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LETTER

Magmatic differentiation by means of segregation and diapiric ascent of anorthositic crystal mush - the Murotomisaki Gabbroic Complex, Shikoku, Japan

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The Murotomisaki Gabbro is a sill-like layered igneous complex that contains several layers of olivine enrichment. In our previous paper (Hoshide et al, 2006), we have identified two zones of olivine enrichment: 'the crystal accumulation zone (AC zone)', formed by gravity settling and accumulation of olivine crystals, and 'the crystal growth zone (GR zone)', in which increase of modal olivine was caused by crystal growth of olivine and not by crystal accumulation.

Based on whole rock compositional data, we have found that the AC zone rocks define a linear compositional trend (termed as 'AC trend') which is consistent with the crystal settling and accumulation hypothesis. However the GR zone data define another linear trend with a slope different from that of the AC trend. Moreover, the compositions of the coarse gabbros and the upper olivine gabbros that occur above the GR zone and an anorthosite vein from the GR zone roughly lie on the same trend, but on the opposite side of the GR zone composition, defining the 'GR trend' as a whole. Some anorthositic veins and wavy pegmatitic veins have plume-like structures, suggesting that these veins are remnant of crystal mushes that have been mobilized and ascended diapirically during magmatic differentiation.

Considering the observed compositional relationships and the mode of occurrences of the anorthosite and wavy pegmatitic veins, we conclude that the segregation and separation of anorthositic material out of semi-solidified crystallization boundary layers was responsible for the formation of the GR zone and the GR trend. Phase equilibrium calculations reveal that the hypothetical anorthosite material was a mixture of fractionated melt and plagioclase crystals that precipitated from the melt. The GR zone represents a residue from the separation of anorthositic crystal mushes and the coarse gabbros and the upper olivine gabbro parts represent mixtures of the crystal mush and the initial melt.

Keywords: Magmatic differentiation, Gabbro, Anorthosite, Crystal mush, Murotomisaki

INTRODUCTION

The Murotomisaki Gabbroic Complex is a sill-like layered intrusion up to 220 m thick, located at Cape Muroto, Shikoku, Japan. The intrusion has attracted much petrological works because of its well-developed layered structure, that was presumably formed through igneous differentiation processes (Yoshizawa, 1953, 1954; Yajima, 1972a, 1972b; Akatsuka et al., 1999; Hoshide et al., 2006). An investigation of olivine crystal size and crystal number densities, identified an olivine-crystal accumulation zone (AC zone) in the lower part of the intrusion and an olivine-crystal growth zone (GR zone) directly above the AC zone (Hoshide et al., 2006). These authors also show that (1) the modal abundance of olivine in the GR zone was produced by crystal growth of olivine and not by crystal accumulation and (2) the olivine growth appears to have been accompanied by a significant increase in the whole rock MgO, FeO and MnO contents compared to the chilled margin value. The change of whole rock composition in the GR zone implies the operation of long-range material transfer in and out of the GR zone, that was thought to be due to fluid dynamic processes (Hoshide et al., 2006). They also noted the abun-

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dances of anorthositic- and wavy pegmatitic- veins in the middle of the GR zone which they considered represent remnants of some unknown fluid dynamic processes. The presence of these anorthositic veins is well known, but they have generally been considered to represent minor features of magmatic differentiation, being segregation products at very late stages of differentiation (Yajima, 1972a). The purpose of the present paper is to explore the formation mechanism of the GR zone using whole rock chemical compositions of constituent rocks. Unlike previous interpretations, we consider the anorthositic veins are significant because they represent frozen crystal mushes that were diapirically ascending from the crystallization boundary layer during the main stages of magmatic differentiation, thereby playing an important role in the magmatic differentiation.

GEOLOGIC SETTING AND LITHOLOGICAL VARIATIONS

Figure 1 summarizes important features of lithological and compositional variations of the intrusion in a vertical section. The intrusion as a whole is gabbroic; the dominant minerals are olivine, augite and plagioclase with a minor amount of orthopyroxene, hornblende, biotite and ilmenite. The mineralogical mode varies rhythmically and has four distinct peaks of olivine abundance (O1, O2, O3 and O4 in Fig. 1). The coarsest-grained part of the complex, the 'coarse gabbro' (abbreviated CG), consists of augite and plagioclase and does not contain olivine.

Hoshide et al. (2006) defined *AC zone* (within 40 m of the base of the sill) that includes lower chilled margin (LCM), lower picritic gabbro (LPG) and lower part of the lower olivine gabbro (LOG) zone and *GR zone* (40-100 m from the base of the sill), that includes the rest of the lower olivine gabbro zone (Fig. 1). In the AC zone, average grain size of olivine is 0.2-0.3 mm, which is comparable to those in the chilled marginal rocks, and the crystal number density of olivine (i.e., total number of olivine crystals per unit volume) is greater than the inferred initial value, which is presented in the chilled margins and the average value of the intrusion (4.7 ± 0.7 grains/mm^3, Hoshide et al., 2006). In the GR zone, on the other hand, crystal number density of olivine has been much reduced from the initial value and yet olivine is significantly coarser-grained and, therefore, its modal abundance is greater than the average value with some vertical rhythmic variations.

An important conclusion of Hoshide et al. (2006) is that the olivine crystals that were suspended in the initial magma had mostly settled down at early stages of magmatic emplacement and accumulated in the lower 40 meter AC zone, without significant growth of olivine crystals. They also argued that significant olivine growth started to occur forming the GR zone just above the AC zone after the major stage of crystal settling. Another

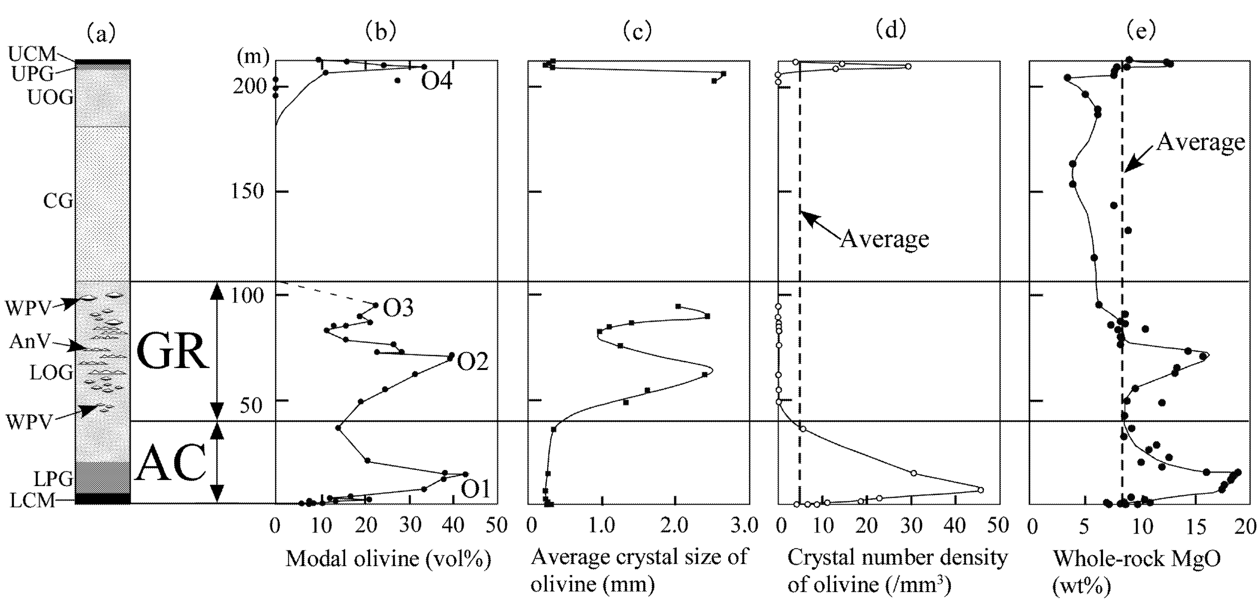

Figure 1. Data synthesis of the Murotomisaki Gabbroic Complex. (a) lithological variation; (b) olivine mode; (c) crystal size of olivine; (d) crystal number density of olivine; (e) whole-rock MgO content. Data for whole-rock compositions from Akatsuka et al. (1999). The broken line in (d) is the average level of crystal number density of olivine throughout the intrusion. The broken line in (e) shows the average level of the whole-rock MgO content throughout the intrusion. AC, crystal accumulation zone; GR, crystal growth zone. LCM, lower chilled marginal zone; LPG, lower picritic gabbro zone; LOG, lower olivine-gabbro zone; CG, coarse gabbro zone; UOG, upper olivine-gabbro zone; UPG, upper picritic gabbro zone; UCM, upper chilled marginal zone; WPV, wavy pegmatitic vein; AnV, anorthositic vein.

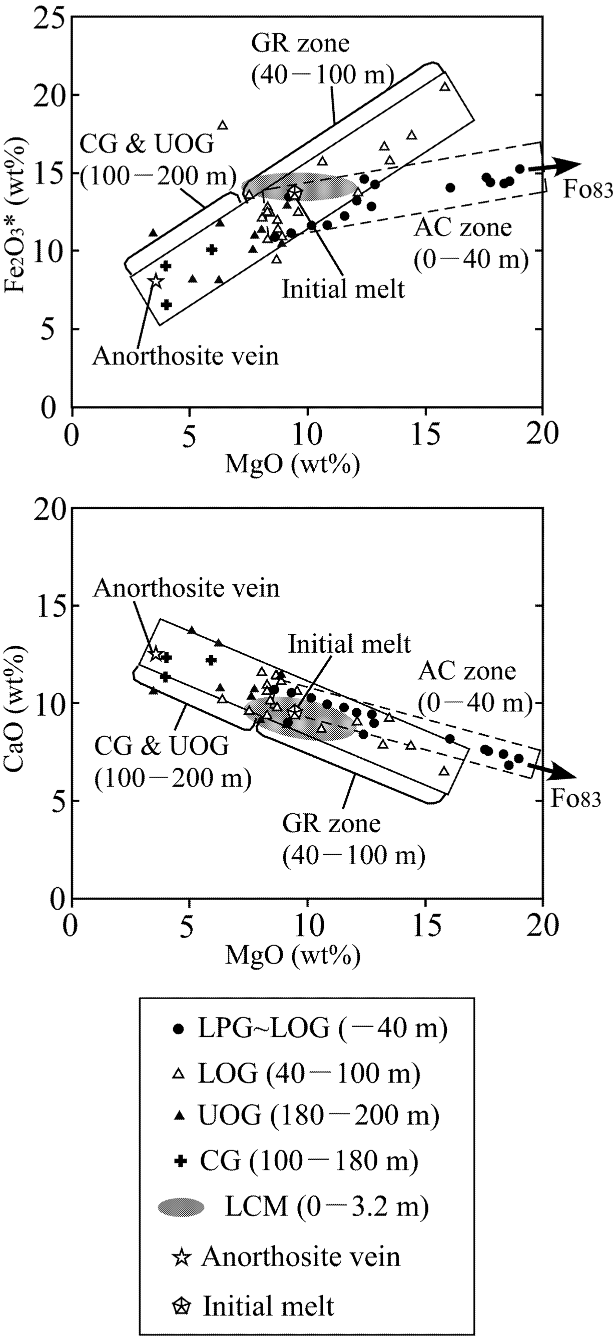

Figure 2. Whole-rock FeO-MgO and CaO-MgO variation diagrams of the Murotomisaki Gabbroic Complex. The whole-rock data from Akatsuka et al. (1999). Abbreviations for the lithological zones are the same as in Figure 1.

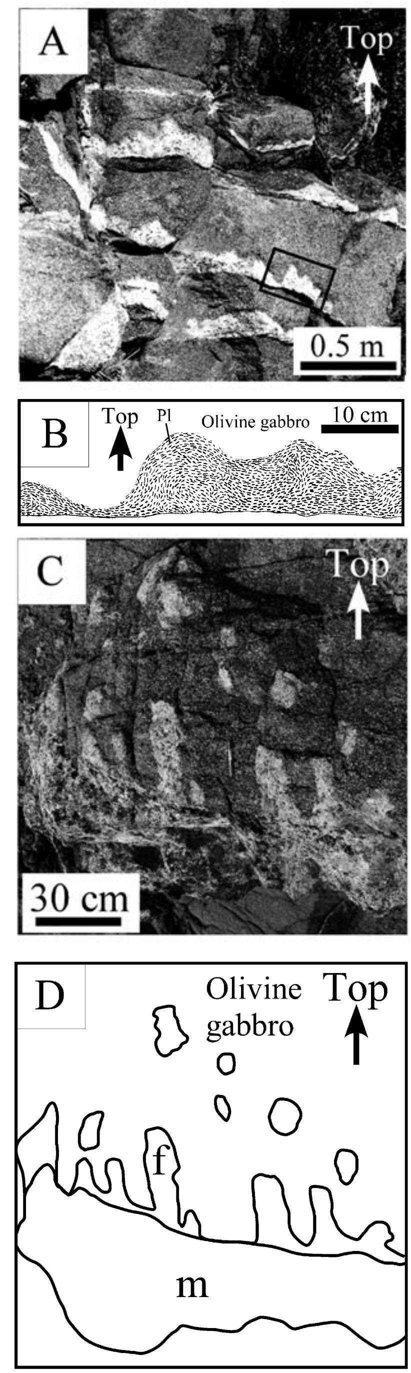

Figure 3. (A) Anorthositic veins (light colored) in olivine gabbro matrix, GR zone (approximately 80 m from the bottom). A frame indicates the sketched area in (B). Modified from Hoshide et al., 2006. (B) Sketch of internal structure of an anorthositic vein marked in (A). Note a flat bottom surface and a wavy upper surface of the vein. Shape preferred orientation of plagioclase crystals is illustrated. (C) and (D), Photograph and its explanatory sketch, respectively, of a wavy pegmatitic vein (approximately 60 m from the bottom), showing plume-like structure of anorthositic parts (f) developed on top of the vein. The mafic bottom part (m) is coarse grained and pegmatitic, being composed of augite, plagioclase and olivine. Arrows indicate the direction to the top of the sill.

important observation in the GR zone is the development of anorthositic- and wavy pegmatitic- veins, which are typically oriented semi-parallel to the compositional banding in the GR zone. They also noted a significant increase of whole-rock MgO, FeO and MnO in the middle of the GR zone (Fig. 1).

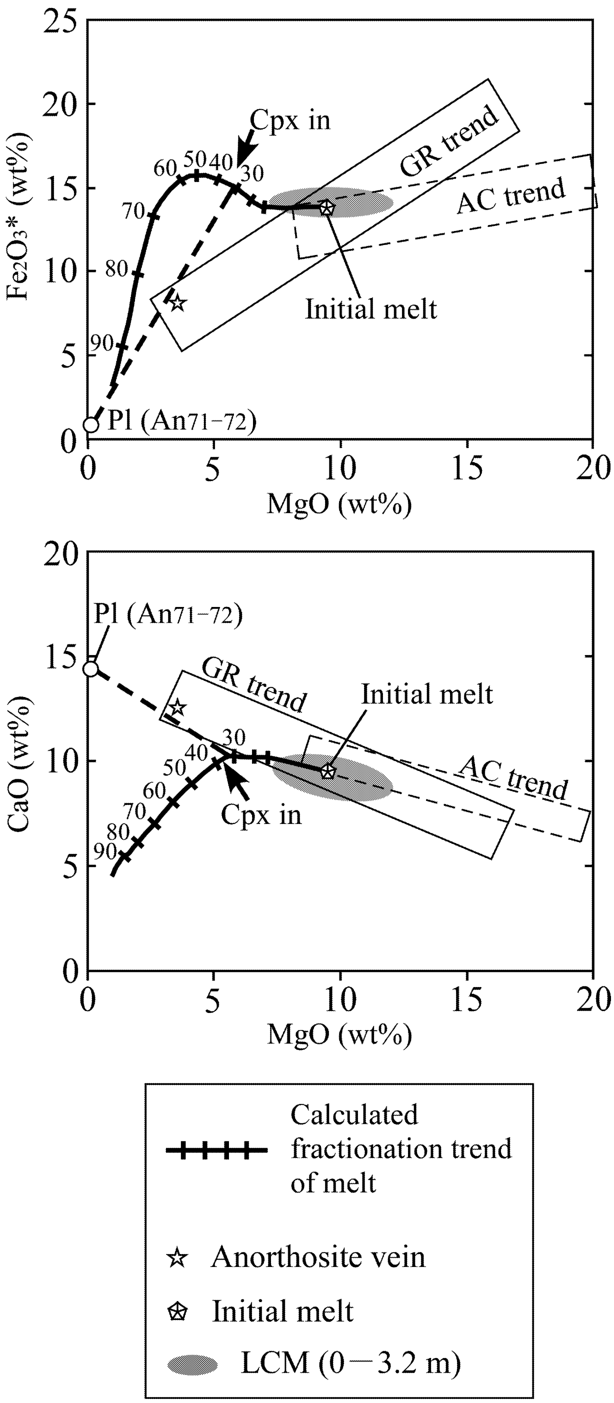

Figure 4. Calculated fractionation trend of the interstitial melt, starting from the initial melt composition. $Fe_2O_3^*$ as total iron. Numbers on the trend lines represent the degree of solidification (in weight percent).

THE WHOLE-ROCK COMPOSITION AND ITS SYSTEMATICS

Whole-rock compositions of various rock types from the Murotomisaki Gabbroic Complex have been reported in Akatsuka et al. (1999) with an illustration of a stratigraphic variation diagram. They are plotted in FeO-MgO and CaO-MgO variation diagrams in Figure 2 for the study of whole-rock compositional systematics. With the recognition of the AC zone and the GR zone, we noted that the AC zone rocks and GR zone rocks define separate trends (Figure 2). The AC zone trend goes through the initial melt composition that had been deduced from chilled marginal composition by Akatsuka et al. (1999) and extends toward the olivine composition of Fo_{83} – the core composition of the phenocrysts of the lower chilled marginal rocks. We interpret this AC trend to represent a mixing between the initial melt and phenocrystic olivine (i.e., olivine-crystal accumulation trend), being guided by the crystal accumulation hypothesis (Hoshide et al., 2006). Many of the GR zone rocks (i.e., LOG), however, plot off the AC trend and define a separate trend with a different slope. We also note that the coarse gabbros (CG) and the upper olivine gabbros (UOG) that occur above the GR zone broadly lie on the extension of the GR-zone trend on the opposite side beyond the initial melt composition, i.e., on the less magnesian side. We refer this entire trend, including the coarse gabbros (CG) and upper olivine gabbros (UOG), to as the GR trend hereafter. These two trends, AC and GR trends, having different slopes, cross each other at a point near the initial melt composition. We also note that the composition of an anorthosite vein taken from the middle of the GR zone lies on the GR trend defining the least magnesian terminal point, which led us to think that the anorthosite vein played a critical role in the formation of the GR trend.

ANORTHOSITIC VEINS AND WAVY PEGMATITIC VEINS IN THE GR ZONE

The GR zone contains abundant anorthositic veins (Fig. 3A) and 'wavy pegmatitic veins' that consist of anorthosite on the top and augite + olivine precipitates on the bottom (Yajima, 1972a). Anorthositic vein is particularly abundant in an olivine-rich horizon at approximately 60–80 m from the base of the intrusion, which is marked O2 in Figure 1. Olivine-rich zone (O3) just above the horizon O2 contains wavy pegmatitic veins as well as anorthositic veins (Fig. 1). Yajima (1972a) did not clearly distinguish between the anorthositic veins and the wavy pegmatitic veins, but considered these veins represent differentiation products precipitated from fractionated melts at very late stages of magmatic differentiation. We, however, envisage that they played an important role during the main stages of differentiation of the intrusion. The anorthositic veins are typically a few tens of centimeter in thickness and reaches up to 1 meter; their volumetric abundance is on average, below 10%. The anorthositic veins and wavy pegmatitic veins typically have wavy upper surfaces (Fig. 3A). Locally this wavy structure has been well developed into plume-like structures, suggesting that plagioclase-rich crystal mushes have been mobilized and ascended diapirically (Fig. 3 C, D). Within the veins, plagioclase crystals are aligned parallel to the upper surface of the veins (Fig. 3B), suggesting that abundant plagioclase crystals were already present at the mobilization stage. The anorthosite consists of plagioclase and augite with an ophitic texture, in which euhedral plagioclase are enclosed in large crystals of augite. Another feature of the GR zone is the presence of modal layering in its lower parts (Fig. 16 in Yajima 1972a), which may represent an incipient stage of the formation of anorthositic veins.

FORMATION OF THE GR TREND

Looking at the compositional and field relationships of the anorthosite and other rock types, we envisage the following scenario for the formation of the GR trend. The GR trend on magnesian side of the initial melt composition may have been produced by the segregation and the separation of the anorthositic material (i.e., a mixture of plagioclase + melt) from partially solidified magmas. That is, it represents a residual trend formed by extraction of the anorthositic material. Much of the anorthositic material must have ascended and got mixed with remaining magma residing above. The GR trend on the less magnesian side is considered to represent a mixing trend between the initial magma (of the initial melt composition) and the anorthositic magmas. Hoshide et al. (2006) noted that olivine growth was accompanied by an increase in whole-rock MgO and FeO contents and suggested that the GR zone was chemically open with respect to these components during the crystal growth of olivine. We can now conclude that the increase of MgO and FeO was the result of the segregation and separation of the anorthositic magmas, i.e., a separation of anorthositic magmas formed a series of residual rocks behind that are enriched in the olivine component.

FORMATION OF ANORTHOSITIC MAGMA

In order to examine if the anorthositic magma can really be generated by crystallization differentiation within the GR zone, we carried out preliminary calculations of phase equilibria to reproduce the differentiation trend of the melt. We utilized the computer software "PELE" (Boudreau, 1999) which is a PC window version of MELTS (Ghiorso and Sack, 1995). Calculations were made starting from the initial melt composition determined by Akatsuka et al., (1999). 1.0 wt% water content was assumed for the initial melt, a typical value for fresh tholeiitic basalts (McBirney, 1993). We also assumed QFM buffer for the oxygen fugacity, and 1 kb for the pressure of crystallization (Yajima et al., 1977). The calculation result is illustrated in Figure 4, compared with actual compositional trend of the Murotomisaki gabbros. According to these calculation, the initial liquidus phase was olivine of composition Fo_{84}, which nearly coincides with the observed value in the core of phenocrysts of the chilled marginal rocks (Akatsuka et al, 1999); and the subsequent liquidus phase was An_{75} plagioclase. As crystallization proceeds, MgO decreases and CaO and FeO slightly increase in the early stages of the fractionated melt. At about 30% crystallization, the melt is saturated with augite, beyond which FeO content further increases, while CaO now decreases. At 60% crystallization, magnetite starts to precipitate and the FeO content of the melt starts to decrease. It should be noted that the calculated melt trend deviates largely from the observed GR trend and does not go through the compositional point of the anorthosite vein, which implies that the anorthosite does not represent a fractionated melt at any stage. It is, however, possible that the anorthosite represents a mixture of a fractionated melt, say at 30% solidification, and plagioclase crystals (An_{71-72}) that are in equilibrium with the fractionated melt. By taking all major elements into account, we calculated the best match of the observed anorthosite composition with theoretically calculated values of the crystal-melt mixtures. The best solution of the present model is a mixture of 60% fractionated melt (of the composition produced by 30% solidification of the initial melt) and 40% plagioclase (An_{72}). The calculation supports the hypothesis that the anorthosite vein represents a crystal mush of plagioclase and fractionated melt. With this amount of melt, the mush would be fluidal enough for segregation to occur and probably buoyant enough for the diapiric ascent to occur. The latter point must be examined more carefully, however, by comparing the average densities between the anorthositic crystal mush and its surroundings - another mixture of melt and crystals.

DISCUSSION AND CONCLUSIONS

An important conclusion obtained in this study is that segregation and ascent of anorthositic crystal mush played an important role in magmatic differentiation of the Murotomisaki Gabbroic Complex.

This process resembles the "boundary layer fractionation" that was proposed by Langmuir (1989), but differs from it in that the material that ascended was crystal mush and not fractionated interstitial melts.

The GR trend is a combination of (a) a residual trend that was created by the segregation of anorthositic crystal mush in the boundary layer and (b) a mixing trend between the original magma and the ascending buoyant crystal mushes.

Anorthositic veins and pegmatitic veins seem to be common in many other igneous intrusions (Larsen and Brooks, 1994; Puffer and Volkert, 2001) and whether the process envisaged in this study is a common phenomenon in magmatic differentiation applicable to other intrusions is an important subject for future studies.

Physical mechanism of segregation of crystal mushes remains uncertain and, for better understanding of the process, fluid mechanical consideration would be a necessary step forward.

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