SERIES

Igneous Rock Associations 17. Advances in the Textural Quantification of Crystalline Rocks

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SUMMARY

During the last 20 years, textural (microstructural) studies have regained their place in the pantheon of petrographic methods. This has happened by quantifying textures, so that models can be developed and tested – an approach that has proved to be so successful for chemical and isotopic studies. The combination of chemical, isotopic and textural methods, especially if applied to different crystal populations, can be a very powerful tool in the clarification of petrologic histories of rocks. Here, I will discuss some recent advances in the application of textural studies to crystalline rocks.

RÉSUMÉ

Au cours des 20 dernières années, les études de texture (microstructure) ont retrouvé leur place au panthéon des méthodes pétrographiques. Cela a pu se produire grâce à la quantification des textures, permettant ainsi de développer et tester des modèles – une approche qui s'est avérée très bénéfique pour les études chimiques et isotopiques. La combinaison de méthodes chimiques, isotopiques et d'analyse texturale, en particulier si elles sont appliquées à des populations distinctes de cristaux, peut être un outil très puissant permettant de définir l'histoire pétrologique des roches. Dans le présent article, je vais discuter de certaines percées récentes dans l'application d'études texturales de roches cristallines.

Traduit par le Traducteur

INTRODUCTION

Petrography started in the 19th century with the development of the petrographic microscope (Fig. 1; Kile 2003). Initial observations were qualitative, except for modal measurements. However, the development of quantitative chemical and isotopic analysis in the 20th century somewhat eclipsed traditional petrographic studies and has come to dominate petrology. This is understandable: quantitative measurements do enable more rigorous testing of petrologic models. However, petrography started to regain lost ground about 25 years ago, when quantitative materials science methodology was first applied to petrologic problems (e.g. Cashman and Marsh 1988). Many of the best studies now use a combination of geochemical, isotopic and textural approaches (see review in Higgins 2006).

As with all analytical methods, the scale of observation, which can also be considered as the analytical volume, is dictated by the methods used and will provide information on different aspects of the petrological evolution of the rock. For instance, a whole rock chemical analysis provides data on a large volume of material whereas microprobe analyses convey information about individual crystals or parts of crystals. In a similar way, some textural analysis methods supply information on whole crystal populations, whereas others can inform us on individual crystals.

There are many definitions of rock texture (microstructure), but the simplest is the geometric arrangement of crystals or other structures in a rock. This is a 'crystal map,' in the sense that it is a simplified representation of the actual structure of a rock. Such maps are actually three dimensional, but are commonly measured or represented in two dimensions (Fig. 2). However, some analytical methods only give information on phases present and cannot distinguish between touching crystals of the same phase. Such methods give 'phase maps' which contain less information than crystal maps.

Advances in the interpretation of igneous textures cannot be completely divorced from technological innovations. These have already opened up new and previously inaccessible fields in textural quantification and will do so in the future. Since geological systems are generally not simple, we commonly need significant numbers of analyses. Therefore, innovations that increase the speed and decrease the effort necessary to quantify textures can have an important effect on the quality of

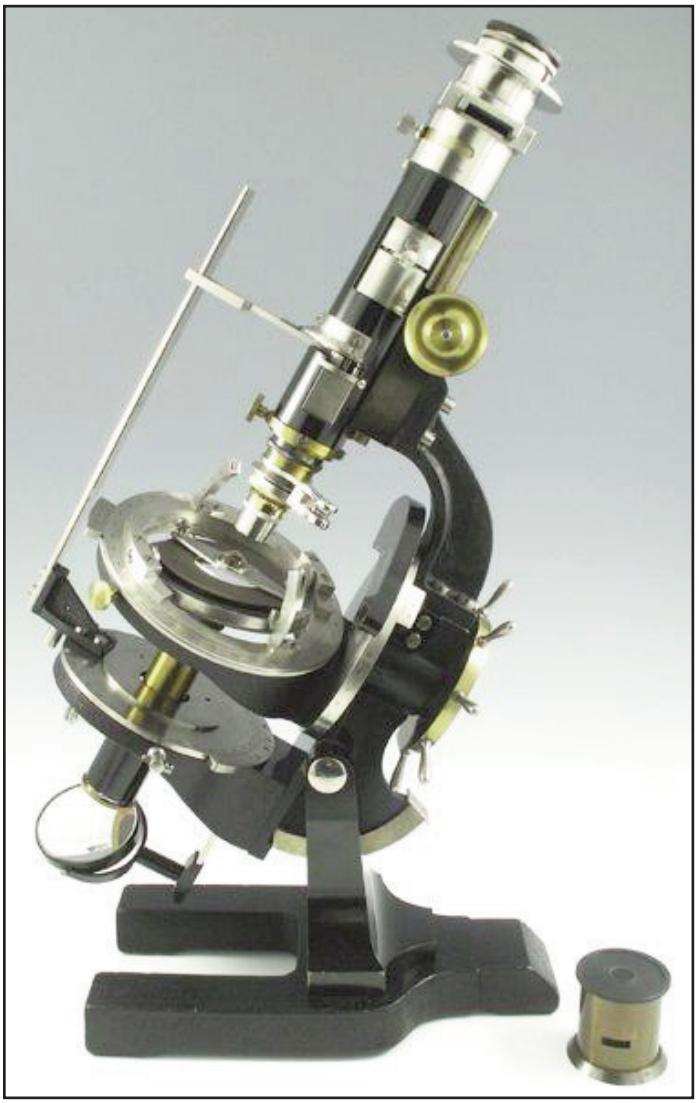

Figure 1. Petrographic microscope with a universal stage (Kile 2009).

petrological studies. Hence, in this brief review I will first discuss a selection of analytical methods, some of which are new and some of which are established but under-utilized by petrologists. I will then show the range of petrologic problems that are being tackled using textural quantification methods.

ADVANCES IN 2D METHODOLOOGY

Most quantitative textural studies carried out over the last ten years have used optical analysis of surfaces and sections, but with some innovations. Digital microscope cameras produce accurate images that can be readily assembled into mosaics. Such digital images can be easily processed and analyzed using general purpose image processing programs (Photoshop™, PhotoPaint™, etc.) or multiplatform freeware such as ImageJ™. There are dedicated programs for this purpose, but their high cost is difficult to justify for most projects.

A common and important optical analytical method uses a document/slide scanner; the low cost of regular scanners which have a resolution of 25 μm enables the rapid analysis of whole thin sections and slabs for very little outlay. It is easy to add Polaroid filters to use cross-polarized illumination. However, the optical system of such machines is not ideal for petrological studies: the light source is diffuse and the reflected light is not orthogonal. Dedicated slide scanners can give slightly better results for transmitted light, but are much more expensive and most can only accommodate regular thin sections.

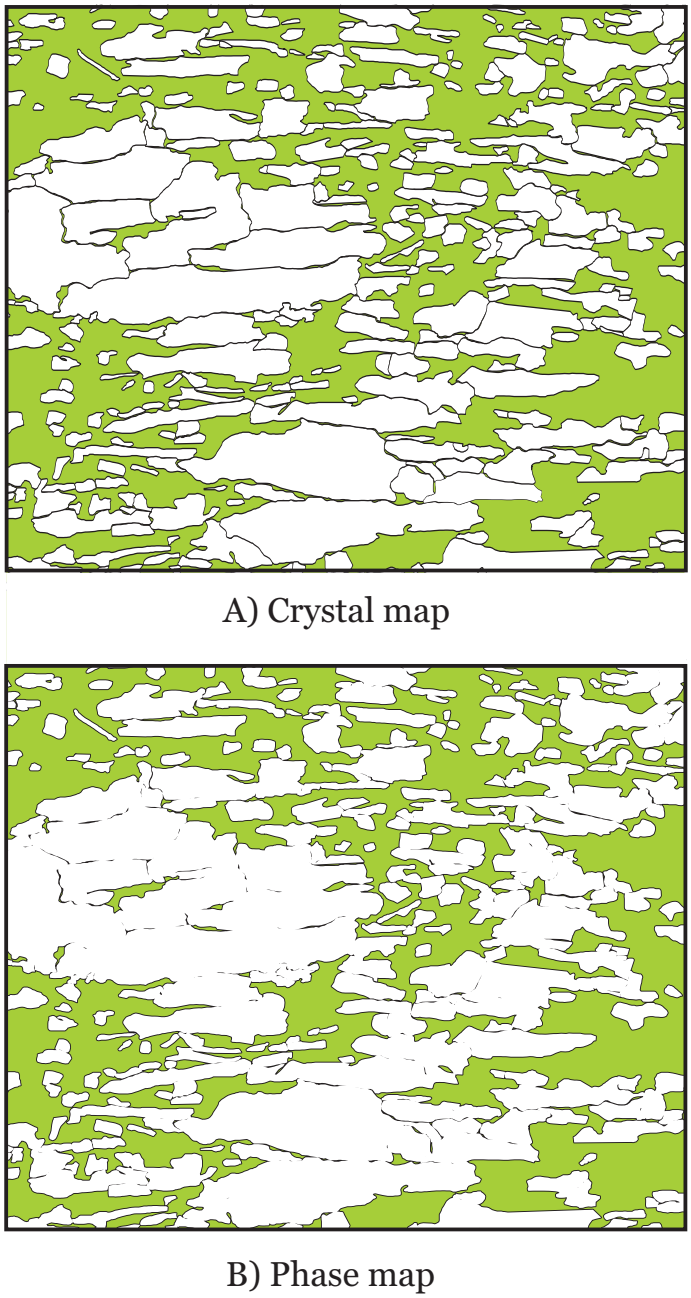

Figure 2. Crystal and phase maps of a troctolite containing plagioclase (white) and olivine (green) (Higgins 1998). A more complete description of the texture of a rock is given by a crystal map (A) in which each crystal is outlined in 2D (here) or 3D. However, many analytical methods only yield a phase map (B) in which touching crystals of the same phase are amalgamated. There is much less information in such a map.

Some special optical techniques can be useful in some studies to resolve specific issues. One such technique is the use of circular cross-polarization instead of the usual linear cross-

polarization (Higgins 2010). With this technique, only crystals viewed along their optic axes are extinct; there are no extinctions accompanying the rotation of the microscope stage. Hence, in a single circular cross-polarized image, almost all crystals are visible and can be measured using simple analytical methods (Fig. 3). It is particularly useful for the analysis of volcanic rock samples. This inexpensive technique is easily used with both microscopes and scanners.

Cathodoluminesence (CL) is a well-known technique, but it has been used more in sedimentology than in the petrological study of crystalline rocks. CL is the light produced during electron bombardment of minerals such as zircon, quartz, feldspars and apatite (Pagel et al. 2000). Most people are familiar with the technique as used in a scanning electron microscope (SEM), but it is time-consuming to map large areas with this instrument. A cold-cathode machine is based on an optical microscope and can easily image areas of several square centimetres. It is particularly useful for the study of feldspars and quartz in volcanic and plutonic rocks, as plagioclase, K-feldspar and quartz have very different CL colours (Fig. 4; Higgins 2011a). This technique has not yet been exploited to its full potential.

Backscattered electron images (BSE) are very useful for mapping mineral species. Until recently, the method has been limited to small areas because of the cost of operating SEMs. However, the recent development of lower-cost, low-maintenance benchtop SEMs will enable BSE images of areas as large as a full thin section. X-ray mapping using an SEM or micro-XRF can also be useful, but is commonly limited by the slow acquisition times and the relatively lower resolution compared to BSE images.

All quantification methods require segmentation or classification of the image into the objects of interest; at the very least, into different phases to produce a phase map and, if possible, into individual crystals or bubbles to produce a crystal or bubble map. The simplest, most accurate, and unfortunately the most laborious method is to outline crystals or bubbles by hand. There have been many proposals for automatic or semi-automatic methods; however, few have been widely adopted, partly because many use proprietary software that is considered difficult to use, expensive to acquire or platform dependant. A number of papers have proposed using geographic information system (GIS) software to identify grain boundaries and handle the dataset (e.g. Barraud 2006; Li et al. 2008). For the moment, most petrographers seem to use a combination of simple thresholding and manual image editing, or crystal outline tracing.

Textural data measured from 2D sections must be converted to 3D parameters such as crystal size distributions (CSD) using stereological methods. The ready availability of easy-to-use programs (e.g. Higgins 2000) means that stereological methods are now used in all well-conducted 2D textural stud-

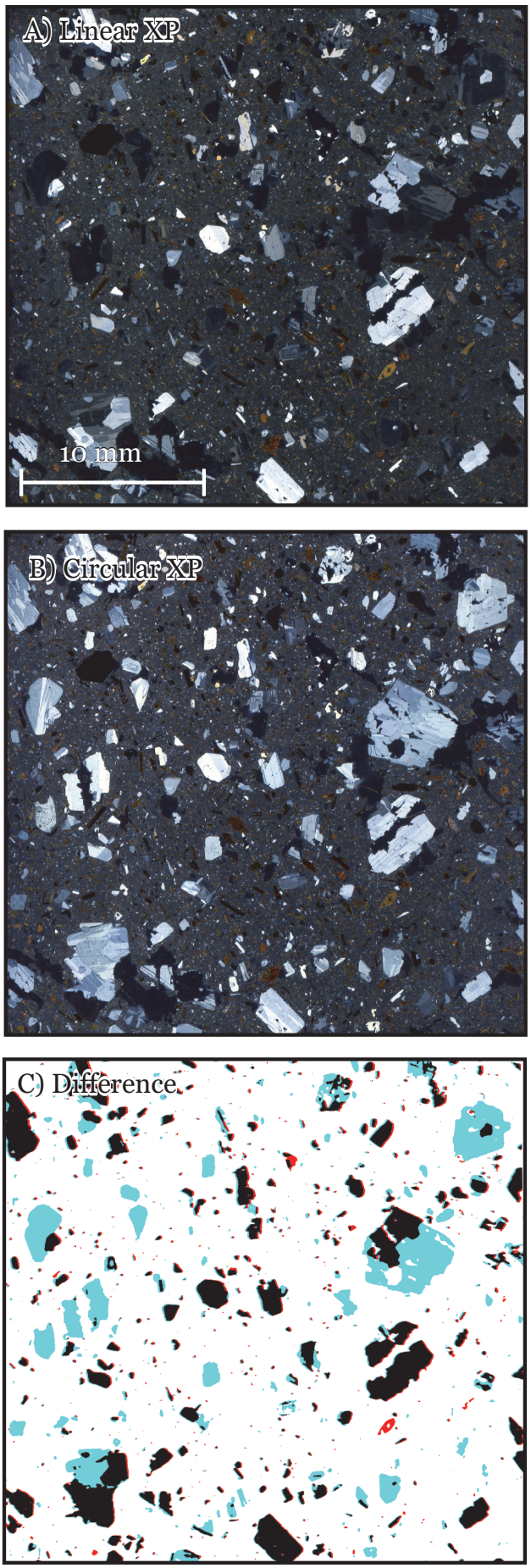

Figure 3. Linear cross-polarized image (A) and circular cross-polarized image (B) of a dacite (Higgins 2010). (C) Comparison of linear and circular cross-polarized images. Black crystals are those visible in both images, whereas blue crystals are only seen in the circular cross-polarized image.

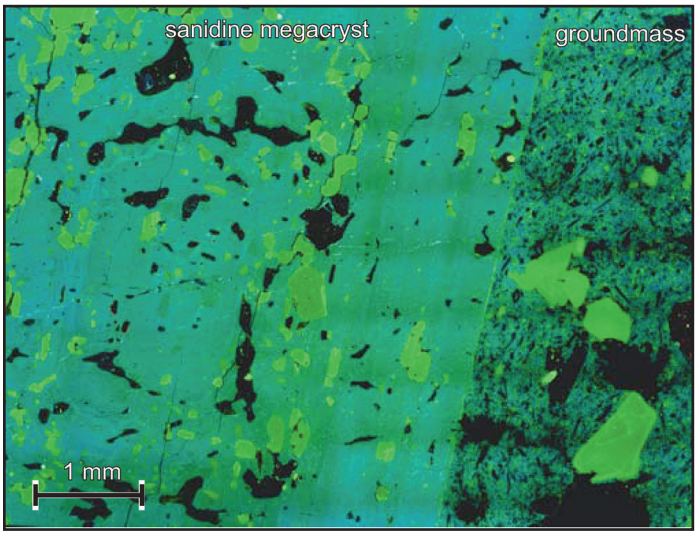

Figure 4. Cathodoluminescence image of a sanidine megacryst and surrounding matrix (Higgins 2011a). Sanidine is pale blue and plagioclase is green. Amphibole crystals, melt inclusions and gas bubbles are black. Growth zones of sanidine can be seen in subtle colour differences.

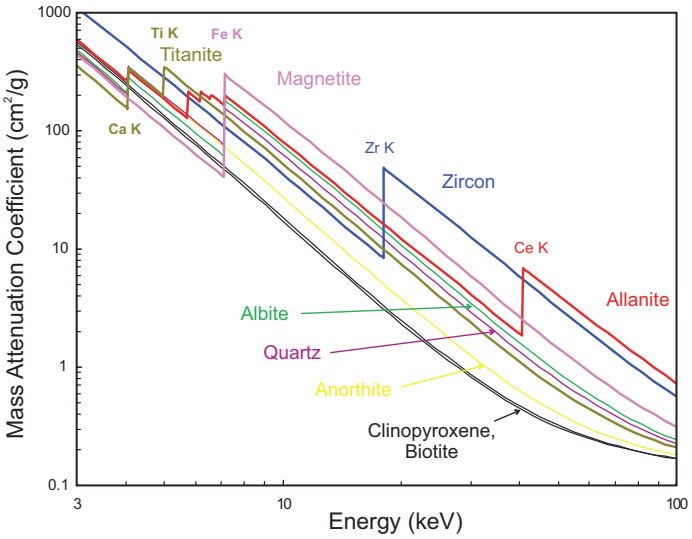

Figure 5. Energy dependence of X-ray absorption (after Gualda et al. 2010). Although absorption increases with decreasing X-ray energy, there are discontinuities at the characteristic energy for each element. Subtraction of images obtained at energies above and below the discontinuity can give an image of that element only.

ies. However, there are clear limitations to the method that derive from the basic mathematics of the process rather than the quality of the data: it is necessary to define a simple, uniform shape for the particles, and errors accumulate as the algorithm proceeds from large to small particle sizes.

X-RAY TOMOGRAPHY

It is important to keep in mind that textures are the 3D structures of rocks; hence, ideally we wish to examine them directly with 3D methods, thus avoiding the need for stereological conversion. Recently, there have been considerable advances in X-ray tomography (XRT) techniques (Baker et al. 2012; Cnudde and Boone 2013), which I will discuss below. However, it should be remembered that XRT is not always the best approach as it produces a phase map in which touching crystals of the same mineral are difficult or impossible to separate (Fig. 2).

The principle of XRT is simple and well-known: the sample is placed in a beam of X-rays and the absorption measured along a line. The sample is then rotated and the measurements repeated. A 2D section of X-ray absorption of the material is then calculated. The whole 3D structure is reconstructed from a series of such slices. It should be remembered that X-ray absorption is isotropic, hence the difficulty in separating touching crystals of the same phase unless they have distinctive shapes or only touch over a small area.

XRT can be carried out on a large range of different instruments, depending on the scale of the study and the material to be analyzed. Initial studies were mostly carried out on instruments designed for medical applications. These are still useful for large samples (Godel et al. 2006); however, most studies are now carried out using recently developed benchtop XRT machines or synchrotron X-ray sources. These have greater penetrations and higher resolution, as there are no restrictions on X-ray exposure to rocks.

Phases are distinguished in the XRT image by differences in the X-ray mass attenuation coefficient. This is commonly thought to be related to mineral density, but in fact is controlled by two different processes (Gualda et al. 2010). At energies over 100 – 150 keV, Compton scattering is important and is proportional to Z (atomic number). At lower energies, photoelectric absorption by the inner electrons of atoms become important and is broadly proportional to Z^{4-5}, but with jumps in the absorption coefficient at energies corresponding to the characteristic X-rays of elements in the material (Fig. 5). Phases are generally better separated at lower energies, but penetration is less and smaller samples must be used.

In most simple XRT machines, different X-ray tubes can be installed to optimize the differences in absorption between different phases, which must be balanced against the greater penetration of higher energy X-rays. Synchrotron X-ray sources are much more intense than benchtop machines, enabling much shorter analysis times. In addition, they produce a wide range in X-ray energies, which can be filtered to produce monochromatic beams for optimizing phase contrast. This can be developed further for specific phases by subtracting two images obtained with X-ray energies on either side of the absorption edges of elements in the phase (Gualda et al. 2010).

TEXTURAL MEASUREMENTS IN EXPERIMENTAL PETROLOGY

Experimental petrology has traditionally been concerned with the appearance and disappearance of phases, which are used to construct phase diagrams and to calculate thermodynamic parameters. However, the textures of experimental changes can also be quantified, giving access to such parameters as growth and nucleation rates for a variety of magma compositions, volatile contents, pressures and temperatures. This field of study has taken off slowly, partly because of the technical difficulties of making charges that are texturally homogeneous and sufficiently large for measurement.

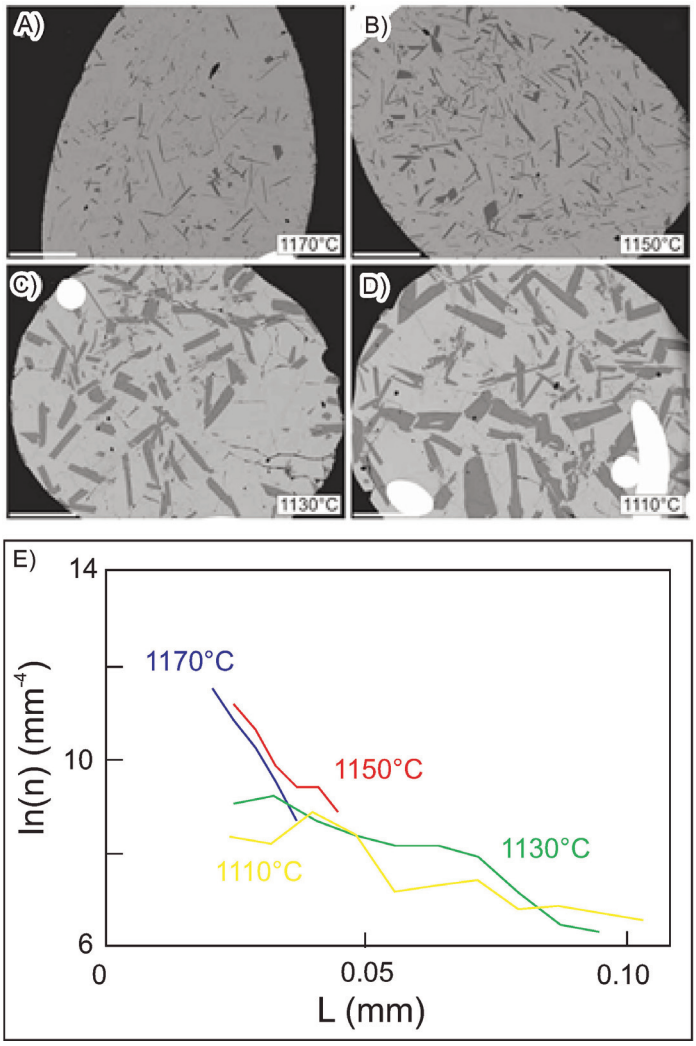

Figure 6. (A–D) Experimental basalt charges at four quenching temperatures for a cooling rate of 1 °C/hour (Pupier et al. 2008). (E) Crystal size distributions for the four experiments. The slope of the CSD generally flattens with decreasing quench temperature, which suggests that coarsening by equilibration is occurring.

Many studies have concentrated on plagioclase, as it is one of the most important phases in the crust and has been texturally quantified in many rocks (Higgins 2006). Pupier et al. (2008) looked at plagioclase crystallization at different cooling rates in basaltic magmas (Fig. 6), and observed that the slope of the crystal size distributions (CSDs) decreased with quench temperature. Very similar behaviour was seen in andesitic melts by Iezzi et al. (2011), except that the CSDs were more strongly curved. Such behaviour was also seen in the basaltic Makaopuhi lava lake and was interpreted as a result of kinetic growth (Cashman and Marsh 1988), but these textures could also be interpreted to reflect coarsening (Higgins 2006).

Schiavi et al. (2009) took another approach to the study of textures in experimental petrology with the development of an experimental cell having transparent sides made of crystals of silicon carbide. Crystallization of silicate melts could be observed *in situ* in this cell. This method has a lot of promise, but there are significant problems before it can be applied more frequently, as there are significant thermal gradients and

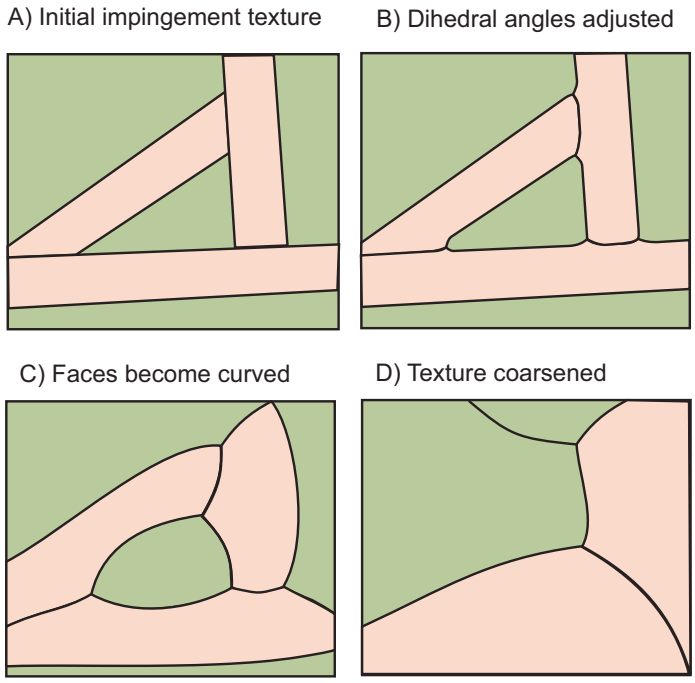

Figure 7. Schematic stages of textural equilibration in a two-phase solidified material, as proposed by Higgins (2011b). A) The growth of pink crystals is stopped when they impinge on each other. The intergranular space is then filled with the green phase. B) Initially, the dihedral angles of the corners are adjusted to a minimum energy configuration. This may be accompanied by crystal growth. C) Face curvature increases. D) Finally, small crystals are absorbed and big crystals grow, coarsening the texture.

the walls constrain the growth of larger crystals in the third dimension.

TEXTURAL EQUILIBRATION

Textural equilibration (relaxation) is probably one of the most important processes in igneous petrology, and its effects are increasingly recognized (Higgins 2011b). Initial growth at higher degrees of undercooling produces a texture in which crystals have a range of sizes and impinge on each other at random angles (Fig. 7A). This is not the minimum energy situation, as the surface area per unit volume of mineral phase is high. Dissipation of this excess surface energy can occur if the system is kept close to the mineral liquidus. This process starts at the corners with the adjustment of the dihedral angles to equilibrium values (Fig. 7B). The process continues as the faces become curved (Fig. 7C) and terminates with coarsening as small crystals dissolve and large crystals grow (Fig. 7D). Complete textural equilibrium is approached but never achieved in rocks. If a rock is completely solid then equilibration will change crystal shapes, but not total phase volumes. However, equilibration may also occur before the rock is completely solid, in which case equilibration may be accompanied by an increase in the crystallinity in an open or closed system.

The process of equilibration has been well documented in many different crystalline rocks. It is commonly observed in layered mafic intrusions, and is recorded by dihedral angles (Fig. 8; Holness 2009; Holness et al. 2013) and textural coarsening in mafic rocks (see review by Higgins 2015). Most granites appear to be coarsened, but except for megacrystic gran-

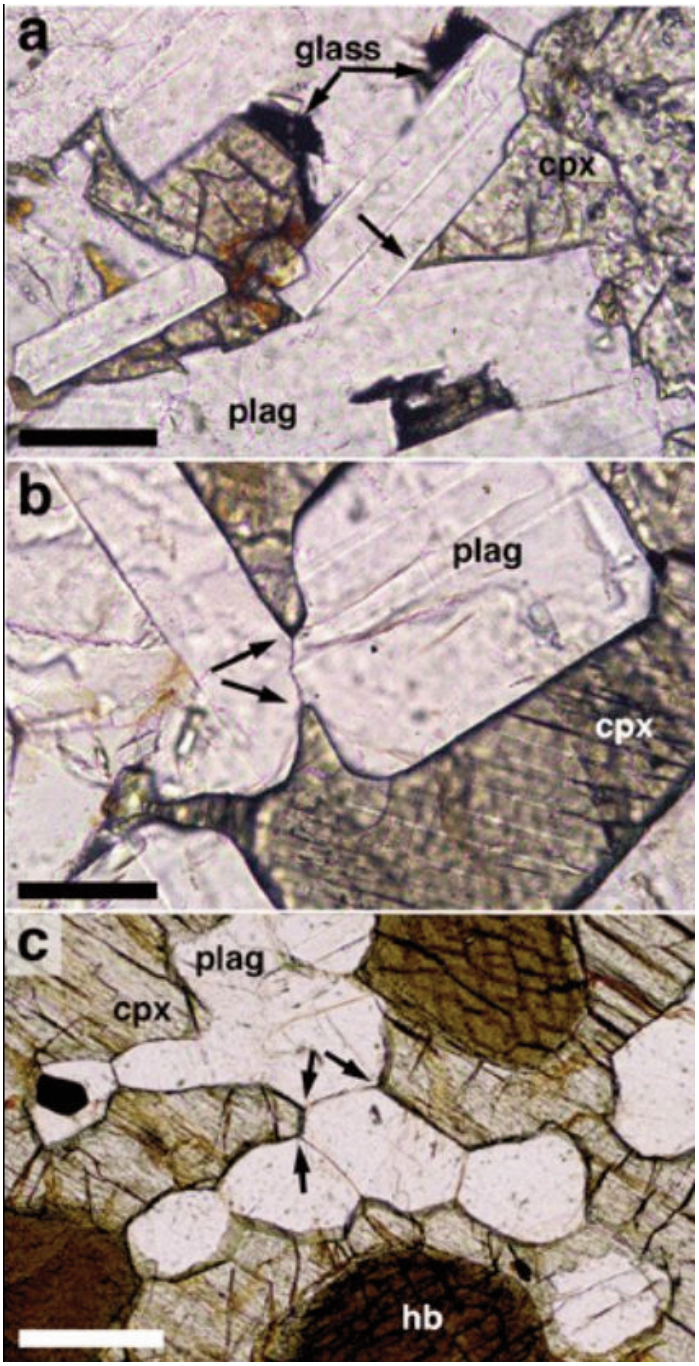

Figure 8. Evolution of plagioclase – orthopyroxene dihedral angles and face curvatures (Holness 2009).

ites, there have been relatively few quantitative textural studies (e.g. Johnson and Glazner 2010), possibly because of the textural complexity of many granites. Coarsening can be observed in some volcanic rocks and this must have occurred in magma chambers or conduits that fed the system (Higgins 2011a). A new facet of petrological diversification is revealed in some volcanoes in which variable degrees of coarsening are observed in chemically homogeneous rocks (Higgins 2009).

Although there is abundant textural evidence for equilibration, early experimental results suggested that the processes rarely occurred under normal geologic conditions. However, recently it was recognized that temperature cycling, even through a small range, can accelerate equilibration considerably (Simakin and Bindeman 2008). This has been confirmed by experimental observation of plagioclase and olivine textures in a basaltic melt (Mills and Glazner 2013). Temperature cycling is inevitable in convecting magma chambers, accounting for the widespread evidence of equilibration in volcanic and plutonic rocks. Although this process has usually been invoked for the coarsening, it may also be responsible for adjustment of dihedral angles.

CRYSTAL POPULATIONS

Technological advances have enabled increasingly detailed studies of the crystallographic, chemical and isotopic compositions of individual crystals in plutonic, and more commonly in volcanic rocks (Davidson et al. 2007; Jerram and Martin 2008). The term 'crystal stratigraphy' is now used to describe such compositional variations as recorded by zonation. As analytical precision increases, it may appear that each crystal has its own history, but this makes synthesis impossible. A more useful and important approach is to decide what variations in the parameters are significant. It may then be possible to define a limited number of crystal populations and characterize their properties. If such analyses can be done for a number of geologically related samples then it may be possible to clarify the overall history of the magmatic unit, such as a pluton or volcanic field.

A recent quantitative textural study of a classic, well-studied location illustrates this point. The lava lake in the Kilauea Iki Crater formed rapidly in 1959 and was sampled by many drill holes during solidification. CSDs of the whole population of olivine crystals are almost constant at different levels, showing that advective velocities were much greater than settling velocities and hence that there had not been any significant crystal accumulation in the lake (Vinet and Higgins 2011). In order to better understand magma chamber processes, crystals were divided into deformed and undeformed populations. The abundances of these populations at different levels suggest that the lava lake was partly filled from the base and not just the top as was generally believed.

The dacite lavas of Quizapu volcano in Chile are another good example of the connections between crystal stratigraphy and magma evolution. Most of the bulk chemical variation of these lavas can be produced by simple mixing of two magmatic end-members (Ruprecht et al. 2012). Chemical zoning of plagioclase crystals can then be used to construct a two layer model of andesite and dacite. However, plagioclase textural variations show considerable complexity and suggest that the magmatic plumbing system is not simple. Therefore, plagioclase crystals were divided into five classes for further textural analysis (Voos 2013). CSDs and abundances of these classes in different lavas (Fig. 9) suggest a complex magmatic plumbing system involving many levels of mixing and storage.

MATERIALS SCIENCE AND APPLIED PETROLOGY

It is always interesting when pure academic petrological methods can be applied to industrial problems or economic geology. Metallurgists and materials scientists commonly work on problems that are not far removed from petrology. For instance, recent advances in steel technology have necessitated better control on the quantity and size of impurities. Common

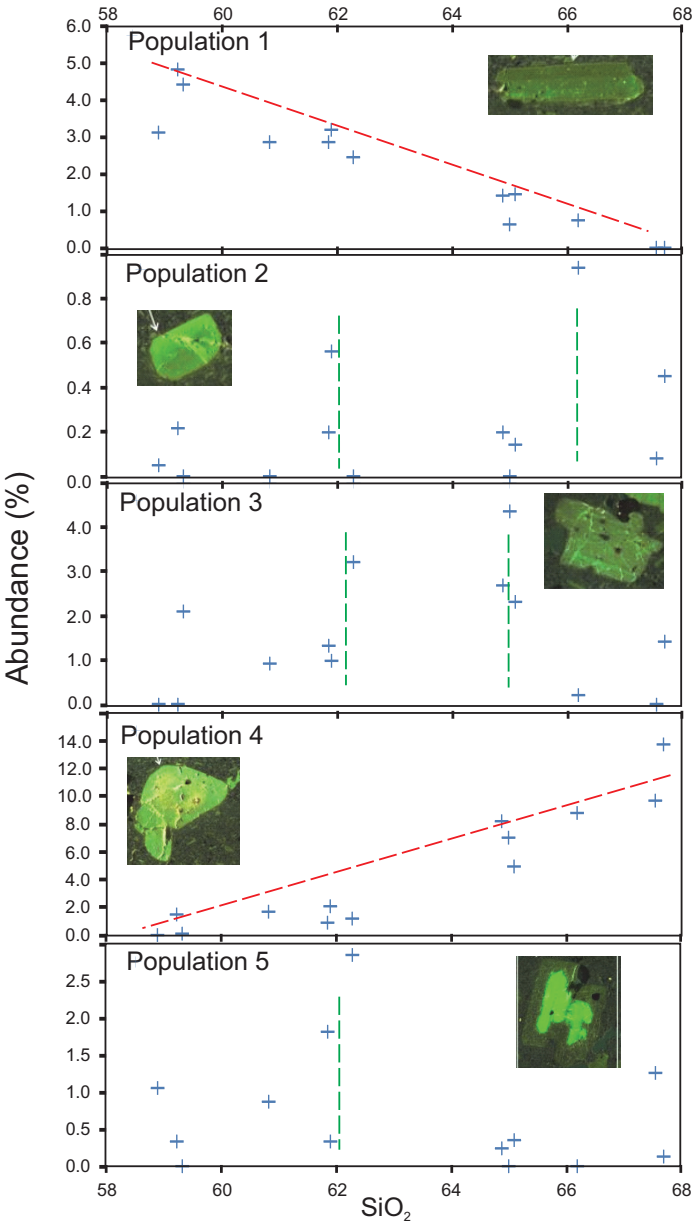

Figure 9. Abundance of five different crystal populations versus overall SiO_2 content in dacite lavas from Quizapu volcano, Chile (Voos 2013). Linear variations suggest that two populations are associated with the andesite and dacite end-members. The other three populations represent specific batches of magma mixed at depth. Such complex mixing behaviour necessitates an elaborate magmatic plumbing system beneath the volcano.

phases are those familiar to petrologists, such as quartz, but the metallic matrix is more unusual. Absorption of X-rays by the metal makes it difficult to use XRT, but 2D methods like those used for the study of rocks can be easily applied (e.g. Zingrebe et al. 2012; Seo et al. 2014).

There are also applications of textural quantification in economic geology, for example in diamond exploration. Some diamond and olivine crystals in kimberlites are xenocrysts that have their source in the mantle. If equilibration has coarsened olivine, then it is possible that diamonds have also been coarsened, increasing their value. For a long time, large numbers of diamond crystal size distributions have been determined by mining companies, but these are only rarely available publicly. Such CSDs are necessarily determined from large volumes of rock and are not always from well-defined, petrographically uniform materials. In contrast, olivine is abundant in many kimberlites and can be easily quantified texturally. Field et al. (2009) looked at olivine and diamond CSDs in the somewhat unusual Snap Lake hypabyssal kimberlite. They examined two different facies and found a correlation in crystal number density (number of crystals/volume) between olivine and diamond, but were unable to compare the CSDs directly. This approach could be quite interesting if researchers would use standard ways to calculate their CSDs and corresponding diamond size information were available.

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