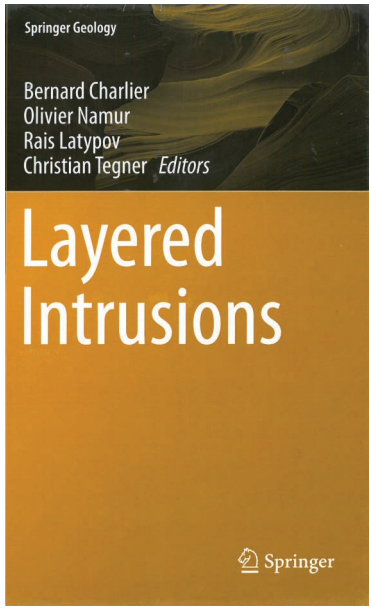
American Mineralogist, Volume 101, pages 2361–2362, 2016

Book Review

Book review: Layered Intrusions. Edited by Bernard Charlier, Olivier Namur, Rais Latypov, and Christian Tegner (2015) Springer, 748 p. $179 (Hardcover), $139 (eBook), ISBN 978-94-017-9651-4.



The book entitled *Layered Intrusions* is a well-sized collection of 15 chapters written by 36 authors—each being an expert in their prevailing sub-discipline. Hence, the book covers all aspects of the emplacement and evolution of large mafic to ultramafic magma chambers. All chapters provide a broad introduction to their topics and are richly illustrated. References appear at the end of each chapter and support the readers' further education on particular topics. The book is well written and intends to aid in further training of graduate and undergraduate students; however, the addition of access to illustrations and figures online would increase its value as a teaching resource. All chapters are available as e-books, so with a little extra effort and expense, if you have the hard cover version, images and figures for teaching can be obtained from these. Each of the 15 chapters are available separately for $29.95. Photographs and photomicrographs are mostly color images, where grayscale images are used, these are labelled to avoid any confusion that might arise.

The book is organized into two main parts that are summarized in the two paragraphs below: the first part includes reviews and new views on the formation processes of layered intrusions. The second part reviews the state of recent cutting-edge research of layered intrusions in the field.

The book begins with the geochronology of layered intrusions. Chapter 1 provides information about advantages and disadvantages of well-known dating methods, e.g., U-Th-Pb, K-Ar and which of these best applied to layered intrusions from different periods in the Earth's history. Cooling rates of the intrusions are determined by choosing various mineral species with different closing temperatures, the temperature at which radiogenic elements are retained in the crystal lattice. The case studies suggest that duration of magmatism of layered intrusions can be restricted to brief spans of ~700 Ka at the Bushveld complex or as long as 3–4 Ma at the Stillwater complex.

Chapter 2 provides insight into the igneous layering of basaltic magma chambers. These processes show surprising similarities to sedimentary processes comprising features such as the analog of turbidites, slumps, and magma currents, showing that layer formation is much more complex than just crystal settling. Economically important chromitite layers show a wide lateral continuity and are thought to originate through mixing of intruding, primitive and resident, fractionated magma. The chapter discusses the different causes that induces crystal growth and layer formation. It ends with observations made in experiments with gels, showing that crystal settling induces upward flow of clear liquids.

Chapter 3 examines rocks in layered intrusions with quantitative textural analysis. Crystal size distributions (CSD), done by petrography with stereologic conversion or X-ray tomography gives insights into the textural development of igneous rocks. As crystals settle through the melt column of a magma chamber, they grow to various sizes; however, grain coarsening of intrusive rocks is facilitated by the Ostwald ripening effect, minimizing the surface energy by solution of small crystals and the growth of larger individuals. Textures are further mechanically modified by shear stresses, thus primary structures are commonly overprinted by late-equilibration processes.

Chapter 4 refines the textural aspects from the previous chapter and focuses on the effect of interfacial energies on igneous microstructures. These interfacial energies gain importance with decreasing cooling rates and also with smaller grain sizes. It explains the direct link between grain aggregation and grain coalescence, where larger crystals consume smaller ones. The chapter also discusses textural changes in the sub-solidus, which lead to metamorphic-like textures.

Chapter 5 introduces the cause and effects that lead to the separation of a parental melt into a Fe-rich and a Si-rich melt. This so called liquid immiscibility is common in the tholeiitic series and is viewed as a reason for the Daly-gap, the lack of intermediate melt compositions between the primitive and evolved

0003-004X/16/0010–2361$05.00/DOI: http://dx.doi.org/10.2138/am-2016-665

end-member. The exact mechanisms by which liquids separate at this point are yet poorly understood, but the authors provide strong arguments for an early separation starting with sub-micrometer emulsions. The chapter shows various processes that influence liquid immiscibility. The inclusion of two contrasting melts, a Fe-rich and a Si-rich, in apatite from Skaergaard, is one of the rare examples for this phenomena found in the field.

Chapter 6 describes the common occurrences of basal reversals of compositional stratification in layered intrusions. Basal reversal are recognized in cumulates that become increasingly more primitive from bottom to top until a crossover horizon is reached; from there, the trend reverses and the mineralogy and composition become more evolved higher in the intrusion. A generalized three-factor model including temperature and geometry of the magma chamber-floor is presented to explain basal reversals.

Chapter 7 examines the significance of magnet fabric in layered intrusions by using the anisotropic magnetic susceptibility tensor, which is mainly influenced by paramagnetic minerals like Fe-silicates. Its graphical representation is an ellipsoid with its long axis corresponding to the direction of magma flow. A deeper understanding of the anisotropic magnetic susceptibility tensor is thought to help understand magma emplacement and intrusion geometries. Additionally, it aids in gaining insights into cumulate formation processes.

Chapter 8 gives insights into the growth and migration of vapor bubbles that grow in magma chambers after substantial volatile saturation occurred in partially molten cumulates. The minimum migration rate for the bubbles to escape the cumulate is defined by the rate of new crystals accumulating onto the top of the pile. Furthermore rates of compaction- and accumulation are discussed as they have a direct impact on the trapping of vapor bubbles.

Chapter 9 presents recent advances in the understanding of ore forming processes of platinum-group element (PGE) deposits in layered intrusions. They occur in different depositional types, such as "contact-types" at the basis and side walls of the intrusion, in association with chromitite layers and in association with Fe-Ti oxide-rich rocks. Furthermore, this section summarizes the processes of PGE-enrichment by partial-melting and fractionation.

The second part of the book reviews locations of layered intrusions. All chapters provide a geological background and information about age, location, and size of the respective intrusion complexes.

The Panzhihua intrusion (chapter 10) in SW China is linked to the Emeishan flood basalts and comprises major Fe-Ti ores. The parental magma to this intrusion is thought to be a high-Ti basalt similar to Eimeshan basalts. Magma-wall interaction with marble lead to a high f_{O_2} and possible facilitated the growth of the Fe-Ti oxides. The complete series differentiated to A-type granitoids near the roof of the magma chamber.

The Sept Iles Intrusion in Canada (chapter 11), valued for their Fe-Ti-P ores, is the third largest layered intrusion in the world. It is made of three magmatic components, namely the layered series, the composite sill and the late-stage gabbros. It has the form of a lopolith, which is shaped like a thickened sill with a subsided center. The layered series is important for its ore deposits. The complete intrusion differentiated from a ferrobasaltic composition via minor intermediate magmas to ferroan granites by following the tholeiitic trend. This intrusion comprises also a Daly-gap, which is thought to develop by melt immiscibility. The ferroan granites accumulated at the uppermost part of the intrusion and are separated by floating plagioclase, acting as an effective membrane for evolved melts, to the lower mafic series.

The Bushveld complex (chapter 12), located on the Kaapvaal craton in South Africa, is world's largest layered intrusion. This intrusion hosts the majority of the world's PGE resources. The Merensky Reef, a chromitite layer, is an intrusion-wide uniform and prominent marker layer that is valued and mined for its high-PGE content. The chromitite layers comprise sharp basal contacts and are intrusion wide uniformly in thickness, pointing toward an abrupt onset of oxide crystallization over the vast volume of the magma column. The Bushveld complex also shows several density inversions with chromitites situated directly on anorthosites.

The Kiglapait intrusion, in Newfoundland, Canada (chapter 13) is the world's eighth largest, single-layered mafic intrusion. It is largely composed of troctolite (olivine + plagioclase). The center of the bowl-shaped structures comprises syenites. This intrusion is seen as an evidence for the existence of troctolitic magmas.

The Ilmaussaq alkaline complex in South Greenland (chapter 14) comprises nepheline-syenites that are highly enriched in REE and HFSE. The intrusion was emplaced by stoping, the cutting and sinking of large blocks of host rock and comprises exotic bitumenous rocks in the late-stage pegmatites. The parental magma is thought to have originated in the metasomatized lithospheric mantle and likely represents a transitional olivine basalt. Furthermore, the chapter gives a detailed insight into the complex cooling history of this intrusion.

The last chapter (chapter 15) describes ophiolitic magma chamber processes with sample locations from the Canadian Appalachians. Ophiolithic magma chambers represent sources for basalts on spreading ridges and are located in an active tectonic setting in comparison with continental layered intrusions, which are emplaced on stable continents in most cases. The magma is emplacement in the ductile ocean crust in form of sills, which crystallized under shear strain. This chapter also introduces "shear pumping," which is a mechanism that utilizes strain to help in melt escape. Ophiolites also bear evidence for gravitational crystal fractionation and late-stage metasomatism of the cumulate pile.

Layered Intrusions is a synthesis of current knowledge on processes that are related to magma-chamber evolution. This book is a good starting point for anyone considering a new project on layered intrusions. It is also suitable for undergraduate to graduate students as processes are broadly explained with a strong involvement of field examples. I recommend this book also from my personal background as an experimental petrologist, since I recognized various patterns of melt emplacement and evolution, as they were described in the book, in my own experiments.

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