Grainautline – a Supervised Grain Boundary Extraction Tool Supported by Image Processing and Pattern Recognition

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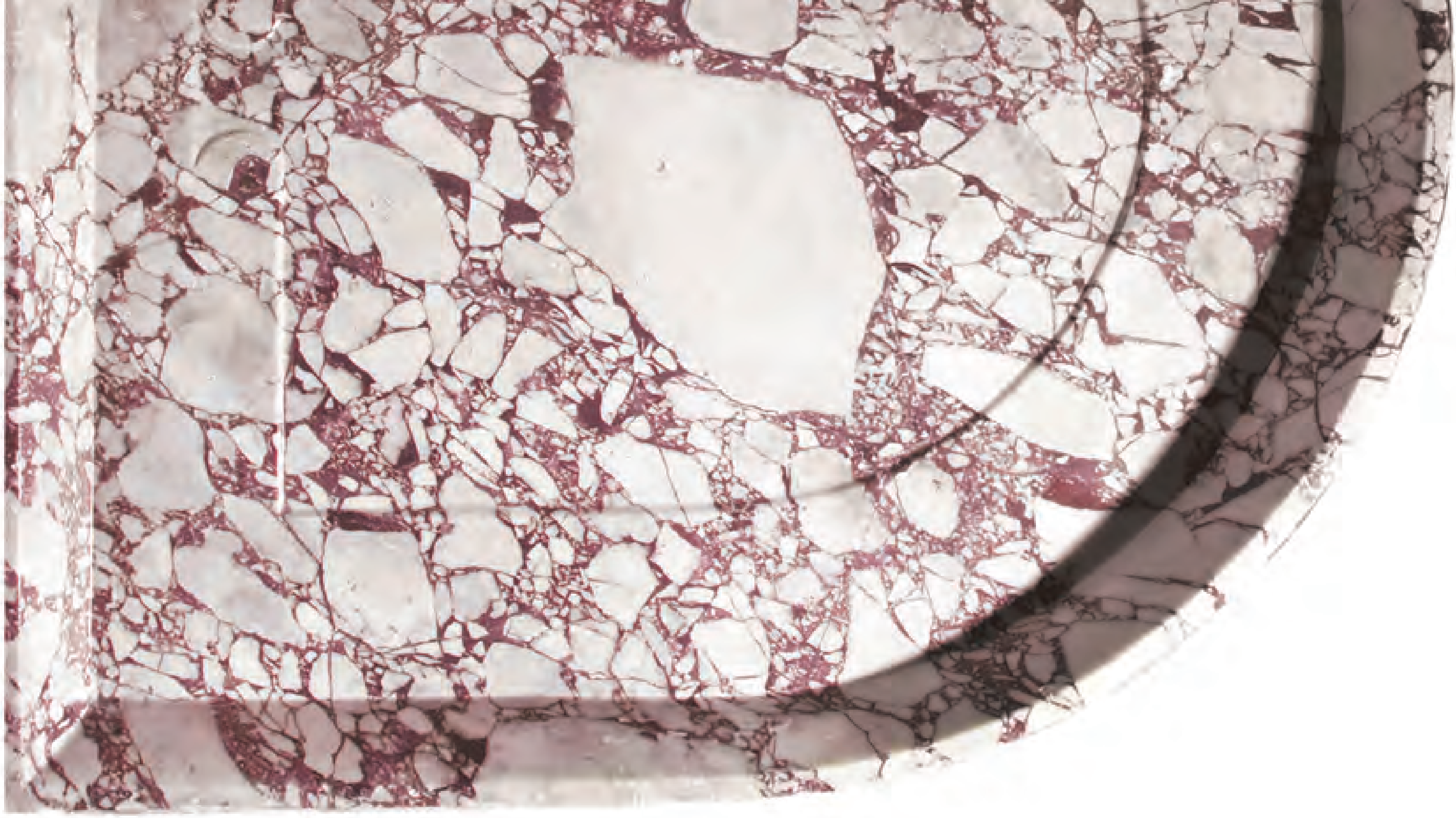

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CONTENT

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GRAINAUTLINE – A SUPERVISED GRAIN BOUNDARY EXTRACTION TOOL SUPPORTED BY IMAGE PROCESSING AND PATTERN RECOGNITION

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Abstract

Marble provenancing is often based on stable isotopic ratios and maximum grain size (MGS). Methods for retrieving a reliable MGS value sufficiently accurate for provenancing require the observation of many grains. As this involves significant work, automation of the process is desirable. GrainAutLine, the software tool proposed in this paper is designed to find grain boundaries in a semi-automatic way and ensure high quality results. This allows marble provenancing approaches to use statistics derived from the exact boundaries, like grain-size histograms. GrainAutLine is like a very specialized drawing program featuring several sophisticated tools for boundary detection and correction. It allows the users to segment thin section, or other high resolution images including twin crystal lines and boundary discontinuities much faster than doing it manually. Segmentation results can then be exported into industry-standard shape files and further analyzed for example by GIS applications.

Keywords
marble, thin section, image segmentation, grain boundary, software tool

Introduction

The extraction of grain boundaries from marble thin sections is an important starting point for several material analysis applications. It is used, for example, to calculate maximum grain sizes (MGS) which has a long tradition in marble provenancing. Earlier, MGS was estimated with the naked eye (e.g. LEPSIUS 1890), later, thin sections were used (e.g. CRAMER 2004; UNTERWURZACHER *et. al.* 2005). However, until some years ago, in most of the cases hardly any numerical results were published on this topic, and furthermore any description of the method used to determine this very important parameter is an exception. In recent years some authors listed detailed results in their works, like (ZÖLDFÖLDI, SATIR 2003; CRAMER 2004; UNTERWURZACHER *et al.* 2005; ATTANASIO *et al.* 2006; MORBIDELLI *et al.* 2007; ZÖLDFÖLDI, SZÉKELY 2004; 2005; 2008; SZÉKELY, ZÖLDFÖLDI 2009). The most comprehensive database of maximum grain size with more than 1300 samples was published by ATTANASIO *et al.* (2006). Their measurement of marble grain size is generally based on the microscopic examination of the thin sections. Since a large number of samples needed to be measured, they used a simpler, rapid method. A cut and polished sample surface is treated with HCL 2N for approximately 30 seconds in order to display the edges of the crystalline grains more clearly. After the sample was rinsed and dried, the crystalline grains, or at least the largest of them, were observed with the aid of a normal reflecting microscope, equipped with a polarising filter. In this way the value of the MGS (maximum grain size), the maximum dimension of the largest microcrystal present in the sample, was measured in mm with the aid of a graduated eyepiece. In some cases, the observation value depends on the direction of the surface cut of the polished section, and for this reason it is often useful to compare the results from two different sections, with cuts that are perpendicular to each other. A series of controls was carried out by ATTANASIO *et al*. (2006) and shows that the classical thin section method and that just described provide MGS results in agreement to within 10 %. This is not true when an estimate of the average value of the crystalline grain size is necessary. Extremely small crystals, in fact, are difficult to observe due to reflection from the polished surface and this reduces the accuracy of the results.

CRAMER (1998) used a different approach while investigating the Telephosfries marbles. In his studies, he measured parameters of the grains along a traverse in the thin section. Of these grains, the longest diameters

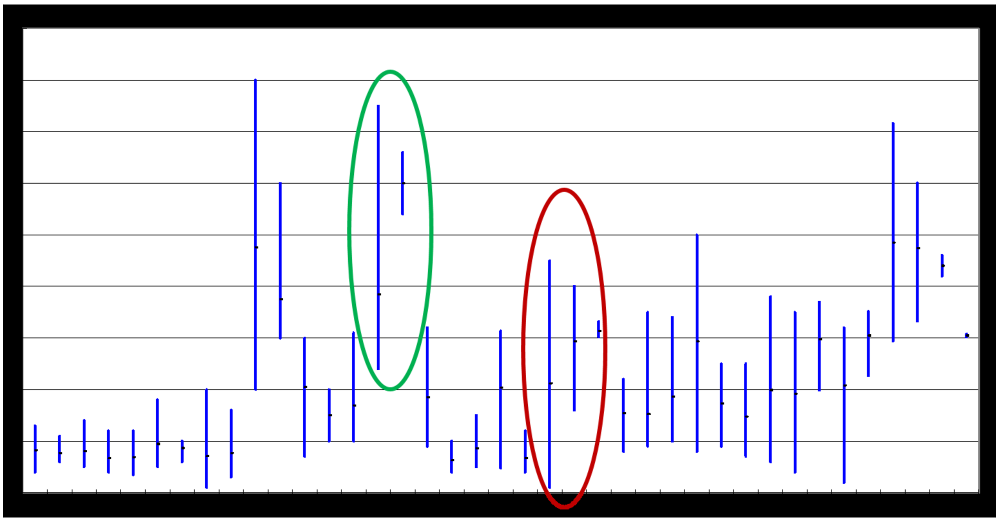

Fig. 1.
MGS measurements may lead to significantly different results even from the same site, emphasizing the need for accurate and standardized measurement methodologies (data from CRAMER 2004; ATTANASIO 2006; ZÖLDFÖLDI 2011)

and, perpendicularly to them, the width of each grain was measured. In his approach, for some cases the "mean grain size" (the "mittlere Kornanschnitt") was also derived, i.e., the measured distance was divided by the number of the grains that was crossed by the track of the traverse. This procedure can result in a smaller grain diameter than with the first procedure. A similar procedure was applied in (CRAMER 2004). However, the measurements were not carried out directly in the microscope. Average grain size (AGS) was calculated by dividing the measured distance by the number of the grains crossed along several measuring traverses on the enlarged image of the thin section. For determining the maximum grain size (MGS) the three biggest punches in each case were measured. The quotient from MGS and AGS can be a measure of the heterogeneity or homogeneity of the crystal lattice structure. Recognizing the ambiguity of the MGS parameter, Cramer used the second largest grain as an important property. These values of the second largest grain are of course lower, however, because of statistical reasons; they describe somewhat better the heterogeneous grain structure, because an isolated big grain cannot accidentally bias the values. Thus, the values often turn out to be larger in the second, which offers a more realistic picture.

Unfortunately, these methods often risk lower accuracy which may significantly influence the classification and the reusability of the results. Figure 1 shows some of the occurrences that were investigated by ATTANASIO (2006), CRAMER (2004) and ZÖLDFÖLDI (2011). For example, in the case of Aphrodisias (today Babadağ), Attanasio measured MGS between 0.2 to 4.5 mm, while Cramer measured MGS between 1.6 to 4 mm and Zöldföldi between 3.0 and 3.4 mm. Similarly, in the case of Proconessos (today Marmara), Attanasio measured MGS between 0.5 and 3.5 mm, but Cramer between 0.3 to 3.2 mm and Zöldföldi between 2.0 and 3.7 mm.

The currently used software methods for automatically drawing the grains are unable to recognize the calcite grains in the marble thin section, because the characteristic appearance of the calcite twinnings. This is why a common approach is the manual drawing of the grain borders, which is a very time consuming procedure. In cases involving many samples, it is unsuitable. Mainly because the significant time requirement, many applications still use a simplified MGS calculation method to avoid the need for boundary extraction.

GrainAutLine is software designed for the automation of thin section evaluation using state-of-the-art image processing and pattern recognition technologies. It is a smart drawing application designed for drawing grain boundaries on a thin section image in a semi-automated way. Significant efforts have been invested into automatizing the boundary recognition and outlining of the grains, nevertheless it is designed with a strong emphasis on user-supervised operations. Every step performed by the automatic tools can be checked and proven or modified by the user, before it is finalized. This ensures a high quality output even if the software does not recognize all boundaries precisely.

High quality boundary extraction allows us not only the accurate estimation of MGS, but as the process is significantly faster than traditional approaches with the same accuracy, GrainAutLine opens a wide range of further applications which were too time consuming to start, until now. Having a fast and easy-to-use processing tool allows for example the analysis of 3 dimensional sequences of thin sections opening access to 3 dimensional reconstruction of the internal grain structures.

The remaining part of this paper is organized as follows: first we summarize the most important approaches for calculating the MGS value for a given marble sample. As we will see, highly reliable results require the measurement of many grains. This leads to

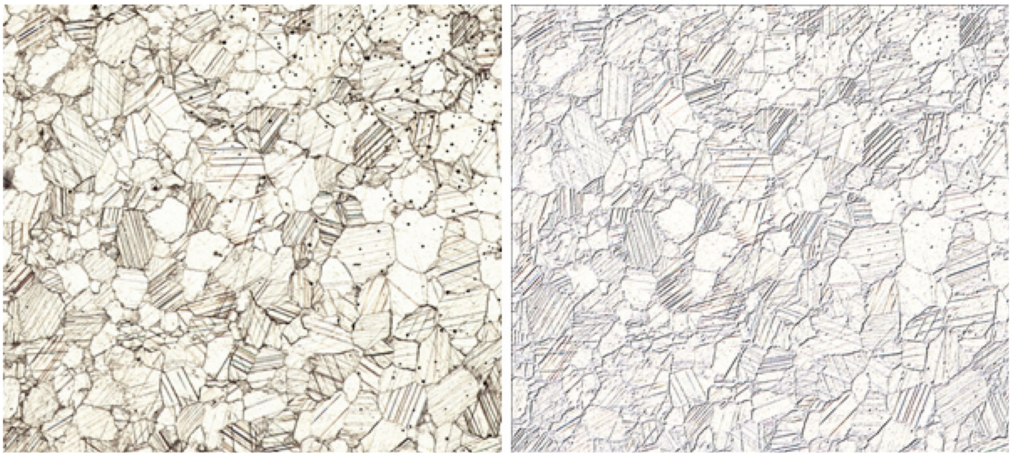

Fig. 2.
A thin section image (left) and the result of edge detection (right). The presence of lines caused by crystal twinnings is the main reason why marble thin section images are still often processed by hand

the GrainAutLine tool we propose for accelerating this process. We first discuss the principal operation of our software solution, then we present experimental results. Finally, we summarize how the reader can start using our tool, and draw conclusions.

Related work

Several methods have been proposed for measuring MGS with various levels of available technology and accuracy requirements. The simplest method is pure visual observation; that is applied when the sampling of the artefact is not possible. This can be improved with microscopes providing a visual measurement grid overlaid on the sample. In a statistical sense, MGS is the maximal value of a probability distribution, a statistical parameter that is not robust: it depends highly on the selection of the sample. Another sample taken from the same piece of marble may have a single, very big grain, which leads to a completely different MGS value. Of course, visual inspection can handle such outlier cases, but especially in the case of a heteroblastic texture, this may lead to different results, and, consequently the result gets less and less objective and thus less reliable.

To overcome this instability in MGS, several improvements were proposed: as detailed above, CRAMER (2004) suggested drawing a line along the sample and measuring the grain diameters only along this line. By taking the average of the 3 maximum sizes, we get a more stable value than by taking only the maximum one. Unfortunately, in this case, we do not measure the maximum diameter of the grains, so we will get a somewhat consistent, but smaller value. Several other approaches were proposed in (MOLLI, HEILBRONNER 1999; GREEN *et al.* 2002; PENTIA *et al.* 2002; OESTERLING *et al.* 2007; ZÖLDFÖLDI 2011).

Finally, there are MGS calculation methods that take the sizes of all grains into consideration: (ZÖLDFÖLDI, SZÉKELY 2004; SZÉKELY, ZÖLDFÖLDI 2009) suggest calculating a more robust statistic using the diameter histogram of the grains. Of course, this requires the measurement of all grains, but if this is available, one can calculate the MGS99 value which is the 99% percentile of the grain diameter distribution. As this measure discards the upper 1% grain sizes as potential outliers (which may be the case in a very heteroblastic texture), with respect to the selection of the sample it is expected to be much more robust than the other methods that do not take all grains into consideration. But in order to calculate the MGS99 value, one needs to know the complete grain size histogram or a significant part of it.

Extracting the grain boundaries is an image segmentation task: the original image has to be divided into several contiguous areas based on the image content. The most common approach to solve this is edge detection (BURGER, BURGE 2009). Usually, edges are recognized as a significant change in brightness relative to the surrounding image area. Using the relative change in brightness instead of absolute brightness is needed to adapt the segmentation method to possible slow brightness changes between different areas of the image.

If the grains can be expected to have different colors, a color-based segmentation approach (ROY CHOUDHURY, MEERE, MULCHRONE 2006, 363-375) may be also viable. In this case, boundaries are detected at significant color changes, avoiding problems arising from boundaries with low contrast parts. Low contrast boundaries may cause the edge-based segmentation to merge multiple grains if the boundary has some gaps.

Color-based segmentation is typically not suitable in the case of marble images, as the grains in our thin section images have similar color. There are some applications using images taken under polarized light that cause the different grains to glow under different polarizations, for example to identify the quartz grains in a sandstone, but it is not possible in the case of marble, because of the very inhomogeneous appearance of the calcite in polarized light, additionally to the problems of twins.

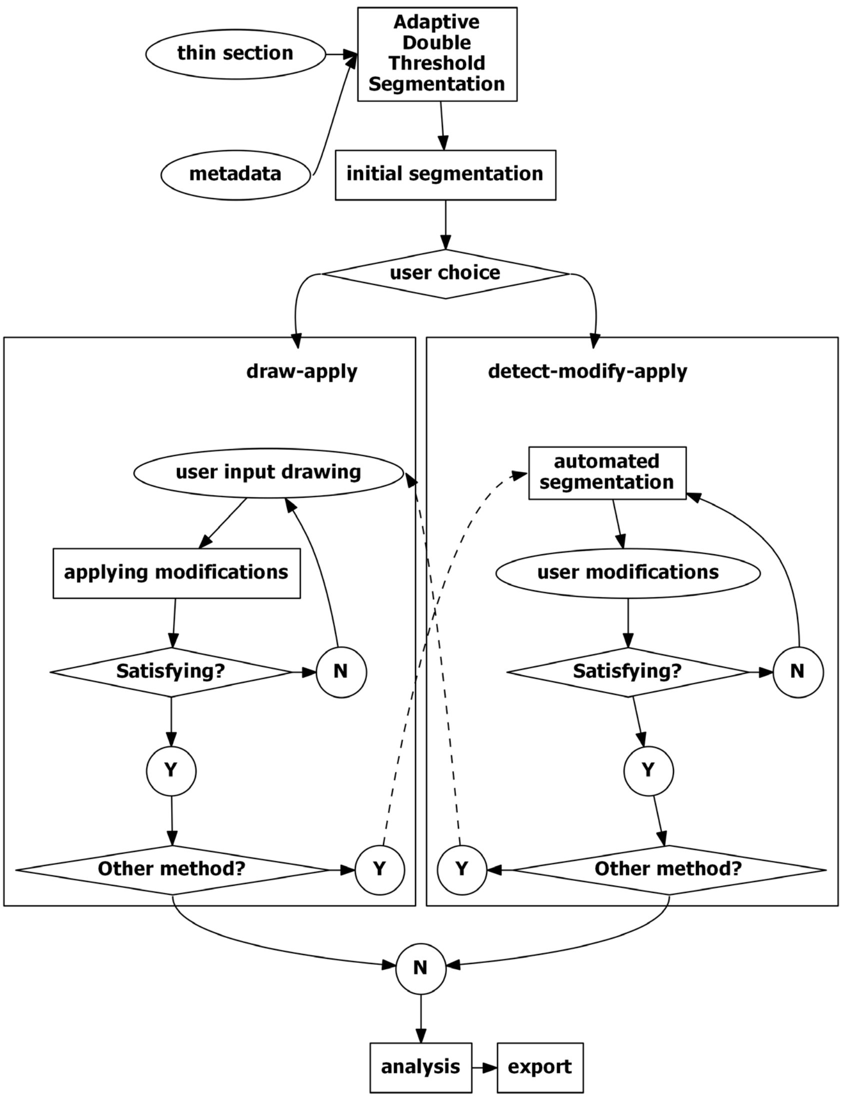

Fig. 3.
Operation of GrainAutLine. A sequence of automatic and semi-automatic steps is applied to the image to achieve a final segmentation suitable for analysis

On its own, traditional edge detection based segmentation fails with marble thin sections due to the presence of crystal twinnings as shown in Fig. 2: in many samples, high contrast lines cover the internal areas of the grains making edge detection methods divide these grains into many small pieces. This means, that edge detection cannot be used without additional means to overcome the twin crystal problem.

The operation of GrainAutLine

The principal operation of GrainAutLine is summarized in Fig. 3. The system uses the image of thin sections and possible metadata as input. Based on the image, automatic and semi-automatic tools help the user to create an accurate segmentation of the grains. As soon as the segmentation is ready, several options are available for further processing: on one hand, statistics can be calculated inside the software and exported, or on the other hand, the user can export the grain boundaries into files suitable to be imported into already well known GIS systems. This allows access to the very wide range of analysis techniques provided by common GIS applications, independently of the statistics capabilities of GrainAutLine.

In this section we will introduce the most important tools available in the software tool named GrainAutLine. We describe the tools in the order of their typical application during a thin section segmentation. For the evaluation, we use the Miss Marble database (ZÖLDFÖLDI *et al.*, 2011) containing many high quality thin section images of marbles collected from several sources.

To reliably ensure a clean segmentation result at the end, all tools provided by GrainAutLine follow one of the following two schema as shown in Fig. 3:

- detect-modify-apply: functions like finding boundaries and segmenting the image along these boundaries follow this concept. They involve some kind of automatic detection and then an operation based on this detection. Between the detection and the application of the results, GrainAutLine gives the user the opportunity to modify the detection results, so that the successive operation is applied using a correct detection.

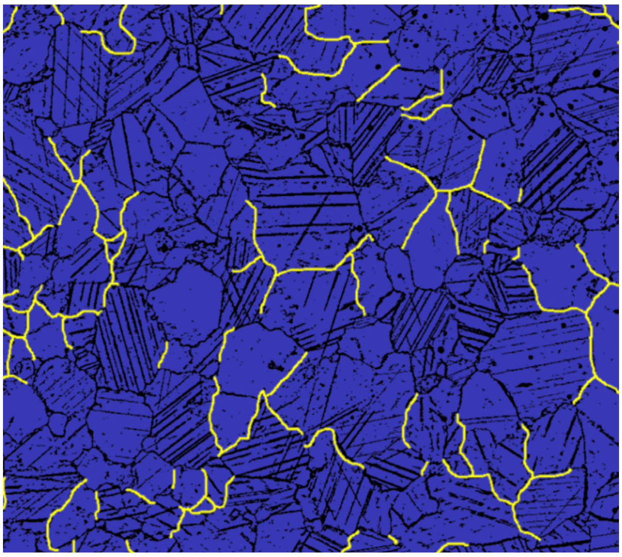

Fig. 4. Original thin section image and result of the Adaptive Double Threshold Segmentation as the initial segmentation step

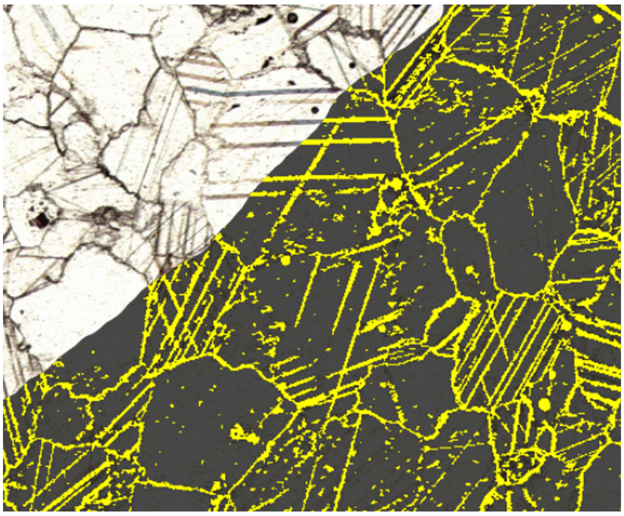

Fig. 5. Drawing additional lines that can be used to cut the blobs covering multiple grains

- draw-apply: there are operations that can be guided by the user via marking areas in the image. In these cases, the user can use drawing functions to prepare the operation before applying it.

Initial segmentation

Creating a clean and correct segmentation of a thin section image usually starts with an automatic, initial segmentation which is followed by manual correction steps to fix issues not handled by the fully automatic segmentation. Currently, GrainAutLine contains an Adaptive Double Threshold Segmentation algorithm (RUSS 2011) which can identify the grain boundaries characterized by their darker color, compared to their direct surrounding. Adaptive means in this case that the image may have darker or lighter areas, and all of them will be handled correctly. The key idea behind double threshold segmentation is that we apply two segmentations: one with a looser threshold, finding more dark areas, and one with a strict threshold finding only a few, darker areas. The final result is built by selecting those connected areas marked by the loose threshold which also contain at least one dark enough area passing the strict threshold as well.

An example for the result of this initial segmentation is shown in Fig. 4. As expected, most boundaries are already found, but twin crystal lines and boundary discontinuities need further corrections.

Adding further boundaries

After the initial segmentation, GrainAutLine can collect the connected components of the image. We call these initial candidates for the grains blobs. The goal of all further steps is to make every grain completely covered by exactly one blob.

If the blobs and the real grains do not match, a combination of the following two cases is possible: either (1) multiple grains were merged into the same blob as their boundary had some gaps which made the two grains belong to a single connected component, or (2) a grain was cut into multiple blobs, for example by a twin crystal line. The first case can be easily solved by drawing the missing boundary into the image. The second case will be handled by merging multiple blobs as described later.

GrainAutLine allows the user to draw arbitrary lines on a separate image layer, called the Aux (Auxiliary) layer as shown in Fig. 5 with yellow lines. These lines can be later used for several operations. In this case, we can subtract these additional lines from the blobs: if a line crosses a blob, subtracting it from the blob will make that blob fall into multiple pieces. This way, cutting the blobs along missing grain boundaries is an easy task.

If two blobs belong to the same grain, they should be merged into one. Although adding a line connecting these blobs would make these blobs get connected, this operation would either require painting the whole false boundary by hand, or it would leave line segments inside the blob. A better solution is to use the merge tool in this case.

Merging blobs

A frequent case is where grains are divided into several blobs by twin crystals. The blob merge tool only needs the user to draw a single stroke of a line connecting every blob which should be merged into one. (Multiple lines are also allowed if they are easier to draw.) After

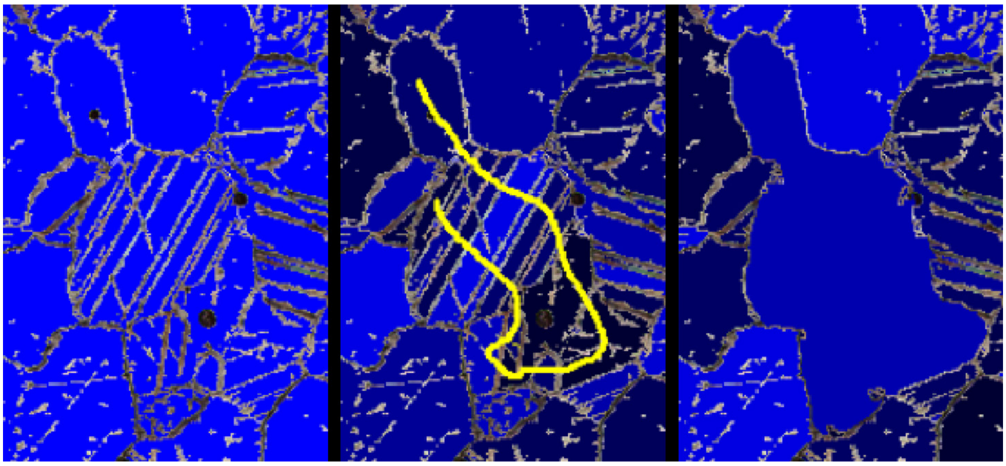

Fig. 6.
Merging blobs with a quick stroke connecting the parts of the grain and using the blob-merge tool

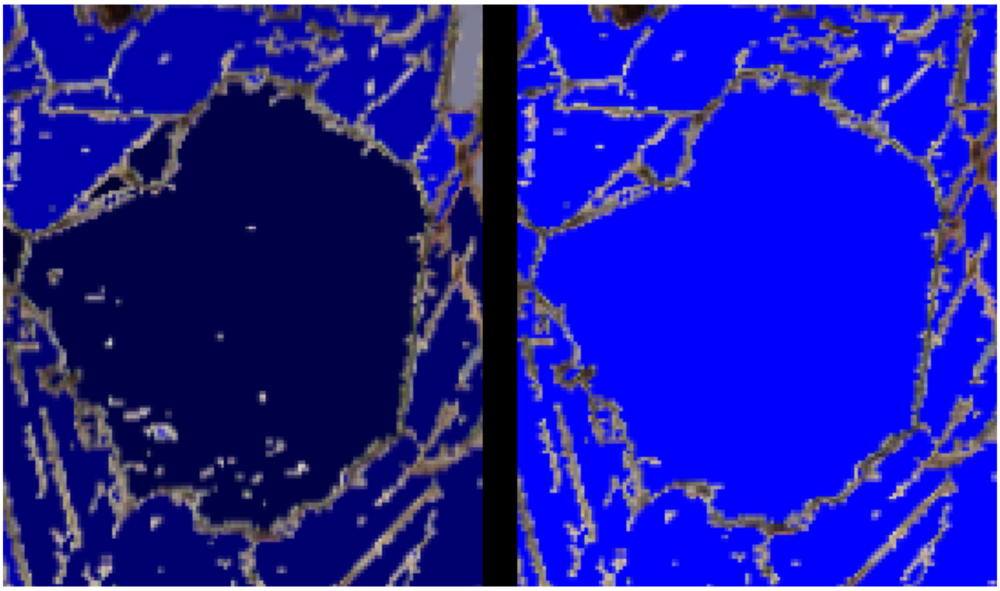

Fig. 7.
The hole-filling function removes all boundaries inside the blobs making the segmentation clean and more suitable for the analysis

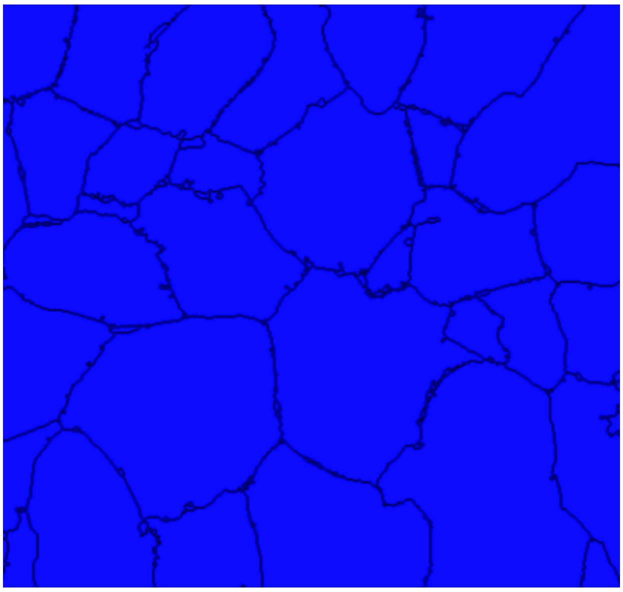

Fig. 8. Part of a clean segmentation of a thin section image processed with GrainAutLine

quickly connecting the to-be-merged blobs with strokes, the blob merge tool is used to merge all blobs connected by these lines. This operation takes care of the remaining unnecessary lines running inside the resulting blobs, ensuring a clean result. This operation is shown in Fig. 6. Using this tool is significantly faster than manually removing all undesired boundary segments.

Filling holes

There may be noises inside the grains that cause blob boundaries inside the blobs. Although these do not conflict with the goal of exactly one blob per grain, they disturb the segmentation and may distort the statistics generated based on it. Filling holes inside all or a set of grains is done by simply using the hole-filling tool as shown in Fig. 7. All boundaries not connected to the outer perimeter of the blobs are removed.

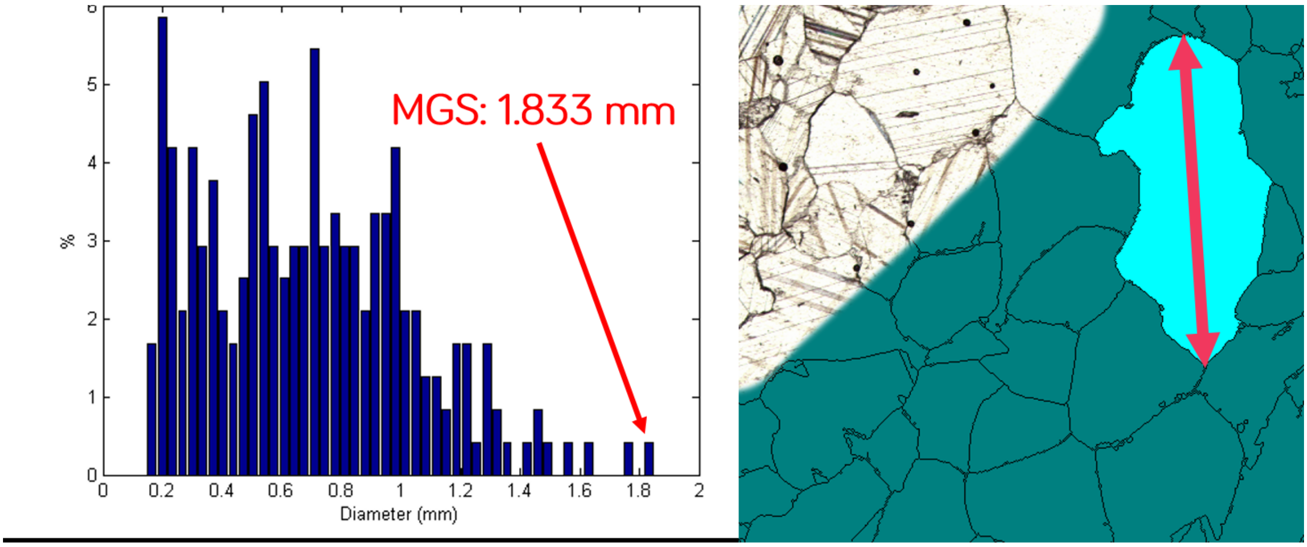

Fig. 9. Histogram of grain sizes retrieved from the resulting thin section segmentation Although it is suitable to identify the maximal grain size, it opens a much wider spectrum of possibilities

Further tools

GrainAutLine is still under active development, so the list of available tools is not final. Tools which are considered stable enough for our users are described in the online documentation in details. Such tools include closing narrow gaps between almost separated grains, automatic recognition of lines caused by crystal twinning, estimating boundaries in low-contrast images, and automatic removal of blobs below a given size to delete noise.

Results

In this section we present results achieved after successfully applying the tool set of GrainAutLine to a marble thin section image. As soon as the clean segmentation result shown in Fig. 8 was ready, it could be exported for further analysis. For convenience reasons, we provide an additional tool that can export the segmentation results from the GrainAutLine file format to standard ESRI Shape File format. This allows the user to perform the analysis in a common GIS system. This way, analysis is not limited by the capabilities of GrainAutLine.

First, we have chosen to investigate the histogram of the maximum grain diameters. Fig. 9 shows the results. The maximum value appearing in this histogram corresponds to the classic maximum grain size, but knowing the full histogram opens a much wider range of possible applications like calculating MGS99 mentioned before.

From the geometric point of view, in addition to the grain size determination, three parameter groups for classification can be integrated (e.g. SZÉKELY, ZÖLDFÖLDI 2009):

- measured grain parameters: long axis, short axis, perimeter, area, convex hull parameters (perimeter and area)
- derivative grain parameters: axial difference, orientation of the long axis, perimeter/area ratio, shape factor
- whole-image parameters: fractal dimension (box counting and information dimension), maximum grain size.

Knowing the grain boundaries makes shape and neighborhood analysis a simple task. Fig. 10 presents the histogram of the number of neighbors a grain has. Although it is less important for marble provenancing, several applications related to microstructure and porosity may benefit from such results, emphasizing the usefulness of GrainAutLine also outside the marble thin section analysis applications.

GrainAutLine as an open source project

GrainAutLine is an open-source project. It can be accessed via its website at http://bmeaut.github.io/grainautline/. Currently a version for Windows is available for download, the development of a Linux version is under consideration, depending on the demand of the community using provenancing techniques. The source code is also available to make it even more flexible and, to support potential collaboration in the development process. The website features an up-to-date user manual and step-by-step hints on how to start using the application. The development team has a strong ergonomic focus, so that one can learn quickly how to use the application.

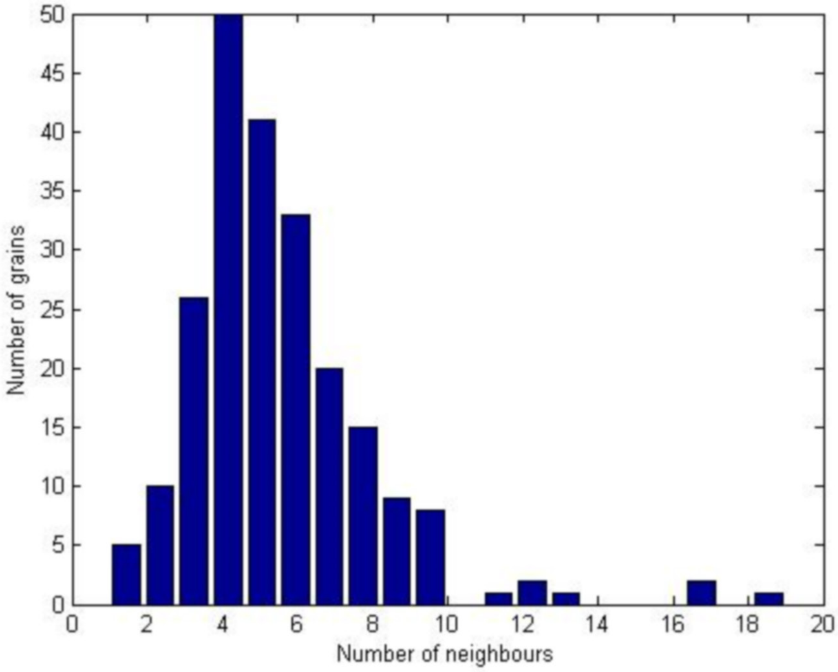

Fig. 10.
Further statistics can be calculated from the clean segmentation of the image including the histogram of the number of neighbors of the grains

Conclusions

Reliable provenancing requires reliable databases containing accurate MGS values for various marble sources. To get an accurate and reliable MGS value, standardized ways of measurement are needed. In a previously published approach, the MGS99 measure was proposed. Using the exact boundaries of 300-400 grains of the sample it is sufficiently reliable to be used in any marble provenancing project.

GrainAutLine is an open source application for the analysis of marble thin sections. Its primary goal is to create statistics from the grain boundaries. Due to twin crystals and possible low contrast grain boundary segments, the image segmentation cannot be absolutely correct, therefore in this tool it is performed in a supervised, semi-automatic way. Most of the work is done by automatic tools as far as is possible, on the other hand the user has full control over the process. The system allows the user to add manual corrections in every stage of the work. This way, the result can be guaranteed to be accurate and suitable for further evaluations.

Although the system can create statistics by its own, it also offers the option to export the grain boundaries into any common GIS application formats. This lets professionals use their well-known working environment for the later analysis steps.

Despite the fact that GrainAutLine was designed for the processing of marble thin sections, it has many generic image segmentation tools that are not limited to these kinds of images: several further geology and material technology related applications can benefit from its capabilities.

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