GEOLOGICA BELGICA (1999) 2/3-4 : 173-180

USING IMAGE ANALYSIS TO ESTIMATE QUANTITATIVELY SOME MICROSTRUCTURAL PARAMETERS OF DETRITAL SEDIMENTS

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(4 figures)

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ABSTRACT. A simple, easy to implement, image analysis method providing quantitative parameters for detrital clay-rich sediments is presented. Photomicrographs from petrographic and backscattered electron microscopes are processed to produce binary images, where black pixels are objects within the clay-matrix. Measurements of the objects allow calculation of the value of several simple indices. These indices are defined to estimate quantitatively the grain-size, shape, orientation, and packing of the objects that constitute the sedimentary microstructures. The methodology advantageously replaces most of the time-consuming and laborious counting and measurements carried out in classical microsedimentological studies. It can be easily modified according to the needs of the user.

KEYWORDS: Image analysis, microstructures, detrital sediments, thin-sections, scanning electron microscopy

RESUME. Utilisation de l'analyse d'images pour estimer quantitativement certains paramètres microstructuraux des sédiments détritiques. Une méthode d'analyse d'image, simple et facile à mettre en oeuvre, est présentée et appliquée à des sédiments détritiques riches en argiles pour en obtenir des paramètres quantifiés. Des photographies de lames minces prises au microscope pétrographique et au microscope électronique en mode rétrodiffusé sont traitées afin de produire des images noir et blanc, dans lesquelles les pixels noirs sont les objets au sein de la matrice argileuse. La mesure de ces objets permet le calculde quelques indices simples. Ces indices sont définis afin de fournir une estimation quantifiée de la granulométrie, de l'aspect, de l'arrangement et de l'orientation des objets qui composent les structures sédimentaires. La méthode remplace avantageusement les longs et laborieux comptages et mesures effectués dans le cadre d'études microsédimentologiques classiques. La technique peut-être facilement modifiée selon les besoins de l'utilisateur.

MOTS-CLES: analyse d'image, microstructures, sédiments détritiques, lames-minces, microscope électronique à balayage

1. Introduction

Image analysis is dealing with all the techniques providing quantitative information from digitised images. The application of image analysis techniques to microscopic geological samples is laborious because of the nature of the images to be analysed: difficulty in discerning poorly contrasted objects, superposition of small features of interest, and use of different illuminations in the identification of minerals with a petrographic microscope. Using image analysis generally involves the implementation of sophisticated devices (Fueten, 1997), complex images processing (Starkey & Samantaray, 1994) and advanced calculation algorithms (Pirard, 1994) or is restricted to fulfil specific or well defined goals (Starkey & Samantaray, 1994; Bryon *et al.*, 1995). Therefore, image analysis systems are slow to find a wide use in Earth Sciences (Fortey, 1995).

Few attempts have been made to use image analysis to quantify fabric in sedimentological studies (Tovey & Hounslow, 1995). Until now, qualitative descriptions are commonly used to characterise detrital sediments in thin sections: "the sediment is strongly perturbed, grains are parallel, silt content is decreasing upwards,...".

This paper describes some applications of basic image analysis procedures on thin-sections of detrital sediments. First, sedimentary indices are defined, and their validity is discussed. Then, it is shown by geological samples that all aspects of sedimentary microstructures are potentially quantified.

2. Image acquisition and processing

Sample preparation and image acquisition have been described extensively in Francus (1998). Petrographic microscope photomicrographs were digitised using the Kodak PhotoCD™ system. Backscattered electron (BSE) images are acquired using the microscope video output channel and are 512 x 512 pixels wide.

A classical image analysis processing layout is applied to images: filtering to reduce noise, thresholding, and binary image editing (Russ, 1990; Francus, 1997, 1998). Images are processed using *NIH Image* (1). In the final binary image, sedimentary objects such as terrigenous grains or diatoms frustules are isolated. On each object of interest in the matrix the following parameters are measured: gravity centre (g), area (A), long (L) and short (l) axes of the object, orientation (a). g is expressed by its X-Y coordinates. A is obtained by counting the number of contained objects. L and l are the axes of the best fitting ellipse (estimated using moment of inertia). a is the counter-clockwise angle that L makes with respect to the horizontal. The number of black pixels in each horizontal line of the picture is also counted. Data are exported to a spreadsheet for indices processing.

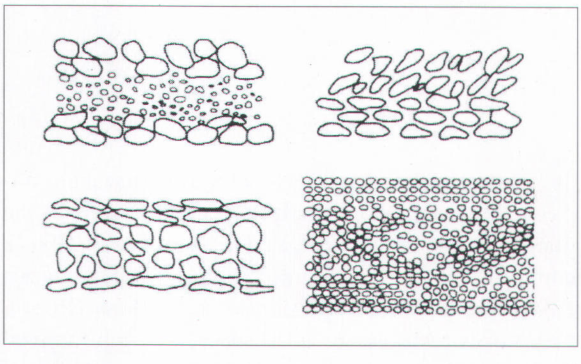

Figure 1. Sedimentary structures are due to variations of size, shape, orientation and packing of elements (after Collinson & Thompson, 1989).

3. Indices

In detrital sediments, beds, layers or laminae result from variations of the composition, size, shape orientation and packing of elements of the sedimentary structure (Fig. 1). Indices are defined to estimate quantitatively all those parameters.

3.1. Size

The size of the grains is estimated by the equivalent disk diameter, D_0 as [1].

$$D_0 = 2\sqrt{\frac{A}{\pi}}\ (\mu m) \qquad [1]$$

D_0 is not the real grain-size since the grain sphericity is an idealisation and random thin-section cutting of spheres under-estimates the diameter. Magnification directly influences the minimum size of objects that are perceptible in the photographs. On the other hand, big objects have less chance of appearing in high magnification images. Therefore, magnification must be carefully chosen according to the grain-size range of the samples to be measured (Russ, 1990; Bouabid *et al.*, 1992). D_0 validity is discussed in detail elsewhere (Francus, 1998).

3.2. Shape

Russ (1990, p. 201) proposes simple indices which allow the distinguishing of objects based on features easy to measure. A simple and robust index, R_i, is selected [2]: R_i is 1 for circles and 0 for elongated objects (lines).

$$R_i = \frac{4A}{\pi L^2} \qquad [2]$$

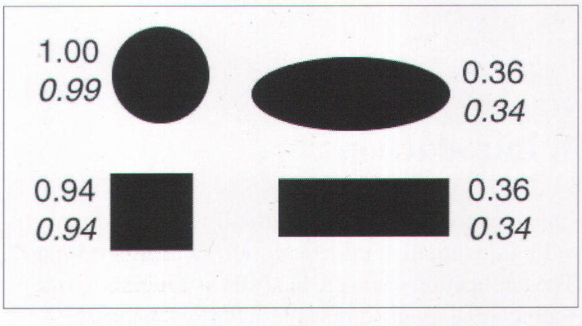

Figure 2. Shape index *Ri* for some grains of different shape. Normal font values are R_i indices and italic values are *l/L* indices.

R_i, discriminates elongated grains from those more circular, without being overly influenced by the angularity of the grain (Fig. 2). R_i cannot be used for discrimination of rounded and angular grains. *Ri values* are close to *l/L*, (in italics in Fig. 2) classically measured in thin-sections.

3.3. Orientation

In general, orientation of the grains in a sediment is visualised by rose diagrams, drawn using measurements made on grains selected according to their shape and their size (Cheel, 1991; Collinson & Thompson, 1989). The same principle is applied to build our orientation diagram. Grain selection is replaced by applying a weighting, p_i, to each grain of the binary image [3].

$$p_i = \left(\frac{L}{l} - 1\right) D_0 \qquad [3]$$

Then, for each of class of 10° angles, Σp_i, is calculated. The percentage that represent the sum of this single class with respect to the sum of all the classes is plotted in an angular histogram. Examples are provided in Figure 3 and Figure 4. All grains in a sedimentary structure are taken into account, but are affected by a weighting that minimises the influence of the small and the circular ones. Considering all the grains in the same way would lead to obtaining orientation diagram without visible variations. Moreover, they would not be comparable with classical rose diagrams (Starkey & Samantaray, 1994).

Quantified information about the orientation could also be obtained computing the resultant vector Q [4] and its strength S [5]. Doing so, one casts off pre-established limits that are orientation classes.

$$\tan\theta = \frac{\sum_i^n p_i \sin\alpha_i}{\sum_i^n p_i \cos\alpha_i} \qquad [4]$$

$$S = \frac{\sqrt{\left(\sum_i^n p_i \sin\alpha_i\right)^2 + \left(\sum_i^n p_i \cos\alpha_i\right)^2}}{\sum_i^n p_i} \qquad [5]$$

Q corresponds to the mean orientation within the structure. Vector strength S potentially estimates the parallelism between objects. S is close to 1 for parallel objects and reaches 0 for randomly disposed objects.

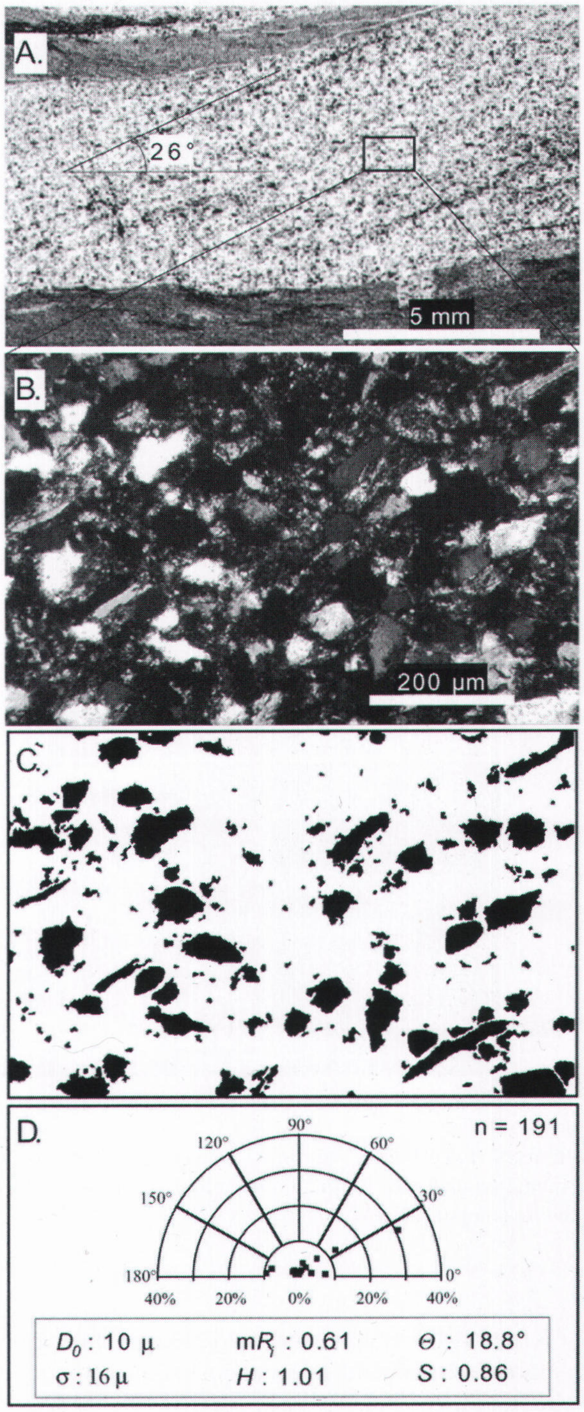

Figure 3. Ripple marks, Solière Formation, Middle Devonian, Nonceveux, Belgium. **(A)** General view. Dip of stratification beds is 26°. **(B)** Petrographic microscope picture, crossed-polarised light. **(C)** Final black & white image after image processing. **(D)** Measured indices from (C). For explanations, see the text.

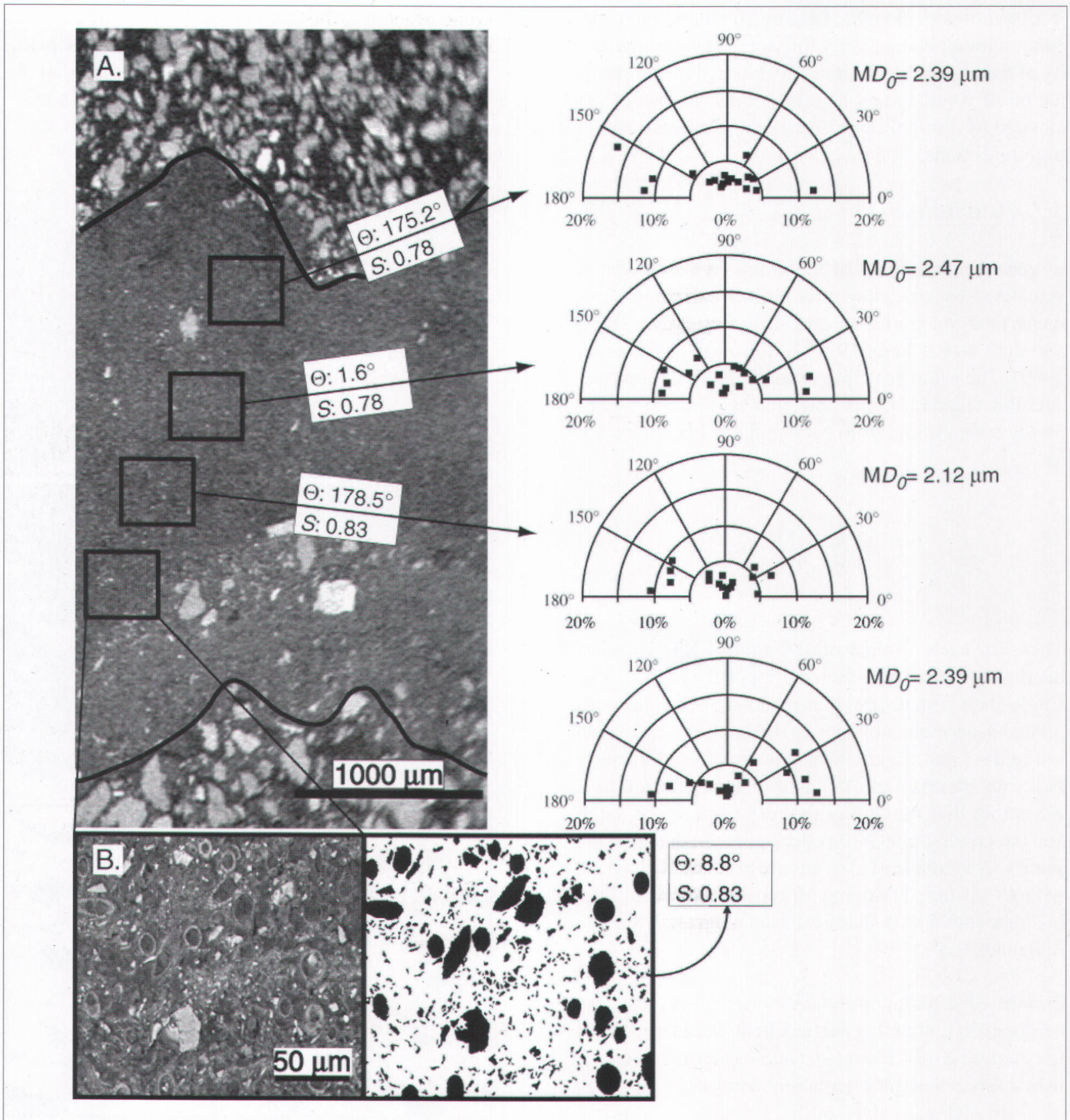

Figure 4. Lake Baikal, station 322, 111.4 to 111.2 cm depth. **(A)** General view of an interrupted grading bed: BSE picture, orientation diagrams (with corresponding *Q* and *S*) and MD_0 of the delimited areas. **(B)** Close view of the lowest region of (A) and its computed B&W image.

Q is significant if *S* is close to 1. Indeed, bimodal, plurimodal or random orientations within a structure will provide *Q* values that do not reflect the reality.

The values of *Q* and *S* depend on the manner in which angle *a* is measured. The origin in our reference system, 0°, is horizontal and pointing to the right. Two grains, similar in shape and size, horizontally disposed at 1° and 179° respectively, have a resulting vector *Q* equal to 90° and a vector strength *S* close to 0. This result is aberrant, because those two grains are almost parallel and horizontal. To avoid this undesirable effect, it is necessary to transpose angular values of the second quadrant (from 90° to 180°) in the fourth quadrant (270° to 360°) before the calculation of *Q* and *S*. Doing this, two grains at 1° and 179° will have a resultant *Q* value of 0° and *S* equal to 1. This later result is coherent with a horizontal and parallel orientation.

3.4. *Packing*

We consider the packing as the manner of arrangement or spacing of detrital grains in the sediment (Jackson, 1997). According to this vague definition, many different ways exist to describe packing. Therefore, one can consider a vast number of indices to estimate quantitatively this concept, but no single index will be sufficient to do it. The paper proposes 3 indices. *P%* index is directly calculated on the binary image (Francus, 1998). *P%* gives an indication of the relative areal size of the clay matrix:

$$P\% = \left(\frac{\#\text{ black pixels}}{\#\text{ image pixels}}\right) \times 100 \qquad [6]$$

H_i index measures the "horizontality" of the objects [7],

$$H_i = \left(\frac{L}{l} - 1\right)\left(2\cos(2\alpha)\right)\left|\cos(2\alpha)\right|\left(\frac{D_0 - MD_0}{s}\right) \qquad [7]$$

where MD_0 and s are the median and the standard-deviation of D_0 of all the objects in one picture. Three major parts can be detailed in the H_i equation. The first term in brackets produces high H_i values for elongated objects, whereas spheres produce an H_i value of 0. The second term in brackets is devoted to the angular information: high positive values (2) are assigned to horizontal objects, negative values (-2) are assigned to vertical ones, whereas zero (0) is given to objects at 45° or 135°. Multiplication by is necessary to reduce H_i for poorly horizontal objects that have an angle near but less than 45° or near but greater than 135°. The last part of the equation gives to H_i a value proportional to the object sizes. D_0 is normalised to allow comparison between microfabrics with different grain-size. In brief, large elongated horizontal objects result in high H_i values, whereas small spherical ones result in low H_i values. H is the mean of H_i calculated on grains which have D_0 greater than MD_0. H values less than one have been reported for randomly oriented microstructures and H greater than 5 for horizontal packing. The use and the validity of H is discussed more extensively elsewhere (Francus, in review).

S also provides information about packing.

4. Examples

Natural geological samples have been processed to show some results using image analysis. Figure 3A displays ripple marks - tidal facies - in a clayey sandstone. Rock is composed of (Fig. 3B) quartz, opaque minerals, micas and calcite; cement is clayey. Image analysis provide indices values in accordance with a visual qualitative observation. Grains are heterometric (MD_0/s < 1). A majority of the grains are poorly elongated considering the mean R_i index: mR_i = 0.61. Horizontal disposition is relatively strong (H = 1.01); H indeed measures the horizontal component of grains instead of the number of horizontal grains. The most obvious feature is the 30% of the 20-30° orientation class in the orientation histogram, in accordance with the apparent 26° dip of the stratification at the location of the image analysis measurements (Fig. 3A). The processed resultant vector Q is 18.8°; this value is not exactly similar to the dip of the apparent stratification, because elongated grains do not necessarily have the same orientations as the dip, and the resultant value is slightly smoothed by counting all grains included, even though a weighting coefficient p_i is introduced.

Figure 4 displays some orientation measurements from lake Baikal. A thin clayey bed lays between two coarse turbiditic beds. Both boundaries of the clayey bed are sharp but sinuous. This thin bed is probably the result of an interflow turbidite (Sturm & Matter, 1978). Orientation diagrams and the Q show clearly that fine sediment orientation is conducted by its intercalation between the coarse beds: parts close to the boundaries show inclinations tangent to coarser beds boundaries (155° for the upper boundary and 35° for the lower one). The part in the middle of the clayey bed is more horizontally disposed. No significant grain-size change is measured (MD_0) within the bed, pointing to a unique and steady sedimentation. Image analysis is of great help here for the understanding of sedimentary processes.

5. Discussion

Indices defined in this paper are simple. The technique is easy to implement: a user-friendly, freeware, image analysis software; a regular spreadsheet software; a petrographic microscope or an electronic microscope with image acquisition capabilities. It does not imply elaborate calculation, or the use of specific software, and the talent of a programmer.

These indices provide results similar to the ones obtained in classical sedimentology studies. *P%* is the first obvious parameter that any sedimentologist tries to estimate using charts for comparison. D_0 is the measure of the apparent grain-size. Orientation diagrams provide results similar to the rose diagrams. R_i provides similar values to the classical l/L ratio generally measured manually in thin-section. For D_0, R_i and H_i indices, it is useful to compute mean, median, or standard deviation, as well as other statistical parameters describing the population of the indices values. The strongest advantage of the method over classical ones is the fast measurement of a great number of objects. The implementation of image analysis therefore allows the consideration of some measurements which have not be considered using classical time-consuming methods. Another advantage is that measurements, such as $P\%$, are less subjective than the estimation of an operator.

More sophisticated techniques could provide better results, but all of them imply longer and time consuming computations. Real grain-size could be approached using stereologic considerations. Mathematical solutions have been developed, such as the coefficients matrix of Saltykov and Cruz-Orive (Russ, 1986). Grain shape could also be quantified accurately. Sedimentologists know Wadell's sphericity indices and the roundness determination charts (Krumbein, 1941). Quantification of both the roundness and the sharpness of grain edges requires application of specific algorithms on each grain (Pirard, 1994). Advanced methods describing the packing and orientation have also been used in structural geology, such as the intercept method (Launeau & Robin, 1996), the mathematical morphometry (Verrecchia, 1996), semivariance computation (Swann & Garrat, 1995), and wavelet transform (Bons & Jessell, 1997).

Bias could be introduced while processing the images (filtering and thresholding). Therefore it is suitable to compare the original image and the final black and white image. Quality and representativeness of the picture submitted for image analysis is also important. The user should always be aware of the limitations and possible errors in automatic analysis and should never use image analysis as a black box to quickly produce pseudo-quantitative results. Because bias could be introduced by image analysis, indices have been built without dimension, except D_0 of course. So, it is possible to compare indices values from sample to sample, if photographs are taken in similar conditions. Grain-size measurements are biased but if the bias is understood, and if comparative measures are required, image analysis could provide useful data in understanding sedimentary processes.

The list of the indices presented in this paper is not exhaustive. Numerous other indices can be created according to the needs of the user. Any sedimentary structure could be defined by its grain-size, shape, packing and orientation. It is probably an illusion to quantify a sedimentary structure with a few numbers. However, indices defined here and their statistic describing parameters could provide a rough mathematical transcription of all the aspects of the sediment fabric (Fig. 1). Parameters proposed here for quantification could be improved, but their accuracy is satisfactory for most geologists dealing with numerous samples (for example out of stratigraphic series). Many uses of this method are shown in Francus (1997, 1998, in review) and Francus & Karabanov (in review) and can be imagined: high resolution (laminae scale) grain-size measurements, graded-bedding characterisation, ice-rafting and/or eolian input quantification, automated laminae counting, microbioturbation quantification in hemipelagic sediments, quantified comparison of magnetic susceptibility and detrital input,... This methodology is developed on lacustrine sediments, but could be applied on all kinds of detrital sediments. The current use of this image analysis method and the setting-up of databases of such kind of measurements will allow the identification of sedimentary structures using indices values.

6. Conclusion

A simple image analysis methodology for characterisation of sedimentary structures in thin-sections is presented. Simple indices are defined to quantify descriptions. They are similar to the indices used in classical sedimentology. They allow the quantification of all aspects of sedimentary structures: grain-size, shape, orientation, packing and composition of the objects. Image analysis allows: (1) quickly obtaining numerous high resolution measurements; (2) comparison of observations without the influence of observer's subjectivity; (3) defining sedimentary structures by indices values; (4) providing a better understanding of sedimentary processes.

7. Acknowledgements

I thank T. De Putter and G. Wansard for reading and improving this paper. I also thank F. Boulvain and E. Pirard for constructive review. F. Keimig (University of Massachusetts) smoothed the English language. Dr. E. Goemaere, Université de Liège, provided the Devonian sample. This work is supported by an OSTC grant (Global Change Belgian Impulse program, Federal Office for Scientific, Technical and Cultural Affairs).

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9. Appendix

(1) developed at the U.S. National Institutes of Health and available on the Internet at http://rsb.info.nih.gov/nih-image/

Manuscript received on 29.09.1998 and accepted for publication on 26.03.1999