Chapter 2
Igneous Layering in Basaltic Magma Chambers

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Abstract Layering is a common feature in mafic and ultramafic layered intrusions and generally consists of a succession of layers characterized by contrasted mineral modes and/or mineral textures, including grain size and orientation and, locally, changing mineral compositions. The morphology of the layers is commonly planar, but more complicated shapes are observed in some layered intrusions. Layering displays various characteristics in terms of layer thickness, homogeneity, lateral continuity, stratigraphic cyclicity, and the sharpness of their contacts with surrounding layers. It also often has similarities with sedimentary structures such as cross-bedding, trough structures or layer termination. It is now accepted that basaltic

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magma chambers mostly crystallize in situ in slightly undercooled boundary layers formed at the margins of the chamber. As a consequence, most known existing layering cannot be ascribed to a simple crystal settling process. Based on detailed field relationships, geochemical analyses as well as theoretical and experimental studies, other potential mechanisms have been proposed in the literature to explain the formation of layered igneous rocks. In this study, we review important mechanisms for the formation of layering, which we classify into dynamic and non-dynamic layer-forming processes.

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Dynamic processes occur during filling of the magma chamber or during its crystallization. They include differential settling or flotation of crystals with contrasted densities and/or grain sizes, flow segregation of crystal-laden magma and crystal segregation during convective liquid movement into the magma chamber. Double diffusive convection, which produces a stratified liquid column in the magma chamber, can also produce layering. Other dynamic processes include magma injection into the chamber, which results in magma stratification or magma mixing, and silicate liquid immiscibility either in the main magma chamber or within the solidifying crystal mush.

Non-dynamic layer-forming processes mainly include rapid changes in intensive conditions of crystallization (e.g. pressure, oxygen fugacity) that disrupt and change the stable liquidus assemblages, and transitory excursions about cotectic curves. Layering can also result from variation in nucleation rates and from mineral reorganization in a crystal mush through grain rotation, dissolution-precipitation due to initial heterogeneity in terms of grain size distribution, mineral modes or differential pressure. Many of these processes are driven by dissipation of energy and can be referred to as equilibration or self-organization processes.

Keywords Dynamic · Non-dynamic · Sedimentary features · Fluid dynamics · Dissipation of energy

Introduction

Igneous layering is a common feature of plutonic igneous bodies and occurs in most mafic-ultramafic layered intrusions (Wager and Brown 1968; Parsons 1987; Naslund and McBirney 1996; Irvine et al. 1998), in syenitic intrusions (Parsons 1979; Hodson 1998), in granites (Barbey 2009), in ophiolites (Nicolas et al. 1998; Jousselin et al. 2012) and at oceanic spreading ridges (Gillis et al. 2014). The origin of layering in mafic magma chambers was initially attributed to a crystal settling process combined with mineral sorting due to a density contrast between the different phases and the melt (Wager et al. 1960). However, experimental and theoretical models have shown that plagioclase is commonly slightly buoyant in basaltic melts (Campbell 1978; Campbell et al. 1978; Scoates 2000; Namur et al. 2011a) and should therefore not accumulate at the floor of the magma chamber. Plagioclase is a major component of basaltic layered intrusions which indicates that crystal settling cannot be responsible for the different kinds of layering in all known occurrences. It is therefore likely that layering formation involves other processes including in situ crystallization close to the margins of the magma chamber (Campbell 1978; McBirney and Noyes 1979; Naslund and McBirney 1996).

Given the wide range of layer types and layering features in terms of texture (including grain-size), mineral mode, composition, morphology, and the way layers are interstratified and repeat stratigraphically, it is unlikely that a single layer-forming process can explain all the known occurrences of igneous layering. Many processes have thus been proposed in the past 50 years to explain the origin of layering in individual localities (Wager and Brown 1968; McBirney and Noyes 1979; Parsons 1987; Naslund and McBirney 1996). Layering can form through processes occurring from the liquidus temperature down to subsolidus conditions (Naslund and McBirney 1996). Broadly, all of these processes can be subdivided into two groups: dynamic layer-forming processes and non-dynamic layer-forming processes (Irvine 1982; Boudreau and McBirney 1997; McBirney and Nicolas 1997).

In this chapter, we review the dynamic and non-dynamic processes that have been commonly proposed to explain the formation of igneous layering and describe examples of layering features resulting from these processes. We also take advantage of recent literature to show convincing examples for layer-forming mechanisms that we attribute to processes that have generally been not considered or not fully described in the past. Finally, we show examples of how numerical and experimental investigations might help to understand the formation of layering in real magma chambers. This chapter does not aim at describing all known occurrences of layering, but to describe important examples of layering features illustrating the most significant and best-documented layer-forming mechanisms occurring during the solidification of ultramafic-mafic magma chambers.

Layers and Layering

Layering is defined as an overall structure of cumulates which develops through the combination of individual layers, each forming sheet like cumulate units and each being a distinctive entity in its compositional (e.g. bulk rock and/or mineral compositions) and/or textural (e.g. grain size, mineral mode) features (Irvine 1982; Naslund and McBirney 1996). Individual layers therefore appear as a sheet-like discontinuity in the crystalline assemblage making up the sequence of rocks (Figs 2.1a–e).

Individual layers can be uniform or stratigraphically variable, therefore showing normal or reversed textural grading (e.g. morphology of the crystals), grain-size grading, modal grading (leucocratic vs melanocratic), or cryptic (chemical) grading (Table 2.1; Irvine 1982). They show a large range of forms (e.g. planar, lenticular, trough-shaped, synformal, antiformal, convoluted or basin-like) and can also be defined in terms of thickness (e.g. thin: 0–5 cm, medium-tick: 5–100 cm or thick: >100 cm) and the nature of their contacts (sharp vs gradational). They can be laterally discontinuous in terms of mineral mode, texture or thickness (Fig. 2.1e). Individual layers may also show termination and locally merge together to form thicker layers (Fig. 2.1f)

Layering in igneous bodies is characterized by the succession of layers that may have variable characteristics in terms of grain-size (grain-size layering), mineral mode (modal layering), crystal shape (textural layering) or composition (cryptic layering; Irvine 1982; Table 2.1; Fig. 2.2). From one intrusion to another, or within a single intrusion, layering may be well defined (prominent layering) or poorly

Fig. 2.1 Examples of layers from various layered intrusions. **a** Alternating chromitite (*Cr*) and anorthosite (*An*) layers, UG1 footwall, Critical Zone of the Eastern Bushveld Complex, Dwars River, South Africa. **b** Troctolitic cumulates (*Tr*) with *thin*, sharply bounded, peridotite (*P*) layers. Younger Giant Dyke Complex, western Tugtutôq, Greenland. At larger scale, these layers show lateral discontinuities and bifurcation. Scale is 30 cm long. Courtesy of B. Upton. **c** Magnetitite layer (*Mt*) overlying leucogabbronorite, *Upper* Zone of the Eastern Bushveld Complex, Magnet Heights. Camera bag is 10 cm across. **d** Peridotite layers within the troctolite cumulates of the Younger Giant Dyke Complex, western Tugtutôq, Greenland. Note the perpendicular feldspar crystals growing up from the peridotite layers. Courtesy of B. Upton. **e** Peridotite layer within the troctolite cumulates of the Younger Giant Dyke Complex, western Tugtutôq, Greenland. Note that the thickness of the peridotite layer is increasing laterally. Courtesy of B. Upton. **f** Chromitite layers within anorthosite cumulates. UG1 footwall, Critical Zone of the Eastern Bushveld Complex, Dwars River, South Africa. Note that some chromitite layers are discontinuous laterally and locally merge in a single *thick* layer

defined, be planar or form other structures (e.g. trough, colloform, wavy, convoluted layering, cross stratified, inch-scale layering; Fig. 2.1f) and can be continuous (laterally and vertically) or discontinuous (or intermittent).

Layering deformation due to blocks falling on the still highly porous crystal mush has been described for the Sept Iles, Skaergaard (Figs 2.3a–b), Fongen-Hyllingen

Table 2.1 Important characteristics of the layers and common types of layering in layered intrusions

Characterization	Description	Important location	Lithology	Reference
Layer				
Thickness				
	Thin (0–5 cm)	Stillwater Complex, USA	Anorthosite—pyroxenite	Hess (1960)
	Medium-thick (5 cm–1 m)	Bushveld Complex, South Africa	Magnetitite	Cawthorn and Ashwal (2009)
	Thick (>1 m)	Bushveld Complex, South Africa	Anorthosite	Cawthorn and Ashwal (2009)
Form				
	Planar	Skaergaard, Greenland	Leucogabbro—melanogabbro	Irvine et al. (1998)
	Lenticular	Kiglapait, Canada	Troctolite	Morse (1969)
	Trough-shaped	Skaergaard, Greenland	Anorthosite—gabbro	Irvine (1987)
	Synformal	Bjerkreim-Sokndal, Norway	Leuconorite—melanonorite	Bolle et al. (2000)
	Antiformal	Skaergaard, Greenland	Leucogabbro—melanogabbro	Irvine et al. (1998)
	Convoluted	Duke Island, USA	Dunite—peridotite	Irvine (1987)
	Colloform	Skaergaard, Greenland	Troctolite-gabbro	Namur et al. (2013)
Interal constitution				
	Homogeneous in mineralogy, grain size, texture	Bushveld Complex, South Africa	Chromite-anorthosite	Voordouw et al. (2009)
	Stratigraphically variable in mineralogy, grain size, texture	Panzhihua, China	Melanogabbro	Zhou et al. (2005)
	Laterally variable in mineralogy, grain size, texture	Duluth Complex	Fine-grained gabbro	Miller and Ripley (1996)
Composition				
	Leucocratic (high proportion of leucocratic phases)	Panzhihua, China	Plagioclase-rich gabbro	Zhou et al. (2005)
	Melanocratic (high proportion of mafic phases)	Panzhihua, China	Oxide-rich gabbro	Zhou et al. (2005)
	Monomineralic	Bushveld Complex, South Africa	Chromite-anorthosite-magnetitite	Eales and Cawthorn (1996)
Graded layers				
	Grain-size graded (variation in grain size of constituent minerals)	Duke Island, USA	Dunite—peridotite	Irvine (1974)

Table 2.1 (continued)

Characterization	Description	Important location	Lithology	Reference
	Modally graded (variation in mineral modes)	Panzhihua, China	Melanogabbro-Leucogabbro	Zhou et al. (2005)
	Cryptically graded (continuous variation of mineral compositions)	Skaergaard, Greenland	Gabbro	McBirney and Noyes (1979)
	Texturally graded (change in texture; poikilitic vs tabular grains)	Skaergaard, Greenland	Gabbro	McBirney and Noyes (1979)
Layer contact				
	Sharp	Sept Iles, Canada	Bottom of magnetitite layers	Namur et al. (2010)
	Gradational	Sept Iles, Canada	Top of magnetitite layers	Namur et al. (2010)
	Concordant	Skaergaard, Greenland	Gabbro	McBirney and Noyes (1979)
	Discordant	Duke Island, USA	Olivine pyroxenite	Irvine (1963)
Layering				
Lithologic variation				
	Modal layering	Ilímaussaq Complex, Greenland	Kakortokite	Sorensen and Larsen (1987)
	Grain size layering	Duke Island, USA	Olivine pyroxenite-peridotite	Irvine (1963)
	Textural layering	Rum Layered Suite, Scotland	Peridotite-allivalite	Brown (1956)
	Cryptic layering	Skaergaard, Greenland	Troctolite-gabbro	Wager and Brown (1968)
Distinctness				
	Prominent	Skaergaard, Greenland	Troctolite-gabbro	McBirney and Noyes (1979)
	Inconspicious	Sept Iles intrusion, Canada	Troctolite-gabbro	Namur et al. (2010)
Regularity				
	Macrorhytmic	Ilímaussaq Complex, Greenland	Kakortokite	Sorensen and Larsen (1987)
	Microrhythmic	Rum Layered Suite, Scotland	Allivalite	Brown (1956)
	Inch-scale (microrhythmic)	Stillwater Complex, USA	Orthopyroxenite-anorthosite	McCallum (1996)
Continuity				
	Laterally continuous	Bushveld Complex, South Africa	Chromitite	Mondal and Mathez (2007)

Table 2.1 (continued)

Characterization	Description	Important location	Lithology	Reference
	Laterally discontinuous	Rum Layered Suite, Scotland	Peridotite-allivalite	Bedard et al. (1988)
	Intermittent	Skaergaard, Greenland	Leucogabbro-melanogabbro	McBirney (1993)

and Sarqata Qaqa intrusions (Thompson and Patrick 1968; Wilson et al. 1981; Irvine et al. 1998; Higgins 2005; Namur et al. 2010; Morse 2011; see also Plates 2a and 3c in Irvine 1965). Layering often shows similarities with sedimentary features such as graded-bedded turbidity current deposits, loading, impact-structures, scour and fill, pinch and swell structures, angular discontinuities, slump structures and lateral grading (Figs 2.2d and 2.3d–f; Irvine 1963). Sedimentary-like features of layered cumulate rocks have been particularly well described for the ultramafic Duke Island intrusion (Irvine 1965) and the gabbroic Skaergaard and Fongen-Hyllingen intrusions (Thy and Wilson 1980; Wilson et al. 1981; Irvine et al. 1998). The vast majority of these structures have been interpreted as resulting from gravitational instability on sloping surfaces. Layering may also be deformed due to high-temperature faulting, generally resulting from currents of crystal-rich magmas (Figs. 2.4a, b). Additionally, layering can locally be recognized in the field due to contrasting degree of weathering of the constituting layers (Fig. 2.4c).

An important parameter of layering is the composition of constituent minerals. Mineral compositions within individual layers can be relatively constant or not showing any obvious stratigraphic evolution (Fig. 2.5a) or change (often continuously; Fig. 2.5b) due to liquid differentiation, or varying trapped liquid fraction (Barnes 1986). Between successive layers (or between layers and homogeneous rocks), mineral compositions can be relatively similar (Fig. 2.5c; see also Conrad and Naslund 1989) or may be different as a result of various processes such as contrasted interstitial liquid fractions (Barnes 1986; Conrad and Naslund 1989), injection of new liquid in the magma chamber (e.g. individual layers crystallized from different parent magmas; (Irvine 1975), interstitial liquid migration and chemical diffusion within the crystal mush (Holness et al. 2007; Namur et al. 2013; Leuthold et al. 2014), change in intensive conditions of crystallization (Pang et al. 2008; Cawthorn and Ashwal 2009), or simply melt evolution due to fractional crystallization. In some cases, some minerals may have similar compositions in successive layers (e.g. plagioclase in Fig. 2.5d), while other minerals may have different compositions (e.g. olivine in Fig. 2.5d) due to disequilibrium crystallization or contrasted effect of the trapped liquid shift (Conrad and Naslund 1989).

Various types of layering features have been described in the petrological literature and it is also worth noting that several of them can be observed in a single layered intrusion (see Fig. 2.6 for the Skaergaard intrusion). Most of these layering features have generally been attributed to two main types of layer-forming processes: dynamic processes and non-dynamic processes. However, as noted by Irvine et al. (1998), this subdivision may be too limited and it is obvious that some

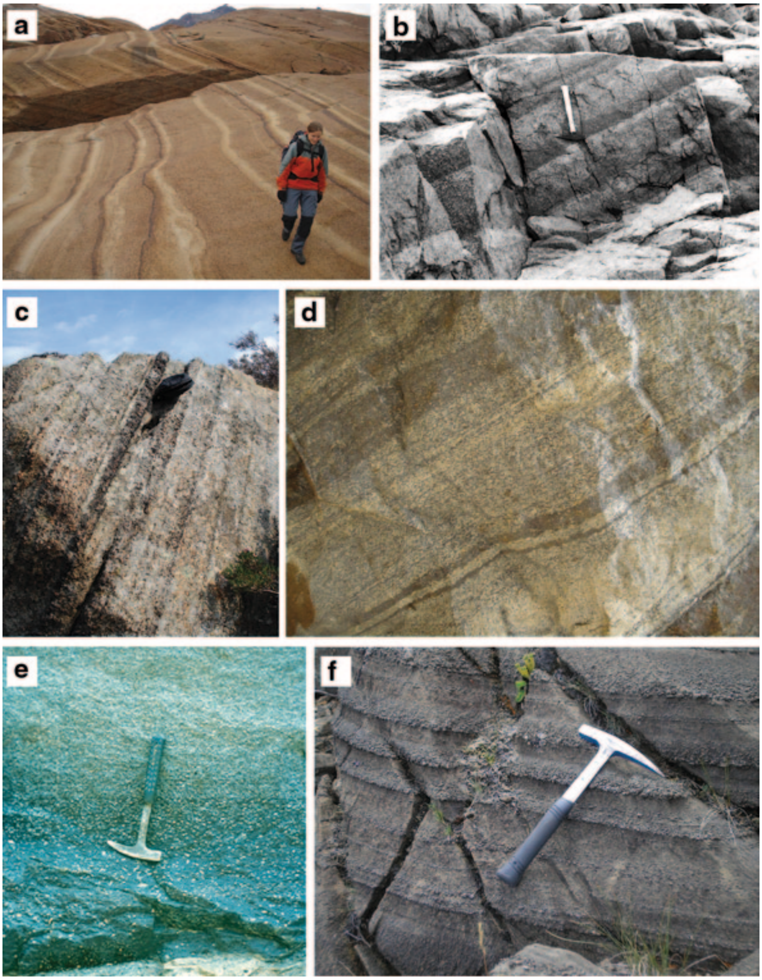

Fig. 2.2 Examples of layering features in various layered intrusions. **a** Macro-rhythmic layering in the Skaergaard UZa, Greenland. Each sequence starts with a layer enriched in Fe–Ti oxides, followed by a clinopyroxene-rich gabbro and finally a plagioclase-rich layer. **b** Modally-graded layering in the Kiglapait intrusion, *Lower* Zone troctolite north of Slambang Bay, Canada; courtesy of S.A. Morse. **c** Micro-rhythmic layering in the Bjerkreim lobe of the Bjerkreim-Sokndal intrusion, Norway. This shows a succession of layers strongly enriched in orthopyroxene and oxide minerals followed by cm- to dm-thick layers dominated by plagioclase. **d** Very-fine scale layering in the Storgangen intrusion, Rogaland province, Norway. **e** Example of modally-graded layering in the magnetite layer 1 at Magnet Heights of the Bushveld Complex, South Africa; courtesy of R.G. Cawthorn. Note the progressive increase of plagioclase mode upwards. **f** Grain-size graded layering of olivine- and pyroxene-rich layers of the Duke Island ultramafic intrusion, Alaska; courtesy of E.M. Ripley

layer-forming processes may have both a dynamic component and non-dynamic component.

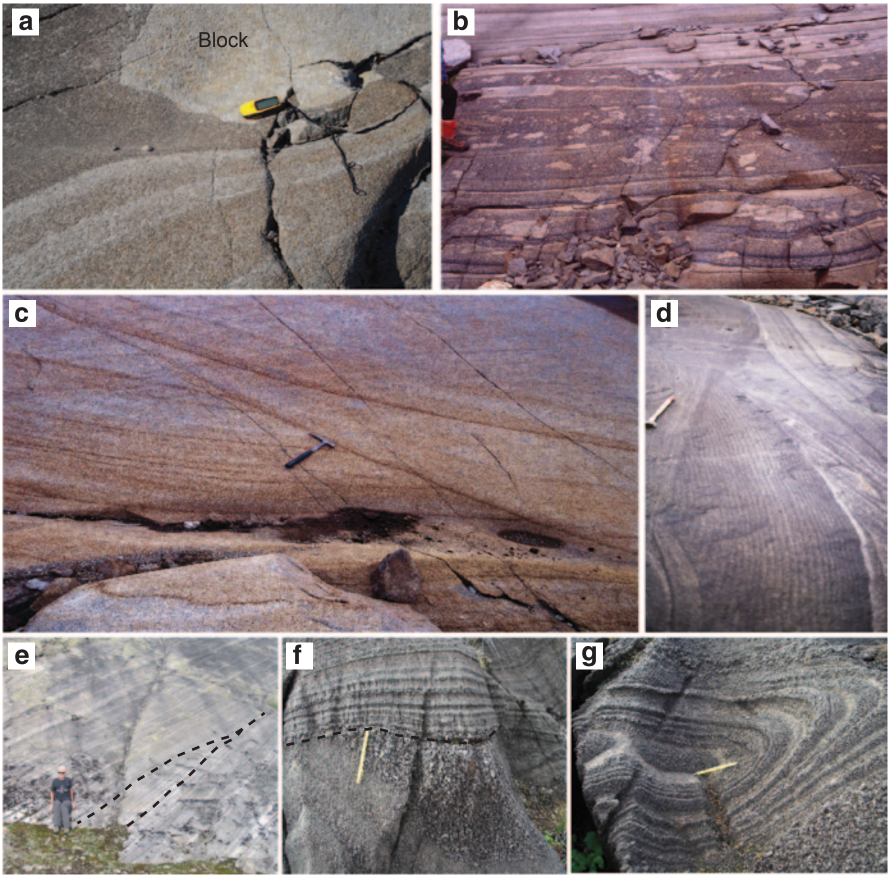

Fig. 2.3 **a**–**b** Example of deformation of igneous layering resulting from blocks falling; *Lower* Zone B of the Skaergaard intrusion on Kraemer Island (A) and *Middle* Zone on Kraemer Island, Greenland (B; courtesy of J. Koepke). **c** Modal layering in the cross-bedded belt of the Skaergaard intrusion, Uttental Plateau; courtesy of J. Koepke. **d** Sedimentary structures and inch-scale layering in Lower Series B gabbros of the Kap Edvard Holm Complex, Southern East Greenland. **e** Angular discontinuity (*dashed lines*) in layering of metagabbro from the Fongen-Hyllingen intrusion, eastern ridge of Fongen mountain. The rocks are two pyroxene gabbros that have been overprinted by amphibolite facies metamorphism but have retained their igneous texture. Many of the layers below the unconformity show modal grading, with relatively sharp, mafic-rich bases and gradually increasing proportion of plagioclase upwards; courtesy of R. Latypov. **f** Angular unconformity (*dashed line*) in the layered ultramafic sequence of the Duke Island intrusion, Alaska; courtesy of E.M. Ripley. **g** Trough feature in the layered ultramafic sequence of the Duke Island intrusion, Alaska; courtesy of E.M. Ripley

Dynamic Layer-Forming Processes

Dynamic layer-forming processes involve internal movement of melt, mush and crystals within the magma chamber and are generally most efficient near the margins of the magma chamber. Various types of dynamic processes have been pro-

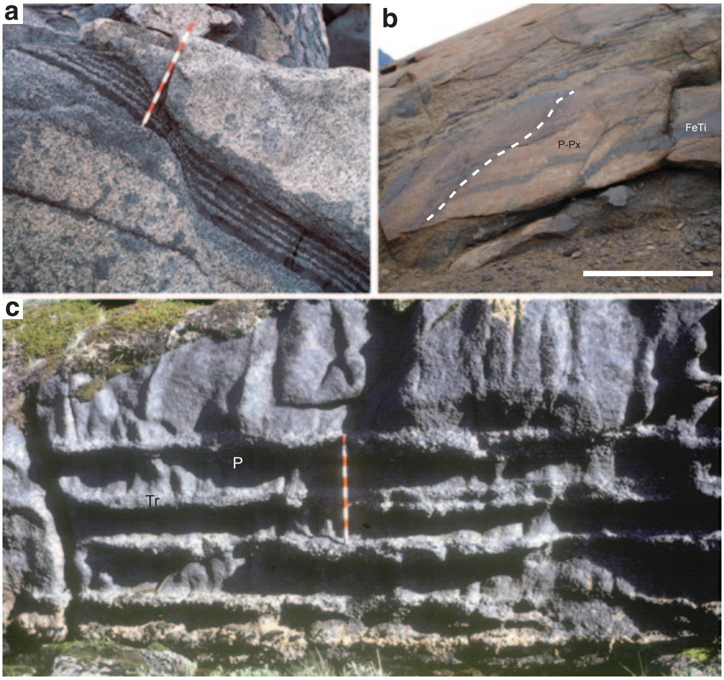

Fig. 2.4 **a** High temperature faulting disrupting the layered sequence of troctolite and peridotite in the Younger Giant Dyke Complex, western Tugtutôq, Greenland. Scale is 50cm long. Courtesy of B. Upton. **b** High temperature faulting (*dashed line*) in alternating Fe–Ti oxide-rich gabbro (*FeTi*) and plagioclase- and pyroxene-rich layers (*P-Px*) at the contact between the Marginal Border Series and the Layered Series of the Skaergaard intrusion. Skaergaard Mini-Peninsula. Bar scale is 2 m. **c** Horizontal layering in the axial zone of the Younger Giant Dyke Complex, western Tugtutôq, Greenland. In-weathering peridotite layers (*P*) alternate with thin, more resistant, troctolite layers (*Tr*). See additional details in Upton et al. (1996). Courtesy of B. Upton

posed to explain the occurrence of some types of layering in various layered intrusions (Table 2.2). Many studies describe the layering associated with flow segregation, magma currents (McBirney and Nicolas 1997), continuous, intermittent or double diffusive convection (Wager and Brown 1968; McBirney and Noyes 1979), crystal settling (Naslund and McBirney 1996) and metasomatism (Boudreau 1982; McBirney 1985). Magma mixing within the main magma body or within the crystal mush is also often considered as an important process of layering formation, especially in the case of monomineralic layers (e.g. Irvine 1975; Holness et al. 2007; Cawthorn and Ashwal 2009).

Other processes such as silicate liquid immiscibility (McBirney and Nakamura 1974; Reynolds 1985) and crystal mush contraction (Petersen 1987) have been described in the literature but have generally not been considered as significant layer-forming mechanisms. In the following, we describe examples that demonstrate that these processes in fact are of major importance for the development of layering in magma chambers (Charlier et al. 2011; Namur et al. 2012a, 2013).

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