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Modelling intrusion of mafic and ultramafic magma into the continental crust: numerical methodology and results

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ABSTRACT

Field studies and geophysical imaging indicate that granitic and non-granitic plutons have both very variable and comparable shapes and sizes. We simulated numerically intrusion of partially molten mantle rocks from a sub-lithospheric magmatic source region (SMSR). Our systematic numerical modelling results show that intrusion typically spans a few hundred kyr spanning three stages: (1) magmatic channel spreading, (2) emplacement and (3) post-intrusive subsidence and cooling. The duration of each of these stages strongly depends on the viscosity of ascending magma. Upward magma transport from sublithospheric depth is driven by the positive buoyancy of the partially-molten rocks with respect to the overriding colder mantle lithosphere. By systematically varying the model parameters we document variations in intrusion dynamics and geometry that range from funnel- and finger-shaped bodies (pipes, dikes) to deep seated balloon-shaped intrusions and flattened shallow magmatic sills. Relatively cold elasto-plastic crust (T_{Moho} = 400ºC) promotes a strong upward propagation of magma due to the significant decrease of plastic strength of the crust with decreasing confining pressure. Warmer crust (T_{Moho} = 600ºC) triggers lateral spreading of magma above the Moho.

KEY WORDS: *intrusion emplacement, numerical modelling, magmatic bodies.*

RIASSUNTO

Modello di intrusione di magma femico e ultra-femico nella crosta continentale: metodologia numerica e risultati.

Studi di terreno e immagini geofisiche indicano che plutoni granitici e non-granitici hanno forme e grandezze sia confrontabili che variabili. Abbiamo simulato numericamente l'intrusione di rocce di mantello parzialmente fuse da una regione di sorgente magmatica sub-litosferica (SMRS). I risultati della nostra modellizzazione numerica sistematica mostrano che l'intrusione tipicamente copre tre stadi su poche centinaia di migliaia di anni: (1) espansione del canale magmatico, (2) messa in posto e (3) subsidenza e raffreddamento post-intrusivi. La durata di ognuno di questi tre stadi dipende fortemente dalla viscosità del magma ascendente. Il trasporto di magma verso l'alto da profondità sub-litosferiche è guidato dalla galleggiabilità positiva delle rocce parzialmente fuse rispetto al mantello litosferico circostante più freddo. Variando sistematicamente i parametri del modello documentiamo variazioni nella dinamica e nella geometria dell'intrusione che varia da corpi a forma di imbuto e colonna (camini vulcanici, filoni eruttivi) a intrusioni profonde a forma di pallone (baloon) e filoni strato appiattiti superficiali. Una crosta continentale elasto-plastica relativamente fredda (T_{Moho} = 400ºC) favorisce una forte propagazione di magma verso l'alto a causa della significativa diminuzione della resistenza plastica della crosta con la diminuzione della pressione confinante. Una crosta più calda (T_{Moho} = 600ºC) stimola l'espansione laterale di magma sopra la Moho.

TERMINI CHIAVE: *messa in posto di corpi intrusivi, modellizzazione numerica, corpi magmatici.*

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INTRODUCTION

Field studies and geophysical imaging indicate that granitic and non-granitic plutons have both very variable and comparable shapes and sizes (e.g. BEST & CHRISTIANSEN, 2001; PETFORD, 1996; CRUDEN & MCCAFFREY, 2001; BOLLE *et alii*, 2002). The dimensions of plutons are therefore rock-type independent. It is generally accepted that plutons grow by collecting and transferring melt from a deep source to higher emplacement levels. Melting (anatexis and dehydration melting of hydrous minerals) of rocks generates these melts, with felsic to intermediate compositions when the source is the continental crust, or mafic and ultramafic compositions when partial melting affects the upper mantle (e.g. RUDNICK & GAO, 2004). However, evidence for sublithospheric magma sources indicates that transfer of non-kimberlitic magma also occurs on a larger scale, through the lithosphere (e.g. ANDERSON, 1994; SCHMIDT & POLI, 1998; ERNST *et alii*, 2005; WRIGHT & KLEIN, 2006). This is especially true for intrusions of mafic and ultramafic bodies into the lower density (by 100-500 kg/m^3) continental crust that are documented for a large variety of tectonic settings spanning continental shields, rift systems, collision orogens and magmatic arcs.

While accepting the conventional ideas concerning plutonism, we are confronting three intriguing questions: (1) How can magma move from sub-lithospheric molten regions to shallower storage chambers? (2) How high-density, ultramafic and mafic magma can ascend into the lower density crust, at odds with the common acceptance that mafic and ultramafic magma stays deep and forms the lower crust (e.g. RUDNICK & GAO, 2004) and (3) how temperature-sensitive rheologies of both magma and country rocks together influence the emplacement of such ultramafic/mafic magmas?

MODELLING TECHNIQUES

We decided to take advantage of recent progress in hardware and software capabilities to generate two-dimensional visco-elasto-plastic numerical models of mafic-ulramafic intrusion emplacement incorporating in particular the temperature-sensitive properties of both magma and country rocks. Thermomechanical modelling of magma intrusion is numerically challenging because it involves simultaneous and intense deformation of materials with very contrasting rheological properties: the country, crustal rocks are visco-elasto-plastic while the intruding magma is a low viscosity, complex fluid (e.g.

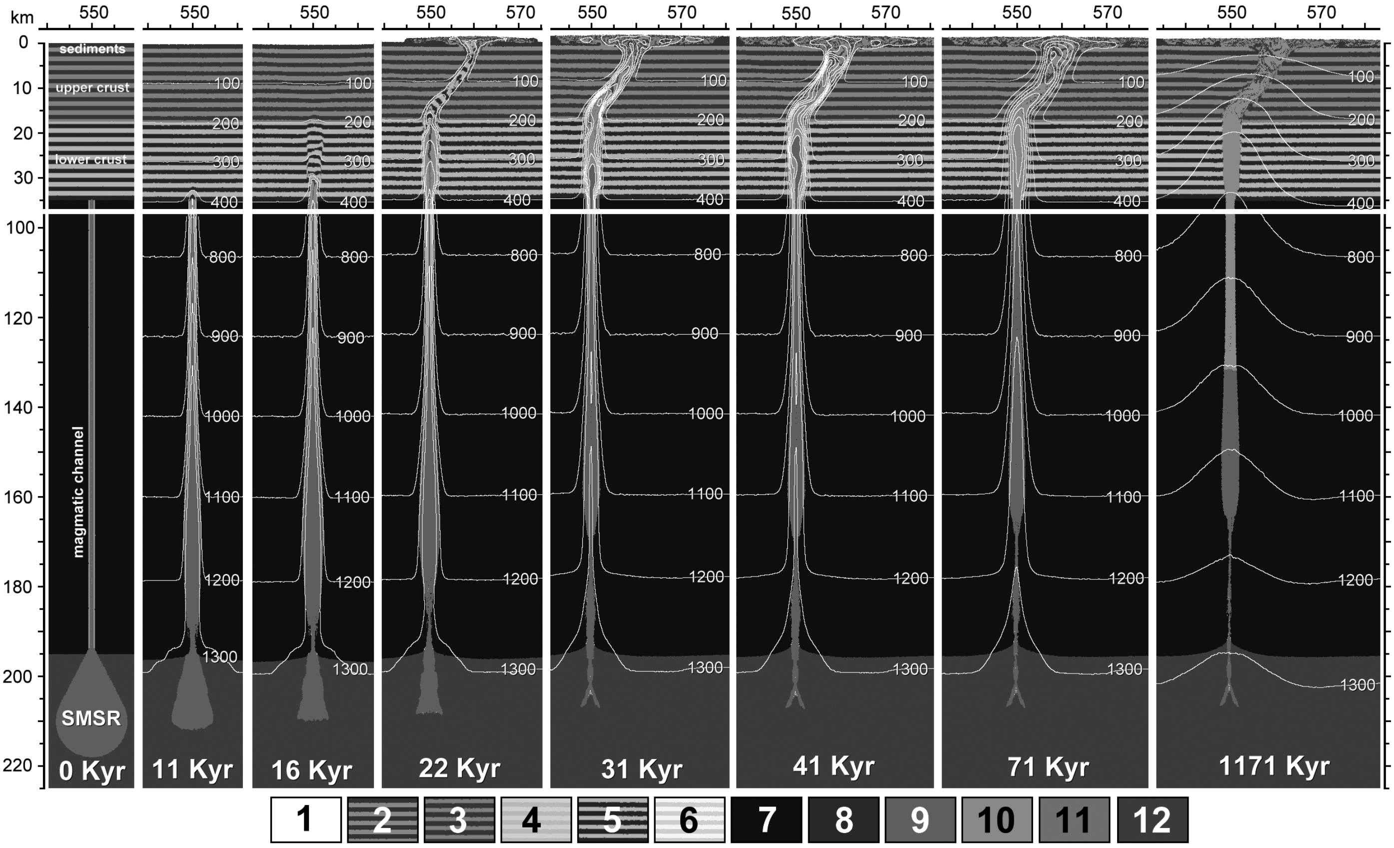

Fig. 1 - Enlarged 20-50 × 215 km areas of the original 1100 km × 300 km reference model. Distribution of rock layers in the intrusion area during emplacement of the ultramafic body into the crust from below the lithosphere via the magmatic channel. LEGEND: 1) weak layer (air, water); 2) sediments; 3, 4) upper crust (3 - solid, 4 - molten); 5, 6) lower crust (5 - solid, 6 - molten); 7, 8) mantle (7 - lithospheric, 8 - asthenospheric); 9, 10) peridotite (9 - molten, 10 - crystallized); 11, 12) gabbro (11 - molten, 12 - crystallized). Time (kyr) is given in the figures. White numbered lines are isotherms in °C. Vertical scale: depth below the upper boundary of the model. Initial numerical setting of this study is shown on the leftmost section of the model (0 Myr). The lithospheric and asthenospheric mantles have the same physical properties, different grey tones are used for a better visualization of deformation and structural development. This is also true for the passive colour-layering in the upper and the lower crust. Initial and boundary conditions are detailed in (GERYA & BURG, 2007).
– *Porzione estesa 20-50 × 215 km del modello di riferimento originale di dimensioni 1100 km × 300 km. Distribuzione dei livelli di roccia nell'area d'intrusione durante la messa in posto del corpo ultra-femico nella crosta da livelli sub-litosferici attraverso il canale magmatico. LEGEND: 1) strato debole (aria, acqua); 2) sedimenti; 3, 4) crosta superiore (3 - solida, 4 - fusa); 5, 6) crosta inferiore (5 - solida, 6 - fusa); 7, 8) mantello (7 - litosferico, 8 - astenosferico); 9, 10) peridotite (9 - fusa, 10 - cristallizzata); 11, 12) gabbro (11 - fuso, 12 - cristallizzato). Il tempo (in migliaia di anni) kyr) è indicato nelle figure. Le linee bianche numerate sono isoterme in °C. Scala verticale: profondità sotto il bordo superiore del modello. La configurazione numerica iniziale di questo studio è mostrata nella sezione a sinistra del modello (0 Ma). I mantelli litosferico e astenosferico hanno le stesse proprietà fisiche; differenti toni di grigio sono utilizzati per visualizzare meglio lo sviluppo della deformazione e delle strutture. Ciò è vero anche per la stratificazione passiva della crosta superiore e inferiore. Le condizioni iniziali e al contorno sono dettagliate in GERYA & BURG (2007).*

PINKERTON & STEVENSON, 1992). We employ the 2-D code I2ELVIS (GERYA & YUEN, 2003a, 2007), which is based on finite-differences with a marker-in-cell technique. The code allows for the accurate conservative solution of the governing equations on a rectangular fully staggered Eulerian grid. New developments allow for both large viscosity contrasts and strong deformation of visco-elasto-plastic multiphase flow. The code was tested for a variety of problems by comparing results with both analytical solutions and analogue sandbox experiments (GERYA & YUEN, 2003, 2007).

We simulated numerically intrusion of partially molten mantle rocks from a sub-lithospheric magmatic source region (SMSR, fig. 1, 0 Kyr). Developments introduced for intrusion simulation allow for both large viscosity contrasts and strong deformation of visco-elasto-plastic multiphase flow, incorporating temperature-dependent rheologies of both intrusive molten rocks and host rocks (GERYA & BURG, 2007). A magmatic channel is a vertical, 1.5 km wide zone characterised by a wet olivine rheology and a low 1 MPa plastic strength throughout the lithospheric mantle. The initial thermal structure of the lithosphere is as usually assumed, with a 35 km thick crust (fig. 1, 0 Kyr) corresponding to a sectioned linear temperature profile limited by 0°C at the surface, 400°C at the bottom of the crust and 1300°C at 195 km depth. The temperature gradient in the asthenospheric mantle is 0.6°C/km below 195 km depth.

The code grey (code colour in the coloured version) identifying rock types is given in figure 1. The discrimination between «peridotite» and «molten peridotite» is thermal, separating material points (pixels) above/below the wet solidus temperature of peridotite at a given pressure. Since the melt fraction is strongly changing with water content, variations within few % of melt fraction at given pressure-temperature condition are possible. Therefore, it is illusory to predict the exact melt fraction at any point of the models, in particular because the simplified linear melting model implemented here (GERYA & BURG, 2007) does not allow a very high precision on this question.

DISCUSSION

Modelling results (cf. GERYA & BURG, 2007, for details of experiments) show that intrusion typically lasts a few hundred kyr spanning three stages: (1) magmatic channel spreading (fig. 1, 0-16 Kyr), (2) emplacement (fig. 1, 22-41 Kyr, fig. 2) and (3) post-intrusive subsidence and cooling (fig. 1, 71-1171 Kyr, fig. 3). The duration of each of these stages strongly depends on the viscosity of ascending magma.

Upward magma transport from sublithospheric depth is driven by the positive buoyancy of the partially-molten rocks with respect to the overriding colder mantle lithosphere. The gravitational balance controls the height of the

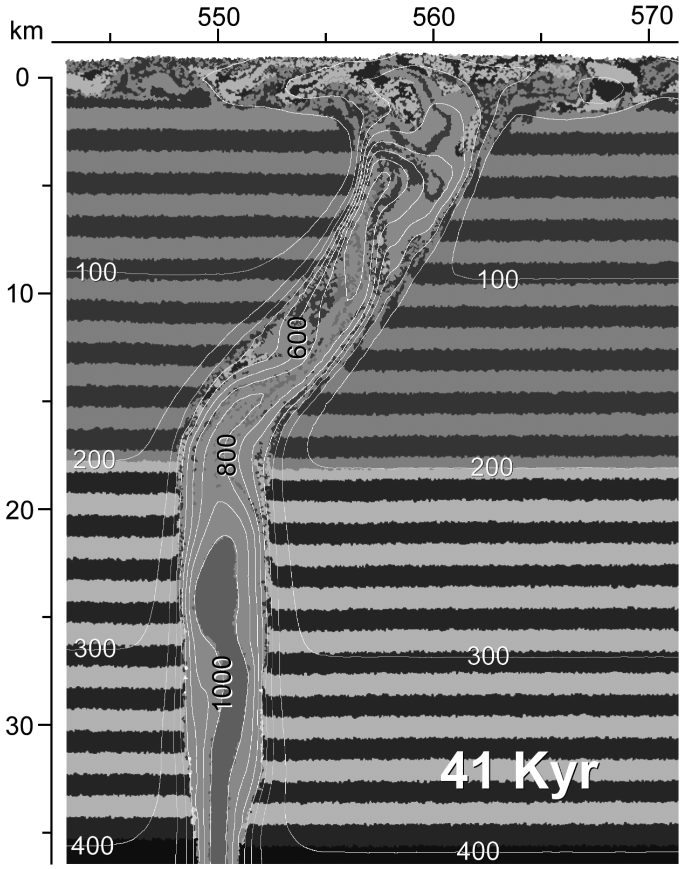

Fig. 2 - Details of temperature distribution (numbered white lines = isotherms in °C) around intrusive body during the active stage of emplacement for the reference model. Rock types are the same as in fig. 1.
– Dettagli della distribuzione della temperatura (linee bianche numerate = isoterme in °C) attorno al corpo intrusivo durante lo stadio di messa in posto attiva per il modello di riferimento. Le rocce sono le stesse di fig. 1.

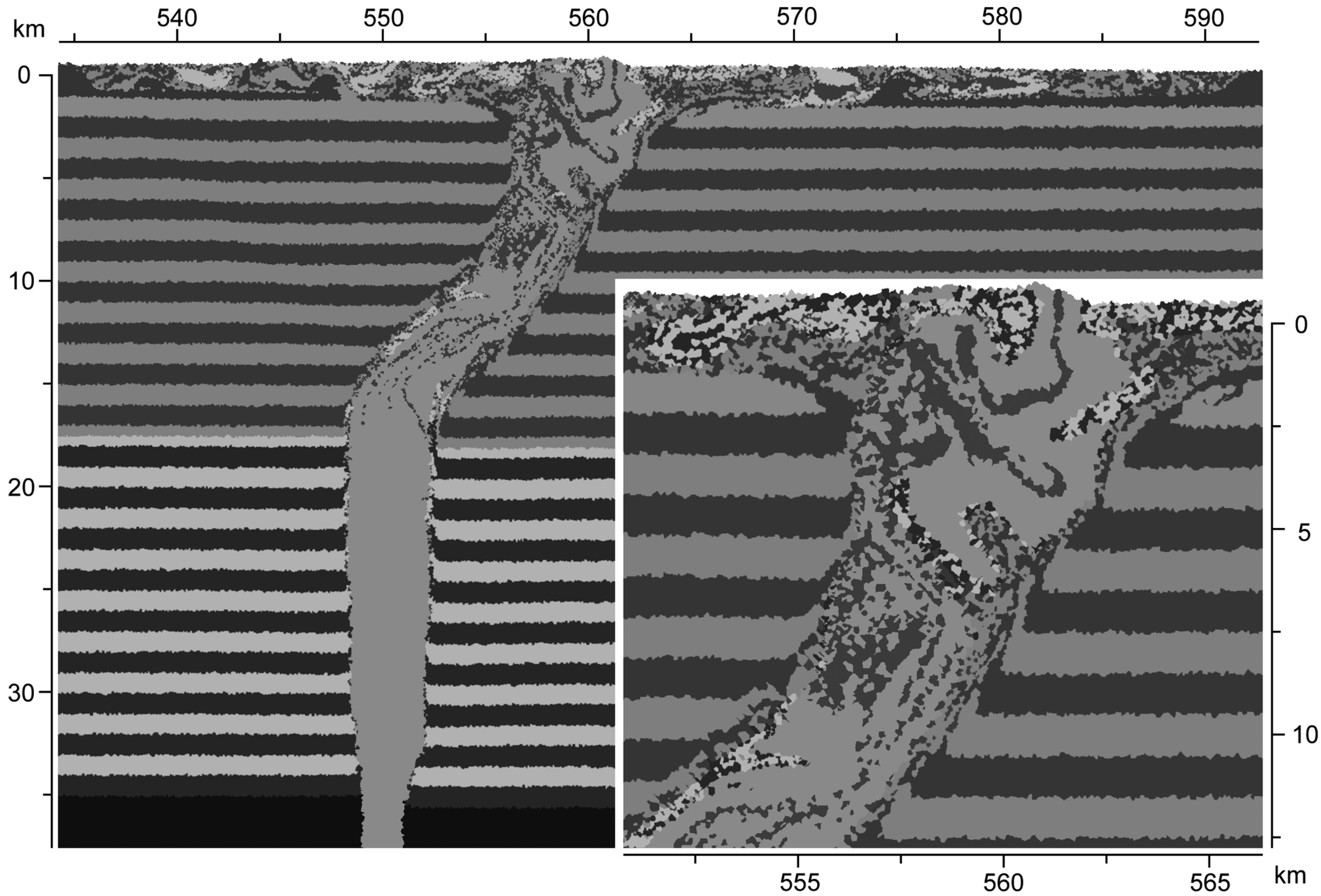

Fig. 3 - Details of culminate intrusive body shape for the reference model. Rock types are the same as in fig. 1.
– Dettagli della forma finale del corpo intrusivo per il modello di riferimento. Le rocce sono le stesse di fig. 1.

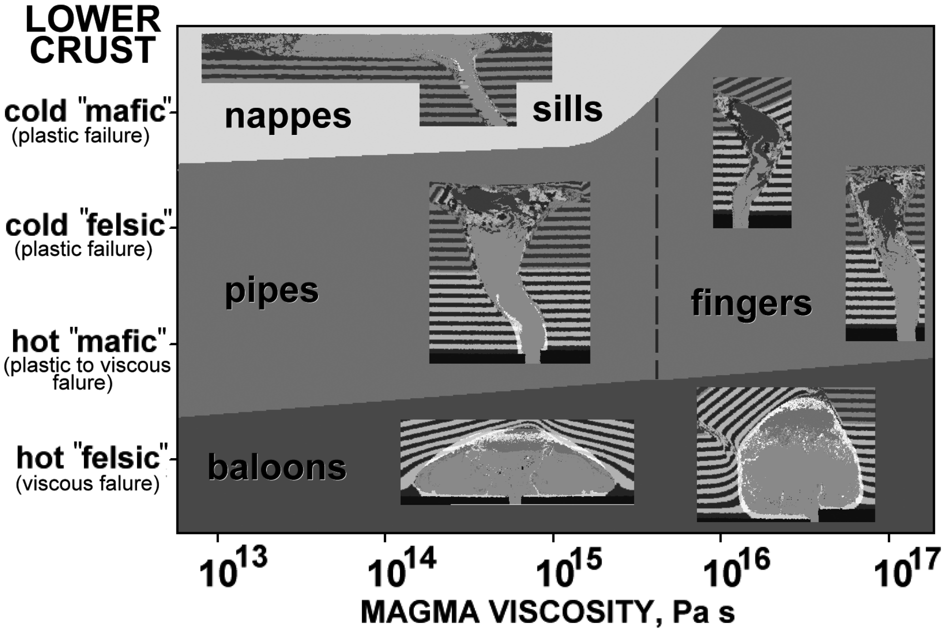

Fig. 4 - Stability of major intrusion shapes as a function of lower crust rheology and magma viscosity. Different color fields correspond to three different types of intrusive bodies (balloons, pipes/fingers and nappes/sills) obtained numerically (Gerya & Burg, 2007).
– *Stabilità dell'intrusione principale in funzione della reologia della crosta inferiore e della viscosità del magma. Differenti toni di grigio corrispondono ai tre diversi tipi di corpi intrusivi (palloni, filoni eruttivi e filoni strato) ottenuti numericamente (Gerya & Burg, 2007).*

column of molten rock but not the volume of magmatic rocks below and above the Moho. The molten rocks are pooling along the crust/mantle boundary only if the lower crust is ductile and very weak (fig. 4, deep grey field or red field in the colour version), which may be expected at the base of island arcs. It seems natural that otherwise, basic – ultrabasic magma is injected into the crust, most commonly as a finger/pipe-shaped body (fig. 4, intermediate grey field or pink field in the coloured version).

Emplacement within the crust exploits the space opened by the displacement of tectonic crustal blocks bounded by localized zones of intense plastic deformation. Temperature is the important player in controlling crustal viscosities, hence either viscous or elasto-plastic mechanisms of crustal deformation, which defines modes and rates of emplacement. Early normal faults (fig. 1, 16 Kyr) produce early surface subsidence in grabens but rapidly become inverted into thrusts (fig. 1, 22 Kyr) responsible for surface uplift while the within-crust pluton inflates and rises in the crust (fig. 2).

Late emplacement phases are responsible for cooling and subsiding of the magmatic body and partial return magma flow back into the magmatic channel below the Moho (fig. 3). This event is linked to subsidence of the surface.

By systematically varying the model parameters we document variations in intrusion dynamics and geometry that range from funnel- and finger-shaped bodies (pipes, dikes) to deep seated balloon-shaped intrusions and flattened shallow magmatic sills (fig. 4). Relatively cold elasto-plastic crust (T_{Moho} = 400°C) promotes a strong upward propagation of magma due to the significant decrease of plastic strength of the crust with decreasing confining pressure (fig. 4, intermediate and light grey fields or pink and blue fields in the coloured version). Emplacement in this case is controlled by crustal faulting and subsequent block displacements. Warmer crust (T_{Moho} = 600°C) triggers lateral spreading of magma above the Moho, with emplacement being accommodated by coeval viscous deformation of the lower crust and fault tectonics in the upper crust (fig. 4, deep grey field or red field in the coloured version).

CONCLUSION

Emplacement of high density, mafic and ultramafic magma into low-density rocks is a stable mechanism for a wide range of model parameters that match geological settings in which partially molten mafic-ultramafic rocks are generated below the lithosphere. We expect this process to be particularly active beneath subduction-related magmatic arcs where huge volumes of partially molten rocks produced from hydrous cold plume activity accumulate below the overriding lithosphere (Gerya & Yuen, 2003b).

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