Dynamic rupture simulation of caldera collapse earthquakes: evidence of rupture complexity

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Abstract

All instrumented caldera collapses at basaltic shield volcanoes generate M_w > 5 very long period (VLP) earthquakes. However, to date, the dynamics of these earthquakes, as well as their coupling with the underlying magma chamber, are poorly understood. We present a self-consistent numerical model using SeisSol (www.seissol.org) capturing the nucleation and propagation of ring fault rupture, the mechanical coupling to the underlying viscoelastic magma, and the associated seismic wave field. We use the model to interpret seismic waveforms from the 2018 caldera collapse of Kīlauea volcano, in terms of the ring fault rupture complexity and magma chamber dynamics.

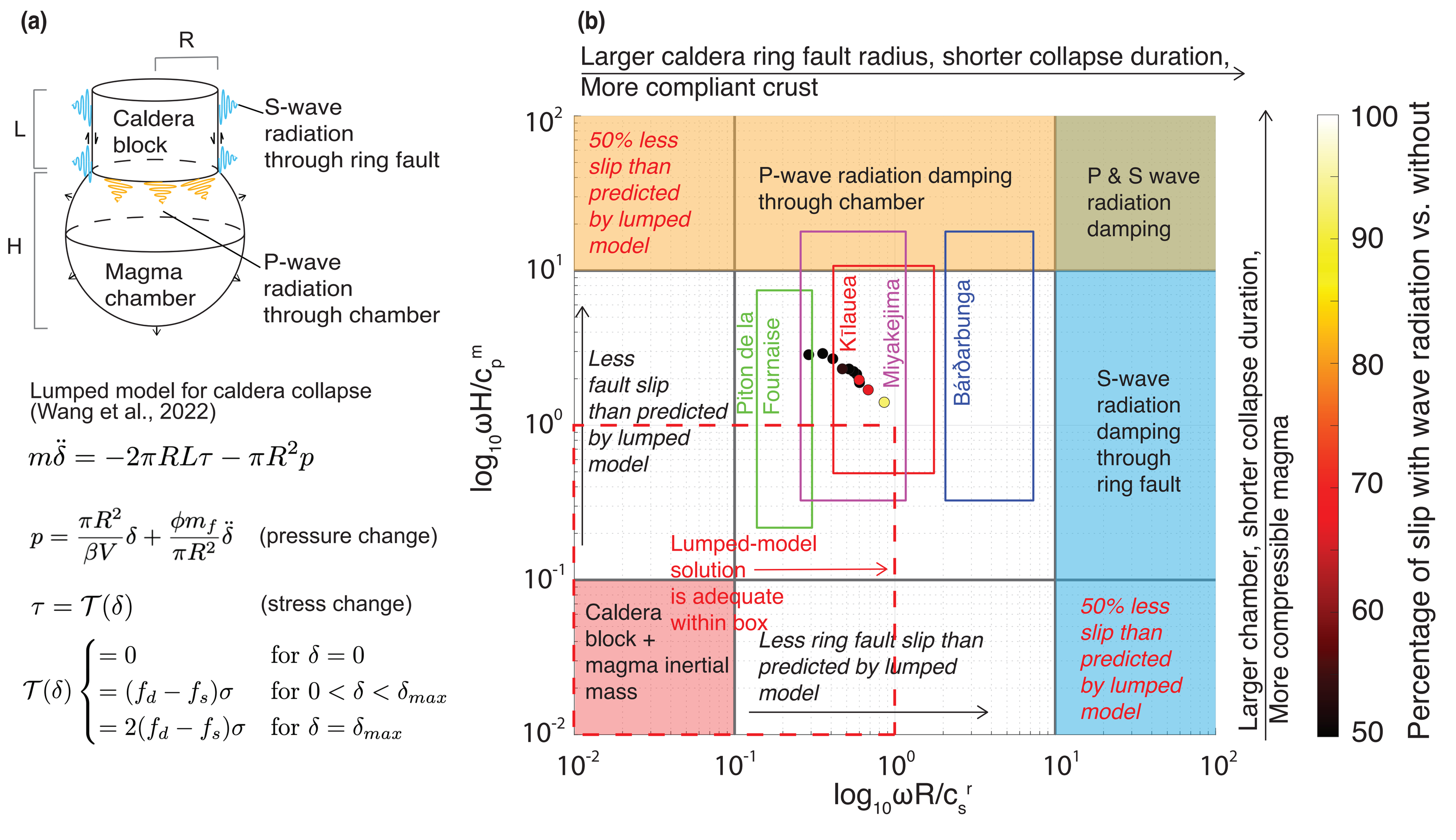


Figure 1. The effect of seismic wave radiation, which is neglected in all previous lumped models.
a) Schematic showing caldera wave radiation from the ring fault and the magma chamber b) Regime diagram for the significance of wave radiation as a function of dimensionless parameters $\omega H/c_p^m$ and $\omega R/c_s^r$ (ω: angular frequency of deformation; H: height of magma chamber; R: radius of caldera block; c_p^m: P wave speed in the magma; c_s^r: S wave speed in the crust). The dimensionless parameters are derived from Fourier series analysis of elastodynamic antiplane ring fault slip problem and a parameter study with SeisSol simulations. Dots on the regime diagram are computed using SeisSol simulations.

Approximate a Maxwell viscoelastic magma with Generalized Maxwell Body (GMB)

Magma is a multi-phase fluid with crystal, melt, and volatile phases. Here we are concerned with the the bulk mechanical properties of magma at time scales relevant to caldera collapse earthquakes and model magma as a homogeneous material. We model basaltic magma as an acoustic fluid (a built-in option in SeisSol), which has zero viscosity. We model silicic magma as a Maxwell material, achieved by utilizing the attenuation feature of SeisSol using the following procedure:

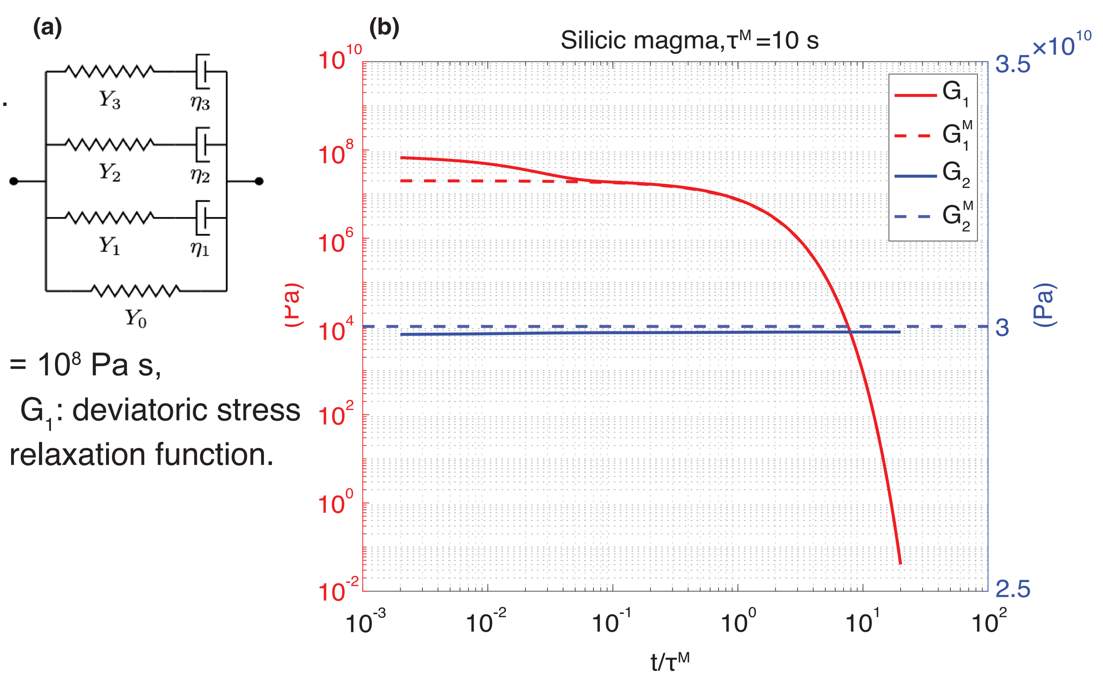
$$\sigma_{ij} = \frac{1}{3}G_2^c \delta_{ij} * \dot{\epsilon}_{kk} + G_1^c * \dot{e}_{ij} \quad \text{(General constitutive relationship for viscoelastic material)}$$

$$= \frac{1}{3}\left(Y_{02} + \sum_{i=1}^{L} Y_{i2} e^{-\omega_{i2} t}\right) H(t)\delta_{ij} * \dot{\epsilon}_{kk} + \left(Y_{01} + \sum_{i=1}^{L} Y_{i1} e^{-\omega_{i1} t}\right) H(t)\delta_{ij} * \dot{e}_{ij} \quad \text{(GMB approximations)}$$

$$L = \left\|\left(Y_{01} + \sum_{i=1}^{L} Y_{i1} e^{-\omega_{i1} t}\right) - 2\mu e^{-\frac{\mu}{\eta} t}\right\|_2 + \left\|\left(Y_{02} + \sum_{i=1}^{L} Y_{i2} e^{-\omega_{i2} t}\right) - 3K\right\|_2$$

Relaxation in deviatoric stress — No relxation in bulk stress

Figure 2. (a) Schematic of a GMB. (b) Example target relaxation functions for Maxwell materials and corresponding SeisSol approximations. The theoretical relaxation functions are specified with the parameters: $\mu = 10^7$ Pa, $\eta = 10^8$ Pa s, $\rho_m = 2.7 \times 10^3$ kg m^{-3}, $K = 10^{10}$ Pa. G_1: deviatoric stress relaxatoin function. G_2: bulk stress relaxation function. Y: stiffness. η: viscosity.



References

1. *Wang, T. A., Coppess, K. R., Segall, P., Dunham, E. M., & Ellsworth, W. (2022). Physics-based model reconciles caldera collapse induced static and dynamic ground motion: Application to k ılauea 2018. Geophysical Research Letters, 49 (8), e2021GL097440.*

Development of boundary layers in Maxwell silicic magma

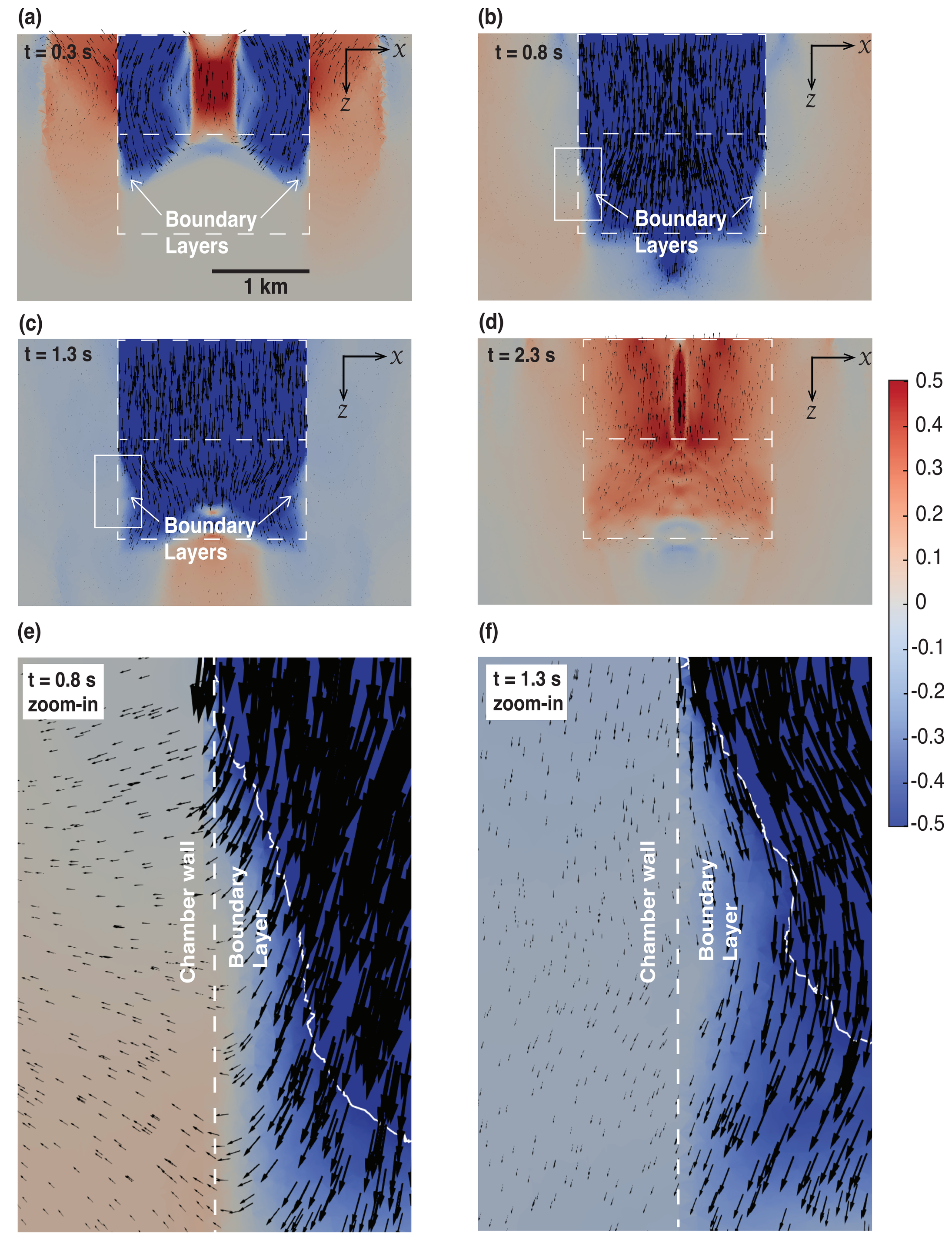


Figure 3. Snapshots of 3D simulation for caldera collapse with silicic magma (Maxwell rheology). (a) - (d): Vertical velocity showing the development of viscous boundary layers along the walls of the magma chamber. (e), (f): zoom-in views of boundary layers. Arrows scale with local fluid velocity.

Simulation of Kīlauea caldera collapse in 2018

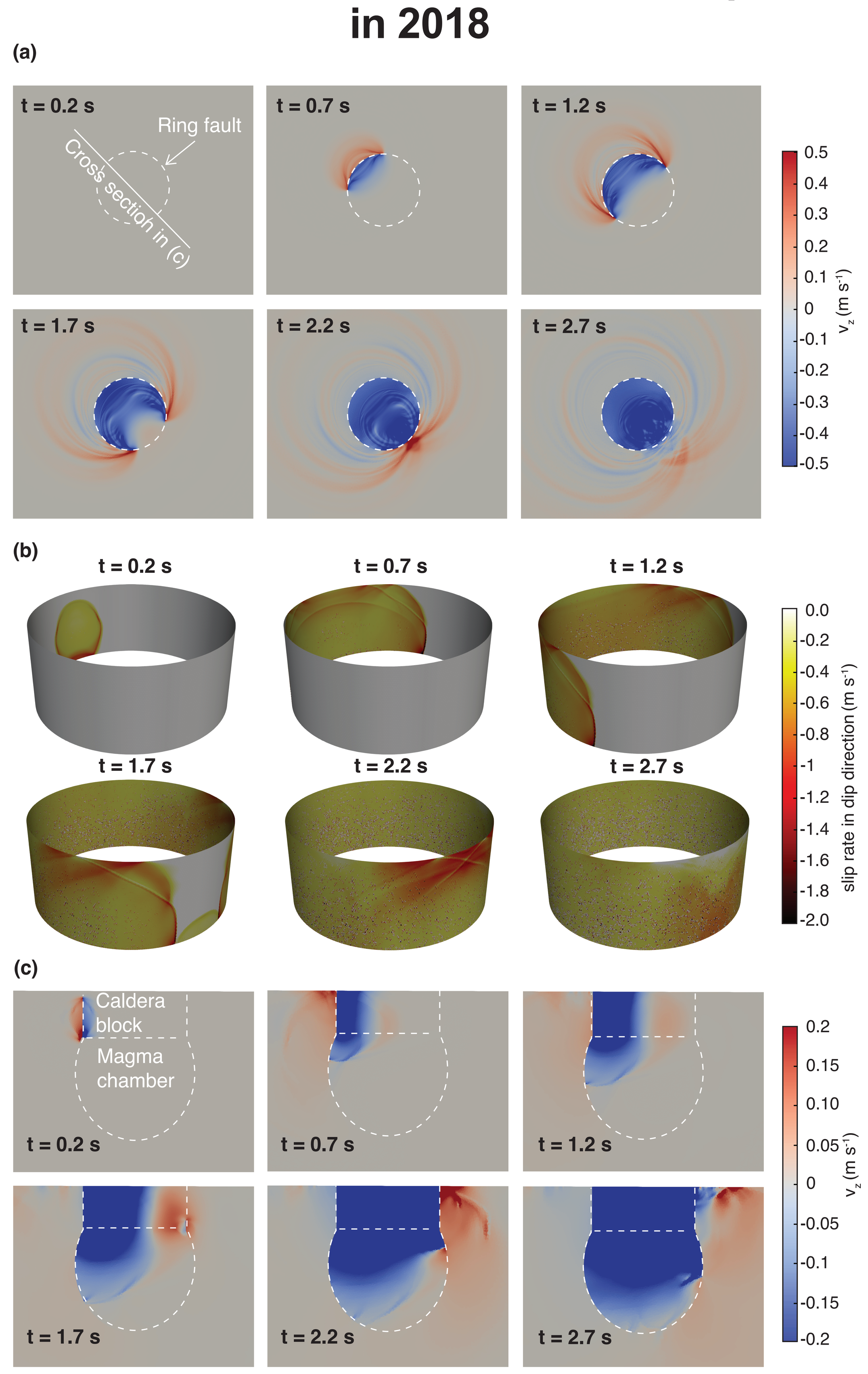


Figure 4. Snapshots of caldera collapse simulation for Kīlauea 2018. (a) Surface vertical velocity. (b) Along-dip slip rate on the ring fault. (c). Vertical velocity along cross section marked in (a).

Collapse dynamics reveled through nearfield seismic waveforms

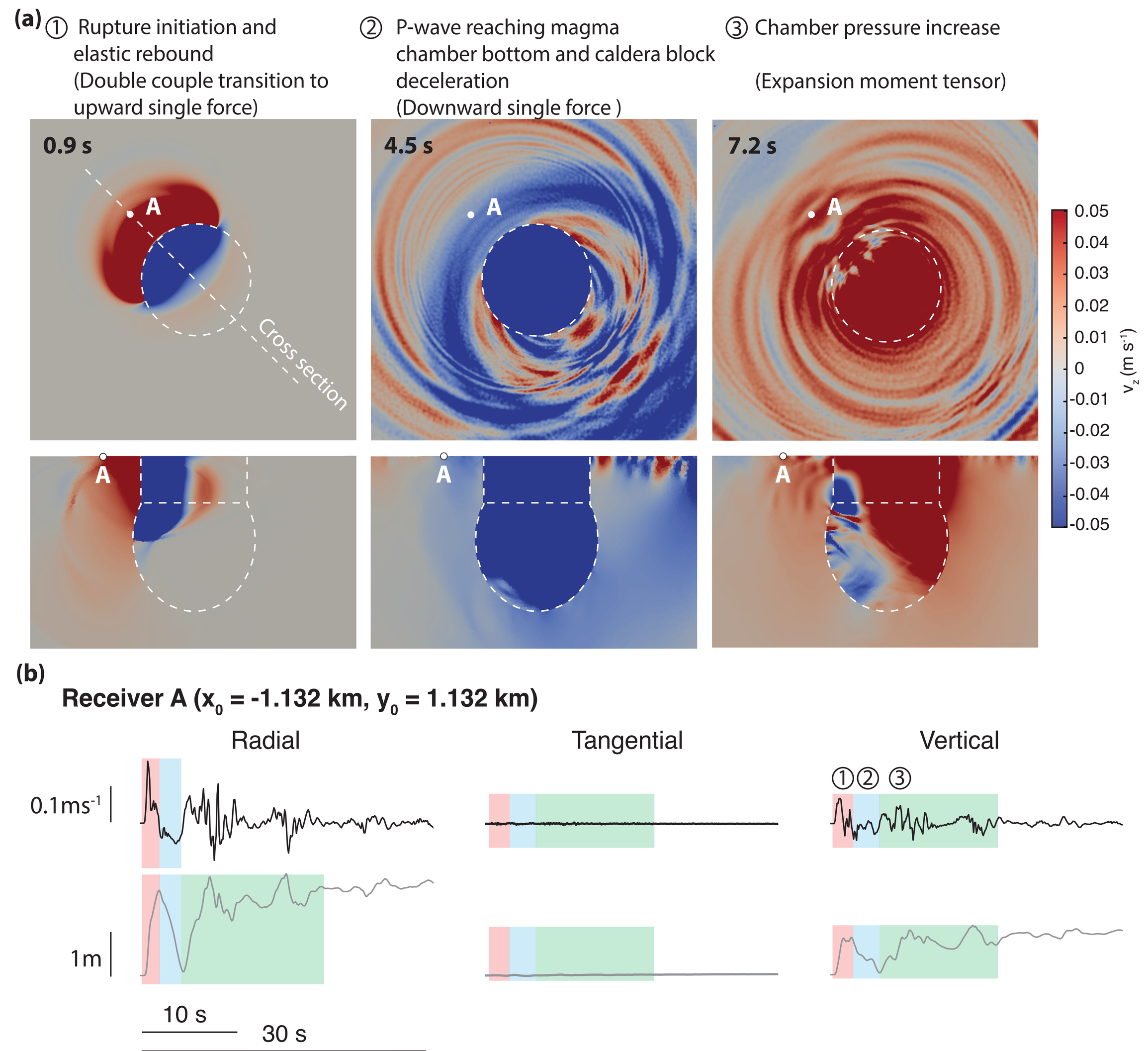


Figure 5. Interpretation of near-field waveforms in terms of collapse dynamics. Upper panels: Vertical velocity in map (first row) and cross section view (second row). The wavefield snapshots correspond to three distinct features of collapse, including elastic rebound outside of ring fault, P-waves reaching chamber bottom/caldera block deceleration, and chamber pressure increase, respectively. These features are identified in velocity and displacement waveforms from synthetic receiver A.

Earthqaukes initiated on the northwest exhibits complex waveforms

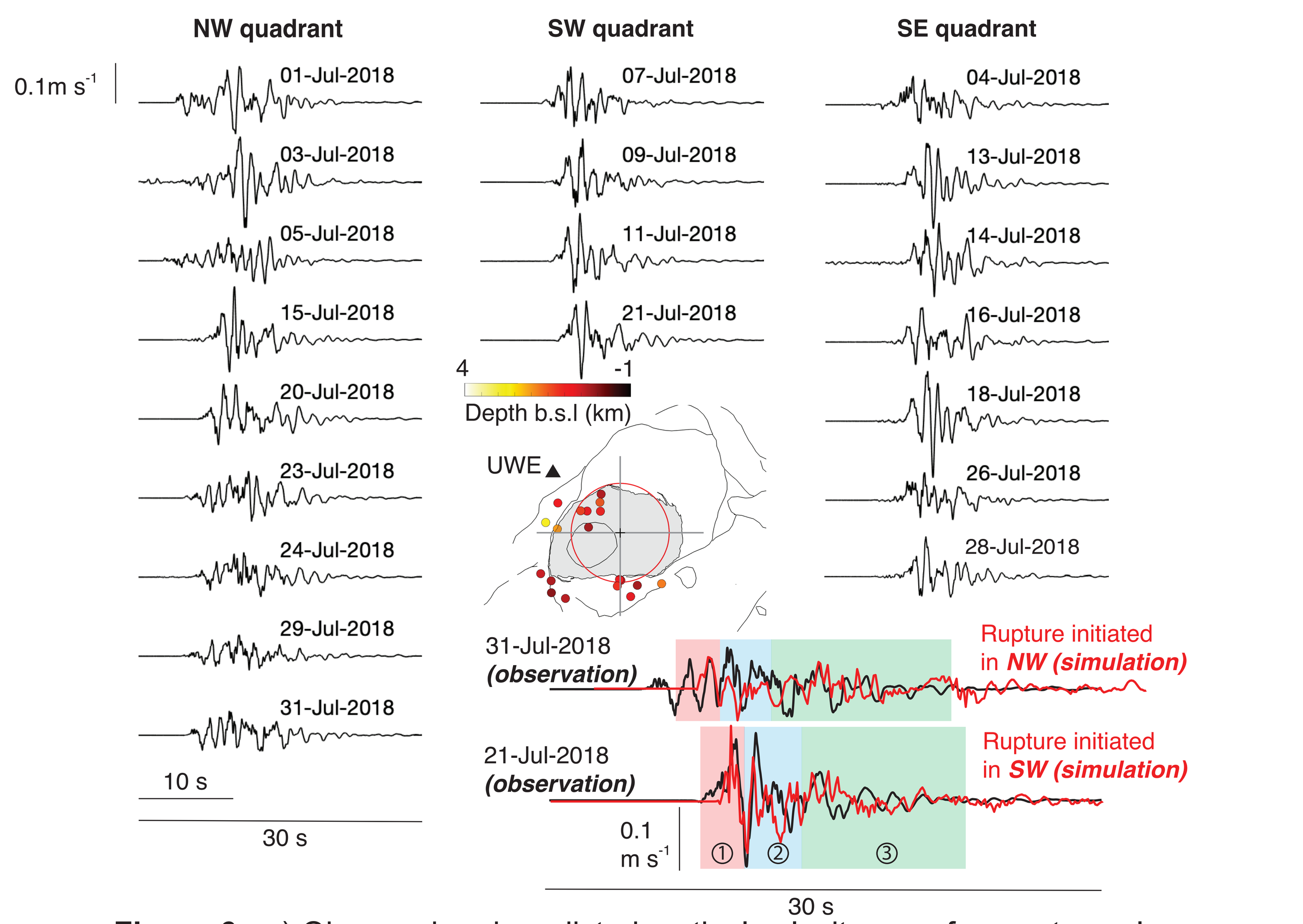


Figure 6. a) Observed and predicted vertical velocity waveforms at accelerometer UWE. Three columns show unfiltered observed waveforms, categorized by the hypocenter quadrants (relative to the approximate center of ring fault; see inset). Relocated VLP epicenters are color-coded by depth. In the lower right, two observed traces of waveforms at UWE with VLP epicenters in the NW and SE quadrants, respectively, are compared to simulated waveforms.

Conclusions

1. Seismic wave radiation through caldera ring fault and magma chamber can reduce magnitude of co-seismic slip by a factor of two.

2. A method to model viscoelastic magma with the built-in attenuation feature of SeisSol is presented.

3. The timing and magnitude of the downward force, which arises due to downward propagating pressure waves and caldera block deceleration, are captured in nearfield seismic waveforms.

4. Earthquakes nucleating on the NW of the ring fault potentially exhibit complex rupture histories due to local fault heterogeneities

Acknowledgments

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