Volcanology, Geochemistry, and Petrology

V11A MCC: 3008 Monday 0800h

Modern Trends in Petrography: Textural and Microanalysis of Igneous Rocks I

Presiding: **D A Jerram,** University of Durham**; B D Marsh,** Johns Hopkins University

V11A-01 0800h INVITED

Using textures to constrain the kinetics and dynamics of eruptive processes

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Volcanic eruptions are dynamic events whose progress depends, in large part, on rheological changes resulting from syn-eruptive vesiculation and crystallization. Bubble and crystal textures preserved in quenched pyroclasts and lava record both conditions of these phase transformations and the flow dynamics of the resulting suspensions. Several examples are summarized below. Volatiles provide the primary driving force for volcanic eruptions. Eruption style (intensity) thus depends on the timing of bubble nucleation, the extent to which volatile exsolution occurs under closed- or open-system conditions, and the mechanism of fragmentation. Analysis of pumice textures shows that silicic pumice is dominated by a large population of small ($< 50\ \mu m$) bubbles that most closely resembles experimental textures produced by homogeneous bubble nucleation under conditions of rapid decompression. Subsequent bubble expansion and coalescence modifies the bubble size distribution and creates permeable bubble networks. As a result, the relative rates of magma ascent, bubble expansion, and coalesence control the extent of closed- or open-system degassing within the conduit. Bubbles also show highly variable degrees of deformation and elongation that indicate large strains along conduit walls, and bubble shapes and orientations can be used to infer the strain history of magma at different locations in the conduit. Magmas crystallize as the result of H2O-saturated decompression in volcanic conduits and of cooling during flow on the Earth's surface. Crystal textures record both the duration of crystallization and the relative importance of nucleation and growth. Syn-eruptive groundmass crystallization produces plagioclase number densities that span several orders of magnitude - a testimony to the sensitivity of crystal nucleation rates to effective undercoolings produced by decompression and cooling on eruptive time scales. Recent decompression experiments help to constrain the kinetics of degassing-induced crystallization in silicic melts; rates of crystallization in basaltic lava flows may be measured directly by sampling along active lava channels. Also important are changes in crystal habit with changes in effective undercooling. Determining the evolution of crystal shapes is important not only for accurate calculation of CSDs, but also for predicting changes in melt rheology with increasing crystal contents of melts. In summary, the textures of volcanic rocks provide a rich repository of kinetic and dynamic information critical for understanding volcanic activity. Challenges for the future include improved techniques for 3D textural analysis at the micron scale and incorporation of textural data into models of magma ascent, eruption and flow on the Earth's surface.

V11A-02 0815h INVITED

Crystal Size Distributions in Igneous rocks: Where are we now?

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Modern Crystal Size Distributions (CSD) studies started in 1988 and have expanded since then, albeit somewhat slowly. We have now measured CSDs in a variety of different compositions and for both plutonic and volcanic rocks. However, the subject still lags far behind chemical petrology and we need many more studies. CSD methodology has advanced considerably, both for 3D and 2D methods, but it is unfortunate that some 2D studies still do not use appropriate stereological conversions or publish their raw data. The nature of the lower size limit is very important, real or measurement artefact, but is not commonly stated. All this is especially important for comparing data with earlier studies. Individual CSDs of minerals are not always very informative. A much better approach is to look at suites of related CSDs. For instance, different minerals within a single sample, ensembles of related whole rock samples, comparison of late and early textures as preserved in oikocrysts, dykes or volcanic rocks. As more data become available it will be possible to compare usefully unrelated suites of rocks. Straight or nearly straight CSDs in volcanic rocks can be produced by steady-state crystallisation. If the growth rate is known then the residence time can be determined. In some rocks there is a good agreement with other chronometric techniques, but others show no such concordance. In the latter case another model may be more appropriate, such as textural coarsening. This model has been applied in some cases in inappropriate situations, which has cast doubt on the whole subject of CSDs. For plutonic rocks exponentially increasing undercooling can also produce straight CSDs. However, many CSDs are slightly curved and other models are possible, especially if no small crystals are present. Within ensembles of straight CSDs the slope and intercept are commonly correlated. This is mostly accounted for by closure and hence this correlation is not significant, although the variation in either slope of intercept is significant and can be related to other parameters. Concave down CSDs, with no small crystals, are commonly encountered in porphyritic, oikocrystic and plutonic rocks. This texture may be produced by textural coarsening (Ostwald ripening, annealing): this occurs when the magma is maintained close to the mineral liquidus. In this situation the nucleation rate is zero, but growth rates are significant. The classic LSW model is not the only solution possible: more modern solutions, such as Communicating Neighbours may be more appropriate. Variable degrees of textural coarsening will produce CSDs that appear to rotate about a single point. This again reflects closure. Concave up CSDs with no lower size limit are very common. They do not generally have a lognormal or fractal size distribution. They can be produced by mixing of two or more magmas, or crystallisation under several different conditions of undercooling. They can also result from alternations of nucleation and growth followed by textural coarsening. Crystal accumulation and fraction should modify existing CSDs in a predictable manner. An exact solution to this problem has not yet been developed, but simplistic models suggest that CSDs should rotate upwards about the size origin for accumulation and downwards for fractionation. However, clear evidence for such effects has not yet been observed, even in well-layered rocks. There are many igneous systems still to be explored using CSDs. An exiting new domain may be the application of CSDs in experimental petrology.

URL: http://wwwdsa.uqac.uquebec.ca/~mhiggins/CSD.html

V11A-03 0830h

Digital Mapping as a Tool for Quantification of Textures in Thin Sections

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The quantification of textural parameters in thin sections of rocks is the first step towards understanding the evolution of microstructural fabric and relating it to rock history. However, this essential stage is seriously limited by the time-consuming nature of manual measurements. Computer-aided edge detection is made difficult by the wide variety of grain birefringence and size, as well as defects such as fractures, alteration and twinning. I have successfully applied a range of new filters and segmentation tools from medical imaging science. The resulting raster image can be easily vectorized, and the outcome of this process is a digital map which can be further analyzed using GIS software. Important improvements using this method are better noise reduction, segmentation, and raster to vector conversion, for a multifaceted two-dimensional analysis. Instead of using the basic median filter for noise reduction, I performed an anisotropic diffusion that preserves the sharpness of grain boundaries. Next, detection of grain-edges was achieved by watershed segmentation, which treats an image as a height function, and grain edges as gradient descents between grains. It classifies pixels into regions analogous to catchment basins in a flooded landscape topology. The conversion from segmented raster image to a vectorial format is then performed and even if there is still some cleaning left, the time required to contour the thousands of crystals of a thin section is greatly reduced. Spatial registration and scaling of the polygons using GIS methods allow analyzing the thin section exactly as a digital map. The Matlab toolbox PolyLX (Lexa, 2003) is used to compute various statistical parameters such as shape descriptors (e.g., aspect ratio, compactness, etc.) and crystal size distribution. I can also produce various maps in order to detect any relationship between a grain attribute and its position. This technique will be applied to a range of plutonic and volcanic rocks in order to assess the influence of crystallization processes on the crystal shape distribution. The chosen rocks show well-defined typical textures that can be related to a known crystallization history. Systematic analysis will then permit identification of the signature and relative importance of mechanisms such as grain growth, pressure solution or textural equilibration in the crystallization history of more complex rocks. Lexa, O., 2003. Numerical approaches in structural and microstructural analyses. Ph.D. Thesis, Charles University, Prague.

V11A-04 0845h

Layering by Self-Made Kinetic Sieves Through Selective Phase Coarsening: Dais Intrusion, McMurdo Dry Valleys, Antarctica

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The Dais Intrusion is a small (400m thick), sheet-like, ultramafic layered body (anorthosite & orthopyroxenite) that is a lobe of the Basement Sill in Wright Valley. Although its overall form, layering and composition are similar to much larger bodies, like Dufek and Bushveld, because of its size it solidified unusually quickly (1000 yrs.), quenching in original, seldom seen, textures prior to serious annealing. As is abundantly clear from its association with the pervasive regional Opx Tongue of the Basement Sill, the Dais body formed by progressive infilling and sorting during flow and avalanching of massive amounts of entrained cumulus opx and finer plagioclase. The large opx (up to 5 x 20 mm) acted during shear as a sieve to the small sugary plagioclase (0.1 mm), forming abundant stringers and layers of anorthosite up to 50 cm thick and leaving overlying massive brows of concentrates of pyroxenite. Overall, there is organization on many scales. The body as a whole gets increasingly felsic upward from massive orthopyroxenite at the base to felsic dolerite at the top, showing both modal and cryptic layering. Within this there are three major felsic bands, each 4-5 m thick, containing distinct small scale, 2-3 cm, layers. Scattered throughout the sequence are numerous well-sorted anorthositic layers (white, buff & tan sandstone-like rock) that laterally pinch in and out in continuing at precise horizons across the body. There are also innumerable delicately sorted pockets and one large trough. Regardless of position within the body, the anorthositic layers are fine grained and the cumulus pyroxene is coarse grained, reflecting more a mechanical sorting process than progressive inward crystallization. Yet there are very curious textures within the fine-grained rocks that reveal the incipient transition to a fully coarse grained body. First, within the purest anorthosite (white) are patches of massive grey rock that in thin section turnout to be large grains (2-3 mm) of interlocking plagioclase. Close inspection shows these large crystals to be formed of many small subgrains quenched in the process of annealing, evidently through grain boundary diffusion, into single large crystals. Second, the buff and tan anorthosites consist of as much as 50-50 mixtures of plagioclase and opx, all of a similar size. In some of these close packed mixtures, the opx has begun to anneal into large (1-2 mm), optically continuous patches, of opx. These patches are very reminiscent of incipient alumino-silicates forming under hornfels grade metamorphism in pelites. All the inter-granular plagioclase is included in the opx patch and the pattern of included plagioclase grains shows an evolution of the shear environment. Careful inspection of the included grains, show them in the early process of rounding, possibly through dissolution, which is also much as in alumino-silicates. Near the opx patches are satellite opx grains, tenuously connected and optically continuous to the patch, quenched in the process of annexation. Clusters of these opx patches are all of the same optical orientation and collectively they, evidently, form an interconnected 3-D sieve through which the remaining plagioclase are draining to form an enriched (white) anorthosite layer. Remarkable enough, the fine-grained rocks are not only coarsening into massive monomineralic rocks, but in the process they are building the mechanical means to further sort and refine the textures. The important lesson is: Were the Dais Intrusion much thicker, it would have had ample solidification time, like all larger layered bodies, to go to textural completion and erase all vestiges of these fundamental processes.

V11A-05 0900h

Nucleation and Growth Rates of Pyroxene, Plagioclase and Fe-Ti Oxides in Basalt

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Rock textures and physical and chemical properties are determined by the time-temperature path of a magma, and the nucleation and growth rates (J, G)

of crystallizing mineral phases. We applied the crystal size distribution theory (CSD) to derived J and G of pyroxene, plagioclase and of Fe-Ti oxides in basalt glass during heat treatment [1,2,3,4]. The glass was sampled from active Pu'u O'o, Kilauea, Hawaii, by hammer-dipping and subsequent quenching [5]. Temperature (T) and time (t) dependent heat treatment of the glass above temperature of nucleation and growth maxima, about 930°C, allows one to derive the activation energy of J and G, E_J, E_G, which are at steady state after about 100 hrs, at 180/200, 353/307, 292/343 kJ/mol (E_J/E_G, for pyroxene, plagioclase and Fe-Ti oxides). On a logarithmic scale, J and G are linear with t. A comparison with growth rates of lava cooled within a lava lobe, from top to bottom [6], suggests that independent of depth, all mineral phases crystallized at T < 1000°C. According to our results of t and T dependent J and G, such rock textures should first crystallize pyroxene, and intersertal plagioclase which is, indeed, observed. Slow cooling or a hold at T > 1000°C, should result in a first crystallization of plagioclase. This is reported in the literature [e.g., 7]. In agreement with this, we detected anorthite nuclei in the glass with HRTEM [8]. [1] Randolph R.D., Larson M.A (1979); Theory of particulate processes. Academic Press, New York. [2] Marsh B.D. (1988); Contrib.Mineral. Petrol. 99, 277-291. [3] Cashman K.V., Marsh (1988) Contrib. Mineral. Petrol. 99, 292-305. [4] Burkhard D.J.M. (2002); Contrib. Mineral. Petrol. 142, 724-527. [5] Burkhard D.J.M. (2001); J. Petrol. 42, 507-527. [6] Burkhard D.J.M. (2003; Bull. Volcanol. 65, 136-143. [7] Lofgren G.E 1983; J. Petrol., 24, 229-225. [8] Burkhard D.J.M., Wirth, R. (2001); EOS Trans. AGU, 82 (47), Fall Meet. Suppl., abstract V51B-1014.

V11A-06 0915h

On the Relation Between Texture, Crystallinity, Nucleation, and Growth in Basaltic Rocks: A Numerical Approach

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One of the most challenging problems in discovering the fundamentals of magma crystallization is finding a proper metric or standard state to which to compare theoretical models of crystallization. This stems from the more basic problem of quantifying rock textures themselves. The critical information is the size, shape, number, and position in local 3D space of all crystals in a sample and then also the variation of these parameters globally within the thermal regime space of the pluton itself. Fortunately, it appears from the Crystallization Axiom (in essence, magmas become holocrystalline regardless of the thermal regime) that the kinetic problem can be separated from the thermal problem (i.e., large Avrami number). CSDs quantitatively link crystal size and number, leaving shape and position, including nucleation and growth reactions with neighbors, yet to be quantified. What we attempt here is to produce textures that first satisfy observed CSDs and then to compare the resulting spatial features of the derived texture to that of the real rock. A stochastic algorithm is used to generate a discretized three-dimensional spatial representation of simultaneous nucleation and crystal growth of randomly orientated and positioned crystals. The algorithm is simplified by assuming large Avrami number, thus allowing crystallinity to be calculated as a function of time using the Avrami method (i.e., JMA equation) and a kinetic model for crystal nucleation and growth. To begin with, we consider a simple kinetic model of exponential nucleation rate and constant crystal growth rate that reconcile observed batch CSD trends in natural samples. The crystallinity function (i.e., bulk crystal content as a function of time) and crystal growth rate model can uniquely determine the number and size of crystals during a simulation and a numerical nucleation rate is calculated as an output variable to compare with the analytical result as a condition for model acceptance. For a given time step during crystallization, having begun with a burst of nucleation, the crystallinity must be satisfied by first allowing growth of randomly chosen, pre-existing crystals and second, if and only if crystal mass is still available (i.e., growth having not satisfied the bulk crystallinity constraint), allowing creation of randomly located nuclei. Results of monomineralic simulations with the same crystallization parameters (i.e., total crystallization time, crystal growth rate, domain length) show that the number and mean sizes of crystals are sensitive to the degree of spatial and temporal discretization within the model. For a particular crystallization parameter group, a running average of the number and mean sizes of crystals with increasing realizations converges and a histogram of those metrics approximate a Gaussian distribution. For some time steps during most simulations, the crystallinity is completely satisfied by crystal growth and no additional nuclei are generated, which suggests that the kinetic model of steady exponential nucleation rate and constant growth rate is incorrect at the detailed level, even though it may appear true in the bulk product. With an increased exponential nucleation rate, however, this occurrence is less common and the numerically calculated CSD approaches a linear trend as naturally observed. The algorithm is also extended to multiphase crystallization, which simulates the simultaneous crystallization of plagioclase and clinopyroxene in tholeiitic basalt. Overall, reasonable adjustments nucleation and growth can lead to realistic histories of crystallization, even though the detailed processes of growth and nucleation may be, in reality, much more involved.

V11A-07 0930h

Monitoring and Quantifying Texture Evolution During Experimental Crystallization and Melting Using Crystal Size Distributions

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A study designed to relate crystal size distributions (CSDs) quantitatively to specific magmatic conditions has been conducted using a series of high temperature heating and cooling experiments with defined initial crystal populations and controlled thermal trajectories. These experiments provide a method for empirically exploring the development of textures under particular conditions and for testing models of crystallization kinetics. Textural evolution during melting was examined by heating a mixture of olivine crystals and synthetic glass at three different temperatures (1545, 1500, 1450 °C) for durations ranging from 0 to 60 min before quenching. CSDs were measured for each sample, and the texture evolution was quantified in terms of the population density as a function of experimental duration. Initially, the population density for the smallest size classes sharply decreased as these crystals melted. With increasing duration, the maximum grain size and the population density in the larger size classes increased. This may have been due to coalescence or crystal growth. Textural evolution during cooling was determined by melting an olivine + glass mixture at 1545 °C for 5 min, and then cooling along a 100 °C/hr gradient. Samples were quenched at different points along the crystallization trajectory. This series of samples serves as a monitor for the texture evolution during a 100 °C/hr cooling run. The CSDs show minor changes in the smaller size classes and major increases in population density in the larger size classes. These changes are interpreted to be the result of ongoing nucleation and rapid growth of skeletal olivine crystals at the top of the charge. The results of these experiments can be used to estimate the olivine growth rate under conditions similar to those experienced by porphyritic olivine chondrules.

V11A-08 0945h

Crystal nucleation theory applied to hydrous magma

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Examination of natural volcanic products shows that the crystal nucleation kinetics determine crystal number density and ultimately crystal size distributions, and thus govern the texture of crystallized materials. Crystallization in hydrous magmas undergoing decompression and devolatilization is especially pertinent in application to volcanological problems. We examine nucleation rate data in the context of kinetic theory and attempt to reconcile observations with aspects of silicate melt structure. Feldspar nucleation rate data obtained by laboratory decompression of hydrous silicate melt are interpreted in view of the classical theory of nucleation (CNT) and a non-classical variation, the diffuse interface theory (DIT). Several simplifying assumptions are needed to compare data with theory, including the Stokes-Einstein approximation, Turnbull's approximation ($\Delta G = \Delta H \Delta T / T_L$) and a means of estimating ΔG of solidification. The crystal-liquid interfacial free energy (σ) is a key parameter in nucleation theory that is difficult to obtain independently. Lack of σ data precludes direct testing of the CNT's validity. Instead, σ is calculated using nucleation rate data assuming the CNT formalism is appropriate; this assumption would be considered valid if each experiment yielded the same value of σ. The interfacial free energies computed in the present case are not constant, but vary by a factor of four (0.024-0.098 J m^{-2}) and decrease systematically with increasing H_2O content (over the range 0.8-4.8 wt.%). The nucleation rate data can be modeled only if σ is allowed to vary as a function of composition, suggesting that a non-classical theory may be justified. The DIT states that a region between the bulk solid (at the core of subcritical clusters) and bulk melt has intermediate thermodynamic properties, and that the interfacial free energy σ may be defined as the difference between the interfacial enthalpy (H_{int}) and interfacial entropy (TS_{int}). If the DIT model is correct, the nucleation rate data for feldspar suggest (1) that dissolved H_2O content controls the spatial gradients of TS_{int} and H_{int} around incipient crystals, and (2) these gradients diverge during devolatilization.

V11B MCC: 3006 Monday 0800h

The Growth and Collapse of Hawaiian Volcanoes I *(joint with OS, T)*

Presiding: **M L Coombs,** U.S. Geological Survey**; B Eakins,** U.S. Geological Survey

V11B-01 0805h

Submarine Rejuvenated-Stage Lavas Offshore Molokai, Oahu, Kauai, and Niihau, Hawaii

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Rejuvenated-stage lavas from the Hawaiian Islands form many distinctive landmarks, such as Diamond Head. They have been relatively well studied due to their primitive, strongly alkaline compositions (alkalic basalt, basanite, nephelinite, melilitite, phonolite). More recently, compositionally similar lavas have been mapped and sampled on the deep seafloor around the islands. Rejuvenated-stage cones also occur on the submarine flanks of the islands. A Pisces V submersible dive collected samples from the only submarine cone on the north slope of East Molokai. The alkalic basalt to basanite composition lava is similar to the subaerial Kalaupapa basalt (Clague and Moore, 2003). MBARI Tiburon ROV dives recovered nephelinite from a lone steep cone on the northeast slope of Oahu, alkalic basalt from two shallow steep cones just west of the Koko Rift, and alkalic basalt from the submarine flank of Diamond Head on Oahu's south flank. These lavas are generally similar to subaerial Honolulu Volcanics, although the isotopic data extend to higher Sr isotopic values. Other MBARI Tiburon ROV dives recovered alkalic basalt and basanite from 8 separate steep cones on the south flank of Kauai. Once again, these lavas are chemically similar to those from the subaerial Koloa Volcanics. Samples from one of these cones contained common xenoliths of upper mantle lherzolite and harzburgite. Seven MBARI Tiburon ROV dives on the northwest flank of Niihau sampled 6 flat-topped cones and 5 pointed cones. The lavas from the flat-topped cones are alkalic basalt similar to rejuvenated Kiekie Basalt on Niihau Island whereas the lavas from the pointed cones are basanite, hawaiite, and tephrophonolite that are chemically distinct from the Kiekie Basalt, but similar to rejuvenated-stage lavas on Kauai and Oahu. Volcaniclastic deposits were observed and sampled at many of the sites offshore Niihau, Kauai, and Oahu, as well as the North Arch. Breadcrust and spindle bombs and spatter were found offshore Kauai as deep as 1500 m, in addition to finer volcaniclastic deposits consisting of vesicular angular glass fragments, which also occur offshore Oahu and in the North Arch as deep as 4100 m (Davis and Clague, submitted). The glass data from all these deposits as well as on pillow and sheet flow rinds from Oahu, Molokai, Niihau, Kauai, North Arch, South Arch, Southwest Oahu volcanic field, and some of the cones between Oahu and Kauai demonstrate that rejuvenated stage lavas did not erupt as near-primary melts, but rather as crystal-rich magmas whose bulk compositions approach primary