Estimation of grain-size distributions and associated parameters from photomicrographs (thin sections) of sediment using ***petrology*** application

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The ***petrology*** freeware is designed to estimate the grain-size distribution (GSD) from a digital image of sediment. The grain size and sorting of clastic sediment exerts a profound influence on reservoir properties, since increasing grain size results in significantly higher permeability. Sorting also influences reservoir quality, with better sorted sands displaying higher porosity and permeability.

The image analysis uses the pixel color and intensity from the photomicrograph to differentiate between various minerals and voids (porosity). The user needs to select the red[R], green[G], and blue[B] color value intensity corresponding to a specific mineral (grain) type. The RGB values can be obtained interactively by clicking (with left mouse button, LMB) on the image window within a grain contour. To get a more representative sample of RGB values representing specific mineral, the process of clicking can be repeated for different grains. This step of image analysis is like data loading in a 'machine learning' approach. Drawing image histogram also allows (for a good quality images) to define the range of RGB values corresponding to different types of minerals and porosity. After the selection is done, original image is filtered out by passing only the user-defined values of RGB channels. The process of RGB values selection and subsequent filtering can be done repeatedly until the user is satisfied with the filtered image, which is displayed in a separate window. Unlike the original (colored or gray scale) image, the filtered image is binarized with white color representing the grains of interest, and black color denoting everything else. The process of RGB values selection for image filtering is highly interpretive with the ultimate criteria to get a well-resolved grains with clear outlines in the filtered image. Unfortunately, it is not always possible to achieve this goal, which can be related to any petrography analysis software.

The grain size is determined by finding the maximum grain diameter from the four predefined directions, 0˚, 45˚, 90˚, and 135˚. Algorithmically, at each pixel of the thin section the 'white' pixels are counted along the above-mentioned directions. The process of pixel counting stops when the 'black' pixel is met at a grain boundary (Figure 1). As follows from the

calculation scheme, each grain is represented with multiple 'diameter' measurements. This approach allows to get a more statistically significant estimate of GSD for a given thin section and allows to discriminate different clusters of grains based on their typical diameter.

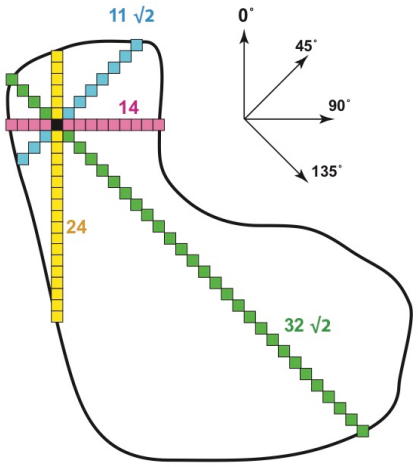

Figure 1. Diagram showing the grain diameter calculation scheme by choosing the maximum number of pixels along the four directions. Note a factor of $\sqrt{2}$ that is used for size calculation along the 'diagonal' directions.

Prior to pushing the 'Grain Size Distribution' button (Figure 2), the user should tell a computer the spatial resolution (in μm/pixel) of a thin section. Every thin section is usually supplied with a linear scale (in micrometers) that should be related to a corresponding number of pixels. This correlation is done by bringing the mouse cursor to the edge of a linear scale and pushing the right mouse button (RMP) when they match. Move the cursor to the other edge while keeping the RMB pressed and release it when they match. The corresponding 'Scale length in pixels' value will appear in the 'Display Manager' window. Now, just divide the scale value in microns by the measured length in pixels and enter the result into the 'Spatial Resolution' box of the 'Display Manager' window.

Based on GUI shown in Figure 2, a typical workflow for the GSD analysis with ***petro-gsd*** should look like follows. (1) Plot the data, (2) specify the range of RGB values to pass, (3) Plot the filtered image, (4) calculate and enter the Spatial Resolution, (5) Select Bin Size for GSD, (6) Smooth image with 3x3 high-cut filter (if necessary), and (7) Grain Size Distribution. Note the GSD button remains dimmed (disabled) until the spatial resolution is entered into a corresponding box (Figure 2).

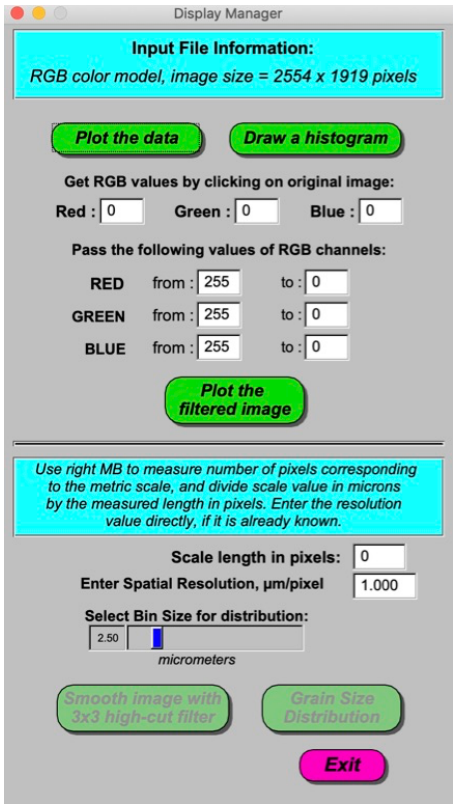

*Figure 2. Display Manager window of the **petro-gsd** graphical user interface (GUI).*

The ***petrology*** program is designed to be automated and thus fast and efficient. It produces a robust estimate of grain-size distributions for a broad range of sands by calculating diameter of each individual grain. However, problems remain with this method, such as for grains having inter-granular aberrations (pockmarks, abrasion hollows, scratches, etc.). A 3x3 high-cut filter incorporated into the GSD workflow is supposed to reduce the influence of these inter-granular aberrations (Figure 3). This filter can be applied sequentially several times but be aware of the GSD shift towards increased values after each application. There is another problem with thin sections analysis when overlapping grains appear in 2D images that are otherwise separated in the 3D space. Unfortunately, this problem is inherent to all 2D photomicrographic images, and ***petrology*** application do not provide a solution in this case.

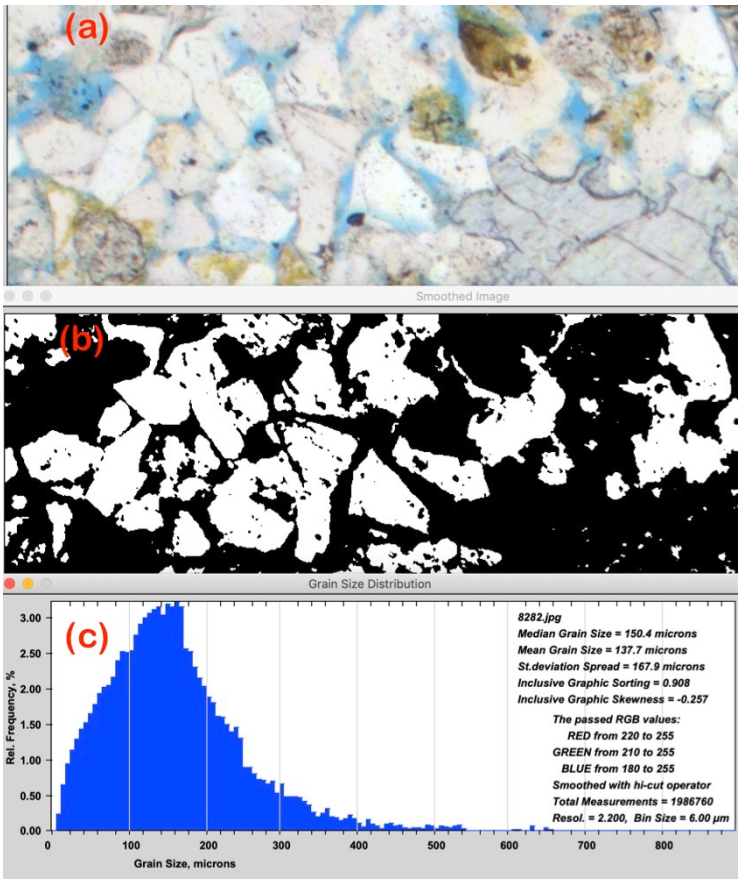

*Figure 3. Different windows generated with **petro-gsd** at different steps of image analysis. (a) Original photomicrograph with grains displayed in light-gray color, (b) binarized image after RGB filtering, (c) grain size distribution histogram with statistical outcomes and parameters used for filtering. Note some small-scale black dots and stripes within the grain contours in panel (b), which can be eliminated by application of the 3x3 high-cut filter.*

A sample image (e.g., Figure 3-a) is subjected to a numerical technique which is sensitive to the statistical distribution of grain-sizes within that image. This generates an array of numbers, which is the signature of the size information obtained within the sediment image (Figure 3-c). The final procedure of the GSD workflow is to convert an arithmetic grain size scale to the logarithmic Udden-Wentworth grade scale (Udden, 1914; Wentworth, 1922), where the boundaries between successive size classes differ by a factor of two. To facilitate statistical manipulation of grain size frequency data, a logarithmic transformation of the Udden-Wentworth scale, introduced by Krumbein (1934) and known as the Phi-scale was used:

$$\phi = -log_2\, d$$

, where d is grain diameter in millimeters. Correlation between metric grain size classification and the corresponding Phi-scale ranges is graphically shown in Figure 4.

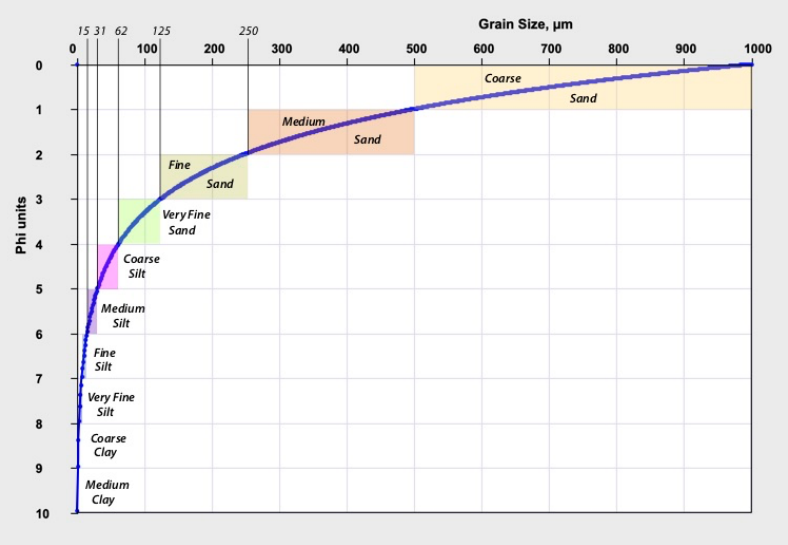

Figure 4. Interpretive grade scale chart relating rocks' grain size (in micrometers) to the logarithmic Phi scale. Based on Udden-Wentworth (1914 and 1922) and Krumbein's (1934) publications.

To characterize the grain size distributions the ***petrology*** algorithm utilizes statistical parameters and formulae proposed by Folk and Ward (1957). The parameters calculated for GSD analysis include:

- "median" – corresponds to the 50th percentile on cumulative curve, where half the particles by frequency of occurrence are larger and half are smaller than median.
- "mean" – is the average grain size determined by the formula

  $$M_z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

  , where $\phi 16$, $\phi 50$, and $\phi 84$ represent the Phi values at 16, 50, and 84th percentile of the cumulative distribution. In this study we measured the mean and median values in Phi units and further convert them to micrometers.
- "spread" or standard deviation – is the measure of the grain size dispersion. The grain size spread is determined as inter-percentile range covering approximately 68% of data by the formula

  $$\sigma = d84 - d16$$

  , where $d16$ and $d84$ represent the size at 16th and 84th percentiles. We measured the spread parameter in micrometers.
- "sorting" – the sorting of grain population represents the magnitude of the spread or scatter of grain sizes around the mean size. The ***petrology*** algorithm uses "inclusive

graphic standard deviation" (Folk and Ward, 1957) as the sorting parameter, which is calculated as follows

$$\sigma_1 = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

, where $\phi 16$, $\phi 84$, $\phi 5$ and $\phi 95$ represent the Phi values at 16, 84, 5, and 95th percentiles. One of the reasons for using Phi values is because of the currently existing verbal classification: σ_1<0.35: very well sorted; 0.35-0.50: well sorted; 0.50-0.70: moderately well sorted; 0.70-1.00: moderately sorted; and, 1.00-2.00: poorly sorted (e.g., Boggs, 2009).

- "skewness" – measures the degree to which a cumulative curve approaches symmetry. Folk and Ward (1957) introduced the "inclusive graphic skewness", which is determined by the equation

$$sk_1 = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} - \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

, where the Phi values represent the same percentages as those for sorting. A verbal classification for skewness suggested by Folk and Ward (1957) includes: from 0.1 to -0.1 as nearly symmetrical; -0.1 to -0.3 as coarse-skewed when a coarse tail is present; and 0.1 to 0.3 as fine-skewed when an excess of fine particles is present in a sample.

Building the ***petrology*** application.

As any freeware, the program description is incomplete unless it is provided with the source code and the way to build an executable application from it. The source code is written in C++ programming language using the Fast Light Tool Kit (FLTK) for graphic user interface. Correspondingly, for conditions of code distribution and use, see the license agreement in http://www.fltk.org/COPYING.php.

To build the ***petrology*** application on a Windows PC, the MSYS2 collection of tools and libraries must be installed first. A user must strictly follow the instructions (bullets 1 to 9) from the http://www.msys2.org site. Importantly, bullet point 7 will create a Linux-type environment on your Windows PC:

```
$ pacman -S --needed base-devel mingw-w64-x86_64-toolchain
```

Note that the Package Manager (pacman) is part of MSYS2 installation (see more on the https://wiki.archlinux.org/title/pacman site).
Next a user needs to install the FLTK graphic toolkit (for info, check https://www.fltk.org). And again, one can do it with the 'pacman' command:

```
$ pacman -S mingw-w64-x86_64-fltk
```

Finally, we are ready to build the program for petrographic grains analysis, ***petrology*** (the C++ source is attached). The easiest way to compile and link the code is by using the *'fltk-config'* script, which is part of FLTK installation. Just type in MinGW terminal the following command:

```
$ fltk-config --use-images --compile petrology.cxx
```

This should create the *'petrology.exe*' executable file. One may start it from the terminal window by typing:

```
$ petrology some_image_file
```

Alternatively, double click the *petrology.exe* icon to launch the graphic user interface, select File->Open and choose the petrographic image file to open.

Currently, the ***petrology*** application supports loading and drawing of Portable Network Graphics (PNG), Windows Bitmap (BMP), and Joint Photographic Group (JPEG) image files.