Contrib Mineral Petrol (1992) 112:312–328

Contributions to
Mineralogy and
Petrology

Constraints on the formation of cyclic units in ultramafic zones of large basaltic chambers

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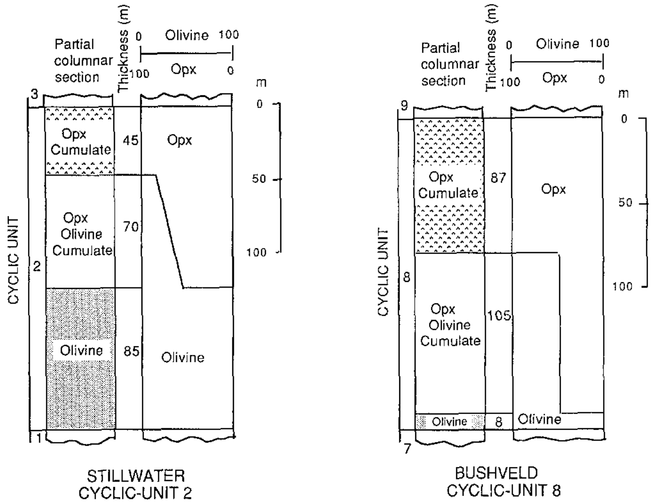
Received October 11, 1990 / Accepted June 25, 1992

Abstract. Petrological models for the formation of cyclic units in ultramafic zones at the base of large mafic layered intrusions are still few and simple. In this study, we develop simple physical constraints, such as the volume balance and density relationships between the various liquids involved. We consider the formation of an entire ultramafic zone, made of *N* cyclic units due to *N* successive reinjections. We tackle the following problems. Are all the injections of the same chemical composition? Are the *N* injections responsible for the formation of the whole magma chamber? Two end-member models are examined. In the first one, the chamber grows with each injection and does not lose any magma (variable volume model, VV). In the second one, the chamber initially forms with a large volume of magma and remains at a constant volume with subsequent reinjections of small volumes balanced by eruptions of equal volume (fixed volume model, FV). Several scenarios for the formation of a cyclic unit are envisioned. Petrological data such as thicknesses of the cumulate layers and their compositions, together with the fractionation density of the cumulate phases, allow the calculation of the density evolution, as a function of the initial density only. Thus, the model yields constraints on the density of the initial liquid, and hence on its chemical composition. The volumes of the injected magmas are calculated as well as the evolution of the densities of the different involved liquids. We apply the calculation to the specific case of the Ultramafic Series of the Stillwater complex. The multiple reinjection models require that the initial liquids densities vary between 2.71 and 2.72 g/cm^3, corresponding to MgO-rich liquids for which there is no field evidence, either in dikes or in chilled margins. They also require that the source produces liquids of different chemical composition. Thus, the evolution of the igneous system requires another, larger reservoir where differentiation takes place prior to injection into the shallower one. Contrary to the multiple reinjection models, a closed system model where crystallization proceeds in an isolated bottom layer does not require any specific value of density for the liquids, provided, of course, that it is of basaltic composition. On the negative side, such a model is not supported by any physical processes which would account for the formation of cyclic units.

Introduction

Crystallization in large basaltic magma chambers produces differentiation on a wide scale (Wager and Brown 1968) with some departure from the general trend on a smaller scale. A striking example of this zig-zag evolution is the repetition of macro-rhythmic units or cyclic units in ultramafic zones at the bottom of large gabroic layered intrusions. These units are thick layers of several tens of meters. They can be defined by their cumulate sequence which is repeated in a regular order from one cyclic unit to another (Fig. 1).



STILLWATER
CYCLIC-UNIT 2

BUSHVELD
CYCLIC-UNIT 8

Fig. 1. Stratigraphic variation of cumulus mineral in typical cyclic-units of the Ultramafic Series of the Stillwater and the Bushveld (after Jackson 1971). Although the sequence of cumulates are identical, the different sublayer thicknesses vary from one intrusion to another

Reconstruction of the plausible scenarios of crystallization from the observed cumulate sequences observed in fossil magma chambers is a difficult task. A magma chamber is a reservoir of various chemical components which are available for the formation of crystals. Simple mass balance calculations given the observed cumulate sequences could be made, however they require various assumptions on the different physical processes involved. For a complete model, the volume of the reservoir and that of each new batch of magma must be specified at all times. A further complexity is due to the poor knowledge of the initial magma(s) composition.

The difficulty with igneous complexes of such large dimensions is to identify all the processes which affected them, and in particular the relationships between the source and the reservoir. One important question is whether the differentiation is taking place only in the chamber or in a deeper reservoir. Stated differently, the question is whether or not the source magmas are of uniform and constant chemical composition. Another question is how the chemical constituents are introduced in the chamber or how such large reservoirs form. The presence of cyclic units in ultramafic zones offers important clues.

The purpose of this paper is to derive constraints on the physical models. I will consider the implication of multiple injections which lead to the formation of these cyclic layers. Each unit is formed after a reinjection of a new magma at the bottom of the chamber. This model has been proposed after the petrological studies of different intrusions, for example the Bushveld (Lombaard 1934) and the Rhum (Brown 1956) and is referred to in the following as the multiple reinjection model (MR). Several physical models for this process can be found in the literature (Huppert and Sparks 1980; Campbell and Turner 1989).

In this work, we focus on volume and density balances. Consider an ultramafic zone comprising N cyclic units. The MR model has been applied to one cyclic unit in the Stillwater (Raedeke and McCallum 1984) and the Rhum (Tait 1985). The formation of the *entire* ultramafic zone with up to 20 injections has strong implications on how the chamber forms. To study the chemical budget of liquid and solid for a whole intrusion, it is essential to know the amount of liquid introduced and ejected, as well as the composition. Suppose that a reinjection of a layer of thickness $H = 190$ m (Tait 1985) is needed to explain a cumulate sequence of a thickness approximately 65 m, and that this sequence is observed $N = 20$ times. The cumulative thickness of the reinjected magmas is 3800 m after the formation of an ultramafic zone. This thickness is large and of the same order of magnitude than the chamber itself. However, it is smaller and hence indicates that other injections are required to finish the chamber. A key point is then that the remaining liquids must be of a different composition to explain the other cumulate sequence. Thus, the generation of the cyclic units cannot be studied without considering how the whole chamber evolves.

In this work, we develop simple physical constraints, such as the volume balance and density relationships between the various liquids involved in the MR model. We consider the formation of an entire ultramafic zone (herein referred to as UZ in the following), made of N cyclic units due to N successive reinjections. We tackle the following problems. Are all the injections of the same chemical composition? Are the N injections responsible for the formation of the whole magma chamber? The volumes (or thicknesses) of the reinjected magmas are calculated and it is shown that the liquids needed for the reinjections must vary in a specific manner. The plan is as follows. Composition is discussed as a petrological data in the second section. Given the petrological data of UZ (thicknesses and cumulate compositions), the reinjected thicknesses are calculated as a function of the reinjected magma density in the third section. Application to the specific case of the Ultramafic Series of the Stillwater complex is made in the fourth section. Discussion of the MR models is made in the final section.

Petrological constraints

The formation of a large magma chamber

The formation of UZ by N ($N > 10$) injections of magma always leads to the formation of a large chamber. Thus, one must consider how the chamber volume evolves during UZ formation. The reinjected magma is called liquid 1 and the resident magma liquid 2. Two end-members

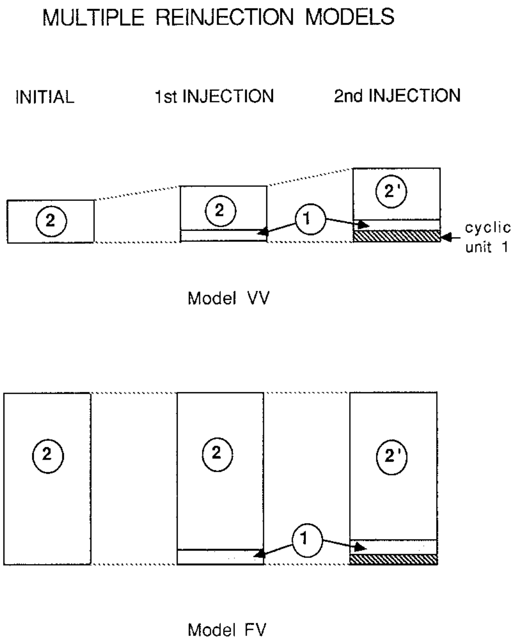


Fig. 2. Schematic representation of the two MR models. The chamber grows with each reinjection in *model VV*. The chamber thickness remains constant in *model FV* and new magma is added to the chamber at the same rate as old magma is lost from tapping at the top. The reinjected liquid at the base of the reservoir is a hot and dense liquid, referred to as *liquid 1*. Its composition is constant and its thickness varies with successive reinjections. The upper reservoir contains a colder but lighter liquid, referred to as *liquid 2*. This liquid evolves and becomes *liquid 2'* after mixing with the residual *liquid 1* and further opx crystallization

Table 1. Different cases for the MR models that can account for the formation of a cyclic unit made of 2 sub-layers. The liquids are indicated from which the different primary phases form. The mechanisms required are specified

Case	1	2	3	4	5
Liquid 1	Olivine	Olivine	Olivine Opx	Olivine Opx	
Liquid 2	Olivine Opx	Opx	Olivine		Olivine Opx
Mechanism	Instability Mixing Reinjection	Instability Mixing Reinjection	Instability Mixing Reinjection	Reinjection	Differentiation in a closed system
VV model	VV1	VV2	VV3		

can be defined (Fig. 2). In the first one, the chamber grows with each injection and does not lose any magma. It will be called variable volume model (VV). Alternatively, the chamber initially forms with a large volume of magma and remains at a constant volume with subsequent reinjections balanced by eruptions of equal volume. This model will be called fixed volume model (FV). Note that in the following, it will be assumed that the horizontal cross section of the chamber remains constant with height. Hence, the thickness and volume are proportional to each other.

How are constrained the MR models?

A cyclic unit is defined by a sequence of cumulate which is repeated in a regular order from one cyclic unit to another. For the sake of simplicity, I assume that a cyclic unit is composed of 2 sublayers, one at the base, essentially formed by cumulate crystals 1, and one at the top formed by cumulate crystals 2. Without losing the generality of the arguments presented here, I assume that crystals 1 and 2 are respectively olivine and opx whose composition must be specified. The sublayer at the base will be called a dunite, and the one at the top a bronzitite.

In the MR models, liquid 1 is introduced in the chamber containing some liquid 2. We have to examine which liquid the olivine and opx crystallize from. There are five different scenarios (Table 1). For example, all olivine crystals may crystallize only from the liquid 1 (no. 2) or from both liquids (no. 1). Alternatively, both olivine and opx may crystallize only from the liquid 1 (no. 4). Case no. 5 could also be considered although it may not require the injection of liquid 1. Dynamically, all these scenarios are not equivalent. In all cases (except no. 5), the important point is to allow the formation of the dunite or part of it from liquid 1. This requires a stable liquid 1 as well as its residual liquid below the residual liquid 2. If this is not the case, there is some mixing before the complete formation of the dunite. Hence, densities of the different liquids involved are not independent parameters. Further, density of the resident magma liquid 2 is modified after mixing between the residual liquid 1 and resident liquid 2 and further opx or ol + opx crystallization. Hence, the formation of a *single* unit requires one injection followed by some mixing and implies some evolution of the *entire* reservoir.

In order to examine the plausible scenarios, one has to perform mass balance calculations and calculate the different residual liquid densities. Thus, petrological data, such as cumulate and magma compositions, as well as observed different thicknesses (chamber, cyclic units, sublayers) have to constrain the models. The key parameter of dynamical MR models is density which is a function of the composition of the liquids. Hence, composition of the different liquids and crystals involved constrains physical modelling.

Composition

Consider first the parental liquid composition. Its determination is fraught with difficulty. As an example, the Skaergaard has been extensively studied but the composition of the initial liquid is still being discussed (Hunter and Sparks 1987, 1990; McBirney et al. 1990). For the Stillwater complex, different liquids have been proposed (e.g., Hess 1960; Longhi et al. 1983; Helz 1985).

Two methods can be used in order to find reasonable candidates for parental liquids. The first one consists in finding chilled margins, or precursor dikes and sills, where parental magmas have been preserved. Melting experiments can then be performed in order to find the crystallization path at the same P, T, and f_{O_2} conditions as in nature and compare it to the observed cumulate sequence in the field. Helz (1985) used this method for the Stillwater, and proposed the mafic norite or the high-MgO gabbro-norite (with MgO varying between 9.64 and 13.9 wt.%). Irvine and Sharpe (1982) reported some very MgO-rich liquid in chilled margins of Bushveld dikes (MgO = 32.31 wt.%) and suggested that a liquid of similar composition could also be a parental magma for the Stillwater. However, Helz (1985) noted that no field evidence has been found in the Stillwater for liquids containing much more than 15–16% MgO. The crystallization path could also be calculated, for example with the method of Ghiorso (1985). Application of the SILMIN program to the mafic norite (Helz 1985, Table 2) does predict the observed crystallization path (ol, opx, opx + an) at a pressure between 2.5 and 7 kb. These calculations show that only 2–3% of Fo_{88} is produced before opx appears on the liquidus. Imagine a 20 m thick olivine layer where the olivine mode is 70%. Its formation requires crystallization of a layer of thickness ≥ 467 m. It only takes 20 injections with the same volume to form the whole complex. This is close to the number of cyclic units. Thus, the implication is that the cyclic units may reflect the filling of the complex.

Table 2. Formation of different residual liquids after crystallization of a layer of liquid *a* of thickness 300 m

Liquid	*a*	*b*	*c*	*d*	*e*	*f*	*g*
SiO_2	50.20	50.70	50.71	50.32	50.67	50.69	50.16
TiO_2	0.22	0.23	0.23	0.25	0.24	0.24	0.26
Al_2O_3	11.20	11.75	11.75	12.47	11.89	11.88	12.67
Fe_2O_3	0.93	0.98	0.97	1.03	1.00	1.00	1.09
FeO	12.30	12.20	12.20	12.32	12.28	12.28	12.61
MnO	0.26	0.27	0.27	0.29	0.28	0.28	0.31
MgO	13.90	12.35	12.35	11.10	11.95	11.95	10.37
CaO	8.29	8.70	8.70	9.23	8.80	8.80	9.41
Na_2O	0.64	0.67	0.67	0.71	0.67	0.67	0.71
K_2O	0.06	0.06	0.06	0.07	0.06	0.06	0.07
Cr_2O_3	0.02	0.02	0.01	0.01	0.02	0.00	0.00
P_2O_5	0.05	0.05	0.05	0.06	0.05	0.05	0.06
H_2O+	1.22	1.28	1.28	1.36	1.31	1.31	1.44
H_2O-	0.09	0.09	0.09	0.10	0.10	0.10	0.11
Liquid density (g/cm^3)	2.7092	2.6997	2.6995	2.7007	2.6998	2.6997	2.7037

Liquid *a* is the Mafic Norite given in Helz (1985, Table 2) with 0.02 Cr_2O_3 added. Liquid *b*, *c* and *d* are respectively the residual liquids obtained after formation of the primary phases in the dunite, chromitite and bronzitite layers. The porosity in each sublayer is equal to 35%. Thickness, mode and cumulate compositions are those given in Table 3a. Liquids *e*, *f*, and *g* are respectively the residual liquids obtained after complete crystallization of the dunite, chromitite and bronzitite layers. In that case, the porosity in each sublayer is equal to 0%. Mode, thickness and composition are those indicated in Table 3b

The second method consists in calculating the parental magma composition from the interpretation of geochemical variations in cumulus rocks. This is difficult when working with adcumulates, where no intercumulus phases representative of the parental liquid remain. If the crystals are orthocumulates, the interstitial minerals do not truly represent the closed system crystallization products of the trapped intercumulus liquid (e.g., Irvine 1980). Phase equilibria and fractional or equilibrium crystallization cannot account simply for the observed cumulate sequences, since there is some exchange between residual liquids in the cumulate pile and the reservoir (Tait 1985; Langmuir 1989). Accurate account of volumes of transferred residual liquids have to be known before phase equilibria can apply.

Consider now the cumulate compositions. This parameter has no unique value for a single unit, however, the variations are slight (Jackson 1970). In case of the Ultramafic Series of the Stillwater, Raedecke and McCallum (1984) report that the Mg/Mg+Fe ratio increases from unit 1 to unit 11 and then remains approximately constant through the rest of the series. Variations are small (between Fo_{86} and Fo_{84} for olivine and En_{86} and En_{84} for opx for the whole Ultramafic Series) and cumulates composition can be considered as constant.

In summary, any hypothesis on the initial liquid composition implies one on density, and hence on the dynamics of the reinjection scenario. Further, they also have implications for the liquid volumes involved. The idea of this work is to show that petrology constrains physical models, although the initial liquid is not known. The UZ formation is considered here as an inverse problem in order to find the density ρ_1 of the injected magma. Here, it is considered as an input parameter which in turn, will lead to some constraints on the liquid composition.

Fractionation density

In the MR models, and for example in model VV2, the crucial point is to maintain the lower liquid 1 stable until the complete formation of the dunite has occurred. Hence, the important parameter is the density of the residual liquid. Although the exact liquid composition is not known, mass balance calculations can still be made, given the cumulate pile thickness and the liquid density from which it crystallizes. For this, the crystal fractionation density (Sparks and Huppert 1984) of each cumulate has to be calculated and compared to that of the liquid 1 and 2. We recall here that the crystal fractionation density is the density of the components in the fluid which have been selectively removed by crystallization. This is an imaginary density which is differ-

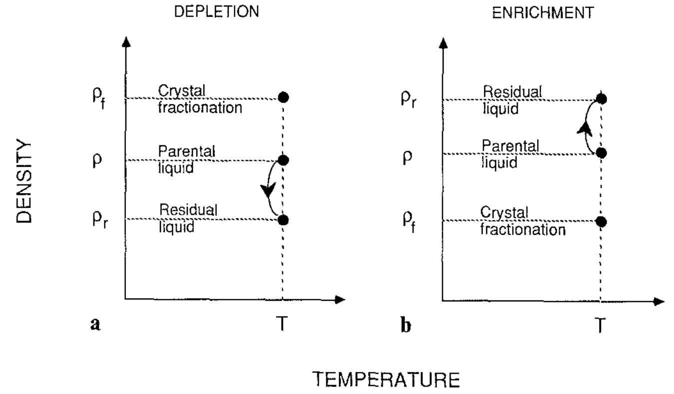


Fig. 3a, b. Schematic representation of liquid density evolution, at constant temperature, during the crystallization of a cumulate of crystal fractionation density ρ_f. **a** If ρ_f is larger than the *parental liquid* density ρ, the *residual liquid* is depleated and its density ρ_r becomes smaller than that of the *initial liquid*. **b** The reverse trend is observed when $\rho_f < \rho$

ent from that of the crystal itself. Removal of a crystal, whose value of fractionation density is larger than the density of the parental liquid, causes the density of residual liquid to decrease (Fig. 3). The opposite trend is observed when the fractionation density is less than that of the magma.

Mass balance calculations

Mass balance calculations are also performed in this work. There are basically three primary cumulate phases in UZ: olivine, opx, both MgO-rich crystals, and chromite. Crystallization of these phases changes all the component contents, however, the larger variations are those of MgO. As an example, mass balance calculations have been performed for the formation of a single unit, taking an initial magma composition of the mafic norite given by Helz (1985, Table 2) and reported here in Table 2 as liquid *a*. It is assumed that all crystal phases form in a 300 m thick layer of magma. A cyclic unit is made of three sublayers, a dunite, a chromitite and a bronzitite. Consider only the primary phases and the mode, cumulate compositions, and thicknesses indicated in Table 3a. The calculation shows that the important parameter for the evolution of liquid composition is the MgO content. Thus, it will be considered as the single input parameter for the composition, although composition of the initial liquid is not precisely known.

Table 3a. Mode, composition and thickness of each sublayer in a cyclic unit of thickness 45 m, considering only the primary phases

Mode	Composition	Dunite	Chromitite	Bronzitite
Olivine	Fo_{85}	100.0	0.0	0.0
Opx	En_{85}	0.0	0.0	100.0
Chromite	$(Cr_{60}Al_{33}Fe_{7})_2$-$(Mg_{46}Fe_{54})O_4$	0.0	100.0	0.0
Residual liquid		*b*	*c*	*d*
Crystal line layer thickness (m)		19.9	0.10	25.0

Table 3b. Mode, composition and thickness of each sublayer in a cyclic unit of thickness 45 m, considering the primary and secondary phases. The mode is the average mode given in Jackson (1961, Table 1)

Mode	Composition	Dunite	Chromitite	Bronzitite
Olivine	Fo_{85}	72.0	3.9	0.0
Opx	En_{85}	18.0	4.2	83.5
Chromite	$(Cr_{60}Al_{33}Fe_{7})_2$-$(Mg_{46}Fe_{54})O_4$	0.0	80.6	0.0
Plagioclase	An_{75}	7.2	6.2	12.30
Augite	$(Ca_{38}Mg_{54}Fe_{8})SiO_3$	2.8	5.1	4.1
Residual liquid		*e*	*f*	*g*
Crystal line layer thickness (m)		19.9	0.10	25.0

The crystallization of the trapped residual liquid in the cumulate pile produces some secondary enlargement of the primary crystals and the appearance of interstitial crystals of different phases. However, the effect on the density and composition is slight. Residual liquids have been calculated after crystallization of the dunite, chromitite and bronzitite, taking into account both effects (Table 2, e–g). The mode and cumulate composition of each sublayer (Table 3b) are those given in Jackson (1961). Compare the density and composition obtained for liquid *b* and *e* or *d* and *g*. The observed trend for the density and the chemical components are not modified, although the values are slightly different. Hence, crystallization of primary crystals will only be considered here.

Finally, crystallization of chromite modifies the density. However, since the chromitite layers are usually very thin, the variations are slight. As an example, 0.02% Cr_2O_3 has been added to the composition given by Helz (1985) in order to perform mass balance calculations on the chromitite layers, and to form a 0.1 m thick chromite layer. This thickness is the maximum that can be formed in a 300 m reservoir, given the initial liquid composition. Density has also been calculated (compare *b* and *c*, Table 3b). Crystallization of this thin chromite layer has a very small influence on the density of the residual liquids. Thus, chromite layers will be neglected in the following.

Physical constraints

Consider the formation of UZ comprising *N* units in the MR models. In the following, the *N* reinjected magmas are considered to have a constant composition, hence constant density. There are several scenarios for the formation of the dunite and the bronzitite (Table 1). First, I will present in detail case no. 2 where all the dunite is formed after crystallization of liquid 1 and all the bronzitite after that of liquid 2. Other cases will be discussed in later sections.

Evolution of the liquids (internal constraints)

In the MR models, liquid 1 is initially heavier that the resident magma and ponds at the bottom of the chamber, or just above the existent crystallized pile. The two liquids do not mix and, following reinjection, evolve separately. While layer 1 cools, olivine crystals form and the residual liquid becomes lighter. Its density eventually becomes equal to that of liquid 2, which triggers mixing with liquid 2. This process is instantaneous on a large time-scale. After mixing, crystallization of liquid 2 (opx) ensues until the next reinjection.

The key feature of the MR model is to maintain the lower liquid 1 stable until the complete formation of the olivine crystal pile. The exact mechanism is not crucial; crystals may remain in suspension due to strong convective motions and then settle (Huppert and Sparks 1980; Martin 1990; Koyaguchi et al. 1990), leaving a depleted liquid 1 which is gravitationally unstable; alternatively compositional convection may develop in the lower cumulate pile (Morse 1986, 1987; Worster 1986; Helz et al. 1989; Tait and Jaupart 1989, 1992; Huppert 1990).

The MR models are constrained by the observed dunite and bronzitite thicknesses, since the instability and injection mechanisms occur respectively, when the olivine and opx crystal piles that have been formed, have the required thickness. The MR model involves different liquids. Their residual liquids produced by crystallization have slightly different composition, hence different density. Thus, the model has strong implications for their densities.

The essential feature of the following calculations is the density evolution of the liquids during UZ formation. Consider the formation of the first cyclic unit. Liquid 1 at the chamber bottom is initially denser than the overlying liquid 2. As layer 1 cools and crystallizes, dense mineral phases (olivine) are formed and the density of the depleted liquid 1 decreases (Appendix A.1). When instability occurs, residual liquid 1 and liquid 2 have equal density. Further opx crystallization of liquid 2 modifies the density of the residual liquid in layer 2. Note that residual liquid 2 is liquid 2 before the second injection.

In order to form the second dunite layer, the instability process must be repeated. This implies that the residual liquid 1 density must again become equal to that of the overlying liquid 2. This condition requires a different residual liquid 1 density, since liquid 2 density has changed. Thus, the residual liquid 1 properties (density and composition) are bound to vary through the formation of UZ (Table 4). It also requries a reinjected thickness $H_1(2)$ different from the first one $H_1(1)$ (see further).

This mechanism also implies that composition of the resident liquid 2 varies through time during UZ formation. Liquid 2 is no longer the magma that was in the chamber before the first injection. It has evolved because of mixing with residual liquid 1 and further opx crystallization. Although the evolution may be slight in case of the FV model, it does exist. The parameters of liquid 2 and its residual liquid (density, composition, and layer 2 thickness $H_2(k)$) also evolve with the successive number k of reinjections. They are listed in Table 4.

Table 4. List of symbols in the multiple reinjection models

Quantity	Layer 1		Layer 2	
	Symbol	Value	Symbol	Value
Density (g/cm^3)				
Liquid	ρ_1	P	$\rho_2(k)$	C
Residual liquid	$\rho_{1r}(k)$	C	$\rho_{2r}(k)$	C
Fractionation	ρ_v	2.93	ρ_x	2.70
Thickness				
Liquid	$H_1(k)$	C[a]	$H_2(k)$	C[a]
Cumulate pile	$d_1(k)$	P	$d_2(k)$	P
MgO content				
Liquid	x_1	P	$x_2(k)$	C[a]
Residual liquid	$x_{1r}(k)$	C	$x_{2r}(k)$	C

C = calculated; P = input parameter

[a] The initial value ($k=1$) is a parameter

Density evolution

The density of the residual liquids depends on the quantity of crystals formed before instability or reinjection occurs. One of the important questions is to determine whether the reinjected liquid composition (i.e., density) can remain constant or changes during the formation of UZ. The assumption of a constant liquid 1 density ρ_1 has been made here in order to show that the density evolution of the different liquids is entirely determined.

Because the liquids are evolving throughout the formation of UZ, their densities have to verify some conditions required for the validity of the MR models. In order to compare solely the effects of crystallization on the density, calculations are performed at a fixed temperature T. A reference value has been choosen as $T=1280$ °C, its exact value has no importance on the implications of the following calculations.

All the conditions can be written simply and are represented on Fig. 4. First, olivine crystallization and sedimentation leave a light residual liquid in layer 1 (Sparks et al. 1980). Thus the olivine fractionation density ρ_v has to be greater that the initial liquid 1 density:

$$\rho_v > \rho_1 \qquad (1)$$

The Fo_{85} olivine fractionation density is equal to 2.93 g/cm^3. Thus, it is an obvious, yet useful constraint, as demonstrated later. Second, gravitational instability occurs when the residual liquid 1 and the overlying liquid 2 have equal densities. The following relation has therefore to be satisfied after each reinjection:

$$\rho_{1r}(k) = \rho_2(k) \qquad (2)$$

where $\rho_{1r}(k)$ and $\rho_2(k)$ are respectively densities of the depleted liquid 1 and overlying liquid 2. Third, the residual liquid in layer 2 after opx crystallization represents the liquid 2 before the next $(k+1)$ reinjection. Its residual density is therefore:

$$\rho_{2r}(k) = \rho_2(k+1) \qquad (3)$$

Equations (2) and (3)show that the evolution of the different liquid densities can be followed by considering only one of them, for example the liquid 2 density.

Considering (2) and (3), it is clear that their evolutions depend on the En_{85} opx fractionation density, noted ρ_x and equal to 2.70 g/cm^3. There is no evolution of liquid 2 density with opx crystallization when:

$$\rho_2(k) = \rho_x \qquad (4)$$

This defines a critical value of liquid 1 density, noted ρ_c whose value can be found in Appendix A. Thus, there are two behaviors for the evolution of the liquid 2 den-

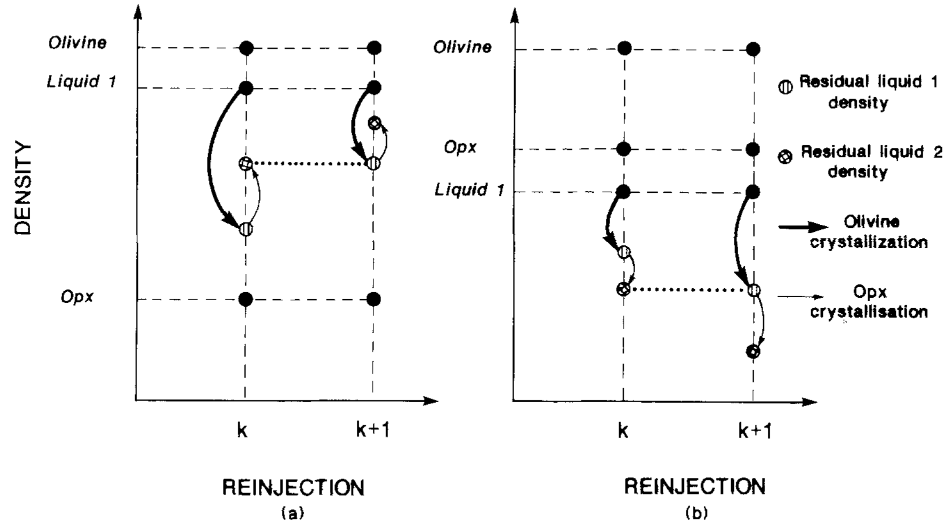


Fig. 4a, b. Schematic representation of the different liquids density evolution during formation of cyclic unit k and $k+1$. The *olivine* and *opx* fractionation density are also reported on an arbitrary scale. All densities are calculated at equal temperature. In all cases, the olivine fractionation density ρ_v is larger than the liquid 1 density ρ_1. Gravitational instability occurs when the residual *liquid 1* and the overlying *liquid 2* have equal density, thus, the residual *liquid 1* density is that of *liquid 2* before mixing. After *opx crystallization*, the residual *liquid 2* represents the *liquid 2* after the reinjection $k+1$. **a** For $\rho_1 > \rho_c$, note the increase of *liquid 2* density with successive reinjections. **b** For $\rho_1 < \rho_c$, the reverse trend is observed

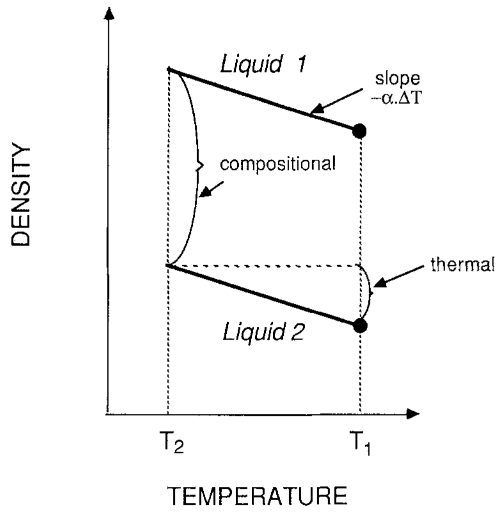


Fig. 5. Schematic representation of compositional and thermal effects on the density. *Liquid 1* is emplaced at temperature T_1 and is hotter than *liquid 2*. *Liquid 1* (or 2) has a density ρ_1 (or ρ_2) calculated at T_1. The *diagonal line* represents the thermal evolution of density and has a slope of $-\alpha.\Delta T$. The compositional effects have to be larger than thermal ones for *liquid 1* to remain stable after reinjection

Table 5. Petrological data observed in an ultramafic zone

Quantity	Symbol	Stillwater[a]
Thickness		
Chamber height	H_t	Calculated
UZ total thickness (m)	H_0	675
Number of cyclic units	N	15
Olivine sublayer thickness	$d_1(k)$	15–25 m
Opx sublayer thickness	$d_2(k)$	20–30 m
Number of sublayers		2
Composition		
Initial MgO content (wt%)	x_0	Parameter
Olivine composition		Fo_{85}
Opx composition		En_{85}
Olivine sublayer mode		100
Opx sublayer mode		100
Average initial porosity	λ	35%

[a] Peridotite Member of the Ultramafic Series

sity $\rho_2(k)$ as a function of reinjection number k (Fig. 4). For ρ_1 larger than ρ_c, opx crystallization yields a denser residual liquid and the liquid 2 density increases uniformly (Fig. 4a). The opposite trend is observed in case of $\rho_1 < \rho_c$ (Fig. 4b).

Further, since residual liquids are considered here, it has to be checked that temperature effects on the density are always smaller than the compositional ones. The temperature contrast between liquid 1 and liquid 2 is noted ΔT. For the MR model to apply, liquid 1 must remain stable after reinjection. Thus, the compositional effect on the density has to be greater than the thermal one (Fig. 5), that is:

$$\rho_1 - \rho_2(k) > \rho_1 \alpha \Delta T \qquad (5)$$

where α is thermal expansion coefficient and ρ_1 and $\rho_2(k)$ calculated at equal T. In case of small evolution of densities, this can be an important constraint (see later).

Finally, these equations allow the determination of the reinjected thickness $H_1(k+1)$, given the data of the observed cumulate layers thicknesses (see Appendix A). It is equal to:

$$H_1(k+1) = (1-\lambda)\, d_1(k) \frac{[\rho_v - \rho_2(k)]}{[\rho_1 - \rho_2(k)]} \qquad (6)$$

where $d_1(k)$ is the thickness of the olivine cumulate pile and λ the porosity. This equation shows that this variable cannot be fixed a priori, since it depends on the evolution of the liquid 2 density.

The evolution of the upper reservoir 2 is entirely determined by this set of equations. The calculations are constrained by the set of the petrological data listed in Table 5, and input parameters indicated in Table 4 by symbol P. Those are the density ρ_1 of the reinjected magma 1, the initial reinjected thickness $H_1(1)$ and the initial thickness of the chamber $H_2(1)$. All other variables are calculated (symbol C).

Reinjected thickness H_1 (k)

The reinjected thickness $H_1(k)$ is calculated from (6) and evolves similarily in model VV and FV. Figure 6 represents the variation of $H_1(k)$ with k for various values of density ρ_1 and keeping all the other parameters constant. The initial value $H_1(1)$ is an input parameter. Note that the single value of ρ_1 determines entirely the evolution of $H_1(k)$. This is a very important result.

$H_1(k)$ decreases uniformly when $\rho_1 \sim \rho_c$, the variations being larger when $\rho_1 < \rho_c$. When $\rho_1 > \rho_c$, the variation of $H_1(k)$ changes and begins to increase. Its increase becomes drastic when $\rho_1 = 2.8$ g/cm^3 for the set of parameters of Fig. 6 and the calculation eventually diverges for larger values of ρ_1. This is because ρ_1 tends towards the olivine fractionation density ρ_v. Consider the end-member of $\rho_1 = \rho_v$. In that case, the fractional crystallization of olivine has no effect on the liquid 1 density. Equations (2) and (3) must be satisfied so that all densities remain equal and greater than the opx fractionation density. As crystallization of opx would change the liquid 2 density, equations cannot be verified for cycle 2 and the calculation diverges. Note that this limit case is only studied for the understanding of the behavior of the model, since a density $\rho_1 = \rho_v$ does not represent that of a liquid.

In model VV, the final chamber thickness H_t after the formation of UZ is calculated. It is equal to:

$$H_t = H_2(1) + \sum_{k=1}^{k=15} H_1(k) \tag{7}$$

It increases with increasing liquid 1 density and eventually diverges for value of ρ_1 close to ρ_v. Suppose now that H_t is given as an input parameter in model VV for the following inverse problem. The total chamber that has been formed has a thickness H_t. The density ρ_1 can be calculated as a function of the initial layer 1 thickness $H_1(1)$ (Fig. 7). It decreases monotonically for an increasing initial thickness $H_1(1)$, the variations being larger for smaller H_t. To understand this behavior, consider first a small initial thickness $H_1(1)$ and a large chamber thickness H_t. Since H_t is much smaller than $N \times H_1(1)$, the reinjected thicknesses must increase with subsequent reinjection. Their variations have to be important, thus, the density ρ_1 must be large (Fig. 6). On the contrary, when $H_1(1)$ is large and $H_t \leq N \times H_1(1)$, the reinjected thicknesses $H_1(k)$ have to decrease. Thus, the density ρ_1 has to be smaller than the critical density ρ_c (Figs. 6 and 7).

Finally, one useful parameter is the fraction crystallized in layer 1. It varies with reinjected thickness and dunite layer thickness. It can be defined as:

$$F(k) = \frac{(1-\lambda)\, d_1(k) \rho_v}{H_1(k) \rho_1} \tag{8}$$

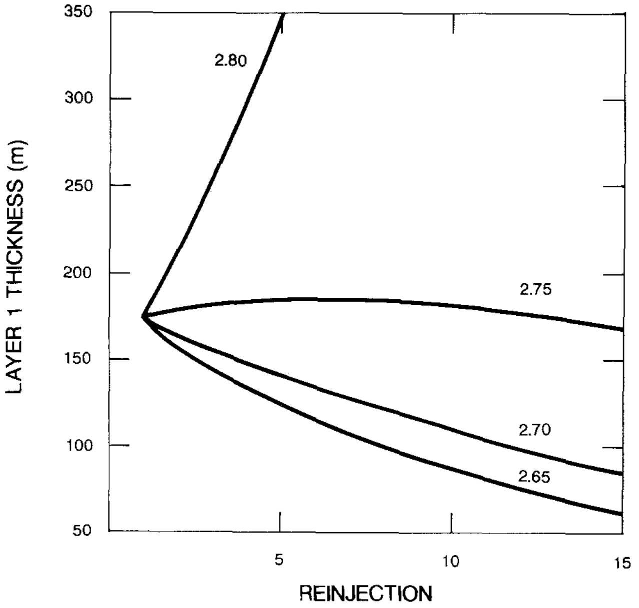


Fig. 6. Evolution of the reinjected liquid 1 thickness $H_1(k)$ with successive reinjections for various values of the liquid density ρ_1 in model VV2. The petrological data are those given in Table 5 and $H_1(1) = 175$ m. $H_2(1) = 260$ m

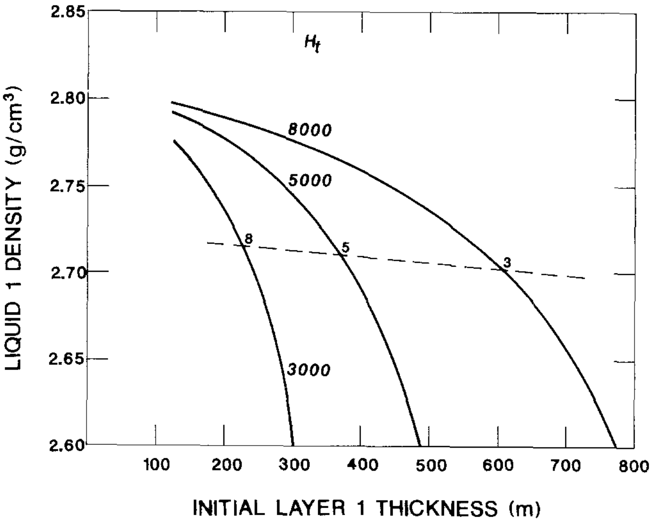


Fig. 7. Liquid 1 density as a function of the initial layer 1 thickness for various total chamber thicknesses H_t (in m). The *dotted line* represents the values of the critical density ρ_c. The amount of fraction crystallized is also indicated along curve

hence, is inversely proportional to $H_1(k)$. It increases (or decreases) for decreasing $H_1(k)$, i.e., for $\rho_1 < \rho_c$ (or $\rho_1 > \rho_c$). Thus, this parameter is roughly constant for a liquid 1 density close to ρ_c. The fraction crystallized at $\rho_1 = \rho_c$ decreases for increasing chamber thickness H_t and is indicated along the dotted line on Fig. 7.

In the model FV, there are no such constraints to form a given thickness H_t. However, the relationships between densities and thicknesses are the same as in model VV. By definition of model FV, the chamber must be tapped from the same volume than that of the reinjected liquid. Since erupted volumes are small compared to chamber volumes, the reinjected thicknesses have to be small, thus, the liquid 1 density has to be smaller than ρ_c.

In summary, volumetric considerations give some constraints on the density of the reinjected liquids.

Other scenarios in models VV

Other scenarios for the formation of a cyclic unit are now examined (Table 1, model VV1 and VV3). In these models, instability occurs in a different state of formation of the dunite or bronzitite. The same behavior for the evolution of reinjected thicknesses is observed for all models VV. For $\rho_1 > \rho_c$ (or $\rho_1 < \rho_c$) reinjected thicknesses decrease (or increase). Let us consider, in further detail, model VV1 where olivine crystallizes from liquid 1 and then again after mixing from liquid 2. The final dunite layer thickness is held constant and equal to that in model VV2 where all olivine crystallizes from liquid 1. The effect on the residual liquid 1 density is smaller than in model VV2, since a smaller amount of olivine crystallizes from liquid 1. Thus, liquid 2 density has to be closer to liquid 1 density than in model VV2 in order to satisfy the model (Eqs. 2 and 3). Since the compositional effect is smaller in model VV1 than in VV2 (Eq. 5), the maximum temperature contrast ΔT between liquid 1 and 2 allowed for stability of liquid 1 is also smaller. Further, it can be shown that the reinjected thicknesses, hence the final chamber thickness H_t, are smaller than in model VV2. Therefore, in order to build the same final chamber thickness H_t, for a given density ρ_1, the reinjected thicknesses are always larger in model VV1 than in VV2 (Fig. 8). The maximum ΔT allowed in both models is also indicated along the curves. Note that it is small (<24 °C) in model VV1. We discuss this point later.

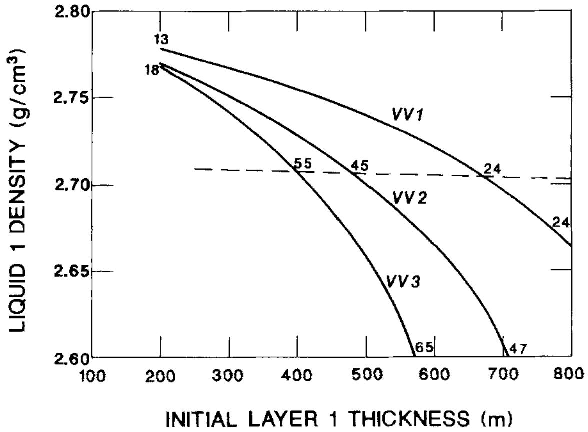


Fig. 8. Liquid 1 density as a function of the initial layer 1 thickness for the different models *VV* where $H_t = 8000$ m. The *dotted line* represents the values of the critical density ρ_c. The maximum ΔT allowed for stability of liquid 1 after reinjection is also indicated

Model VV3 is now considered in which opx crystallises from liquids 1 and 2. This implies a larger effect on the residual liquid 1 density than in model VV2, hence ΔT can be larger. For a given density ρ_1, the initial thickness is larger than in model VV2. Note also that the formation of a cyclic unit is not possible in model VV3 if olivine crystallization is followed by opx crystallization, in case of $\rho_1 > \rho_c$. Opx crystallization produces as increase of residual liquid 1 density. Since its density must be equal to that of liquid 2, instability occurs after olivine crystallization.

In summary, for given H_t and density ρ_1, the initial thickness $H_1(1)$ in model VV3 is smaller than in model VV2, which in turn is smaller than in model VV1 (Fig. 8). Note that the maximum ΔT allowed decreases from model VV3 to VV2 to VV1.

Mass balance calculations

We consider now the composition of liquid 2. It is modified by mixing between the residual liquid 1 and liquid 2. Further opx crystallization produces some residual liquid 2. Since the reinjected magma and the cumulate layers thicknesses evolve with successive reinjections, the composition of the liquid 2 as well as that of the residual liquids 1 and 2 also vary. The initial MgO content of the chamber before the first injection is also an input parameter, denoted $x_2(1)$. It is smaller than the MgO content of liquid 1, denoted x_1, and assumed to be constant.

In the case of model VV, it decreases with successive reinjections when the reinjected thicknesses $H_1(k)$ decreases (i.e., when $\rho_1 < \rho_c$) and the chamber thickness H_t is small (<4000 m). In case of a large chamber thickness H_t (>4000 m), the upper reservoir is always enriched in MgO, whatever the initial density, since only a small percent of MgO in liquid 1 is used to form the dunite, the rest of it being mixed to the overlying liquid 2. As a specific character of model FV, an enrichment in MgO of liquid 2 is always observed during the formation of UZ (Fig. 9a). This result is independent of the value of density ρ_1, and initial thickness $H_1(1)$. Since the chamber volume is fixed, an equal volume of liquid 2 is tapped from the top of the chamber during reinjection of liquid 1. The injected liquid 1 keeps its composition constant, while the upper reservoir loses liquid 2 which is less MgO-rich. Thus, the amount of MgO brought into the upper reservoir increases. This enrichment will be more important if the initial chamber volume $H_2(1)$ is small (Fig. 9b), since the ratio between initial MgO in the chamber to MgO brought by injections is small.

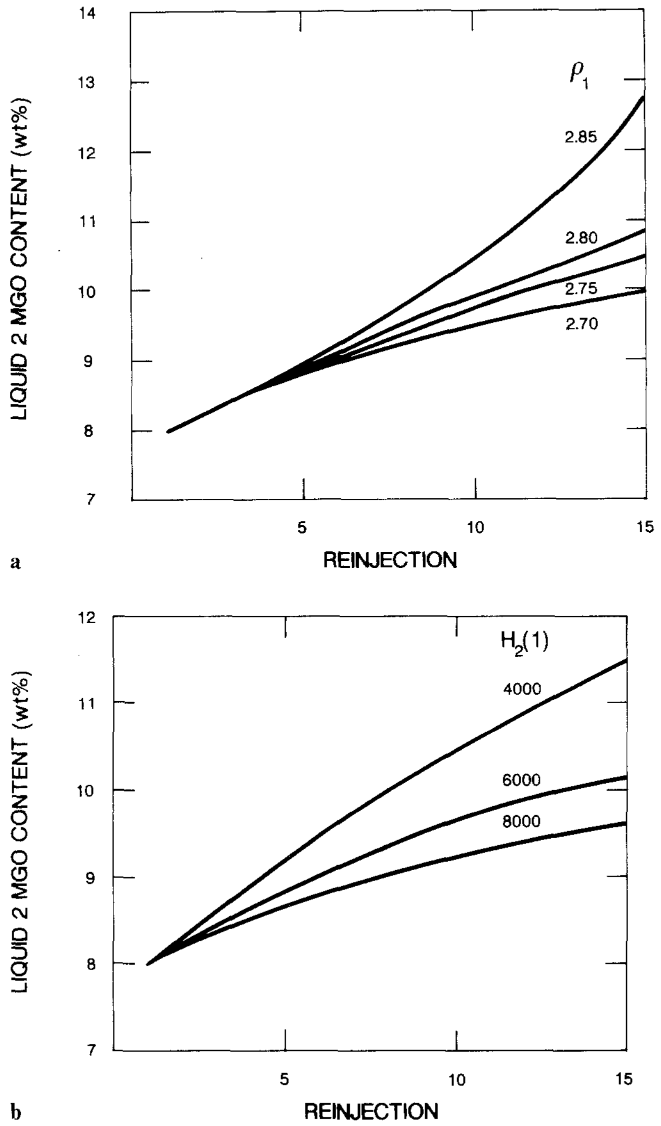


Fig. 9. a Evolution of the MgO content of liquid 2 with successive reinjections for different values of the liquid 1 density in model FV. The petrological data are those given in Table 5, with $H_1(1)=175$ m and $H_2(1)=6000$ m. Note that the liquid becomes enriched in MgO during the formation of UZ. **b** Evolution of the MgO content of liquid 2 with successive reinjectins for different values of the initial reservoir thickness $H_2(1)$ in model FV. The petrological data are those given in Table 5, with $H_1(1)=175$ m and $\rho_1=2.70$ g/cm^3

Summary of main characteristics of MR models

All the scenarios have been considered for the formation of a cyclic unit. In the fixed volume model (FV), an enrichment of MgO is always observed in the reservoir. For all models VV, if a small chamber thickness, H_t has been built after formation of UZ, a decrease of MgO is observed in the upper reservoir for $\rho_1<\rho_c$. The fraction crystallized is large ($\geq 7\%$) as well as the maximum allowed temperature contrast ΔT (>50 °C). The variations or reinjected thickness are small. If a large chamber is built ($H_t>4000$ m), a slight enrichment in MgO of the chamber is always observed. The fraction crystallized must be small ($<2\%$).

In summary, although a cyclic units is thin compared to the thickness of the chamber, it has been shown that N injections, that can account for the formation of UZ, determine the mode of formation as well as the composition of the whole chamber. Volumetric and mass balance calculations are strong constraints to the models.

Application to the Stillwater

Petrological description of the Stillwater Ultramafic Series

Application of these models to the specific case of the Ultramafic Series of the Stillwater is made in this work. The numerical values for all the required petrological data (Table 5) can be found in the extensive studies of Jones et al. (1960), Hess (1960), Jackson (1961, 1970), McCallum et al. (1980) and Todd et al. (1982) among others. The values (thickness and composition) that have been considered here for the Stillwater (Table 5) need some comments.

Thickness. The Stillwater Ultramafic Series has a stratigraphic thickness of approximately 1050 m. It overlies the Basal Series which is about 100 m thick, and underlies the Banded Series (about 4500 m). The complex has a stratigraphic thickness of about 5.6 km and the upper contact of the intrusion is missing.

The stratigraphic divisions are based on the change of cumulate sequences. The base of the Ultramafic Series is defined as the horizon where olivine cumulate crystals are observed. Fifteen to twenty cyclic units have been identified in its lower part, called the Peridotite Member (about 675 m thick). The cumulate sequence within most of the cyclic units is, from base to top, olivine (oc), olivine + opx (obc), and opx (bc) (Fig. 1). There are, however, some cyclic units beheaded (no bc) or foot less (no oc). Some units include thin (<1 m) chromitite sublayers. From bottom to top of the intrusion, the thickness of oc tends to decrease while that of bc increases. The olivine pile thickness varies between 10 m and 28 m for normal cyclic units in the Mountain View area (Page and Shimek 1972). The upper part of the Ultramafic Series is the Bronzitite Member which is a thick layer (about 400 m) of opx cumulates. The Banded Series overlies the Ultramafic Series, and begins sharply with the appearance of plagioclase as a cumulate phase. A platinum horizon (J-M reef) is observed in this zone, 400 m above the Ultramafic Zone.

For the following calculations, I assume that the Ultramafic Series has an average thickness, $H_0=675$ m and is made of 15 normal units. The exact value for N considered here is not crucial as we are carrying out mass balance calculations based on all the observed cumulate phases for the whole thickness H_0. For the sake of simplicity, the unit thickness is taken to be constant and equal to 45 m. It could be made to vary, however the results would be modified only slightly. Each unit is presumed to be formed by two sublayers, one olivine-rich at the base and one opx-rich at the top. The chromitite layers are not considered here. Although their thickness may be as thick as 1 m in one or two cyclic units, they are elsewhere much smaller (Howland 1955). Thus, their thicknesses are negligible compared to that of the olivine and opx layers and chromite crystallization has a very small influence on the overall density and mass balances calculations (Table 2). For simplicity, the olivine layer thickness is assumed to vary linearly between 25 m (base) to 15 m (top). Once again, small deviations from these trends are not significant. In order to have a constant unit thickness, the opx pile thickness varies linearly between 20 and 30 m.

Cumulate compositions. The composition of olivine and orthopyroxene cumulates vary slightly. Raedeke and McCallum (1984) reported that they become more magnesium-rich as one moves up from unit 1 to unit 11 and then more iron-rich from unit 12 to 15. However, the variations are small (between Fo$_{86}$ and Fo$_{84}$

for olivine and En_{86} and En_{84} for opx). Thus, they will be assumed to be constant and equal to Fo_{85} and En_{85} for these calculations. They could be made to vary but the results would be modified only slightly (Brandeis 1986). Another important constraint for the mass balance calculations is that crystals in the Ultramafic Series are mostly adcumulate. In order to consider solely the residual liquids after primary crystallization, the initial porosity must be specified. It is reported to vary between 25% and 40% (Jackson 1961). Only an average value is needed here. Thus, it will be assumed to be constant and equal to 35% which correspond to the maximum packing density of crystals settling randomly (Marsh 1981). Secondary enlargement of olivine and opx after primary crystallization will not be considered (see second section).

Application of the MR models to the Stillwater

As explained, the MR models are constrained by the petrological data. Models VV are first considered. It has been shown that the evolution of the reinjected thicknesses is entirely determined by the two input parameters: ρ_1, the density of the reinjected liquid 1 and H_t, the thickness of the chamber that has been built after the formation of the Ultramafic Series.

Since there is no significant evolution of the cumulate compositions in the Ultramafic Series, and that it has been assumed a constant reinjected liquid 1 composition, it can also be assumed that the fraction crystallized does not vary significantly with successive reinjections. This is verified for all models VV for $\rho_1 \sim \rho_c$, since the variations of reinjected thicknesses are small. Note that in that case, it is possible to form the entire UZ with all models (Fig. 10a). However, the maximum ΔT allowed decreases from model VV3 (55 °C) to VV1 (24 °C). Consider now $\rho_1 < \rho_c$ (Fig. 10b). It is not possible to form UZ with a single model VV. Keeping $F(k)$ rather constant, the mode of formation of a cyclic unit evolves from crystallization of olivine in both layers (VV1), to crystallization of olivine in layer 1 (VV2) and then, to olivine and opx crystallization in layer 1 (VV3), and eventually, for a small density, to the entire formation of the unit in layer 1. The opposite direction is observed where $\rho_1 > \rho_c$ (Fig. 10c). Note that there is also a forbidden regime.

We have considered all the possible cases for the formation of a cyclic unit. It sounds more reasonable to consider the formation of the whole Ultramafic Series with a single model. This assumption simply bounds the value of the densities. The reinjected liquid 1 density ρ_1 has to be close to $\rho_c \sim 2.71$ g/cm^3 and the liquid 2 density has to be close to the opx fractionation density 2.70 g/cm^3 in order to satisfy the model. In that case, mixing and opx crystallization modify only slightly the density of the upper reservoir.

Furthermore, note that the input parameter H_t determines the fraction crystallized in the dunite layer, without specifying a priori the input value of the liquid 1 density (indicated along the curve in Fig. 7). The largest H_t, the largest $H_1(1)$, hence, the smallest $F(k)$. It also determines the maximum thermal contrast ΔT between the two layers.

Consider now the MgO content of the reservoir. In case of small H_t (≤ 3000 m), the liquid 2 has a composition very close to its initial one after the formation of the Peridotite Member (referred to as PeM). Crystallization can still proceed on the opx phase, and the formation of the Bronzitite Member (referred to as BrM) is plausible. In case of large H_t (≥ 5000 m), significant enrichment in MgO of liquid 2 is observed during PeM formation. Large volumes of residual liquid 1 richer in MgO than the upper reservoir mix with the overlying

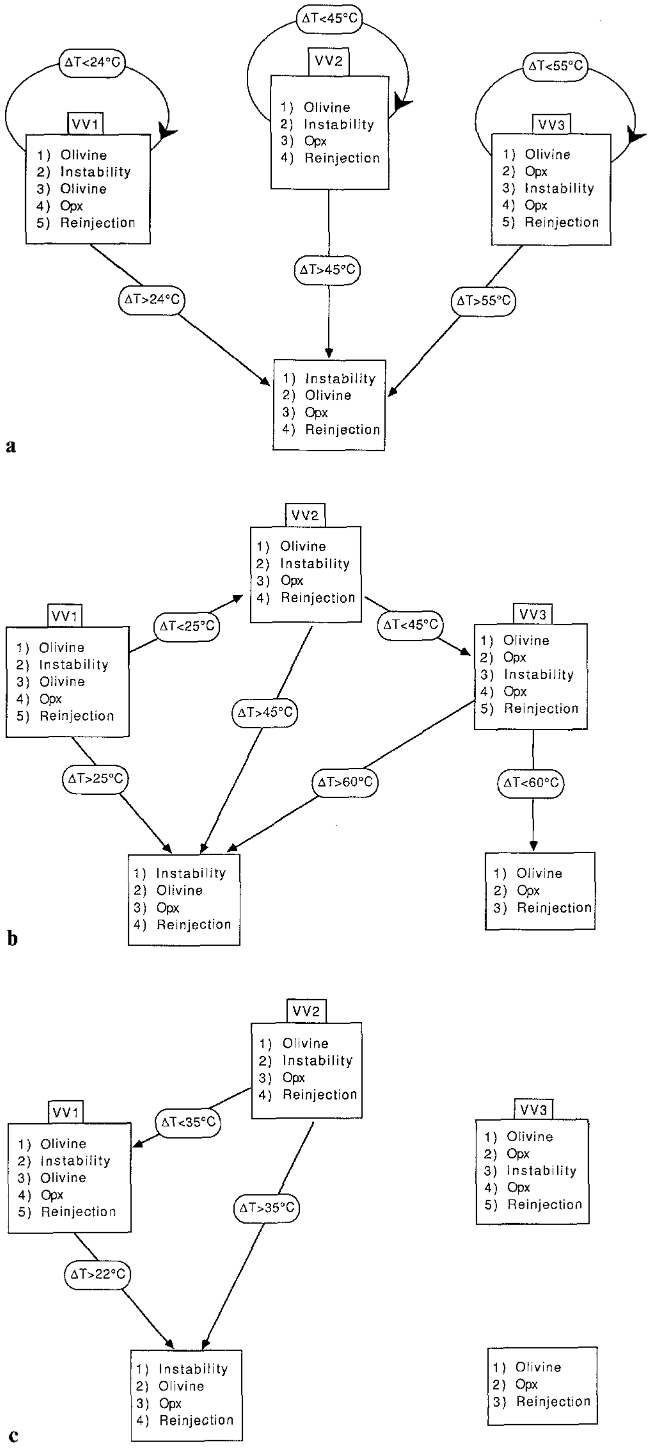


Fig. 10a–c. Schematic representation of stability of models VV, assuming a roughly constant fraction crystallized in layer 1 for: **a** $\rho_1 \sim \rho_c$; **b** $\rho_1 < \rho_c$; **c** $\rho_1 > \rho_c$

liquid. This is not consistent with the petrological observation of constant opx composition. Thus, the assumption of constant composition for the reinjected liquid 1 is in contradiction with the observations.

As a result, models VV imply small reinjected volumes of liquid 1 of constant composition (≤ 250 m) or large volumes of variable composition. With small volumes, they also imply large fraction crystallized ($\geq 8\%$) prior to adcumulus growth. The chamber thickness that has been formed is ≤ 3000 m, hence much smaller than the total thickness of the intrusion. Thus, the whole chamber has to be established by further reinjections. Further, the top of PeM also marks a change of cumulate composition, thus, a change of composition must also be invoked. With large volumes, the fraction crystallized is small (about 2–3%) and the chamber is formed by the 15 injections.

Model FV is now considered. As in model VV, the liquid 1 density has to be close to 2.71 g/cm^3 in order to have small variations of fraction crystallized. In terms of composition, an enrichment in MgO is observed in the chamber during the entire formation of PeM (Fig, 9a, b). As stated, this is not consistent with the observation of constant opx composition. Furthermore, the BrM formation (made of opx cumulates only) has also be considered. Suppose that it occurs in a closed system. Crystallization of opx brings liquid 2 into a state very close to the initial one. If the MgO content of liquid 1 is $x_1 > 0.12\%$, the end result will be an enrichment in MgO of liquid 2 after the formation of the Ultramafic Series. This result does not depend on the initial volume of the chamber. Hence, the appearance of plagioclase which marks the beginning of the Banded Series requires yet another magma reinjection of different composition.

In summary, the results for model VV show that it may be possible to form the Ultramafic Series by N reinjections of small volumes of magma of constant composition. They imply a large percent of fraction crystallized. However, other magmas of different composition have to be invoked to explain the formation of the whole chamber and the Banded Series. The calculations also imply that a large chamber can be formed in the VV models by N injections but is the result of large reinjected volumes of variable composition. In model FV, we also find that the source magma must evolve during or after the reinjections. Thus, in all models, the source must evolve chemically.

Discussion

The MR models

The MR models have been applied to the formation of the Ultramafic Series of the Stillwater. It has been shown that all models are strongly constrained by the liquids involved, in particular their densities and volumes. These need to be discussed.

Consider first the density of the different liquids 1 and 2 involved in the MR process. In all the models considered here, they are respectively close to 2.71 g/cm^3 and 2.70 g/cm^3. We have to examine whether they correspond to some estimated parental liquids. We recall here that all the calculations have been performed at a fixed temperature 1280 °C in order to compare solely the compositional effects. Liquid 1 has olivine on the liquidus, thus its MgO content is high. The mafic norite ($x_{\mathrm{MgO}} =$ 14 wt.% MgO) given by Helz (Table 2, 1985) might be a good candidate. However, its density calculated by the method of Bottinga et al. (1982, 1983) is only equal to about 2.69 at 1280 °C and hence is slightly too low for the MR model. Thus, liquid 1 should have a greater MgO content, although there is no field evidence for such liquids (Helz 1985). It could be, for example, a picrite, such as that found in Hawaii (Clague et al. 1991), with $x_{\mathrm{MgO}} = 17.1$ wt.% and a calculated density equal to 2.71 at 1280 °C. Liquid 2 is presumed to have a basaltic composition and to have opx in its liquidus. If it does not have plagioclase in the liquidus as well, as required by the observed cumulate sequence, the value of 2.70 g/cm^3 is also slightly too high for a basalt (Bottinga and Weill 1970; Murase and McBirney 1973; Stolper and Walker 1980; Lange and Carmichael 1987, 1990). This discussion shows that density constraints lead to rather stringent petrological constraints.

Consider now the composition of the injected magmas. The MR mechanism requires two liquids of different composition because the first cyclic unit requires a denser, hence more primitive magma than the resident one. If there is only one source, the basaltic liquid 2 in the upper reservoir should arise by fractional crystallization or contamination of an initial injection of liquid 1 during ascent and emplacement. If this is not the case, two chemical sources are required. Consider the chamber before the formation of the first cyclic unit. The Basal Series which is situated between the lower contact and the Ultramafic Series has already been formed. It is a thin layer (100 m) of intermediate composition, containing some plagioclase, opx, and cpx cumulate crystals. In model VV, the liquid in the chamber after the formation of the Basal Zone could be derived by fractional crystallization from the first small injection. This cannot be the case in model FV, as the Basal Zone is very thin and the initial injection very large. This implies that the liquid has not had enough time to evolve significantly before the formation of the first cyclic unit. The upper liquid could be the result of contamination of liquid 1 during its ascent, however Helz (1985) showed that contamination of the intrusive rocks by their wall-rocks is rather slight. Therefore, model FV requires two different liquids, thus two different sources of reinjected magma. Liquid 2 is that for the initial formation of the large volume chamber. It has then to be followed by several smaller injections of a more primitive liquid 1 in order to allow the formation of the Ultramafic Series.

Consider now the composition of the reinjected liquid 1. The results do not support the assumption of a constant composition. Another simple case to study is an MR model with an assumption of constant reinjected volumes. Equations for this case are also those given in Appendix A and show that the liquid evolutions are entirely determined, either by the liquid 1 density law or by its reinjected thickness law. Thus, this model also leads to reinjected liquids of variable volume and composition (Brandeis 1986).

Consider now the volumetric constraint. The petrological observation of small variations of fraction crystallized prior to adcumulus growth provides a strong constraint on the reinjected volumes, thus on the formation of the chamber. Its value determines the chamber thickness H_t that is built in the VV models. As an example, calculation of the liquids path with the method of Ghiorso (1985) for the mafic norite given in Helz (1985) gives a small percent of fraction crystallized (about 2–3%) before opx appears. This percent is realistic for a high-MgO liquid. Considering such a figure implies the building of a large chamber H_t, hence large reinjected volumes of variable composition. Further, the calculations show that the temperature difference between the appearance of olivine and opx at the liquidus decreases with increasing pressure (100 °C at 3 kb to 15 °C at 6 kb). This gives a constraint on the depth of formation of the Ultramafic Series. Since the maximum thermal contrast ΔT between the two layers has to be small ($<$ 45 °C in model VV1, Fig. 10a), depth has to be greater than 10 km. These results hold for all the MR models considered here. Further, all MR models require a variable and decreasing reinjected thickness. The cyclic unit thickness has been set constant, however, it could have been made to decrease with the stratigraphy, as observed by Jackson (1970). A decrease of the reinjected thickness with a larger variation would also be observed. Finally, in the case of model VV, the MR mechanism requires an initial injection of a thickness comparable to that of the succesive injections. Each injection implies a rather large volume. For model FV, the MR mechanism requires an initial large injection followed by periodic smaller ones. Therefore two magmatic sources with different composition and volume are required.

In summary, the consideration of the formation of the whole Ultramafic Series gives some important volumetric and compositional constraints on the MR models. Model VV requires large injections of slightly changing volumes and composition. Differentiation has to occur in the shallower reservoir prior to injection as well as in the deeper one on the appropriate time scale. Model FV is even more constrained as it requires two different sources to explain both differences of volume and composition between the first large injection of liquid 2 and the later periodic smaller ones of liquid 1. It also requires some differentiation at the source in order to explain chemical changes towards the Banded Series. From a physical point of view, the MR models, therefore, are demanding.

The internal evolution

An alternative theory is that of an evolution in a closed system, at least during the formation of the Ultramafic Series of the Stillwater and the Bushveld (or part of them). The similarity of the cyclic unit thickness in many intrusions of different age, volume and setting (Jackson 1970) suggests that the formation of the cyclic units is due to a local mechanism of instability, in the crystallizing boundary layer which would develop independently of the total volume of the intrusion.

Let us examine the thermal conditions in a cooling magma chamber. The interior temperature can be considered to be quasi-uniform through the whole depth and close to the liquidus during most of the dynamic life of the chamber (Jaupart et al. 1984; Brandeis and Marsh 1989; Marsh 1989). Thermal gradients are observed in the boundary layers, between the "isothermal" magma and the country rocks. Crystallization proceeds inwards in these layers. The bottom boundary layer is colder than the overlying magma and is thus stable. This configuration leads to the formation of a stagnant bottom layer (Jaupart et al. 1984) which is not penetrated by convective plumes (Jaupart and Brandeis 1986). Differentiation can, therefore, occur more rapidly in this stagnant layer because it is of a smaller thickness than the main body.

The mass balance for the Ultramafic Series has been made in Appendix B and shows that a closed system behavior leads to very reasonable compositions. Crystallization is presumed to occur in an isolated stable layer at the bottom of the chamber as suggested by Jackson (1961). This internal mechanism only requires a minimum layer thickness. The layer should have a thickness greater than 200 m. This thickness is of the same order than that predicted by Jaupart and Brandeis (1986). The internal mechanism requires also a minimum MgO content. Any basaltic or more mafic liquid would satisfy this condition. Thus, this is a very weak requirement.

However, the physical mechanism responsible for the periodicity still needs to be identified. In the Ultramafic Series, crystal textures are complex and show important adcumulus growth after primary crystal deposition. Their formation requires different mechanisms taking place simultaneously during cooling of a mush at the bottom of the chamber such as settling and compositional convection in a porous medium (Kerr and Tait 1985, 1986). Other processes might also occur such as compaction (Petersen 1987) or chemical instabilities developing at the interface of an upward moving crystallization front such as those observed in the metallurgy by Copley et al. (1970), Sample and Hellawell (1984), Hellawell (1987) and recently in viscous fluid by Tait and Jaupart (1989, 1992). This list is not exhaustive but simply shows that crystallization in a closed system at the bottom of the chamber is a very complex process. All these different phenomena can produce complex patterns of differentiation which could lead to periodic instabilities. To discuss in further detail the exact mechanism of instability requires elaborate calculations which are beyond the scope of this study. They should take into account crystallization in situ, phase diagrams, settling and differentiation processes and require careful prescription of the thermal gradient prevailing at the bottom of the chamber.

Conclusion

The analysis presented in this study emphasizes the usefulness of testing the petrological models with physical constraints. Two different models of multiple reinjections for the formation of the entire Ultramafic Series of the Stillwater have been examined as well as different scenarios for the formation of a cyclic unit. All these models require very specific densities which do not correspond to any liquids observed in and around the Stillwater complex. They also require that the reinjected liquids evolve chemically and are produced in variable volumes. Chemical differentiation must, therefore, operate before residence in the chamber. More generally, a model that considers that each cyclic unit corresponds to an injection and repeats this mechanism over the *whole* sequence of cyclic units is highly constrained. As an alternative theory, an evolution in a closed system has weak requirements. However, no physical mechanism has been identified yet. Further investigations are clearly needed to understand these processes of internal differentiation. As we have attempted to show in this paper, simple models can easily be ruled out by including the density and volume consideration.

Acknowledgements. Many thanks to Claude Jaupart who shared many ideas and whose discussions have always been very fruitful. I enjoyed discussions with Rozalind Helz and Mike Zientek on the outcrop and with Bruce Marsh and John Fournelle in Baltimore. Critical reviews by Steve Tait, Margaret Mangan, Bruce Marsh, Rozalind Helz and two anonymous reviewers greatly improved the manuscript. The first draft of this manuscript was partly written when I was a postdoctoral fellow at the Johns Hopkins University and was partly supported by the NSF grant EAR-86-11362. This study was supported by CNRS/INSU. This is DBT contribution 498 (thème Instabilités 91).

Appendix A: the multiple reinjection models

Consider the UZ formation by N injections of liquid 1 at the base of the reservoir containing some liquid 2. The evolution of densities, reinjected thickness and composition of residual liquids 1 and 2 are followed with the successive reinjections k. They are constrained by the petrological data listed in Table 5, as well as the input parameters (Table 4):

- ρ_1, the liquid 1 density
- $H_1(1)$ and $H_2(1)$, respectively the thickness of the first injection of liquid 1 and the initial thickness of the upper reservoir
- x_1 and $x_2(1)$, respectively the liquid 1 (assumed to be constant) and the initial liquid 2 MgO content (in wt.%).

A.1. Density

Consider the reinjection number k and first calculate the residual liquid 1 density $\rho_{1r}(k)$ after crystallization and sedimentation of olivine crystals, just before the mixing with the upper layer. This is given by (Sparks and Huppert 1984):

$$\rho_{1r}(k)=\frac{\rho_1\cdot\left[1-\frac{\rho_v}{\rho_1}\cdot\frac{V_v}{V_1}\cdot X\right]}{\left[1-\frac{V_v}{V_1}\cdot X\right]} \tag{A1}$$

where ρ_v is the olivine fractionation density, V_1 and V_v the liquid 1 and olivine molar volume, and X the molar fraction of crystallized olivine. Considering an initial porosity of 35% after sedimentation, and a constant thickness across the whole surface area of the chamber, the molar fraction X is equal to:

$$X=\frac{0.65 d_1(k)}{H_1(k)}\cdot\frac{\rho_v}{\rho_1}\cdot\frac{M_1}{M_v} \tag{A2}$$

where M_1 and M_v are the liquid 1 and olivine molar weight. Considering a dunite layer of thickness $d_1(k)$, this yields a residual density:

$$\rho_{1r}(k)=\frac{\rho_1-0.65\frac{d_1(k)}{H_1(k)}\cdot\rho_v}{1-0.65\frac{d_1(k)}{H_1(k)}} \tag{A3}$$

After sedimentation, gravitational instability occurs when the residual liquid 1 and the overlying liquid 2 have equal density, i.e.,

$$\rho_{1r}(k)=\rho_2(k) \tag{A4}$$

where $\rho_2(k)$ is liquid 2 density. After mixing, crystallization of opx proceeds in the upper reservoir until the next reinjection. From (A3–A4), the residual liquid 2 has therefore a density $\rho_{2r}(k)$:

$$\rho_{2r}(k)=\frac{\rho_{1r}(k)-0.65\frac{d_2(k)}{[H_1(k)+H_2(k)-d_1(k)]}\cdot\rho_x}{1-0.65\frac{d_2(k)}{[H_1(k)+H_2(k)-d_1(k)]}} \tag{A5}$$

where ρ_x is opx fractionation density and $d_2(k)$ and $H_2(k)$ are respectively the bronzitite and upper reservoir thicknesses. As the residual liquid in layer 2 represents the liquid 2 before the next reinjection ($k+1$), the relationship:

$$\rho_2(k+1)=\rho_{2r}(k) \tag{A6}$$

has also to be satisfied.

Finally, the critical value for the liquid 1 density, noted ρ_c, which determines two different behavior for $\rho_2(k)$ (see density evolution) can be calculated. It corresponds to an initial liquid 2 density $\rho_2(1)$ equal to the opx fractionation density. In that case, the opx crystallization does not deplete liquid 2, thus, ρ_c is equal to:

$$\rho_c=\rho_x+0.65\,(\rho_v-\rho_x)\,d_1(k)/H_1(1) \tag{A7}$$

A.2. Thicknesses

The densities relationships (A1–A7) and the observed cumulate layers thicknesses allow the determination of the reinjected thickness $H_1(k+1)$. It is equal to:

$$H_1(k+1)=0.65\,d_1(k)\,[\rho_v-\rho_2(k)]/[\rho_1-\rho_2(k)] \tag{A8}$$

Finally, the evolution of the upper liquid reservoir thickness $H_2(k)$ has also to be calculated. In model VV, it is always increasing and is equal to:

$$H_2(k+1)=H_2(k)+H_1(k)-d_1(k)-d_2(k) \tag{A9a}$$

In model FV, the upper liquid reservoir thickness decreases with increasing number of reinjections, as the volume of the chamber remains constant. It is equal to:

$$H_2(k+1)=H_2(k)-d_1(k)-d_2(k) \tag{A9b}$$

A.3. Mass balance

After crystallization and sedimentation of olivine crystals, some residual liquid 1 is trapped in the cumulate pile with an initial porosity of 35%. Subsequent adcumulus and interstitial growth are not considered here (see mass balance calculations). The residual liquid 1 which mixes with the upper layer 2 has an MgO content $x_{1r}(k)$ equal to:

$$x_{1r}(k)=\frac{x_1-\dfrac{0.65\,\rho_v m_v}{H_1(k)\rho_1}\cdot d_1(k)}{1-\dfrac{0.65\,\rho_v}{H_1(k)\rho_1}\cdot d_1(k)} \tag{A10}$$

where m_v and m_x are respectively the MgO weight proportion in olivine and opx crystal. The residual liquid 1 mixes with the upper layer 2 which has a MgO content $x_2(k)$. This yields a MgO content in the reservoir before opx crystallization equal to:

$$y_2(k)=\frac{x_{1r}(k)\cdot[H_1(k)-d_1(k)]+x_2(k)\cdot H_2(k)}{H_2(k)+H_1(k)-d_1(k)} \tag{A11}$$

After opx crystallization and before the $(k+1)$ reinjection, the MgO content in the upper reservoir is equal to:

$$x_{1r}(k)=\frac{y_2(k)-\dfrac{0.65\,m_x d_2(k)}{H_2(k)+H_1(k)-d_1(k)}\cdot\dfrac{\rho_x}{\rho_2(k)}}{1-\dfrac{0.65\,d_2(k)}{H_2(k)+H_1(k)-d_1(k)}\cdot\dfrac{\rho_x}{\rho_2(k)}} \tag{A12}$$

A.4 Stillwater Ultramafic Series

The petrological data are given in Table 5. The formation of the Bronzitite Member has also been envisioned. It is presumed to occur in a closed system after the formation of the Peridotite Member. To evaluate the composition of the magma in the reservoir at the beginning of the formation of the Banded Series, a mass balance has been made by substituting in (A12) $y_2(k)$ by $x_2(16)$, and $[H_2(k)+H_1(k)-d_1(k)]$ by $H_2(16)$.

Appendix B: the internal evolution

B.1. Quantitative analysis

Consider now that the formation of UZ occurs in a closed system. Crystallization and sedimentation occur in an isolated stable boundary layer of thickness H_1, at the bottom of a large reservoir. N periodic convective overturns are assumed to mix the residual liquid produced in the bottom layer with the upper reservoir. After the mixing, the bottom layer rebuilds and the formation of the next cyclic unit proceeds.

In that case, only one magma is required. However, by analogy with the MR model, the liquid in the lower layer will be referred to as liquid 1 and the overlying liquid as liquid 2. Before the formation of the first cyclic unit, the bottom layer contains some liquid 1 which is the same as the liquid 2 of the upper reservoir. As cooling proceeds, olivine and opx crystallize and sedimentation produces some residual liquid 1′ in the bottom layer. The liquid 2 in the upper reservoir is still unchanged. When the residual liquid in the bottom layer reaches the same density as the overlying fluid, it becomes unstable and mixes with the upper liquid 2. This creates a new liquid 2′ and thus the upper magma also slowly evolves. A bottom layer containing some liquid 2′ is reestablished and the process repeats again. The mechanism looks like the reinjection process, the major difference being that it is governed by the internal evolution of the chamber itself.

The purpose of these calculations is to make a mass balance of the MgO content. The input parameters of this model are (Table 6):

- H_1 and H_t, which are respectively the bottom layer and the whole reservoir thicknesses
- x_0 the initial MgO content in the whole reservoir
- ρ_0 the magma density

Table 6. List of symbols in the internal evolution model

Quantity	Layer 1		Layer 2	
	Symbol	Value	Symbol	Value
Thickness				
Liquid before formation of:				
Cyclic unit 1			H_t	P
Cyclic unit k	H_1	P	$H_2(k)$	C
Cumulate pile:				
Olivine	$d_1(k)$	P		
Opx	$d_2(k)$	P		
MgO content				
Liquid before formation of:				
Cyclic unit 1	x_0	P	x_0	P
Cyclic unit k	$x_1(k)$	C	$x_2(k)=x_1(k)$	C
Residual liquid	$x_{1r}(k)$	C	$x_{2r}(k)$	C

C = calculated; P = input parameter

To perform a mass balance on MgO, consider the formation of cyclic unit number k. After crystallization and sedimentation of both olivine and opx crystals, the residual liquid in the bottom layer has a MgO content $x_{1r}(k)$ equal to:

$$x_{1r}(k)=\frac{x_1(k)-\dfrac{0.65\,m_v\rho_v d_1(k)+0.65\,m_x\rho_x d_2(k)}{\rho_0 H_2(k)}}{1-\dfrac{0.65\,\rho_v d_1(k)+0.65\,\rho_x d_2(k)}{\rho_0 H_2(k)}} \tag{B1}$$

After instability and mixing with the upper reservoir, the composition in the whole reservoir is:

$$x_{2r}(k)=\frac{x_{1r}(k)\cdot[H_1-d_1(k)-d_2(k)]+x_2(k)\cdot H_2(k)}{H_2(k)+H_1-d_1(k)-d_2(k)} \tag{B2}$$

In fact, the residual liquid 2 is the liquid which is in both the bottom layer and the whole reservoir at the beginning of the formation of the $(k+1)$ cyclic unit. Thus, the compositional evolution is governed by the following laws:

$$x_1(k+1)=x_{2r}(k) \tag{B3a}$$

$$x_2(k+1)=x_{2r}(k) \tag{B3b}$$

The last parameter evolution to specify is that of the liquid reservoir thickness:

$$H_2(k+1)=H_2(k)-d_1(k)-d_2(k) \tag{B4}$$

The initial conditions are:

$$x_1(1)=x_2(1)=x_0 \tag{B5a}$$

$$H_2(1)=H_t-H_1 \tag{B5b}$$

These mass balance calculations give a minimum value for the thickness of the bottom layer H_1 (Fig. B1). In order for the residual liquid in the bottom layer to have a positive MgO concentration throughout the formation of UZ, H_1 has to be greater than a minimum value. The evolution of the magma in the main reservoir is also reported on Fig. B1. During UZ formation, the magma in the whole reservoir evolves gently towards less mafic compositions, producing some internal differentiation on a large scale.

The influence of varying the value of the whole chamber thickness H_t is now investigated. The evolution of the MgO content of the residual liquid in the bottom layer is reported on Fig. B2 for different values of H_t. The liquid which replenishes the bottom

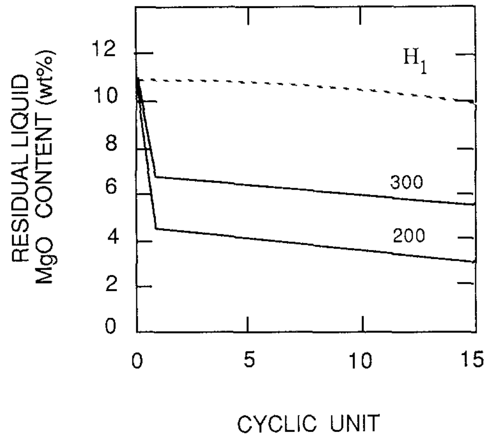


Fig. B1. Evolution of the residual liquid composition in the bottom layer (*solid line*) with successive cyclic units for different values of H_1 in the internal system evolution. With the chosen parameters, the model requires H_1 to be greater than 150 m in order to have a positive mass balance. The evolution of the total residual liquid of the whole reservoir is also reported (*dotted line*). Note the smooth evolution of the whole reservoir

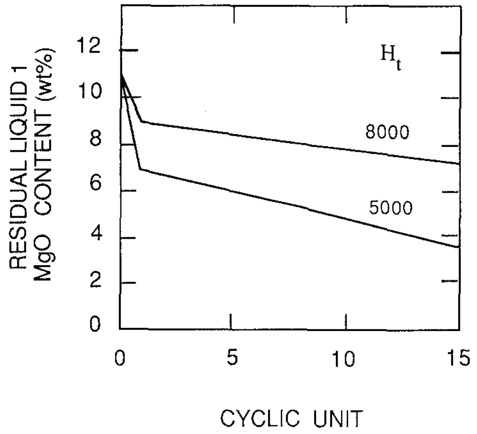


Fig. B2. Evolution of the residual liquid composition in the bottom layer with successive cyclic units for different values of the initial thickness H_t of the chamber in the internal system evolution. With the choosen parameters, the model requires H_t to be greater than 4000 m in order to have a positive mass balance. Large initial thicknesses are favored in this model

layer does not have a fixed composition but evolves slowly throughout the formation of UZ. In order to form UZ in a closed system, the magma chamber has, therefore, to be sufficiently large for the MgO content to remain positive (Fig. B2).

B.2. Application to the Stillwater

We consider the petrological data given in Table 5 in order to calculate the thickness of the lower layer H_1. The internal evolution requires a minimum value $H_1 = 200$ m. Note that it is nearly an order of magnitude greater than the cyclic unit thickness itself. If a somewhat more complex model is adopted in which both cumulate compositions and H_1 are allowed to evolve during formation of successive cyclic units, this result does not change significantly (Brandeis 1986).

This model also requires a minimum initial thickness of the chamber H_t equal to 4000 m. This is consistent with the fact that the Stillwater is a large intrusion. Finally, note that the calculations do not depend strongly on the value of the density. It has not been made to vary here, however, its variations are weak during the formation of the Ultramafic Series. Therefore, the internal evolution does not require a specific density.

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Editorial responsibility: I.S.E. Carmichael