Sticky issues arising from high-viscosity magma: Settling arguments on magmatic structures

James K. Russell*
University of British Columbia, Department of Earth, Ocean and Atmospheric Sciences, Vancouver, British Columbia V6T 1Z4, Canada

LAYERING OF IGNEOUS BODIES

Differentiation of magmas, as argued by Bowen (1928) and tested and refined by petrologists over the subsequent 50 years (cf. Carmichael, et al. 1974; Yoder, 1979; Cox, et al., 1979; Hargraves, 1980), contributes to the chemical, mineralogical, and textural diversity of igneous rocks on Earth. Differentiation requires chemical (e.g., crystallization) and physical processes (e.g., crystal settling, convection) to create new magma compositions (i.e., differentiates). Volcanic rocks represent the erupted products of subsurface magma bodies, and their mineralogy and textures directly inform us on the styles, conditions, rates, and efficiency of differentiation processes (Costa and Chakraborty, 2004; Morgan and Blake, 2006; Bachmann et al., 2007; Perugini et al. 2010).

The extent to which compositions, mineralogy, and, especially, structures (e.g., layering) of plutonic rocks record these same differentiation processes (e.g., Clarke and Clarke, 1998; Glazner et al. 2008; Streck and Grunder, 2008; Solgadi and Sawyer, 2008) remains a highly controversial and topical line of research as indicated by the number of sessions on that topic at national and international meetings (e.g., in Technical Sessions 87 and 119 at the Geological Society of America Annual Meeting, Denver, Colorado, 27–30 October 2013). Bachmann et al. (2007, and references therein) provide a superb review of the pros and cons of there being a strong petrogenetic relationship between volcanic and plutonic rocks.

One impediment to resolving these questions is that few, if any, large igneous bodies preserve textures that represent interactions between melt and magmatic crystals only. Because of the protracted cooling histories, mineral compositions, textures and even the mineralogy of plutonic rocks can be shaped by compaction, near- to sub-solidus recrystallization, and solid-state diffusion-controlled processes (e.g., Boudreau and McBirney, 1997; Bachmann et al., 2007). In the past, many of our theories on the origins of layering within igneous bodies have been derived from mass balance arguments based on integrated field, mineralogical, petrological, and geochemical data sets (e.g., McBirney, 1995; Marsh, 2004). However, the high number of degrees of freedom characteristic of magmatic systems that may be open to mass fluxes (e.g., magma replenishment or contamination events) means that mass balance modeling cannot yield unique solutions (Allègre and Minster, 1978; Albarède, 1995). Recently, computational modeling (thermodynamic and physical) and analog fluid dynamical models have become increasingly important tools for testing the thermochemical and physical feasibility of the processes responsible for layering and other structures in plutons (e.g., Turner and Campbell, 1986; Brandeis and Jaupart, 1987; Marsh, 1988; Clarke and Clarke, 1998; Hodge et al., 2012). High-precision, geochronometric studies of layered plutons are also making important advances in our understanding of the assembly of large intrusions and the origins of their mineralogical, structural, and compositional variations (e.g., Glazner et al. 2004; Miller et al. 2007; Scoates and Friedman 2008; J.S. Scoates and C. Wall, 2014, personal commun.).

A PARADIGM AT REST

Glazner (2014, p. 935 in this issue of *Geology*) explores the implications of the viscosity of magmas for the "common-wisdom" magmatic processes commonly ascribed to intermediate-felsic magma systems (e.g., Clarke and Clarke, 1998; Solgadi and Sawyer, 2008). He presents an elegant and simple set of arguments cautioning against the interpretation of "layering and other pseudo-sedimentary structures" (e.g., modal layering, "scouring" of layers) in terms of analogous sedimentological processes (e.g., erosion, transport, and deposition). His thesis is developed specifically for structures preserved in bodies of intermediate to silicic magmas with high viscosities ($\geq 10^{4.5}$ Pa). Conventionally, pseudosedimentary structures such as layering, grading of minerals, cross-bedding, and scours preserved in intrusions are ascribed to physical processes involving particle sedimentation, density currents, or flow segregation (e.g., McBirney, 1995; Clarke and Clarke, 1998). In contrast, Glazner (2014) suggests that layering, grading, cross-lamination, and other features in such intrusions probably result from nonlinear, dynamical-chemical processes operating under conditions far from chemical equilibrium (e.g., Brandeis and Jaupart, 1987; Boudreau, 1995; Boudreau and McBirney, 1997).

Viscosity of natural silicate melts can, on Earth, vary by more than 11 orders of magnitude, and is strongly negatively correlated with temperature and dissolved water content: hotter and wetter melts have lower viscosity. Magmas comprise an amalgam of melt plus entrained solids (i.e., crystals) and fluid (i.e., exsolved volatiles) and their bulk or effective viscosity (and rheology) is strongly controlled by melt composition, the proportions of melt-solid-fluid, and strain rate (e.g., Caricchi et al. 2007). Intermediate to felsic magmas have emplacement temperatures of usually less than 1000 °C and, generally, the coexisting melts have higher SiO_2 and higher H_2O contents than the bulk magma. Thus, the viscosities of these melts are likely to be greater than 10^5 Pa·s except at exceedingly high H_2O contents (>4 wt%) (e.g., Whittington et al., 2009) and confining pressures.

As used by Glazner (2014), the Reynolds number (Re) is a dimensionless number used to track the relative importance of inertial forces (numerator) to viscous forces (denominator):

$$Re = \frac{\rho_l \ L \ U}{\eta}.$$

It comprises intrinsic and extrinsic variables, where the former include properties of the melt (density, ρ_l, and viscosity, η) and the latter include velocity (U) and a characteristic length (L). The high viscosities and the other physical (i.e., density) and geological (length scales and velocities) parameters impose very low (<<1) Re on these systems. The low Re's characteristic of these magma systems dictate that inertial forces relative to viscous forces are negligible. As a consequence, processes that rely on, or operate through, inertial forces (i.e., gravitational settling and sorting; tractional currents) are impossible—they are aphysical. For example, even the most optimistic (i.e., high) estimates of terminal settling velocities predicted by Stokes Law for crystals in these melts result in $Re < 10^{-7}$, at which Re's inertial forces are negligible to absent.

CLOSING THOUGHTS

Textures and structures in rocks, whether sedimentary, metamorphic or igneous, are a key source of information on "relative timing" of events. However, their interpretation in terms of physical and chemical processes can be ambiguous. The origins of layering and other pseudosedimentary

*E-mail: krussell@eos.ubc.ca

GEOLOGY, November 2014; v. 42; no. 11; p. 1023–1024 | doi:10.1130/focus112014.1
© 2014 Geological Society of America. For permission to copy, contact editing@geosociety.org.

Downloaded from http://pubs.geoscienceworld.org/gsa/geology/article-pdf/42/11/1023/3544943/1023.pdf
by guest

structures in intrusive igneous bodies, as elucidated by Glazner (2014), are an excellent example of such ambiguity.

If these features are indeed produced by processes analogous to sedimentary ones (e.g., fluid transport of particles, deposition, currents, and erosion), then they reflect the melt-solid interactions attending subsurface magmatic differentiation. The organization of these rocks, their structures, mineralogy, and bulk compositions would comprise a "negative" echo of the mineralogical and chemical diversity of volcanic rocks. The compositions of these plutonic rocks would record the material left behind by the eruption processes creating the volcanic rocks (Boudreau and McBirney, 1997; Bachmann et al. 2007; Streck and Grunder, 2008). The structures would speak directly to the nature and timing of the physical and chemical processes driving magmatic differentiation.

Conversely, if these structures are not the products of physical processes akin to sedimentation or flow segregation, other explanations are required. Glazner suggests that thermochemical processes are more likely to explain the layering and other pseudosedimentary structures in these intrusions (e.g., Brandeis and Jaupart, 1987; Boudreau, 1995; Boudreau and McBirney, 1997). If near-solidus chemical processes (e.g., crystal ripening, fluid infiltration reaction fronts, diffusive and advective layer formation) are responsible, then the mineralogy, geochemistry, and textural information in these intrusive rocks will tell us little about magmatic differentiation. In this case, the petrological and chemical information in plutonic rocks begins to be decoupled from the diversity of volcanic rocks.

Glazner does not extend his arguments to query the origins of similar features within mafic intrusions, but the question is implicit and is an "elephant in the living room." Further analysis could establish the range of threshold conditions under which inertial forces in magmatic systems become significant, thereby allowing a transition to regimes where settling and tractional processes can operate efficiently. It seems an opportune time to re-evaluate the origins of layered igneous rocks as we now begin to interpret igneous rocks on Mars (e.g., Francis, 2011).

REFERENCES CITED

Albarède, F., 1995, Introduction to geochemical modeling: Cambridge, UK, Cambridge University Press, 543 p.

Allègre, C.J., and Minster, J.F., 1978, Quantitative models of trace element behavior in magmatic processes: Earth and Planetary Science Letters, v. 38, p. 1–25, doi:10.1016/0012-821X(78)90123-1.

Bachmann, O., Miller, C.F., and de Silva, S.L., 2007, The volcanic-plutonic connection as a stage for understanding crustal magmatism: Journal of Volcanology and Geothermal Research, v. 167, p. 1–23, doi:10.1016/j.jvolgeores.2007.08.002.

Boudreau, A.E., and McBirney, A.R., 1997, The Skaergaard layered series. Part III, Non-dynamic layering: Journal of Petrology, v. 38, p. 1003–1020, doi:10.1093/petroj/38.8.1003.

Boudreau, A.E., 1995, Crystal aging and the formation of fine-scale layering: Mineralogy and Petrology, v. 54, p. 55–69, doi:10.1007/BF01162758.

Bowen, N.L., 1928, Evolution of the Igneous Rocks: Princeton, New Jersey, Princeton University Press, 334 p.

Brandeis, G., and Jaupart, C., 1987, The kinetics of nucleation and crystal growth and scaling laws for magmatic crystallization: Contributions to Mineralogy and Petrology, v. 96, p. 24–34, doi:10.1007/BF00375522.

Caricchi, L., Burlini, L., Ulmer, P., Gerya, T., Vassalli, M., and Papale, P., 2007, Non-Newtonian rheology of crystal-bearing magmas and implications for magma ascent dynamics: Earth and Planetary Science Letters, v. 264, p. 402–419, doi:10.1016/j.epsl.2007.09.032.

Carmichael, I.S.E., Turner, F.J., and Verhoogen, J., 1974, Igneous Petrology: New York, McGraw-Hill, 739 p.

Clarke, D.B., and Clarke, G.K.C., 1998, Layered granodiorites at Chebucto Head, South Mountain batholith, Nova Scotia: Journal of Structural Geology, v. 20, p. 1305–1324.

Costa, F., and Chakraborty, S., 2004, Decadal time gaps between mafic intrusion and silicic eruption obtained from chemical zoning patterns in olivine: Earth and Planetary Science Letters, v. 227, p. 517–530, doi:10.1016/j.epsl.2004.08.011.

Cox, K.G., Bell, J.D., and Pankhurst, R.J., 1979, The interpretation of Igneous Rocks: London, Allen & Unwin, 450 p.

Francis, D., 2011, Columbia Hills: An exhumed layered igneous intrusion on Mars?: Earth and Planetary Science Letters, v. 310, p. 59–64, doi:10.1016/j.epsl.2011.08.003.

Glazner, A.F., 2014, Magmatic life at low Reynolds number: Geology, v. 42, p. 935–938, doi:10.1130/G36078.1.

Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., and Taylor, R.Z., 2004, Are plutons assembled over millions of years by amalgamation from small magma chambers?: GSA Today, v. 14, n. 4/5, p. 4–11, doi:10.1130/1052-5173(2004)014<0004:APAOMO>2.0.CO;2.

Glazner, A.F., Coleman, D.S., and Bartley, J.M., 2008, The tenuous connection between high-silica rhyolites and granodiorite plutons: Geology, v. 36, p. 183–186, doi:10.1130/G24496A.1.

Hargraves, R.B., 1980, Physics of Magmatic Processes: Princeton, New Jersey, Princeton University Press, 585 p.

Hodge, K.F., Carazzo, G.M., and Jellinek, M., 2012, Magmatic structures in the Tuolumne Intrusive Suite, California: A new model for the formation and deformation of ladder dikes: Contributions to Mineralogy and Petrology, v. 164, p. 587–600, doi:10.1007/s00410-012-0760-6.

Marsh, B.D., 1988, Crystal capture, sorting, and retention in convecting magma: Geological Society of America Bulletin, v. 100, p. 1720–1737, doi:10.1130/0016-7606(1988)100<1720:CCSARI>2.3.CO;2.

Marsh, B.D., 2004, A magmatic mush column Rosetta Stone—The McMurdo Dry Valleys of Antarctica: Eos, Transactions, American Geophysical Union, v. 85, p. 497–502, doi:10.1029/2004EO470001.

McBirney, A.R., 1995, Mechanisms of differentiation in the Skaergaard Intrusion: Journal of the Geological Society, v. 152, p. 421–435, doi:10.1144/gsjgs.152.3.0421.

Miller, J.S., Matzel, J.E., Miller, C.F., Burgess, S.D., and Miller, R.B., 2007, Zircon growth and recycling during the assembly of large, composite arc plutons: Journal of Volcanology and Geothermal Research, v. 167, p. 282–299, doi:10.1016/j.jvolgeores.2007.04.019.

Morgan, D.J., and Blake, S., 2006, Magmatic residence times of zoned phenocrysts - introduction and application of the binary element diffusion modelling(BEDM) technique: Contributions to Mineralogy and Petrology, v. 151, p. 58–70, doi:10.1007/s00410-005-0045-4.

Perugini, D., Poli, G., Petrelli, M., de Campos, C.P., and Dingwell, D.B., 2010, Time-scales of recent Phlegrean Fields eruptions inferred from the application of a 'diffusive fractionation' model of trace elements: Bulletin of Volcanology, v. 72, p. 431–447, doi:10.1007/s00445-009-0329-z.

Scoates, J.S., and Friedman, R.M., 2008, Precise age of the platiniferous Merensky Reef, Bushveld Complex, South Africa, by the U-Pb zircon chemical abrasion ID-TIMS technique: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 103, p. 465–471, doi:10.2113/gsecongeo.103.3.465.

Solgadi, F., and Sawyer, E.W., 2008, Formation of igneous layering in granodiorite by gravity flow: A field, microstructure and geochemical study of the Tuolumne intrusive suite at Sawmill Canyon, California: Journal of Petrology, v. 49, p. 2009–2042, doi:10.1093/petrology/egn056.

Streck, M., and Grunder, A.L., 2008, Phenocryst-poor rhyolites of bimodal, tholeiitic provinces: the Rattlesnake Tuff and implications for mush extraction models: Bulletin of Volcanology, v. 70, p. 385–401, doi:10.1007/s00445-007-0144-3.

Turner, J.S., and Campbell, I.H., 1986, Convection and mixing in magma chambers: Earth-Science Reviews, v. 23, p. 255–352, doi:10.1016/0012-8252(86)90015-2.

Whittington, A., Bouhifd, M.A., and Richet, P., 2009, The viscosity of hydrous NaAlSi3O8 and granitic melts: Configurational entropy models: The American Mineralogist, v. 94, p. 1–16, doi:10.2138/am.2009.2892.

Yoder, H.S., 1979, The Evolution of the Igneous Rocks, Fiftieth Anniversary Perspectives: Princeton, New Jersey, Princeton University Press, 588 p.

Printed in USA

Downloaded from http://pubs.geoscienceworld.org/gsa/geology/article-pdf/42/11/1023/3544943/1023.pdf
by guest