = \frac{1}{(M-x)(N-y)} \sum_{i=1}^{M-x} \sum_{j=1}^{N-y} f_{ij} f_{i+x,j+y}$$  \hspace{1cm} (3)$$

To transform $S_2(x, y)$ into a direction-independent, one-dimensional two-point correlation function, $S_2(r)$, $S_2(x,y)$ should be averaged for all values of $(x, y)$ satisfying $r = \sqrt{x^2 + y^2}$. As this radial averaging process computation is relatively slow when using MATLAB, computation time was reduced by implementing ‘ImageJ’ software and an ImageJ macro to calculate the radial average of the correlation function of a binary image [https://imagejdoc.tudor.lu/macro/ radially_average autocorrelation]. The output obtained from ImageJ is the normalised correlation function, $A \Phi$ (Figure 4E), and the image’s porosity. To get the non-normalised correlation function $S_2(r)$, satisfying $S_2(r = 0) = \Phi$, and $S_2(r \rightarrow \infty) = \Phi^2$ (Figure 4F), a simple linear transformation was used:

$$S_2(r) = \Phi^2 + A(\Phi - \Phi^2)$$  \hspace{1cm} (4)$$

**FIGURE 2** Lisan Formation samples of laminae fragments and thin sections and their SEM images: (A) Fragment of undeformed laminae (aragonite – White, detritus – Greyish brown), (B) Fragment of deformed laminae taken from the detachment surface, (C) Thin section showing displaced laminae, (D) Thin section with undeformed laminae (upper and lower parts), a micro fault (marked with arrows), and folded laminae (middle and bottom part), (E–M) SEM images for the different areas: Aragonite lamina (E and H), detritus lamina (F and I), deformed laminae (detachment surface, G), a contact area (marked with dashed line) of aragonite (upper part) and detritus (lower part; J), folded aragonite (K), folded detritus (L), and fault zone in aragonite (M). The scanned areas of figure E-M are marked in red squares in figure A–D and labelled by small letters for each image. The length of the scale bar in figure E–M is 40 μm.
3.3.2 Physical properties obtained by the correlation functions

The two-point correlation function $S_2$, provides a quantitative estimate of the porosity, specific surface (contact) area and the mean grain size of an image (Figure 5). By using these properties, the following properties can be calculated: mean pore size, hydraulic diameter and the Kozeny–Carmen relationship to obtain the permeability of the porous medium (Blair et al., 1996).
Specific surface area: Specific surface area, $s$ [$\mu m^{-1}$], is defined for the 3D case. For 2D images, it is the ratio between the total contact length of the pore-grain interface and the total area of the porous material. This ratio is affected by porosity, the packing shape of the material, and the size and shape of the grains. For $r \to 0$, the slope of $S_2$ is proportional to the specific surface area of the material; therefore, $S_2$ can also be used to quantify the roughness of grains in an image. This proportionality relationship is defined as follows (Blair et al., 1996):

$$s = -4 \cdot S_2'(0) \quad (7)$$

Mean grain size: By using the correlation function of a particular image, it is possible to get an estimate of its mean grain size (diameter), $r_g$. The mean grain size is equal to $r_c$, for which the first minimum of the correlation function $S_2(r)$ is obtained (Figure 5).

Hydraulic diameter: Hydraulic diameter is a theoretical concept used to calculate flow and pressure loss in pipes whose cross-sectional area is not rounded, hence it provides an alternative gauging diameter to areas in the material that are not round. The hydraulic diameter is related to the specific surface area and is used to calculate the mean pore size and the permeability (Blair et al., 1996):

$$D_H = \frac{4\phi}{s} \quad (8)$$

Where $\phi$ is the porosity, $s$ is the specific surface area, and $D_H$ is the hydraulic diameter.

Mean pore size: Following the method of Berryman and Blair (1986), the mean pore size (radius), $r_c$, was estimated. In a linear approximation of $S_2(r)$ for small values of $r$, the line crosses the asymptote of $\phi^2$ (Figure 5) at a separation distance $r_c$:

$$r_c = D_H(1 - \phi) \quad (9)$$

Permeability: Fluid permeability is an important physical property of porous material with connected void spaces. The rate at which a viscous fluid will flow through such a porous medium obeys Darcy’s law. It is proportional to the pressure gradient, where the constant of proportionality is the Darcy’s constant or the permeability $k$ (Berryman & Blair, 1986). The permeability of a medium depends not only on the value of the porosity, but also on the shapes of the pores in the medium and their level of connectedness. The most commonly used expression for the permeability is obtained from the Kozeny–Carman equation (Berryman & Blair, 1986; Henderson et al., 2010; Martins et al., 2007; Mauran et al., 2001; Torquato & Pham, 2004; Xu & Yu, 2008; Yu & Cheng, 2002), whose general form is:

$$k = \frac{\phi r_H^2}{c} \quad (10)$$

where $r_H$ is the hydraulic radius (half of the hydraulic diameter $D_H$), and $c$ is a constant related to the pore geometry. For circular tubes, $c = 2$ (Berryman & Blair, 1986).

### 3.4 Pore/grain segregation

To confirm the $r_g$ and $r_c$ parameters obtained from the correlation function, a MATLAB code that calculates the average grain size and the average pore size of each image was used to analyse 201 images obtained from six samples. A watershed segregation technique (Meyer, 1994) (Appendix S3) was applied by a MATLAB code on the binary image to separate overlapping grains and to define the boundaries between pores and grains. By the MATLAB code, the pore and grain-size distribution and the average size for each image were found.

### RESULTS

Two of the physical properties, the mean grain size and mean pore size (Table 2) can be calculated either from the image segregation or the correlation function techniques.
Porosity calculations revealed that the aragonite laminae have a higher porosity compared to those of detritus laminae and they do appear to be more spacious (Figure 2E and F). Figure 8A describes the specific surface area as a function of the porosity of all of the samples studied in this work. The general trend indicates that an increase in porosity is compatible with an increase in specific surface area. Therefore, it is expected that a greater value will be obtained for the specific surface area occupied by the aragonite laminae, as indeed is observed (Figure 7B). It is interesting to note that according to these results of the specific surface area, water adsorption should be more significant in the aragonite laminae compared to the detritus. On the other hand, the mineralogical difference between aragonite and detritus may cause the opposite effect, as the latter is rich in clays that tend to absorb more water than aragonite.

Mean grain size: On Figure 2E and F it may be difficult to distinguish the grain sizes of the aragonite from that of the detritus laminae. In the case of detritus laminae, the grain definition is relatively clear, however, for aragonite laminae, the radial growth of elongated crystals from a common centre makes the definition of the grain boundaries more subtle. In this work, the grain is defined according to the automatic identification applied in the image analysis; hence, usually a collection of crystals in hedgehog shape constitutes a grain. Haliva-Cohen et al. (2012) calculated the grain sizes of Lisan Formation undeformed detritus laminae from the Peratzim Valley area and Masada area, using a Mastersizer Laser. The range of values they obtained (ca 8–10 μm) is within the range obtained in the present work for samples of laminae fragments and thin sections using SEM analysis (3.9–10 μm). The range obtained in this work includes values lower than those obtained by Haliva-Cohen et al. (2012) and the difference may be explained by the different measuring methods used. The use of SEM images enables a better resolution and the ability to identify smaller grains.

Permeability: Figure 8B describes the permeability as a function of the porosity. The graph shows the results obtained for all samples studied in this work. The general
Table 2: Analysis results for the quantitative evaluation of the physical properties, for laminae fragments (fragments #1–4) and thin sections (thin sections #1 and 2) from the Lisan Formation. Information from samples, including laminae fragments and thin sections, taken from the same area were averaged.

| Sample            | Type of Sediment | Num. of Images | Φ [%] | s [μm⁻¹] | r_g [μm] | D_H [μm] | r_c [μm] | k [mD]   |
|-------------------|------------------|----------------|-------|----------|----------|----------|----------|----------|
| Undeformed Fragments #1&3 | Aragonite        | 27             | 22.4–41.5 (30.5 ± 4.4) | 0.36–1.2 (0.63 ± 0.28) | 2.9–13.6 (7.9 ± 2.9) | 1.2–3.7 (2.2 ± 0.7) | 0.8–2.4 (1.5 ± 0.5) | 59–583 (199 ± 134) |
| Thin Sections #1&2 | Aragonite        | 56             | 26.1–49.6 (39.3 ± 4.2) | 0.36–0.96 (0.64 ± 0.17) | 3.3–16.8 (9.4 ± 2.5) | 1.6–4.1 (2.6 ± 0.6) | 1–2 (1.6 ± 0.4) | 118–903 (354 ± 183) |
| Fragments #1&3    | Detritus         | 18             | 10.2–19.7 (13.9 ± 2.5) | 0.21–0.71 (0.49 ± 0.15) | 3.9–10 (6.3 ± 2.1) | 0.8–2 (1.2 ± 0.3) | 0.7–1.8 (1 ± 0.3) | 11–50 (26 ± 11) |
| Thin Sections #1&2| Detritus         | 6              | 5.4–14.5 (11.2 ± 3.8)  | 0.11–0.36 (0.26 ± 0.11) | 4.7–8.9 (7.6 ± 1.5) | 1.6–2.1 (1.8 ± 0.2) | 1.4–1.9 (1.6 ± 0.2) | 25–49 (42 ± 9) |
| Deformed Fragments #2&4 | Detachment Surface | 36          | 8.1–25.6 (16.7 ± 4)    | 0.24–0.76 (0.49 ± 0.15) | 4.1–18.9 (7.3 ± 3) | 0.9–2.4 (1.5 ± 0.4) | 0.8–2 (1.2 ± 0.3) | 8–116 (48 ± 28) |
| Thin Section #1   | Folded Aragonite | 29             | 36.5–48.5 (42.5 ± 2.4) | 0.43–0.75 (0.57 ± 0.09) | 4.6–13.5 (8.1 ± 1.9) | 2.4–4.1 (3.1 ± 0.5) | 1.3–2.2 (1.8 ± 0.3) | 287–974 (520 ± 190) |
|                   | Folded Detritus  | 14             | 3.3–15.8 (10.5 ± 4.5)  | 0.09–0.41 (0.26 ± 0.11) | 3.6–27.6 (10.2 ± 6.2) | 0.8–2.6 (1.7 ± 0.6) | 0.8–2.4 (1.5 ± 0.5) | 5–83 (43 ± 28) |
|                   | Fault Zone in Aragonite | 15       | 37.6–45.1 (41.4 ± 2.1) | 0.4–0.75 (0.58 ± 0.12) | 7.2–14.7 (10.5 ± 2.5) | 2–4 (3 ± 0.7) | 1.3–2.4 (1.8 ± 0.4) | 189–832 (491 ± 226) |

Notes: These are fragments #1 and 3 (fragments of undeformed laminae), parts from thin section #1 and thin section #2 (undeformed laminae thin section), and fragments #2 and 4 (fragments of deformed laminae). Mean values are given in parentheses. The +/- are standard deviations.

*Permeability k computed using c = 2 in Equation 10.
trend supports the preceding expectation that an increase in porosity yields an increase in permeability (Equation 10). Figure 8 indicates a clear separation between the porosity and permeability values of the aragonite laminae (marked by x’s in Figure 8B), which are higher when compared to those of the detritus and deformed laminae (marked by triangles and circles respectively).

4.2 | Deformed laminae

4.2.1 | Deformed versus undeformed laminae

As indicated in Figures 6, 7 and 8, the deformed aragonite and detritus laminae show only little differences in their physical properties. The values of the deformed layers physical properties fall mostly within the standard deviation of the undeformed ones and vice-versa. These results agree with the qualitative impression obtained from the SEM images in Figure 2 (compare for instance Figure 2H with Figure 2G and Figure 2I with Figure 2L).

4.2.2 | Mixed layer – Detachment surface

The deformed laminae fragments (detachment surface; e.g. Figure 2G) showed porosity, specific surface area, hydraulic diameter, mean pore size and permeability values that are well within the values obtained for the undeformed aragonite and detritus laminae (except for the mean grain size), with a tendency towards the detritus laminae values (Figure 7). For example, Figure 2E
(aragonite), F (detritus) and G (detachment surface) show that the detachment surface contains needle-shaped aragonite fragments that have been mixed and compacted with the detritus lamina as a result of the shearing process along the detachment surface. Therefore, porosity values are similar to those of detritus laminae (Figure 7A). For the mean pore size, the values obtained for the detachment surface range between the aragonite and detritus as would be expected when mixing the two substances (Figure 7E). Figure 8A and B describes the specific surface area and the permeability as a function of the porosity of all the samples studied in this work, respectively. Here as well, the deformed laminae fragments (detachment surface, marked with circles in Figure 8) have values that are in between the values of the undeformed aragonite (marked with x's in Figure 8) and the undeformed detritus (marked with triangles in Figure 8) with a tendency towards detritus laminae values.

### 4.3 Fragments versus thin sections

Two types of sample were used: laminae fragments and thin sections. In general, both types of sample suggest similar values for the estimated microscopic-scale physical properties. Nevertheless, some slight differences are observed in the porosity, specific surface area, pore size and permeability, as discussed below:

(i) Porosity of aragonite laminae fragments and thin sections (Figure 7A) - the difference in porosity is reflected by an increase of about 9%, obtained for the aragonite laminae thin sections. However, for the detritus, the opposite seems to occur where sub-micron grains fill the pore space between relatively large grains decreasing the porosity value. For the aragonite, similar pores are empty (here filled by epoxy). Therefore, in a thin section (ca 30 μm thick)
many of the sub-micron grains can be seen, while in the aragonite, they are absent, and only the large minerals can be seen. Actually, the aragonite fragments are no longer a 2D case. If the thin section could have been made much thinner, it can be hypothesised that the same porosity difference could be observed for the detritus samples.

(ii) The specific surface area values obtained for the detritus laminae fragments and thin sections are different (Figure 7B). As shown in Figure 2F and I, the latter (detritus thin sections) samples have a smaller interface between the grains and pores compared to that of the detritus laminae fragments, and therefore, the specific surface area obtained for the detritus thin sections was lower. A possible explanation for these differences could be the type of sample. The thin section preparation may cause cracks in the detritus laminae, which leads to a change in the specific surface area.

(iii) The average mean pore size values obtained for the aragonite laminae fragments and thin sections are similar, however, for the detritus laminae, the pore sizes are higher for the thin sections when compared to the laminae fragments (Figure 7E). There are two possible explanations for this difference: (1) the samples were collected in different areas (laminae fragments from the Peratzim Valley and thin sections from the Masada area, Figure 1), (2) the method of sample preparation differed, as specified in the methodology section. Note that the pore sizes of the undeformed laminae fragments and thin sections were different. However, contrary to expectations, when comparing the thin sections, the same mean pore size value was obtained for both detritus and aragonite laminae. A possible explanation for this result could be the sample type and the way it was prepared. It is possible that cracks in the detrital material were generated during thin section preparation, as can be seen in the upper part of Figure 2I and L. In the automatic image analysis, these cracks are considered to be pores.

(iv) The permeability obtained for the undeformed aragonite laminae fragments was $199 \pm 134$ mD, compared to an order of magnitude lower value ($26 \pm 11$ mD) for the detritus laminae. Whereas, the permeability for the undeformed laminae thin sections, obtained for $k$, was higher than the permeability obtained for the aragonite laminae fragments ($354 \pm 183$ mD) and the detritus laminae fragments ($42 \pm 9$ mD; Figure 7F). This slight difference may be because of the dependence of the permeability on the porosity (Equation 10; Figure 8B). As mentioned previously, there seems to be a difference in the porosity values reflected by an increase of about 9% for the undeformed aragonite laminae fragments and thin sections.

4.4 Discussion

Six microscopic-scale physical properties of samples from the Lisan Formation lacustrine soft sediments were quantified. This is the first time that image processing techniques were applied to various SEM images of the Lisan Formation, including: well-bedded laminae (undeformed) and samples collected from areas that were significantly
deformed—detachment surface, folded aragonite, folded detritus and fault zone in aragonite. The analysis involved two types of image samples, laminae fragments and thin sections, and included the use of image processing methods and correlation functions to evaluate six properties: porosity, specific surface area, mean grain size, hydraulic diameter, mean pore size and permeability. It was verified that the correlation function $S_2$ can be used to determine the porosity, the specific surface area and the mean grain size. The three additional properties were calculated by substituting the values obtained in well-accepted empirical equations.

The porosities of aragonite laminae (22.4%–49.6%) differ significantly from the detritus laminae (5.4%–19.7%). The upper range of measured values contains values obtained in previous laboratory measurements of the bulk Lisan Formation porosity (33%–47%) (Arkin & Starinsky, 1982). It is hypothesised that this high porosity reflects the fact that most of the material in their studied sample was aragonite, and only a small part was detritus. Consequently, the overall bulk result reflects the aragonite porosity. The mean grain diameter of the detritus laminae, about 3.9–10$\mu$m, overlaps with the range of diameters obtained by Haliva-Cohen et al. (2012) of ca 8–10$\mu$m. Also, in the work present here, the fit is for the high range of measurements and it is assumed that the relatively small values of the grain sizes that were measured (<8$\mu$m) are due to better grain-separation using SEM image processing methods for micrometre-scale particles.

The results presented here revealed that although sample preparation might affect the evaluation of the material’s physical properties, the general trends between the different layers do not change significantly for each type of sample. For example, the difference between the aragonite and detritus laminae is retained for both lamina fragments and thin section.

5 | CONCLUSIONS

The purpose of this work was to find the microscopic-scale physical properties of the Lisan sediments, as a step towards the determination of the seismites’ macroscopic mechanical properties. Those are required to correctly simulate the sediment response to earthquakes and subsequently quantitatively relate the observed SSDS with their triggering earthquakes. In conclusion:

(i) The physical properties of the aragonite and detritus laminae in the Lisan Formation are different. For example, the porosity values for aragonite are 22.4%–49.6%, and 5.4%–19.7% for the detritus. This suggests that when modelling the mechanical deformation of these layers, they cannot be treated as a single material but rather as a complex multi-layer material.

(ii) The physical properties of the detachment surface are very similar to those obtained for the detritus laminae (for example the pore size values are 0.8–2$\mu$m for the detachment surface, and 0.7–1.9$\mu$m for the detritus), suggesting that when aragonite and detritus are mixed, the properties of the mixed laminae are mostly determined by the detritus component.

(iii) In this study, it seems that it is not possible to distinguish between the physical properties of deformed and undeformed laminae. Whether this suggests that deformation does not cause a robust change in the sediments’ microstructure is still an open question.

(iv) Sample type and sample preparation process may affect the quantitative evaluation of the physical properties of a material. Preparation of fragments for analysis was the least destructive method and some of the physical properties obtained for them (porosity and mean grain size) were closer to the values obtained in previous works. However, the use of thin sections seems to be crucial when looking at deformed laminae.

(v) The methods used in this work can be generally applied to study the microstructure of sediments (available upon request).

6 | FOLLOW-UP RESEARCH

As mentioned in the previous section, it is still an open question whether macroscopic deformations affect the sediment microstructure, and if so, how the change in the microstructure feeds back on to the macroscopic resilience of the sediments when further shear stress is applied. From preliminary measurements, performed by this research group, it appears that the Lisan sediments behave like viscoplastic materials whose resilience to shear stress decreases as further stress is applied (the phenomena of shear thinning). It is therefore expected that such macroscopic behaviour will be accompanied by substantial changes in the microstructure of the sediments. The lack of any significant changes between the deformed and the undeformed laminae is unexplained, however we suspect that the amount of deformation in the samples was too modest to affect the microstructure. Hence, repetition of the analyses, presented here, on Lisan sediment samples from strongly deformed laminae is planned to try to determine a quantitative threshold from which macroscopic deformations affects the microstructural physical properties of the sediments.
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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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