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Combined quantification of anisotropy and inhomogeneity of magmatic rock fabrics – An outcrop scale analysis recorded in high resolution

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ABSTRACT

Magmatic mineral distribution patterns in a syntectonic syenite pluton have been recorded at high resolution over several square metres on quarried faces. The anisotropy and inhomogeneity of K-feldspar and mafic mineral distribution patterns have been quantified using two methods originally based on fractal geometry. (1) Map-counting, based on box-counting, illustrates an inhomogeneity on the decimetre to metre scale and highlights diffuse structures that can be related to mafic schlieren or felsic dykes that are not visible on the rock surface. (2) We have developed a mapping of rock fabric anisotropy (MORFA) method that leads to the detection of further magmatic structures that are not visible in the field. With MORFA a magmatic lineation and its variation over large areas is determined, as well as fabrics on the decimetre to 1 m scales, which possibly represent flow or fracture structures in the crystallising magma.

1. Introduction

The presence of melt affects the rheology of the Earth's crust and, vice versa, regional deformation and crustal rheological instabilities play an important role in the ascent and emplacement of melt (Hutton, 1982; Hollister and Crawford, 1986; D'Lemos et al., 1992; Petford et al., 2000; Rosenberg and Handy, 2005; Brown, 2007). The development of magmatic rock fabrics from micro- to macro-scale depends on melt properties (e.g. temperature, chemical composition), physical conditions of crystallisation (e.g. regional stress fields) and kinematics of flow (magnitude of displacement gradient). Such fabrics are generally represented by geometrical properties of material domains on different scales (patterns) – from micro- to kilo-metre scale in the case of magmatic bodies. In particular, the arrangement and orientation of crystals, crystal-size distributions and crystal shapes are of importance. In recent years, successful attempts were made to use magmatic fabrics at various scales to analyse kinematics of melt emplacement as well as deformation-cooling histories of magmatic bodies and their wall-rocks (Paterson et al., 1989, 1998; Büttner, 1999; Vernon, 2000; Rosenberg, 2001; Albertz, 2006; Zak et al., 2007; Peternell et al., 2010).

Quantification and analysis of magmatic rock fabrics face a number of difficulties: (1) The preferred alignment and concentration of crystals forming the magmatic foliation, schlieren, cumulates or magma mingling features are often too large to be recorded in a thin section; (2) magmatic fabrics are frequently too diffuse for precise conventional measurements (e.g. orientation measurements with a compass); and (3) their geometry is often irregular and, consequently, small scale measurements cannot be extrapolated to larger scales without difficulty. In many cases magmatic rock fabrics can only be described qualitatively and, therefore, methods for quantification of such fabrics are needed.

The methods available for quantification of magmatic rock fabrics include (1) measurement of magnetic susceptibility (AMS – Rochette et al., 1992; Tarling and Hrouda, 1993; Martín-Hernández et al., 2005), (2) crystal-size distributions (CSD – Marsh, 1988; Higgins, 1996, 2000), and (3) grain or mineral-phase orientation with the inertia tensor method (Launeau and Cruden, 1998), the star length distribution method (Smit et al., 1998), the normalised optimised anisotropic wavelet coefficient (NOAWC) method (Gaillot et al., 1997), the inverse SURFOR wheel (Panozzo, 1987), and the intercept method devised by Launeau and Robin (1996). However, all these methods do not quantify the complexity of a rock fabric. Complex, i.e. statistically self-similar and thus fractal, rock patterns can be quantified by fractal geometry methods

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(Mandelbrot, 1967), such as the ruler/divider method (Mandelbrot, 1977; Kaye, 1989; Kruhl and Nega, 1996), the area-perimeter method (Kaye, 1989; Takahashi et al., 1998), or box-counting (Mandelbrot, 1977; Feder, 1988; Kaye, 1989). These fractal geometry approaches result in single numbers that are representative for the whole analysed area: thin section, rock sample or an outcrop photograph. Anisotropy and inhomogeneity, both important characteristics of rock fabrics, are accounted by the modified Cantor-dust method (MCDM, Velde et al., 1990; Volland and Kruhl, 2004; Gerik and Kruhl, 2009) and map-counting (Peternell et al., 2003, 2010; Kruhl et al., 2004), respectively. However, quantification of fabrics over larger areas and with high resolution, an essential precondition for an extended analysis of magmatic fabrics, is beyond the capabilities of these methods and has not been done so far.

In this paper we present two automated methods for high-resolution rock fabric quantification on large scales. Both methods are tested and applied on field photographs of metre-sized outcrop surfaces of the Piquiri Syenite Massif from Southern Brazil (Fig. 1).

2. Tectonic setting and structure

The last stages of the Neoproterozoic Brasiliano/Pan-African orogenic cycle in southernmost Brazil are marked by voluminous syntectonic magmatism (650–580 Ma) in a post-collisional setting. Continued magmatism under mid-crustal conditions along the Southern Brazilian Shear Belt lead to the construction of a granitic batholith, which parallels the coast from southern Brazil to Uruguay (Fig. 1a).

The Piquiri Syenite Massif (Fig. 1b) is a crescent-shaped pluton with an area of approximately 150 km^2, dated at 611 $\pm$ 3 Ma (Pb–Pb on magmatic zircons; Philipp et al., 2002). It is intrusive into high-grade gneisses and syntectonic granitoids, medium- to low-grade metapelites, and acid metavolcanic rocks.

Medium- to coarse-grained alkali feldspar-syenites and quartz-syenites are the main lithological types, with fine-grained monzonitic and syenitic varieties identified at the pluton margins. In the pluton centre there are co-genetic syenogranites and alkali feldspar-granites (Nardi et al., 2008). A magmatic foliation is present throughout the pluton, and is better developed in the internal part rather than in the outer rim. The foliation is mostly sub-vertical (Fig. 1b) and its orientation is generally conformable to the pluton's external contacts.

The main syenite (Figs. 1b and 2) contains cm-scale K-feldspar crystals ($\sim$60%) and mafic aggregates composed of micrometre to millimetre-sized pyroxene (3–10%), amphibole (5–20%), titanite, apatite, opaques, and minor amounts of biotite. The K-feldspar crystals are aligned and together with the elongate mafic mineral aggregates define the magmatic foliation (Fig. 2e, f). No linear fabric is visible, either at outcrop or thin section scale (Fig. 2b, c). Local variations of magmatic foliation intensity and geometry at outcrop scale are indicated by planar or sigmoidal geometries of K-feldspar alignment (Fig. 3a) and narrower spacing of foliation planes within cm- to dm-wide zones. A magmatic foliation is oriented either parallel or at high angles to a compositional banding that is locally present as an early-formed structural feature. The mafic layers, composed of coarse-grained cumulus pyroxenes and amphiboles, are either continuous or disrupted, giving rise to a local schlieren layering (Fig. 3b). The segregational character of such layers is enhanced by the presence of country-rock xenoliths, chilled-margin fragments, mafic cumulatic autoliths, and microgranular enclaves, as described by Nardi et al. (2007). Approximately equal, cm-sized K-feldspar crystals are locally concentrated in elongate portions where mafic aggregates are subordinate and interstitial; these are interpreted as felsic cumulates.

No solid-state deformation structures are visible (Fig. 2c, f). Rare micro-cracking of K-feldspars, weak chessboard subgrain patterns in interstitial quartz, and local flame albitization of feldspar rims at the contact between two feldspars occur.

3. Sampling and image processing

For the analysis of rock fabric inhomogeneity and anisotropy field photographs of the syenite were taken at two sites within a large quarry (Fig. 2). The active part of the quarry (Fig. 2a) consists of vertical and subhorizontal surfaces cut parallel and perpendicular to the magmatic foliation. In contrast, the inactive part of the quarry, approximately 500 m to the southwest (Fig. 2d) contains subhorizontal surfaces, generally more irregular than in the active part, and partly weathered. The magmatic foliation is sub-vertical with slightly variable strikes, from NE–SW in the active quarry (Fig. 2a) to approximately E–W in the inactive one (Fig. 2d).

For large-scale analyses several digital colour photograph series from different rock surfaces of the syenite were taken within the quarries and stitched together. Sections 1 and 2 are photograph series from freshly sawn vertical surfaces of the active quarry (Figs. 2a and 4a, b). Section 3 represents the partly weathered base of an old berm in the inactive quarry (Figs. 2d and 4c, d). All three sections show clear evidence of schlieren and of up to approximately 10 cm sized mafic microgranular enclaves. In Section 3, an elongate body of more felsic and coarser grained syenite is crosscut by the main foliation (Fig. 4c, d). For cm-scale analysis, an approx. 0.2 m $\times$ 0.2 m $\times$ 0.3 m oriented sample was taken from the inactive quarry. The sample was sawn parallel (sample 1, Fig. 2b) and perpendicular (sample 2, Fig. 2e) to the NE–SW striking foliation and scanned. In addition, 11 polished thin sections were prepared for micro-scale analyses; 9 parallel to the magmatic foliation (Fig. 2c, but taken parallel to sample 1 to enable the investigation of a similar area) and 2 approximately parallel to Section 3 (Fig. 2f).

The photographs were stitched together and were converted to grey-scale images in order to separate the mafic and felsic phases of the syenite. The image processing is illustrated in Fig. 5 (exemplified on one input image) and contains 3 main steps: (1) An image cleanup using Photoshop® followed by the image stitching procedure with PtGui software, (2) a mineral segmentation algorithm based on a water-flow/watershed model (Vincent and Soille, 1991; Kim et al., 2002) and (3) conversion of the images into black-and-white images. White in the output image (Fig. 5) represents the felsic phases (K-feldspar and minor amounts of quartz), and black represents the mafic minerals (pyroxene, amphibole, titanite, opaques, and minor amounts of biotite). Within this work, the distribution and orientation of microgranular mafic enclaves were not investigated and therefore, they were manually erased in the grey-scale images (Fig. 6). As a consequence, the enclaves are treated as artificial impurities.

4. Quantification methods

The two applied methods are map-counting (Peternell et al., 2003, 2010; Kruhl et al., 2004) and the new mapping of rock fabric anisotropy (MORFA) method (Peternell, 2007). For the first time, automated versions of both methods are used. The software (Matlab® functions and scripts) *map-counting* and *MORFA* are available from the corresponding author.

4.1. Map-counting

Map-counting is a modified box-counting method to determine inhomogeneities in object distribution patterns. Box-counting (Mandelbrot, 1977) is a powerful tool to quantify the degree of