Emplacement dynamics of laccoliths, sills and dykes from dimensional scaling and mechanical models

Alexander Cruden\textsuperscript{1,3} and Andrew Bunger\textsuperscript{2}

\textsuperscript{1} University of Toronto, Canada – cruden@geology.utoronto.ca
\textsuperscript{2} CSIRO Earth Science & Resource Engineering, Melbourne, Australia – Andrew.Bunger@csiro.au
\textsuperscript{3} Monash University, Melbourne, Australia

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Tabular intrusions are characterized by a spectrum of length ($L$) and thickness ($T$) values (Fig. 1) that can be described by a range of power-law scaling relationships for different types of intrusive structures (Cruden and McCaffrey 2006). The empirical power-law scaling of tabular intrusions is:

$$T = bL^a$$  (1)

where $a$ is the power-law exponent and $b$ is a constant (McCaffrey and Petford 1997). The exponent $a$ differentiates between growth behavior in which the aspect ratio $L/T$ is increasing ($a < 1$, “lateral spreading”) and decreasing ($a > 1$, “uplifting”). For laccoliths, the growth regime favors uplifting with $a > 1$. Indeed, when applied to individual provinces, $a$ has been observed to be as large as 1.5 (Rocchi et al. 2002). In contrast, plutons, large mafic sills, mafic dykes and felsic sills favor lateral spreading with $a < 1$. This contribution focuses on new and previously compiled dimensional data and scaling relationships for laccoliths, mafic and felsic sills, and mafic dykes (Fig. 1).

Current research is aimed at understanding the mechanical basis for these scaling relationships along with some of the observed geometric characteristics such as the classical flat-topped morphology of laccoliths. To this end, we first consider intrusions which do not interact with Earth’s surface. These include most dykes as well as sills for which the radius is much smaller than the emplacement depth. Under conditions where the magma pressure is spatially uniform and the growth of the intrusion is implied by $K_e = K_{fr}$, where $K_i$ is the mode I stress intensity factor and $K_{fr}$ is the mode I fracture toughness of the rock, LEFM predicts (e.g. Olson 2003):

$$T = \frac{K_{fr}}{E} \left[1 - \frac{v^2}{\pi \sqrt{8}}\right] \sqrt{T} \sqrt{L}$$  (2)

where $E$ is Young’s modulus and $v$ is Poisson’s ratio. The exponent of the $L$-$T$ scaling for mafic dykes (Delany and Pollard 1981; Olsen 2003; Schultz et al. 2008a,b) and small mafic and felsic sills (this study, see Fig. 1) is therefore consistent with this LEFM prediction. However, as noted in previous studies, $K_{fr}$ values 10 to 1000 times laboratory values are required to fit the different data sets (Delany and Pollard 1981; Olson 2003; Schultz et al. 2008; Cruden et al. 2009). For example, best fit curves that bracket the dyke and sill data in Fig. 1 are computed for values $E = 100$ GPa, $v = 0.3$ and $K_{fr} = 300$ to 3000 MPa m$^{1/2}$ whereas typical laboratory rock toughness values range from 0.5 to 2 MPa m$^{1/2}$. If large effective $K_{fr}$ values can be accounted for by scale effects, fracture network branching or cooling/solidification at fracture tips (viz., tip screen out) then LEFM accounts satisfactorily for the scaling of these intrusion types. Furthermore, this model is favored relative to the LEFM model under conditions of uniform magma pressure that is also constant as the intrusion grows, which is at odds with the data because it predicts $a \sim 1$ (Olson 2003). Furthermore this model is favored relative to models that consider viscous flow to be predominant because the magma viscosity range required to bracket the data is implausibly high (Cruden et al. 2009).

While the data for intrusions that do not interact with the surface can be explained, at least to some extent, through application of existing LEFM models, the existing theories do not fare as well for laccoliths and large mafic sills. These intrusions almost always attain a radius that is similar to, or in many cases, much larger than the emplacement depth. Elastic plate theory (e.g., Pollard and Johnson 1973) predicts bell-shaped thickness profiles, which is at odds with the observed flat-topped thickness profiles of these intrusions. Nor can plate theory account for the $L$-$T$ scaling of large mafic sills. The classical punch model of Gilbert (1877) and the laminar-sliding plate theory of Koch et al. (1981) are consistent with flat-topped thickness profiles.
(essentially as a result of the models assuming this shape \textit{a priori}), but fail to make appropriate predictions of the $L$-$T$ scaling for either laccoliths or large mafic sills. In an effort to provide a model that is more consistent with the data, we have revisited elastic plate theory in light of the fact that previous elastic plate-based predictions have not taken into account an appropriate fracture propagation condition, fluid flow in the growing intrusion, and, importantly, the influence of the weight of the magma on intrusion growth (Bunger and Cruden 2010). We present a model for the growth of circular intrusions that accounts for all of these factors. The model predicts the appropriate geometry for both laccoliths and large mafic sills. The predicted thickness-to-length relationships are also consistent with field data. Hence, while it may sometimes be appropriate, there is in general no fundamental need to appeal to large scale rock plasticity in order to explain observed intrusion geometries and it may in fact be appropriate to understand the growth of laccoliths and large sills in light of a single underlying mechanical model.

References


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