Igneous petrology

Discordance in layered intrusions

from R.S.J. Sparks

LAYERED intrusions are the frozen remains of magma chambers. Their distinguishing characteristic is a vertical variation in mineral abundance, giving rise to a horizontal layering superficially resembling that seen in sedimentary rocks. The study of their geology and petrology has played a central role in the development of ideas on the origin of magmas. Intrusions such as the Skaergaard in Greenland provide almost perfect natural examples of crystallization under closed-system conditions. Other intrusions, such as Rhum in Scotland and Stillwater in Montana, record the history of long-lived open-system magma chambers. The classic method of investigating a layered intrusion is to collect samples through the stratigraphy and to document variations in the composition and abundance of minerals. Usually one vertical section has been taken to represent the entire intrusion. In a recent paper, J. R. Wilson and S. B. Larsen[1] describe the first comprehensive two-dimensional study of a layered intrusion — the Fongen-Hyllingen intrusion in Norway. The relationships they report provide important new facts which any theory on the origin of layered intrusions must seek to explain.

Detailed geological mapping and systematic petrology provide the key to understanding large layered intrusions, which typically cover areas of hundreds of square kilometres. This kind of study is thus a substantial and time-consuming enterprise. Indeed a layered intrusion often becomes associated with one particular scientist who may have devoted considerable time to its study; perhaps the most notable link is between L.R. Wager and the Skaergaard intrusion. Wilson and colleagues at Aarhus University in Denmark have devoted over fifteen years to investigating the Fongen-Hyllingen intrusion and they have now produced one of the most significant studies of a layered intrusion for many years.

The variation in mineral composition observed in these intrusions is termed cryptic layering, whereas the presence or absence of minerals defines the phase layering. On the scale of outcrops, the layering is made visible by small changes in the relative abundances of minerals, here termed modal layering. Wilson and Larsen document dramatic lateral variations in mineral composition and show that the modal layering observed in the field is strongly discordant to crytpic and phase layering.

The Fongen-Hyllingen intrusion was emplaced as a sill-like body at 12-20 km depth during the Caledonian orogeny, roughly 425 Myr ago. The intrusion and its metamorphosed envelope of basic and pelitic country rocks are now part of a nappe complex and prolonged erosion has exposed a longtitudinal cross-section 33 km in length. The northern part (the Fongen and Ruten Series) has the greatest stratigraphical thickness (6.2 km) and is complicated by folding. Primitive ultramafic rocks occur at the base of the sequence and there are many reversals in the mineral compositions, a certain sign of an open-system magma chamber. The southern part (the Hyllingen Series) consists of 3.6 km of modally layered rocks. and is documented in detail by Wilson and Larsen.

Both the floor (the western margin) and the roof (the eastern margin) are exposed in the Hyllingen area. Geological mapping reveals intimate interfingering of country rock with layered rocks in the southern region. Swarms of huge country-rock inclusions, with individual metabasic xenoliths up to 1 km long and a few hundred metres wide, are found throughout the sequence. The layering is completely undisturbed by these xenoliths and they seem to be in their original positions rather than having fallen in from the roof or walls. The igneous rocks are highly evolved ferrogabbros and ferrodiorites, with quartz-bearing syenites occurring next to the roof. Minerals include olivine, Ca-rich and Ca-poor pyroxenes, amphibole, plagioclase, Fe-Ti oxides, zircon, apatite, biotite and allanite. The very high Fe/Mg ratio of ferromagnesian minerals shows that all the rocks have crystallized from highly differentiated magmas. In any one vertical profile four stages of magma evolution can be recognized. Stage I is an unlayered gabbro. Stages II and IV record initial open-system behaviour with relatively constant mineral compositions followed by progressive differentiation. Stage III in the middle of the sequence records a major reversal with minerals gradually becoming less fractionated towards the top of the section.

The most important results of the study are the recognition of lateral variations in mineral compositions, which are almost as great as those recorded in vertical profiles and provide evidence by changes of mineral abundances on millimetre or centimetre scales. These layers strike north-south, parallel to the floor and roof with no deviation at the southern contact or locally around enormous xenoliths. However, mineral compositions (defining cryptic layering) change dramatically along the strike with minerals becoming more evolved towards the southern margin. For example, at the boundary between stages III and IV the olivine and plagioclase vary from Fo_{75}: An_{63} to Fo_{13}: An_{42} over a 10 km strike length. The stage boundaries are parallel to field layering, showing that changes in the differentiation trend occurred simultaneously at the same stratigraphical level. With eleven separate vertical profiles Wilson and Larsen have been able to contour lines of constant mineral composition. The contours are discordant to the modal layering by angles which are typically 20° but are as much as 90° at the southern margin. As described in their preliminary account[2], boundaries recording the appearance of new cumulus minerals (zircon and apatite) are also highly discordant to the rhythmical layering.

Conventionally, the visible modal layering is thought to represent the trace of the ancient magma-chamber floor and therefore each layer is a time-plane. If this is so then the implication of the discordance is that the magma chamber must have been compositionally stratified throughout its evolution. Wilson and Larsen argue that the dramatic lateral gradients and the lack of disturbance of layering by xenoliths eliminate crystal settling. They believe that the crystals grew *in situ* along the floor. They propose that the floor was gently tilted so that increasingly differentiated magma in a zoned chamber was in contact with the floor in the (southerly) upslope direction. Thus, the minerals systematically change composition and new phases appear up the slope. Addition of magma from the north complicated the picture by elevating the zoned magma column and causing gradual reversals as lower and more primitive magma migrates up the slope. A more elaborate model, based on the work of Irvine, Keith and Todd[3], envisages lateral accretion of layers, in which the field layering, mineral-composition layering and the accretion front (the time-plane) are all discordant.

Recent petrological literature contains several new ideas on the processes that form layered intrusions. Several workers have argued that double-diffusive convection plays an important role[3-6]. There is also field and theoretical evidence that compaction of cumulate piles and post-cumulus migration of melt[7,8] can lead to changes in mineral compositions, which further complicates interpretations of their petrogenesis. Irrespective of the merits of recent thinking and speculation, the discoveries of major lateral variations and discordances in layered intrusions must be central facts on which different hypotheses will succeed or founder. Wilson and Larsen's work should herald a new phase of research in layered intrusions, in which documentation of lateral changes will be as important as vertical variations. □

1. Wilson, J.R. & Larsen, S.B. *Geol. Mag.* **122**, 97 (1985).
2. Wilson, J.R. & Larsen, S.B. *Nature* **299**, 625 (1982).
3. Irvine, T.N., Keith, D.W. & Todd, S.G. *Econ. Geol.* **78**, 1287 (1983).
4. McBirney, A.R. & Noyes, R.M. *J. Petrol.* **20**, 487 (1979).
5. Huppert, H.E. & Sparks, R.S.J. *A. Rev. Earth planet. Sci.* **12**, 11 (1984).
6. Turner, J.S. & Gustafson, L.B. *Econ. Geol.* **73**, 1082 (1978).
7. Irvine, T.N. in *Physics of Magmatic Processes* (ed. R.B. Hargreaves) 325 (Princeton University Press, 1980).
8. McKenzie, D.P. *J. Petrol.* **25**, 713 (1984).

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