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Nota técnica

Constituent and microstructure concentration indexes for microsedimentological analysis in thin sections

Índices Concentrações de Constituintes e de Microestruturas para análise microsedimentológica em seções delgadas

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Abstract: The starting point for explaining a geomorphological process relies on describing the fundamental properties of the morphology-forming materials (aggradational morphogenesis). Microsedimentological analysis has been used for decades to address issues within Quaternary Geomorphology and slope processes. However, the descriptive criteria for thin sections concerning the abundance of coarse fraction constituents and microstructures remain qualitative and/or based only on absolute percentages. Nonetheless, a more comprehensive, quantitative criterion, which also considers the area of occurrence in the calculation can provide greater descriptive objectivity. Thus, this study presents a constituent concentration index (Cci) and microstructure concentration index (Mci) for the coarse fraction to enable comparison among the laminae ("strata") of a given thin section. These indices mitigate subjectivity in describing the proportionality of coarse fraction constituents and their respective sedimentological microstructures relative to the analyzed area. They are also readily available to researchers and can be applied to a wide range of constituents and microstructures.

Keywords: microstratigraphy, microsedimentology, sedimentological index, laminae, microstructures.

Resumo: O ponto de partida mais importante para a interpretação de um processo geomorfológico é a descrição das propriedades morfológicas formacionais dos seus materiais (morfogênese agradacional). A análise microsedimentológica tem sido aplicada há décadas para resolver problemas de Geomorfologia do Quaternário e de processos de encosta, porém os critérios descritivos de lâminas delgadas quanto à abundância dos constituintes da fração grossa e microestruturas são variados, qualitativos, e/ou exclusivamente quantitativos baseados em percentuais absolutos. Entretanto, um critério quantitativo teria maior objetividade descritiva se os percentuais calculados/observados levassem em consideração a área em que eles ocorrem. Assim, este estudo apresenta o índice de concentração de constituintes (Cci) e o índice de concentração de microestruturas (Cmi) da fração grossa que possibilitam a comparação entre estratificações ('strata') visíveis em uma lâmina delgada ou entre lâminas delgadas. Estes índices reduzem a subjetividade ao descrever a proporcionalidade da fração grossa e das respectivas microestruturas sedimentológicas da área analisada. Eles são de rápida obtenção por parte dos pesquisadores e podem ser aplicados a uma ampla variedade de constituintes e microestruturas.

Palavras-chave: microestratigrafia, microsedimentologia, índice sedimentológico, laminação, microestruturas.

1. Introduction

Description of the basic properties of morphology-forming materials, known as aggradational morphogenesis, often serves as the fundamental starting point for explaining geomorphological processes (GOUDIE et al., 1981). In the literature on Quaternary Geomorphology and hillslope processes, microsedimentological analysis has been employed for decades as a descriptive criterion, partially using similar nomenclature to soil micromophology given the pedogenetic inheritance of the sediments (MÜCHER; MOROZOVA, 1983; BERTRAN; TEXIER, 1995; MENZIES; ZANIEWSKI, 2003; MÜCHER et al., 2010; van der MEER; MENZIES, 2011; NIEUWENDAM et al. 2020; MENZIES 2022; MENZIES et al., 2023; PAISANI et al., 2023a). Microsedimentology applied to hillslope processes remains a developing scientific field, with further discoveries emerging as an increasing number of researchers delve deeper into understanding the characteristics of source materials (regolith or sediment), sedimentation processes, and syn- and post-depositional modifications across various geographic environmental contexts (MÜCHER; MOROZOVA, 1983; BERTRAN; TEXIER, 1995; MODENESI-GAUTTIERI; TOLEDO, 1996; BERTRAN; TEXIER, 1999; TEXIER; MEIRELES, 2003; MENZIES; ZANIEWSKI, 2003; MÜCHER et al., 2010; van der MEER et al., 2011; PAISANI; PONTELLI, 2012; PAWELEC; LUDWIKOWSKA-KĘDZIA, 2016; PAISANI et al., 2023b; ZÁRDOROVÁ et al., 2023; RANULPHO et al., 2024). Notably, this scientific field has greatly benefited from archaeological contributions, particularly in the identification and nomenclature of sedimentary microstructures (ARAÚJO et al., 2013; 2017; MACPHAIL; GOLDBERG, 2018; KARKANAS, 2018; KOSHOVSKII et al., 2019; MEYER-HEINTZE et al., 2020)

Microsedimentology also involves thin sections extracted from undisturbed specimens collected in the field, which are subsequently hardened and laminated, similar to specimens used in the geological petrographic analysis of soft rocks. As such, the criteria for describing thin sections vary between authors based mainly on their own experience. Nonetheless, in all cases, the primary objective is to identify the constituents of the coarse fraction and their respective microstructures (van der MEER; MENZIES, 2011). Coarse fraction constituents encompass isotropic or anisotropic primary minerals, undisturbed saprolite or bedrock fragments, archaeological artifacts, pedosediments (fragments of relict soils that are incorporated in a sediment), and biodebris (MACPHAIL; GOLDBERG, 2018; PAISANI et al., 2023a, b). Microstructures of the coarse fraction exhibit variations according to the geographic/geologic context and the processes involved, such as fluid escape and injection, or galaxy/rotation, comet, and banded structures, among others (BERTRAN; TEXIER, 1999; MÜCHER et al., 2010; PAISANI et al., 2023b).

In fact, although coarse fraction microstructures usually receive nomenclature similar to that used in soil micromorphology, they represent distinct sedimentological contexts and organizations, such as the banded (or band or laminar) structure that expresses intercalation of different arrangements or grain sizes. Microsedimentology also encompasses the horizontal or inclined alignment (at various angles) of coarse fraction grains. Within the framework of microsedimentological analysis, this structure can also represent diffuse cross-lamination or deformation, depending on whether the matrix is sandy or muddy (MENZIES, 2000; KARKANAS, 2018; PAISANI et al., 2023b). Furthermore, the galaxy deformation structure, which can be referred to as turbate or microcircle, can occur in both granular and cohesive sediments (BERTRAN, 1993; HIEMSTRA; RIJSDIJK, 2003; MENZIES; ZANIEWSKI, 2003; PHILLIPS, 2006; PAISANI et al., 2023a,b).

Microsedimentology applied to Quaternary Geomorphology and hillslope processes requires its own specialized nomenclature (MÜCHER, 1973; MÜCHER et al., 2010). However, establishing a universal criterion for describing the proportionality (i.e. representativity) of specific coarse fraction constituents (i.e., constituent concentration) and the sedimentological microstructures present (i.e., microstructure concentration) in each thin section remains a challenge. Descriptive criteria currently range from qualitative (e.g., rare, frequent, abundant) and semi-quantitative (e.g., <2%, 5–10%) to quantitative in absolute percentages (e.g., 10%). Therefore, a robust quantitative criterion would enhance descriptive objectivity, particularly when the area of occurrence of both constituents is considered as part of the calculated/observed percentages. Notably, the area of occurrence of coarse fractions and microstructures within the thin section is a commonly omitted factor. By incorporating the reference area into the description of constituent proportionality (percentual of representativity), the subjectivity of thin section interpretations can be significantly minimized.

Thus, this study proposes the establishment of a quantitative constituent concentration index (Cci) and a microstructure concentration index (Mci) for the coarse fraction, with both indices based on the area of occurrence. The use of such indexes reduces subjectivity when compared to current techniques, enhancing the interpretation of physical processes related to the analyzed deposits. Furthermore, these indices can be readily obtained by researchers and enable comparison between the laminae ('strata') of a given thin section or between several thin sections.

2. Data Acquisition

Data acquisition relies on analysis of the thin section itself. Thin section data are extracted from images acquired through: (i) image capture using a petrographic microscope equipped with a low magnification lens (1.25x recommended) or capture of a sequence of overlaying images to produce a larger image (i.e. mosaic) of larger magnifications, for example 4x; and (ii) complete digital photography with resolution of 12 MP of the thin section. Preceding the application of the numerical indices, a graphic scale is added to the image to individualize both thin section constituents and their microstructures, as well as the laminae edges. The images of the thin sections are imported into software capable of extracting the areas of occurrence from the laminae (Ai) as well as the entire thin section area (Ats). Subsequently, the following parameters measured in each thin section are extracted, according to the index used (either Cci or Mci). To determine the concentration of Cci constituents, the percentage of constituent data in each laminae (denoted as %Ci, where i = number of laminae in each thin section) is initially determined through digital image classification (PAISANI; HENDGES, 2010) or visual comparison with a frequency chart (FITZPATRICK, 1980).

In both traditional methods (i.e. digital image classification or visual comparison with a frequency chart), the percentage of constituent data (%Ci) in each lamina does not consider the area of occurrence (e.g., the area of the laminae or the total area of the thin section). The present method seeks to address this issue, whereby the area (Ai) of each of the laminae in each thin section is subsequently determined in order to individualize the area. In this study, CorelDRAW 2020 was used to perform the laminae area measurements (Ai and Ats) using the macro curve meter, according to the instructions provided in the link: https://www.youtube.com/watch?v=GYj4ReRdyEA. Nonetheless, any software with an area calculation tool could also be used. The next step involved calculating the total area of the thin section (Ats), i.e, the sum of all individualized laminae, satisfying the following rule: $\sum_{i=1}^{n} \mathrm{Ai} = Ats$. The percentage of the area of each lamina (%Ai) relative to the total area of the thin section was then computed (%Ai = Ai/Ats).

The same sequence was followed for the microstructure concentration index (Mci) replacing the constituent percentage (%Ci) with the percentage of a given microstructure in each of the laminae (%Mi).

3. Constituent concentration index (Cci) and microstructure concentration index (Mci) for the coarse fraction

After obtaining the %Ci (based on digital image classification or visual comparison with a frequency chart) and area (%Ai) using Corel Draw 2020, the impact of each constituent relative to its specific area of occurrence within each lamina was assessed by multiplying these terms, resulting in ICci = (%Ci * %Ai). The parameter ICci then denotes the concentration index of the coarse fraction constituents for each layer. Finally, the constituent concentration index of the coarse fraction (Cci) was established by dividing ICci by the sum of each lamina value of ICci ($\sum_{i=1}^{n} \mathrm{I}Cci$).

$$Cci(\%) = \frac{\mathrm{I}Cci}{\sum_{i=1}^{n} \mathrm{I}Cci}$$

The Cci represents a quantitative criterion considering the calculated/observed percentages in relation to the individualized area of occurrence. The result corresponds to the percentage each constituent (%Ci) represents in relation to 100% of the laminae (Ast).

On the other hand, traditional techniques (FITZPATRICK, 1980) are often generalist and may fail to quantitatively evaluate the amount of coarse fraction present in the lamina and its representativeness within the whole thin section. Without the quantitative criteria provided by the Cci index, sedimentological features may be under- or overestimated in thin-section analyses, leading to physical processes related to sedimentation being misinterpreted. Additionally, the absolute value of the index (Cc_i) can be used for comparisons between thin sections, or it can be converted into a percentage to compare laminae from the same thin section (Cci). The microstructure concentration index (Mci) of the coarse fraction was then calculated by replacing %Ci with the previously obtained %Mi.

4. Example of application

Three thin sections are presented as examples (Fig. 1), considering various types of hillslope deposits: a quaternary paleogully infilling (BIFFI; PAISANI, 2019; 2021), a modern ephemeral gully (OLIVEIRA et al. 2001; FERREIRA; OLIVEIRA, 2006), and modern colluvium (PAISANI et al., 2023b). All thin sections have laminae coded from I to III or V. The quaternary paleogully infilling is characterized by pedosediments (soil aggregates and nodules with different degrees of impregnation) with undisturbed saprolite or bedrock fragments, and quartz organized in parallel-laminated beds on an outcrop (Macroscale). On a microscale these characteristics remain the same; however, the laminae are laterally continuous to discontinuous wavy, with loose to bound soil aggregates and nodules (average-size medium sand) at various proportions (Fig.1a). Sediments of the modern ephemeral gully fan present laminated beds in macroscale, primarily composed of quartz; however, they are discontinuous to continuous wavy on a microscale with intercalation of muddy sand laminae (Fig. 1b). A modern colluvium thin section shows internally laminated beds predominantly comprised of soil aggregates (Fig. 1c.). Lamina IV has massive fabric, while the others present diffuse-cross laminated fabrics, which can be also called banded laminae.

The criteria used by the authors to describe all three thin sections of hillslope deposits were based on soil micromorphology, without highlighting lithofacies at the microsedimentological scale. In this study, we recognize the following lithofacies: massive gravelly sand (Fig.1a – II, IV, V) and massive sand (Fig.1a – I, III), with a tendency to close packaging for the thin section of the paleogully infilling; and massive sand (Fig.1b – I, III) and massive muddy sand (Fig.1b – II), tending to close packaging for the thin section of the modern ephemeral gully. The thin section of the modern colluvium hillslope deposit contains lithofacies of massive gravelly sand (Fig.1c – IV), massive to diffuse-cross gravelly sand (Fig.1b – II), and diffuse-cross-laminated sand (Fig.1c – I, III) (PAISANI et al., 2023b).

Thus, the described methodology was applied to all three thin sections. The constituent concentration index (Cci) of the coarse fraction for nodules and quartz was calculated in the quaternary paleogully infilling (Fig. 1a) and the modern ephemeral gully fan (Fig. 1b), while the microstructure concentration index (Mci) of the coarse fraction was applied to the diffuse-cross laminated fabrics observed in the modern colluvium (Fig. 1c). The results for each parameter obtained (%Ci, %Mi, Ai, and Ats, ICci, Cci, IMci and Mci) are presented in Table 1.

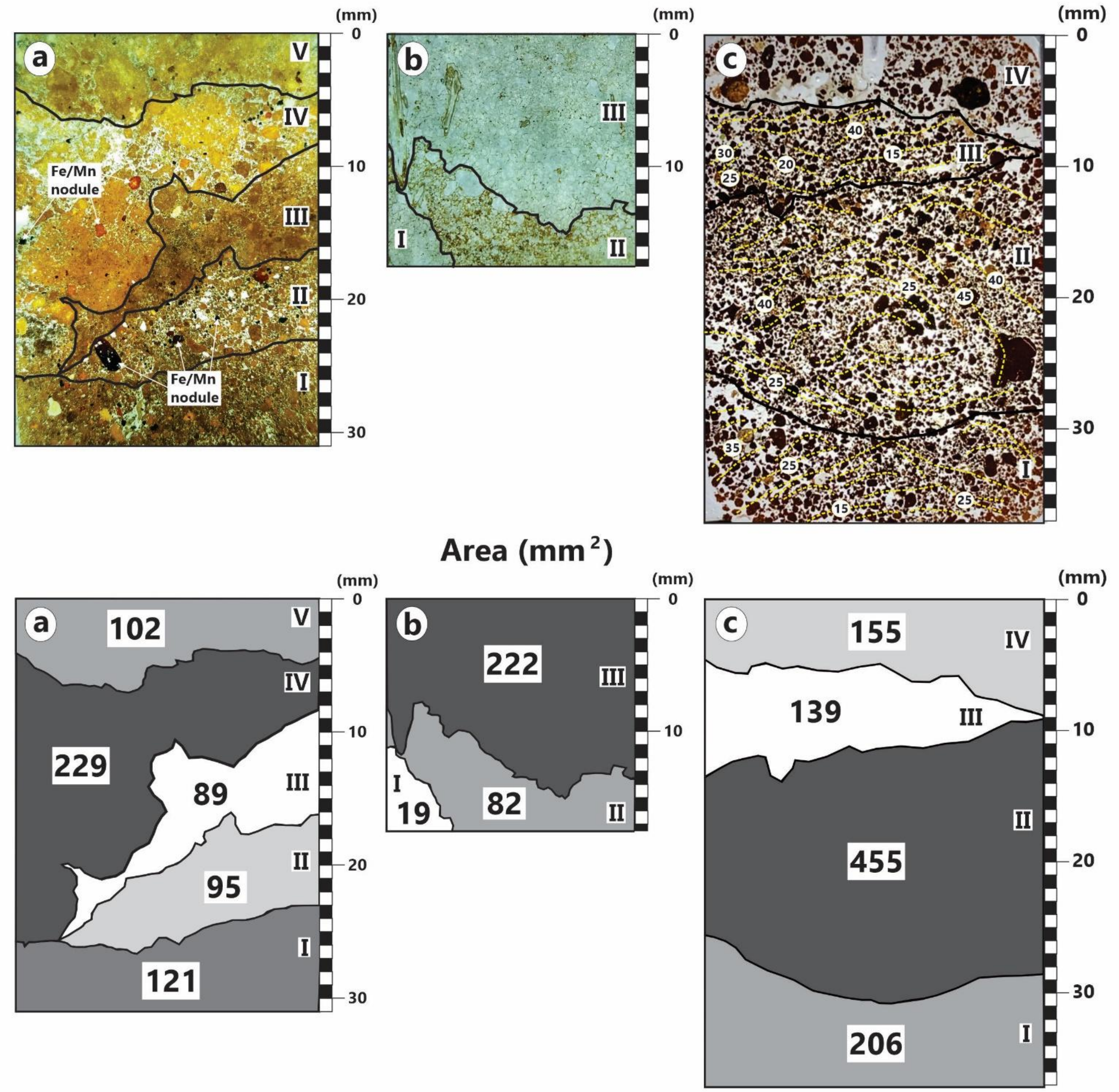

Figure 1. Thin sections of quaternary paleogully infilling (a); modern ephemeral gully fan (b); and modern colluvium (c); the latter adapted from Paisani et al. (2023a). Yellow dashed lines indicate diffuse-cross laminated fabric with their respective inclination angles. Grayscale diagrams of the sampled thin sections highlight the areas of the laminae. Roman numerals are laminae codes, for example I, II, III, etc.

Based on the results shown in Table 1, the occurrence of nodules (coarse fraction %Ci) obtained using traditional methods (i.e. digital image classification or visual comparison with a frequency chart) in the quaternary paleogully infilling laminae (Fig. 1a) range between 2% and 20%, with similar values observed between laminae II and IV. However, when considering the influence of the respective areas of occurrence within the all the laminae, it can be observed that the nodule concentration (Cci) in lamina IV (Cci = 36.3%) is 2.4 times higher than in lamina II (15.1%), and is almost equal to the highest nodule concentration observed in lamina I (Cci = 38.4%). These results clearly demonstrate the importance of considering the area of occurrence to avoid biased results and interpretations. In the traditional method, the absence of this parameter fails to provide a sense of representativeness, that is, how much a specific part contributes to or is important in relation to the whole. A lamina may contain many coarse fraction constituents (as in sections II and IV), but if it occupies a small area within the thin section, its representativeness would be low or less significant. Nonetheless, by using the Cci index proposed in this study, we ensured that the results obtained for each lamina in the thin section truly reflect their significance within the whole.

Table 1. Application of the Constituent Concentration Index (Cci) and the Microstructure Concentration Index (Mci) for the coarse fraction.

Constituent concentration index (Cci) of the coarse fraction					
Paleogully infilling (a)* - Fig. 1a					
Obtained/calculated by	Fitztpatrick (1980) Method	Corel Draw 2020 'macro curve meter'		%Ci * %Ai	$\frac{ICci}{\sum_{i=1}^{n} ICci}$
Laminae	**%Ci**	**Ai (mm²)**	**Ats (mm²)**	**ICci**	**Cci (%)**
V	2	102		0.3	3.20
IV	10	229		3.6	36.3
III	5	89	636	0.7	7.10
II	10	95		1.5	15.1
I	20	121		3.8	38.4
		Σ 636		Σ 6.1	
Ephemeral gully fan (b)** - Fig. 1b					
Laminae	**%Ci**	**Ai (mm²)**	**Ats (mm²)**	**ICci**	**Cci (%)**
III	98	222		67.4	76.1
II	65	82	323	16.5	18.6
I	80	19		4.7	5.30
		Σ 323		Σ 88.5	
Microstructure concentration index (Mci) of the coarse fraction					
Modern colluvium (c)***- Fig. 1c					

Obtained/calculated by	Fitztpatrick (1980) Method	Corel Draw 2020 'macro curve meter'		%Ci * %Ai	$\frac{ICci}{\sum_{i=1}^{n} ICci}$
Lamina	%Mi	Ai (mm²)	Ats (mm²)	IMci	Mci (%)
IV	0	155		0	0.0
III	40	139	955	5.8	20.3
II	30	455		14.3	49.7
I	40	206		8.6	30.0
		Σ 955		Σ 28.7	

Applied to nodule (*), quartz (**), and diffuse-cross laminated fabric (***).

A similar trend is observed regarding the occurrence of diffuse-cross laminated fabrics (Fig. 1c) in the modern colluvium between laminae I and III, where the lower value of %Mi presents the highest concentration of Mci among all the laminae. On the other hand, when the higher %Ci occurs in the high area of influence (Laminae III on the ephemeral gully fan) (Fig. 1b – Table 1), Cci tends to predominate in all the laminae (Cci = 76.1%).

5. Conclusions

The constituent concentration index (Cci) and the microstructure concentration index (Mci) for the coarse fraction were introduced to enable comparison of microstratigraphic features between the laminae ('strata') of a given thin section or across different thin sections. Both indexes incorporate the representativeness of each constituent in relation to the whole area, and, unlike digital image classification or visual comparison with a frequency chart used to determine the percentage of constituents (%Ci or %Mi), they better reflect the true concentration of a given sedimentological feature (constituent or microstructure). These indices also reduce the subjectivity in microsedimentology analysis of aggradational morphogenesis (properties of morphology-forming materials), providing a fast, accessible method for researchers that can be applied to a diverse range of constituents and microstructures. The three distinct hillslope deposit thin sections used as examples demonstrate the range of application of these indices for lithofacies with heterogeneous laminae from sand to sandy mud, expanding the spectrum of applicability in the field. Finally, the improvement of descriptive criteria in microsedimentological analysis contributes to strengthening microsedimentology as a sedimentological tool for understanding sediment supply, flow types, and end-member deposits, as well as syn- and post-depositional modifications relevant to hillslope processes and Quaternary Geomorphology.

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Rafael Manica: Writing – review and editing, writing – original draft, visualization, validation, supervision, methodology, investigation, Formal analysis, Data curation, Conceptualization.

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