Viscoelastic crustal deformation in the Aira caldera before and after the 1914 eruption of the Sakurajima volcano

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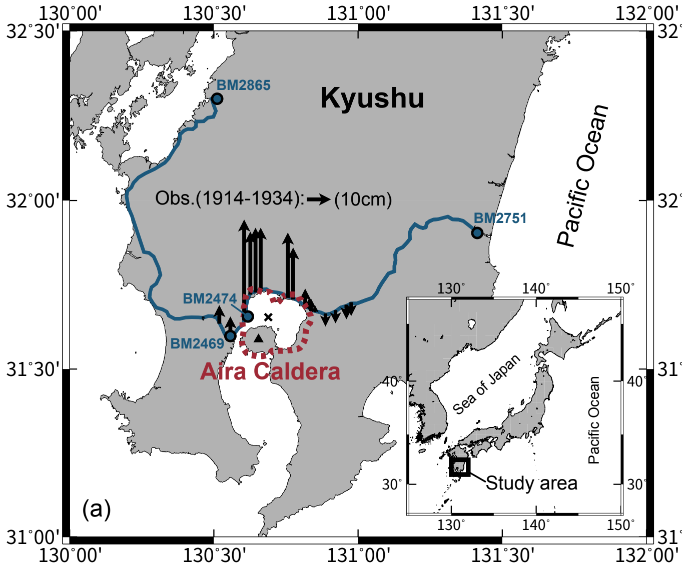
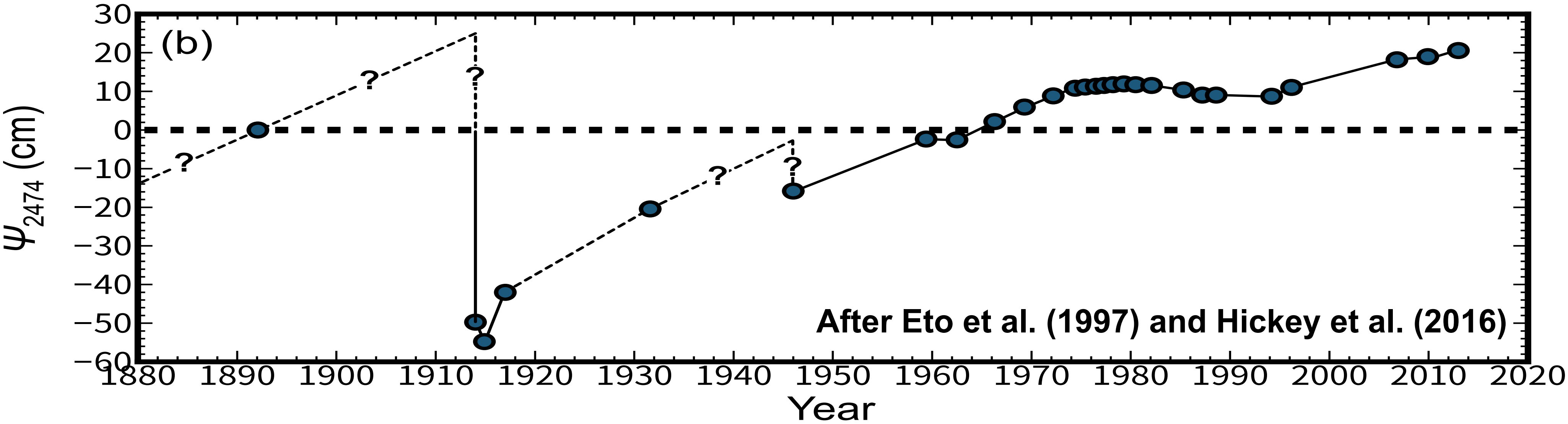
1. INTRODUCTION

1.1 The uplift of the Aira caldera before/after the 1914 eruption



• Geodetic data in the Aira caldera, southern Kyushu, Japan, provides an excellent opportunity to examine the effect of crustal viscoelasticity on the surface deformation associated with magma supply and discharge in the upper crust.

How does viscoelasticity affect post-eruption surface uplift?



1. INTRODUCTION

1.2 What this study tries to achieve

This study examines how the viscoelastic crust behaves in response to magma discharge due to an eruption, for which pre- and post-eruption magma supply into a sill-like magma emplacement in the upper crust is introduced into the model.

(1) We first describe general model behaviour.

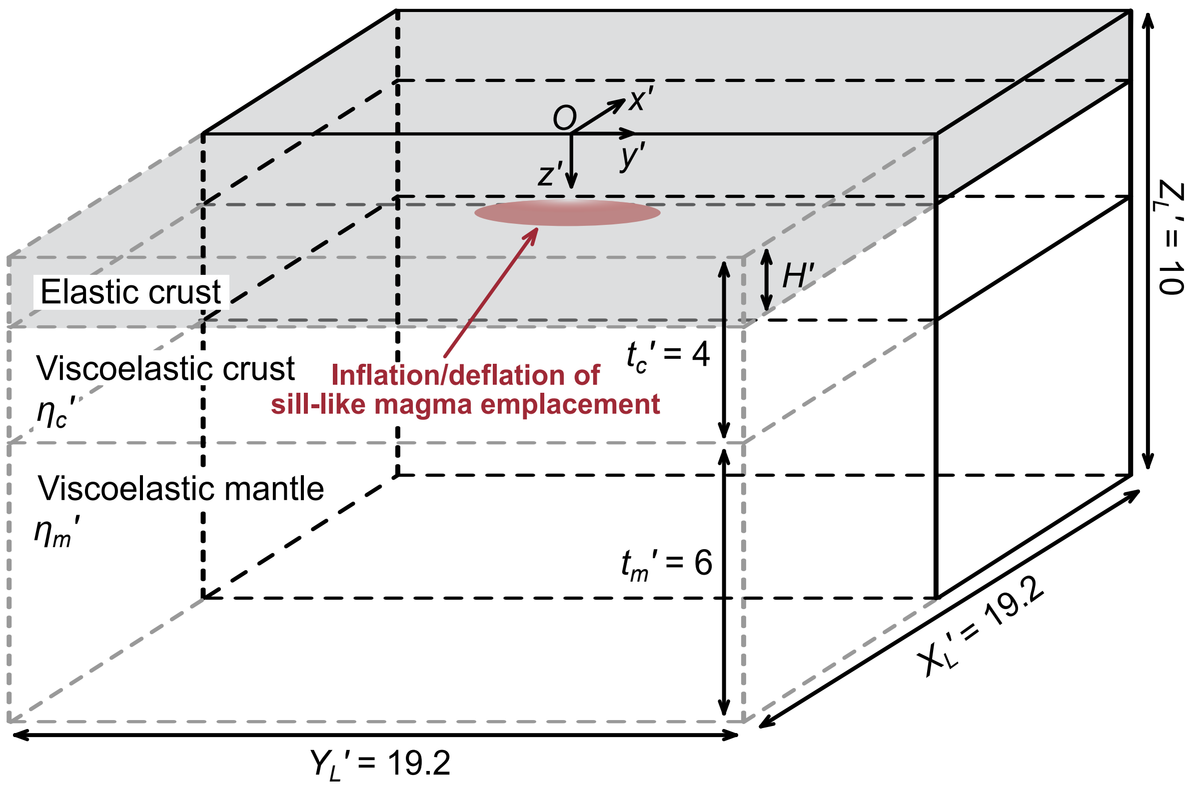
(2) Then the model behaviour is adopted for the geodetic data in the Aira caldera before and after the 1914 eruption of the Sakurajima volcano, giving constraints on the model parameters that describe the configurations of magma emplacement and crustal viscosity.

2. MODEL DESCRIPTION

2.1 Schematic figure of the 3D model used in this study

A parallelized 3-D finite element code, OREGANO_VE [e.g., Yamasaki and Houseman, 2012; Yamasaki et al., 2018; Yamasaki and Kobayashi, 2018], is used to solve the linear Maxwell viscoelastic response of the crust and mantle to a spatio-temporal development of sill. An inflation and/or deflation of sill is implemented by the split node method of Melosh and Raefsky [1981].

A rectangular modelled box adopts the linear Maxwell viscoelastic constitutive law. Tractions on the upper surface are assumed zero, and shear tractions and normal displacement are zero on any other boundary surfaces. All variables are non-dimensionalized; length by L_0, viscosity by η_0, displacement by a reference thickness of sill d_0, time by a reference Maxwell relaxation time τ_0 (= η_0/μ, where μ is the shear modulus) .



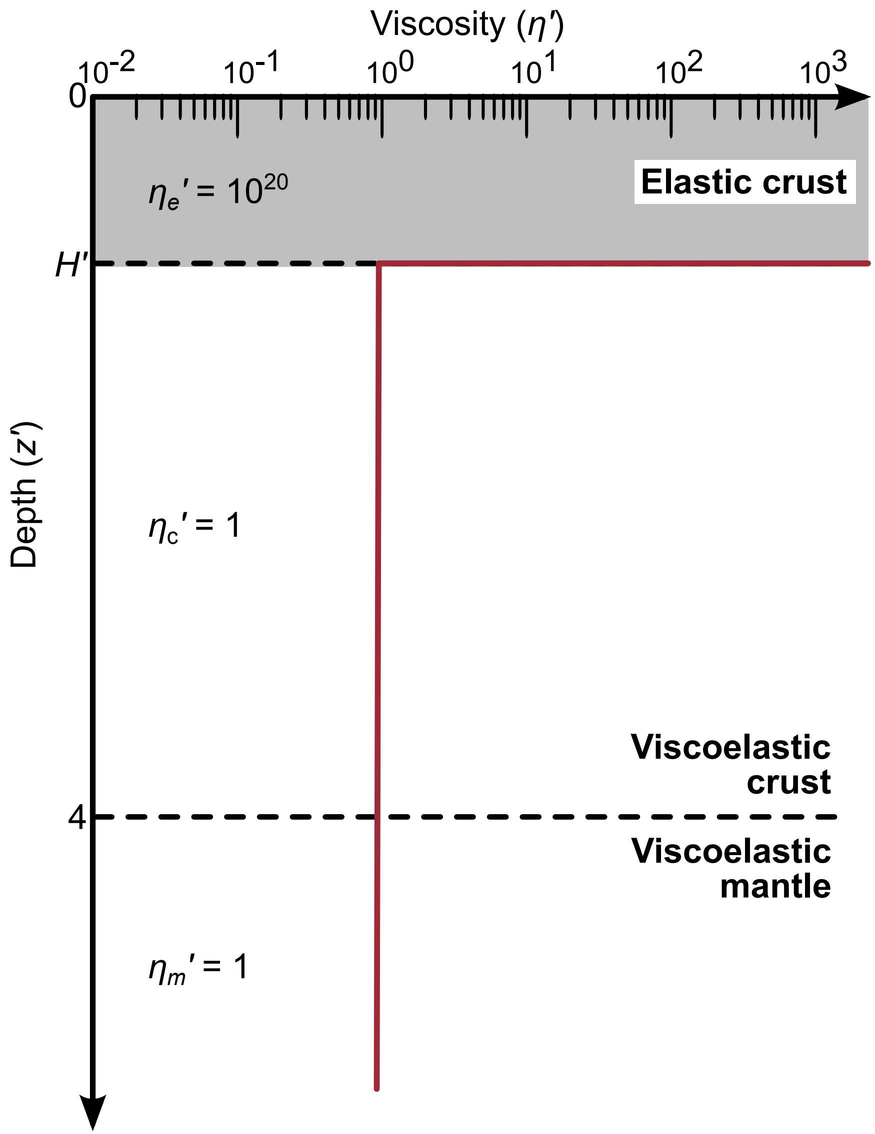
2. MODEL DESCRIPTION

2.2 Simple viscosity structure; $\eta_c' = \eta_m' = 1$

The modelled domain is composed with viscoelastic crust and mantle. The thicknesses of the crust and mantle are, respectively, Z_c' **(=** Z_c/L_0**) = 4** and Z_m' **(=** Z_m/L_0**) = 6**.

High viscosity η_e' **(=** η_e/η_0**, where** η_0 **is a reference viscosity) =** 10^{20} is given to the uppermost crust with the thickness H' **(=** H/L_0**)**, so it deforms effectively in an elastic fashion.

The underlain crust and mantle have constant viscosity values of η_c' **(=** η_c/η_0**) = 1** and η_m' **(=** η_m/η_0**) = 1**, respectively. Poisson's ratio v **= 0.25**, and Young's modulus $E' = E/\mu = 2(1+v) = 2.5$, where μ is the shear modulus, are constant everywhere.



2. MODEL DESCRIPTION

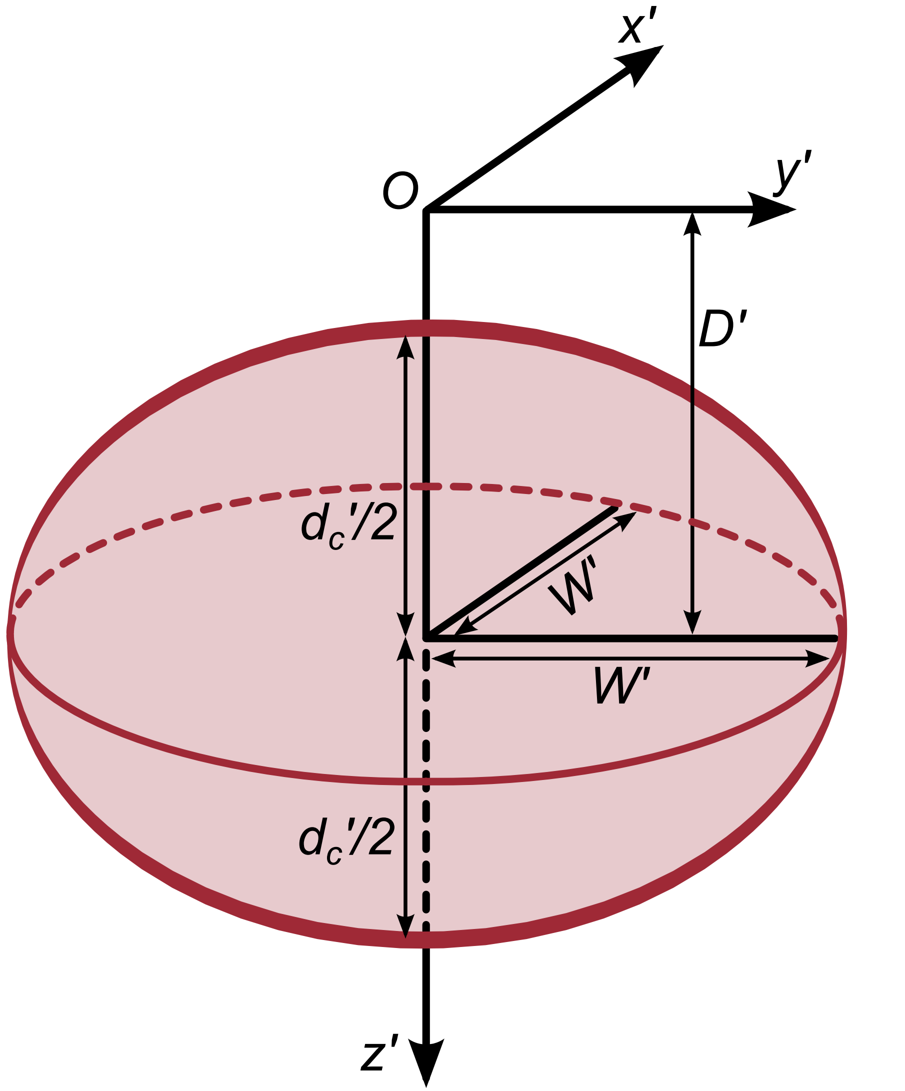
2.3 A sill-like magma emplacement as a deformation source

2.3.1 The geometry; a spheroidal sill

This study approximates the geometry of magma chamber as a spheroidal sill in this study, whose thickness $d'(x',y')$ is governed by an equation of:

$$\boldsymbol{d'(x', y') = d_c' [1 - (x'/W')^2 - (y'/W')^2]^{1/2}}$$

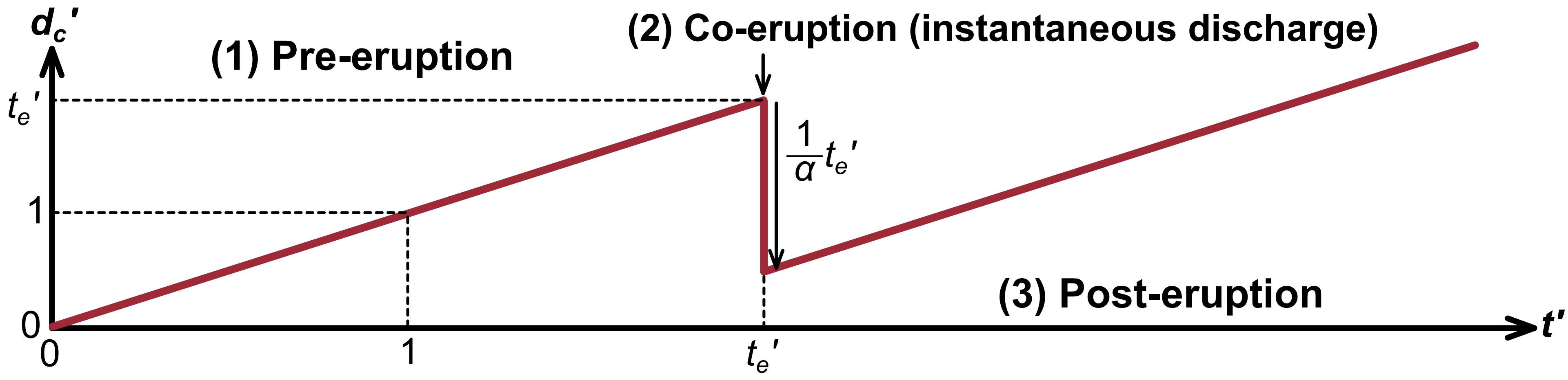
where d_c' is the thickness at the centre of the sill, x' and y' are horizontal coordinates on the surface $z' = D'$, which is defined as a depth of the sill, and W' is an equatorial radius of the sill.



2. MODEL DESCRIPTION

2.3 A sill-like magma emplacement as a deformation source

2.3.2 Development of the sill inflation/deflation



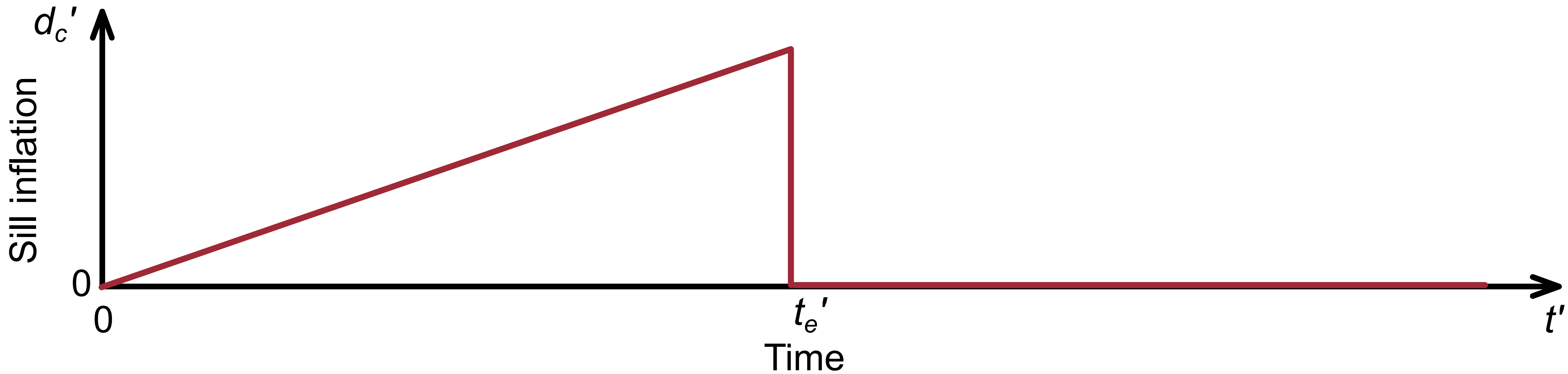
The sill thickness at the centre ($d_c' = d_c/d_{c0}$) before and after an eruption is governed by an equation of:

$$d_c' = t'$$

where t' is the time, normalised by the Maxwell relaxation time τ. d_c' linearly increases with time so as that d_c' becomes 1, i.e., $d_c = d_{c0}$, at $t' = 1$, i.e., $t = \tau$. At $t' = t_e' = t_e/\tau$, d_c' instantaneously drops to be $(1-1/\alpha)t_e'$ due to the magma discharge. At $t' > t_e'$, d_c' linearly increases with time, with the same gradient. The surface displacement U by the reference displacement scale d_{c0}.

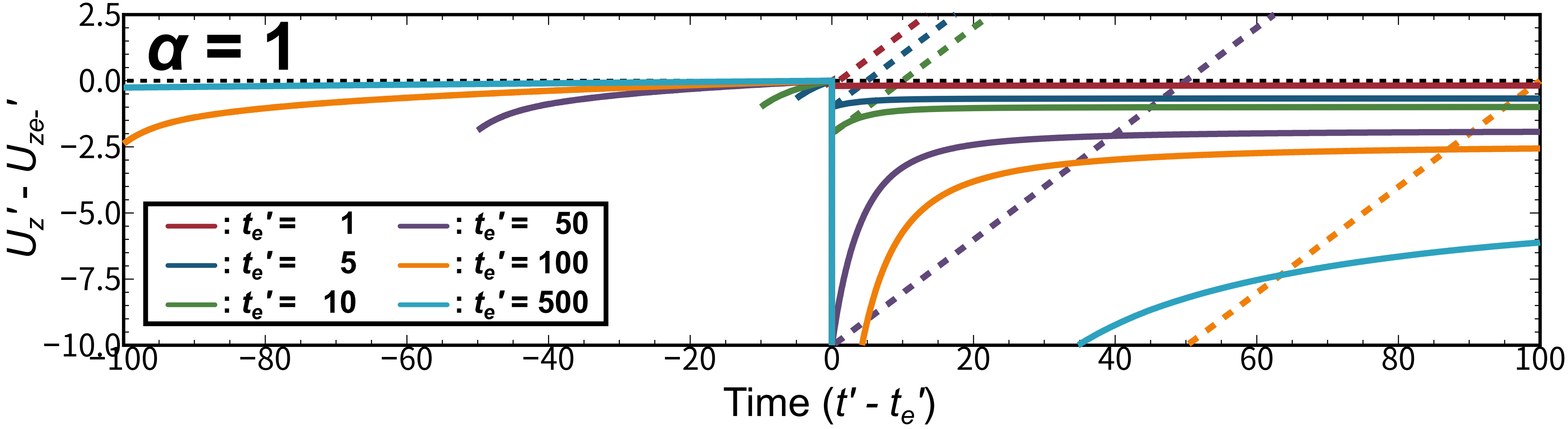
3. GENERAL MODEL BEHAVIOUR

3.1 Models with no magma recharge after an eruption



For models with $H' = D' = 0.5$ and $W' = 0.5$

The dashed lines indicate the elastic model behaviour, where the post-eruption sill inflation with the constant rate.



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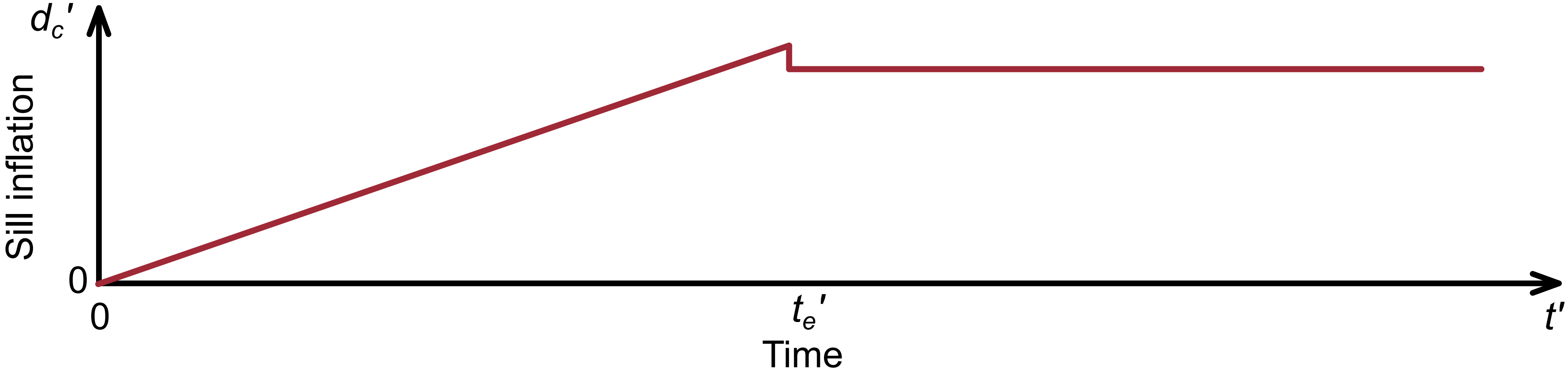

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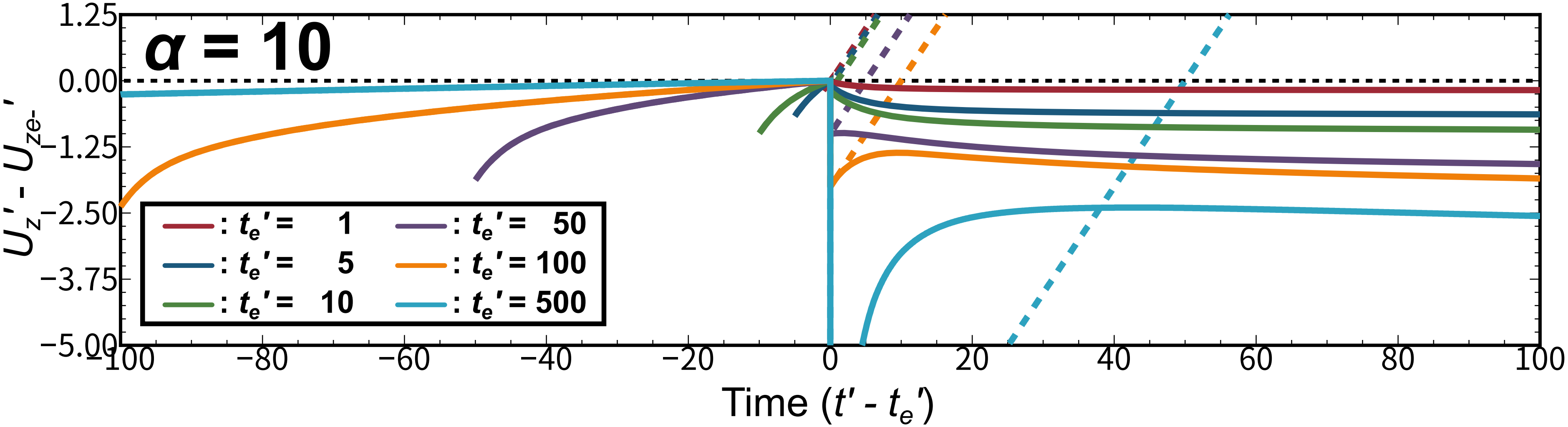

3. GENERAL MODEL BEHAVIOUR

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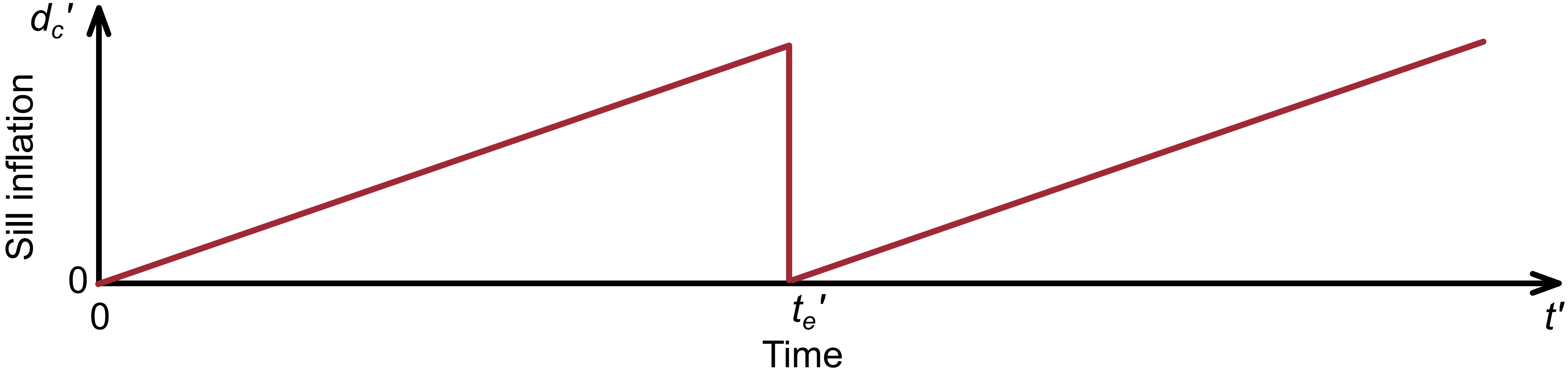

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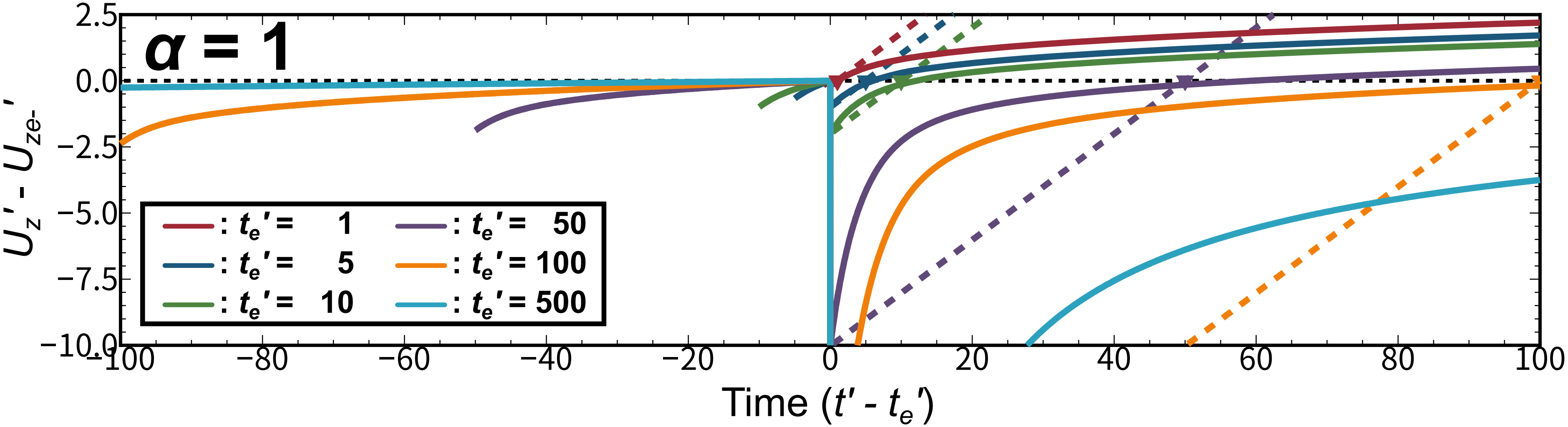
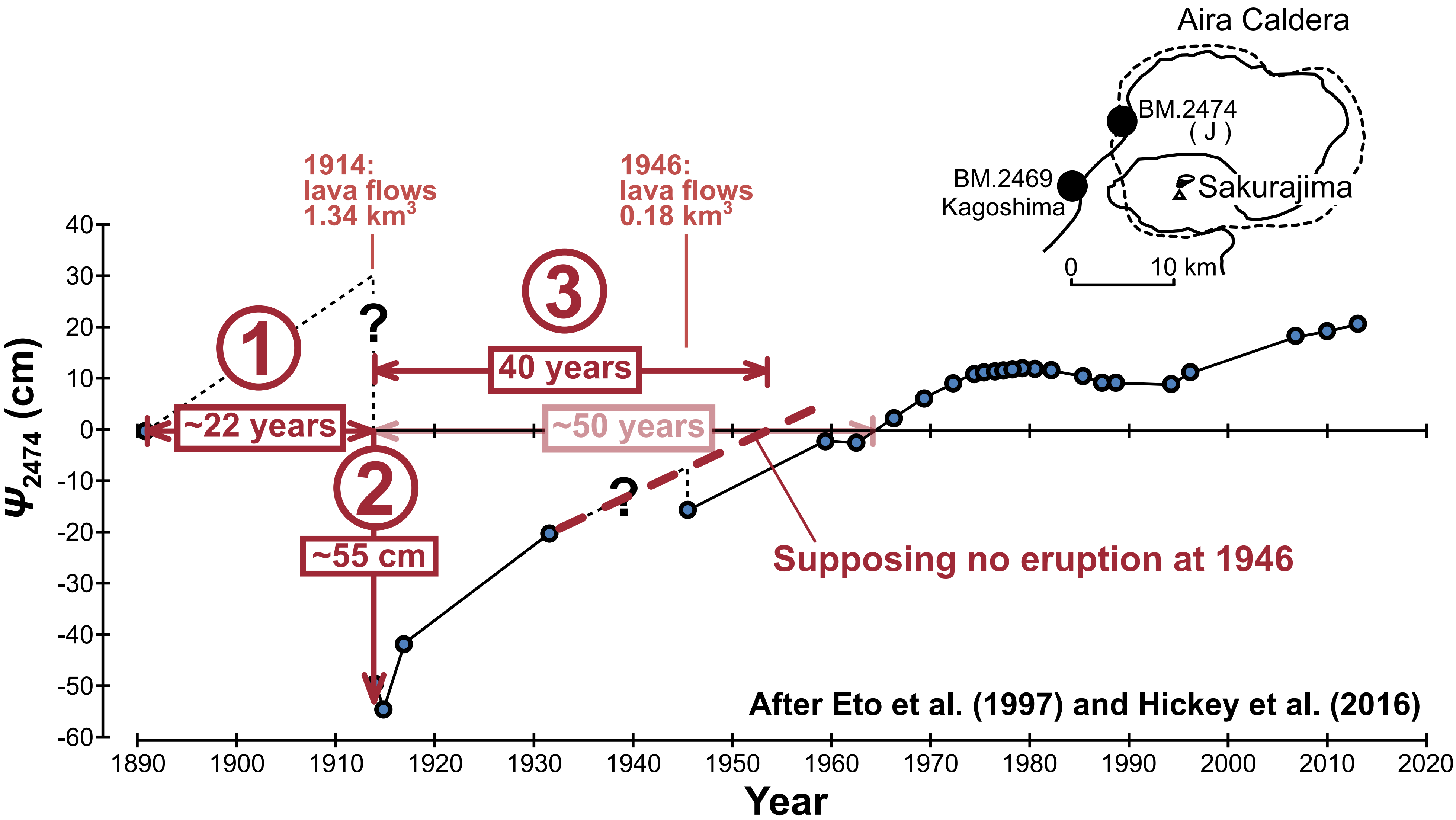


4. APPLICATION TO AIRA CALDERA

4.1 Constraints on the viscoelastic model from ψ_{2474}



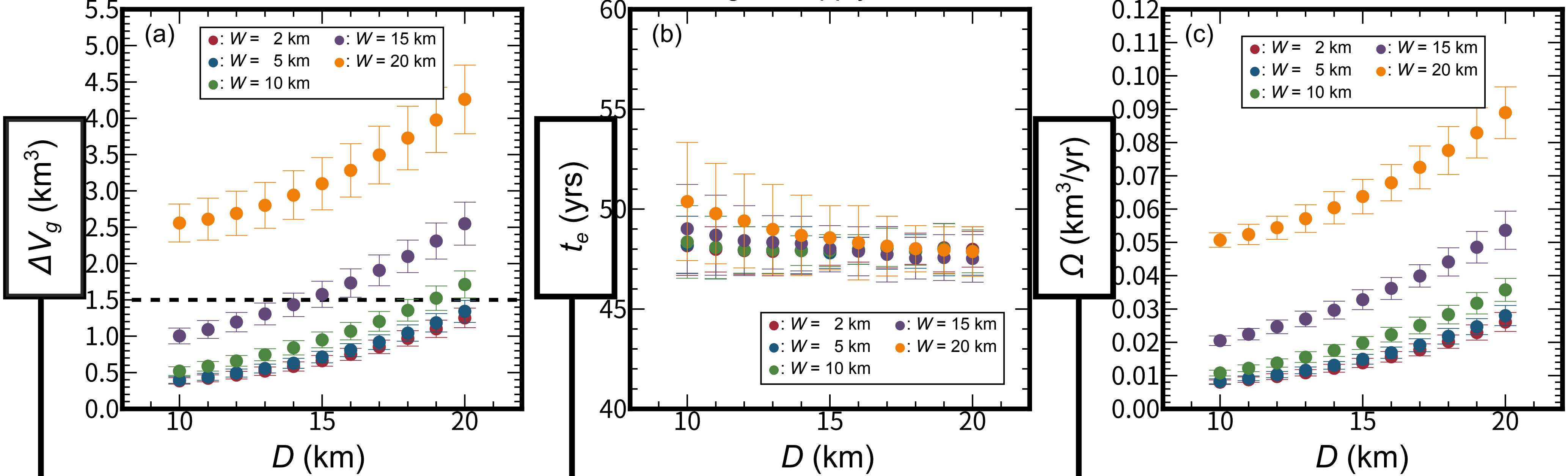
4. APPLICATION TO AIRA CALDERA

4.1 Constraints on the viscoelastic model from ψ_{2474}

ΔV_g: Sill deflation at the eruption

t_e: Eruption time after the initiation of magma supply

Ω: Inflation rate of sill



No observations provide no constraints

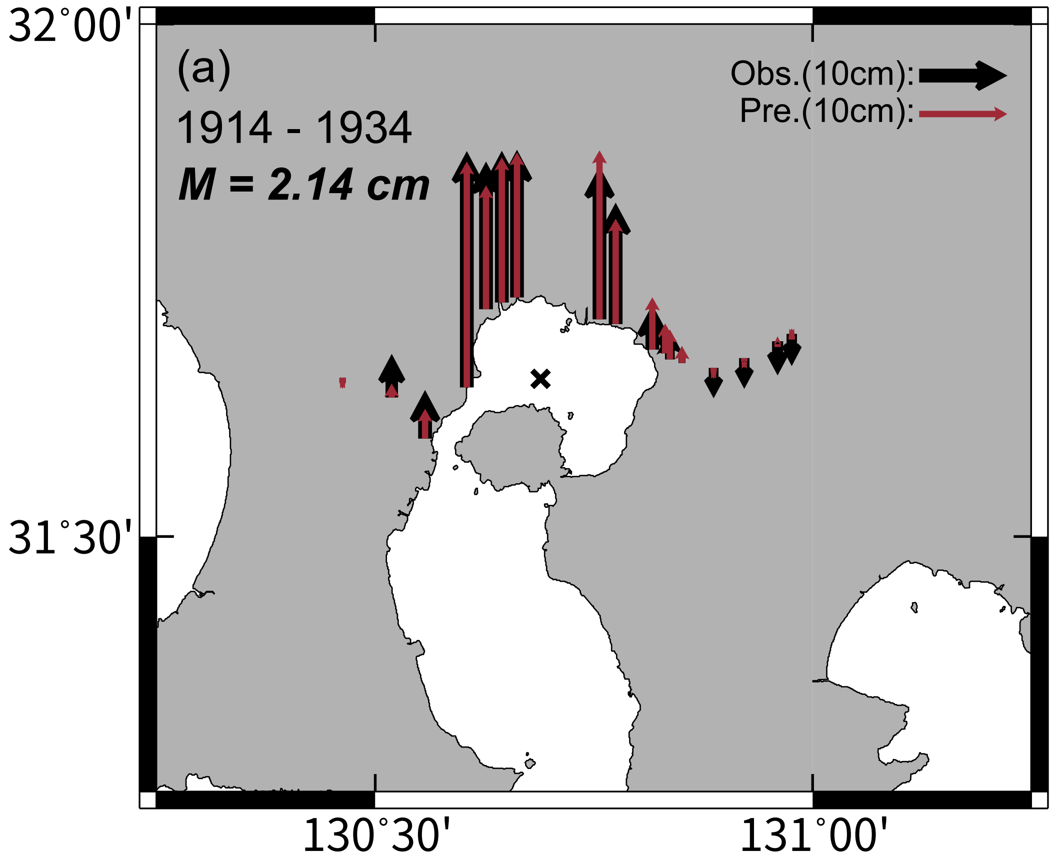
An eruptive volume of magma, which was measured on the ground surface to be ~ 1.5 km^3 (Ishihara et al., 1981), constrains ***W*** to be less than ~15 km, in which ***W*** should be smaller for greater ***D***.

4. APPLICATION TO AIRA CALDERA

4.2 Constraints from overall deformation field

The model, with which the observed overall displacement field in the period from 1914 to 1934 is best explained, has:

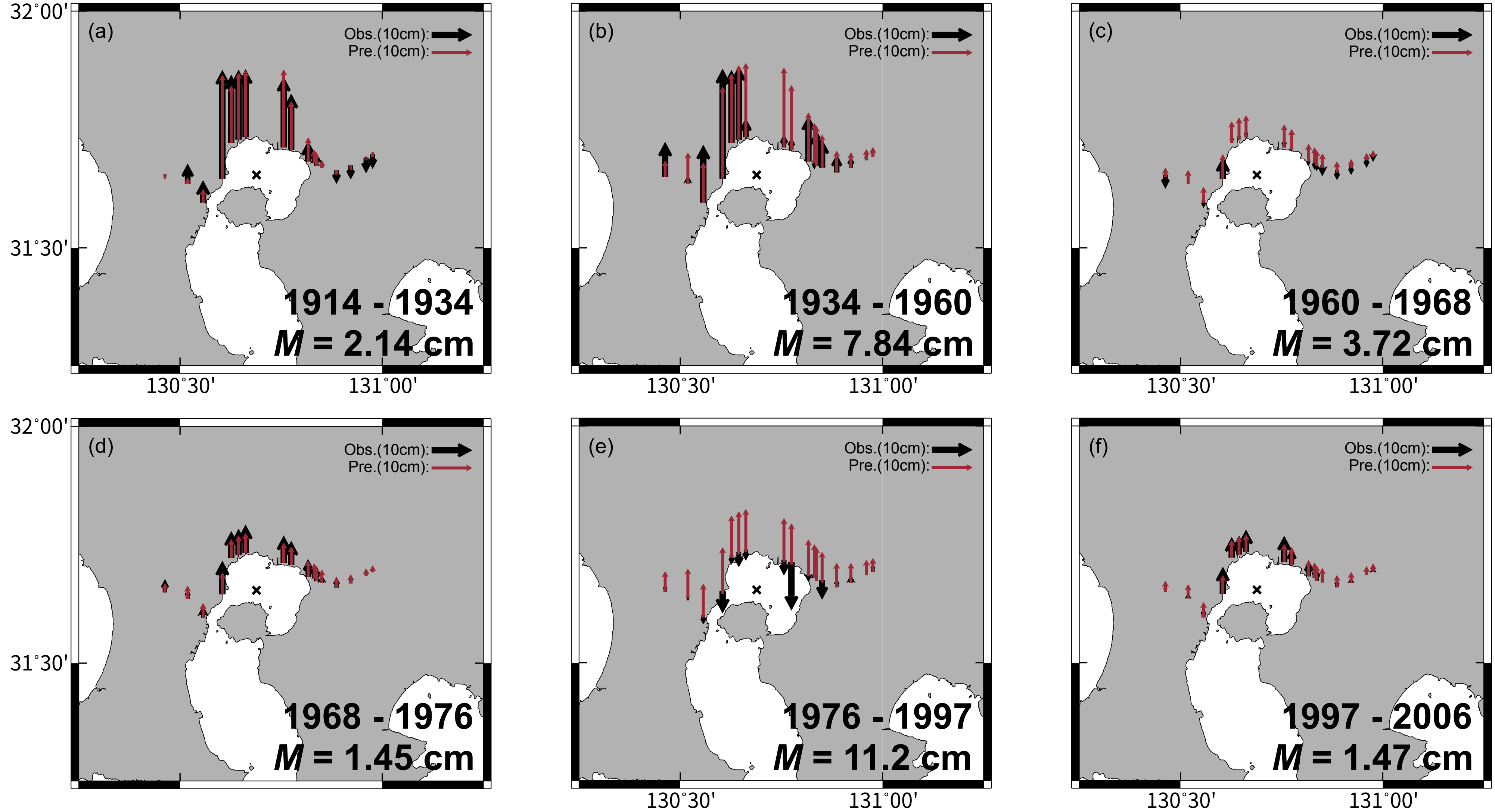
- ***D* (= *H*) = 11 km**
- ***W* = 2 km**
- **η_c = 5x10^{18} Pa s**



The levelling data were re-compiled in this study, for which the database stored in the Geospatial Information Authority of Japan, including the technical report of the Geospatial Information Authority of Japan (B3-No.1 - No. 52), was referred.

4. APPLICATION TO AIRA CALDERA

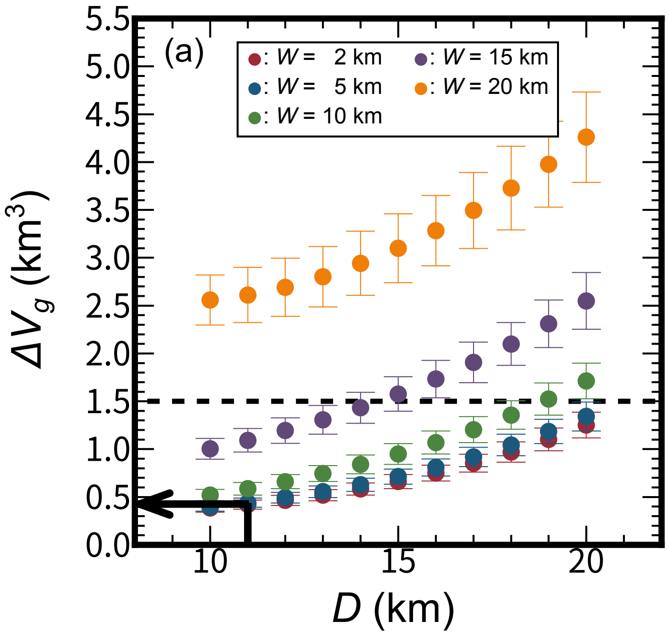
4.2 Constraints from overall deformation field



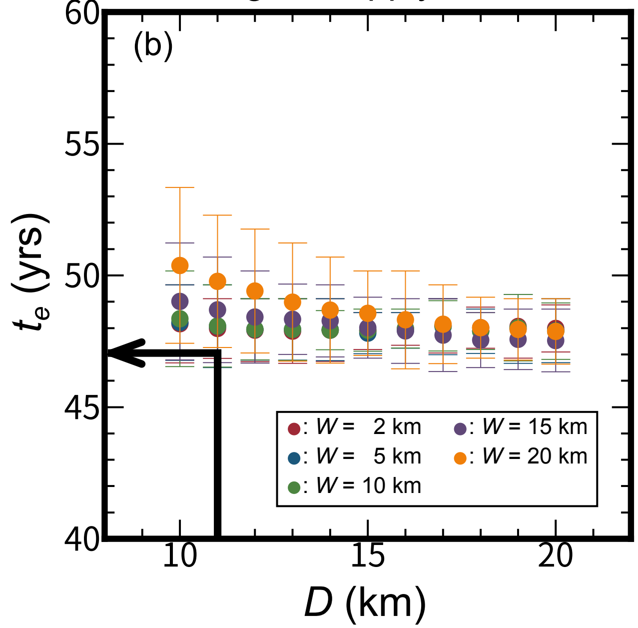
4. APPLICATION TO AIRA CALDERA

4.2 Constraints from overall deformation field

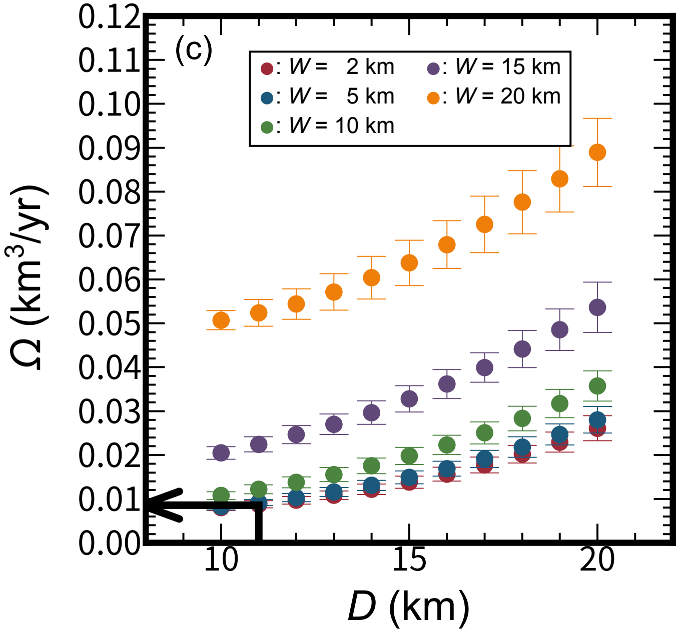
ΔV_g: Sill deflation at the eruption



t_e: Eruption time after the initiation of magma supply



Ω: Inflation rate of sill

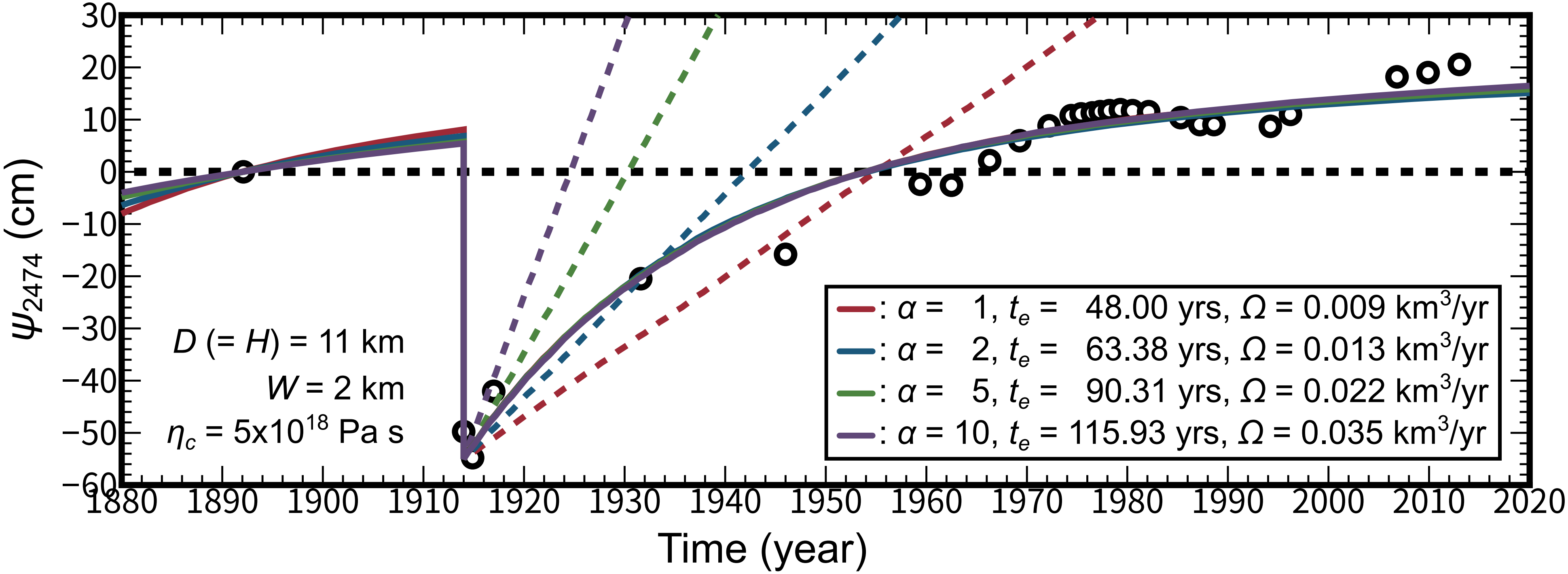


The best-fit model predicts:

- ΔV_g **= ~0.4 km**^{3} → V_m**(= ~1.5 km**^{3}**)/**ΔV_g **~ 3.75**
- t_e **= ~47 years**
- Ω **= ~0.009 km**^{3}**/yr**

4. APPLICATION TO AIRA CALDERA

4.3 Dependence on *α*



・The post-eruption uplift due to viscoelastic relaxation is greater and smaller than the elastic uplift due to magma recharge earlier and later in the post-eruption period, respectively.

・On the other hand, if only a small part of an accumulated magma is discharged, an insignificant magma recharge may allow the post-eruption viscoelastic relaxation to cause continuous subsidence.

5. CONCLUSIONS

In the present study, a 3-D finite element model has been adopted to examine the viscoelastic crustal response to both magma supply and discharge in the upper crust, for which it is assumed that a sill-like magma chamber is inflated with a constant rate at the bottom of the elastic layer, during which the magma discharge due to an eruption occurs once instantaneously. We have found:

(1) Pre-eruption viscoelastic response to magma supply controls post-eruption surface recovery.

(2) A crustal viscosity of ~$5x10^{18}$ Pa s is suggested beneath the Aira caldera.

(3) The magma emplacement beneath the Aira caldera occurs at a depth of ~11 km.

(4) Geodetic data in the Aira caldera requires the emplaced sill to inflate with a constant rate of ~0.009 km^3/yr due to magma supply.