Science Advances
AAAS

Supplementary Materials for

Forecasting mechanical failure and the 26 June 2018 eruption of Sierra Negra Volcano, Galápagos, Ecuador

Patricia M. Gregg *et al.*

Corresponding author: Patricia M. Gregg, pgregg@illinois.edu

Sci. Adv. **8**, eabm4261 (2022)
DOI: 10.1126/sciadv.abm4261

This PDF file includes:

Figs. S1 to S6
Tables S1 to S3

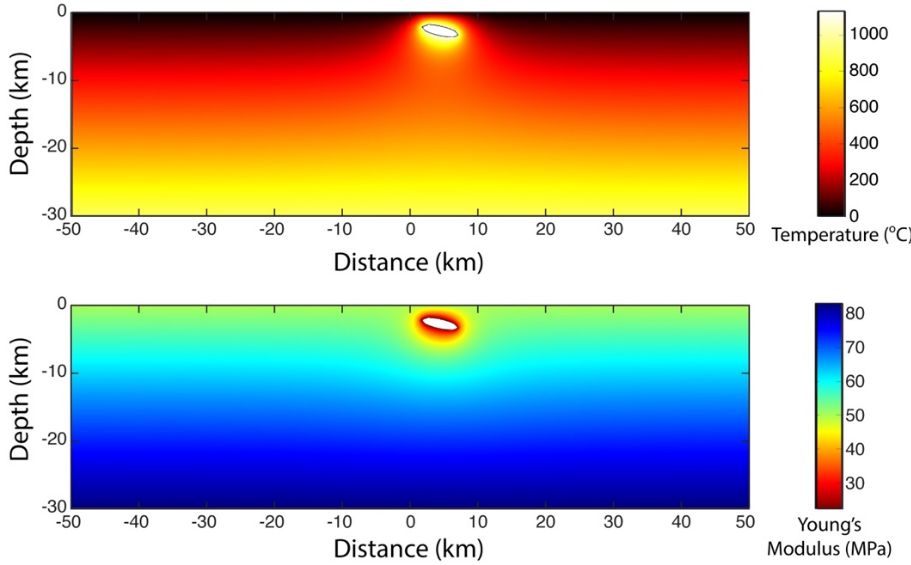

Fig. S1. Thermal structure and Temperature-dependent Young's Modulus.

(Top) The steady-state thermal structure calculated for the mean EnKF model in the temperature-dependent hindcast (nTd) for June 26, 2018. (Bottom) The calculated temperature-dependent Young's modulus for the mean EnKF model in the temperature-dependent hindcast for June 26, 2018.

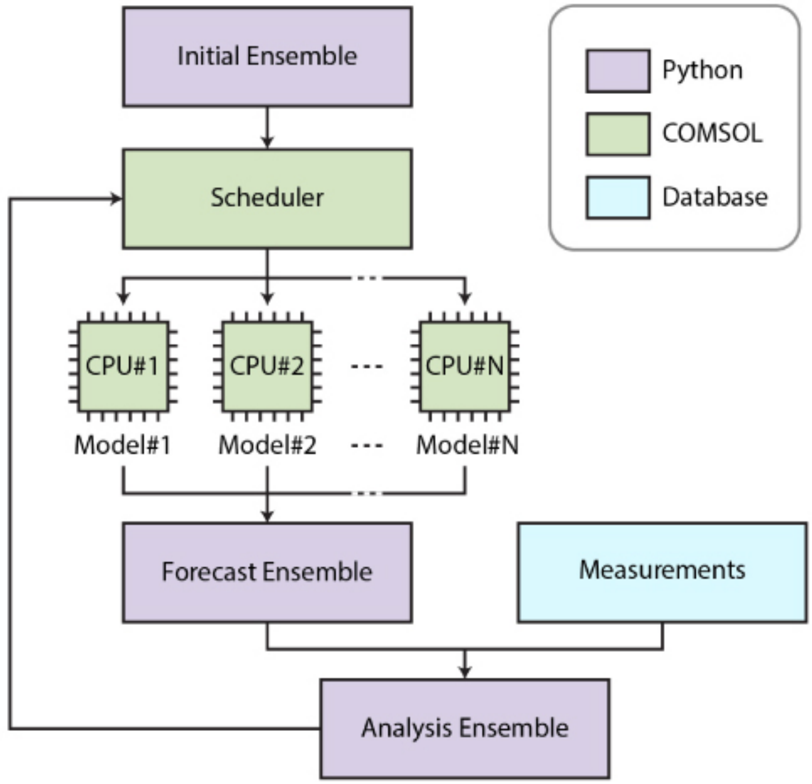

Fig. S2. The HPC EnKF workflow.

A Monte Carlo suite produces the initial ensemble with N models using Python. The models are distributed across CPU's using the COMSOL scheduler ("Cluster Sweep") using a command line approach. The COMSOL models are calculated to produce the forecast ensemble, A, which contains the model state parameters and variables as well as outputs. The forecast ensemble is combined with available measurements using the EnKF analysis (Eq. 5). The updated Analysis matrix, A^a, is then used for the next time step.

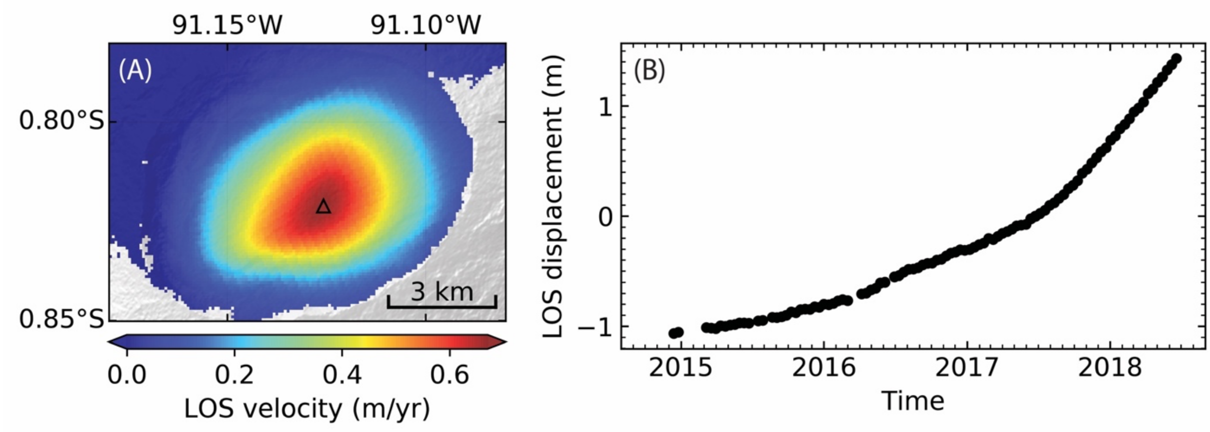

Fig. S3. InSAR time-series from Sentinel-1 descending track 128. (A) Average velocity in line-of-sight (LOS) direction estimated from the displacement time-series. (B) Displacement time-series of the pixel within the caldera center (marked as triangle in (A)) in LOS direction.

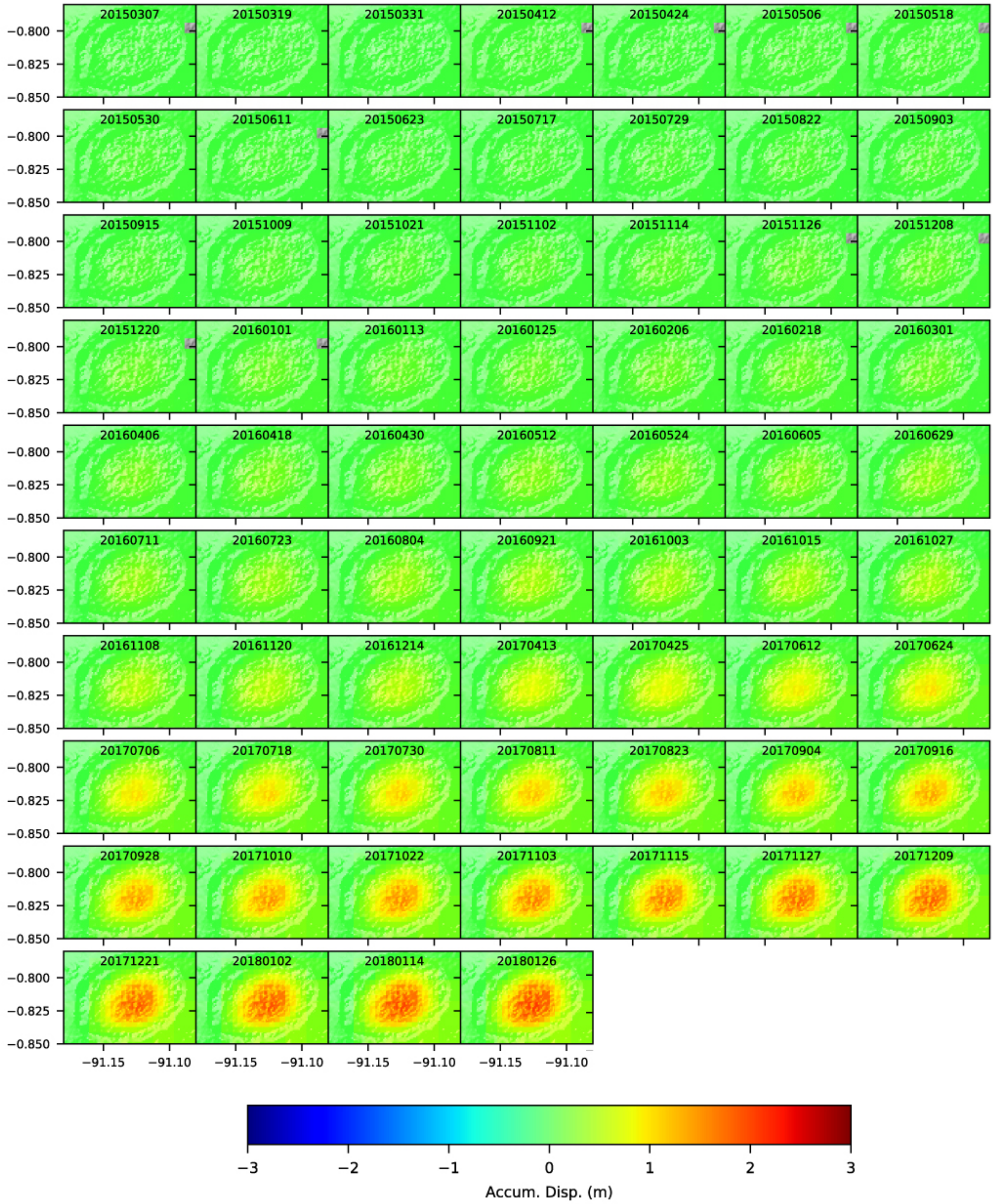

Fig. S4. InSAR LOS displacement data utilized in the EnKF forecast. The January 26, 2018 forecast utilized 67 timesteps derived from the 69 acquisitions, Track 128.

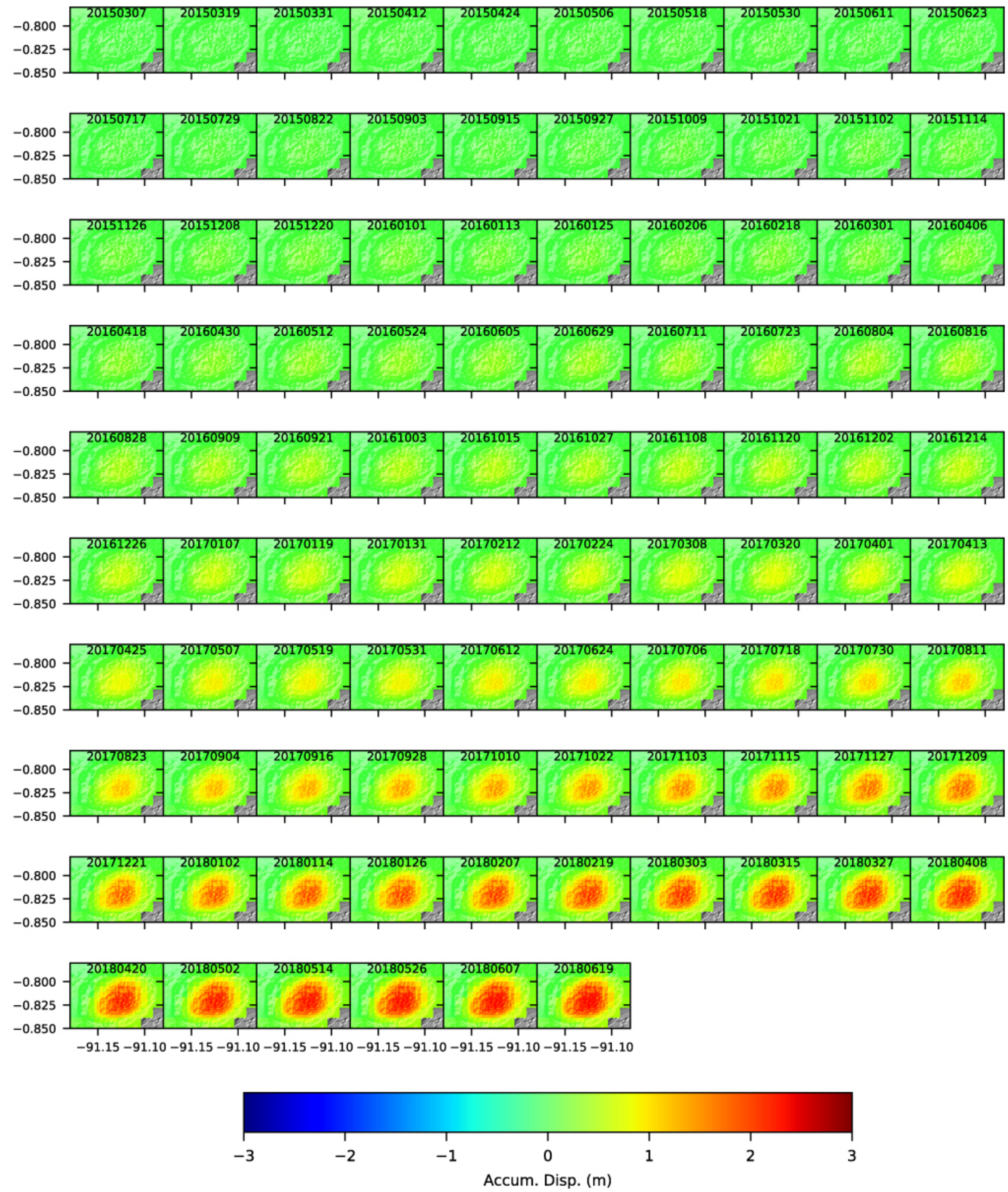

Fig. S5. InSAR LOS data utilized in the EnKF hindcasts. 96 descending InSAR observations (Track 128) leading up to the June 26, 2018 eruption that were used to complete the Temperature-dependent (Td) and non-Temperature dependent (nTd) EnKF hindcasts.

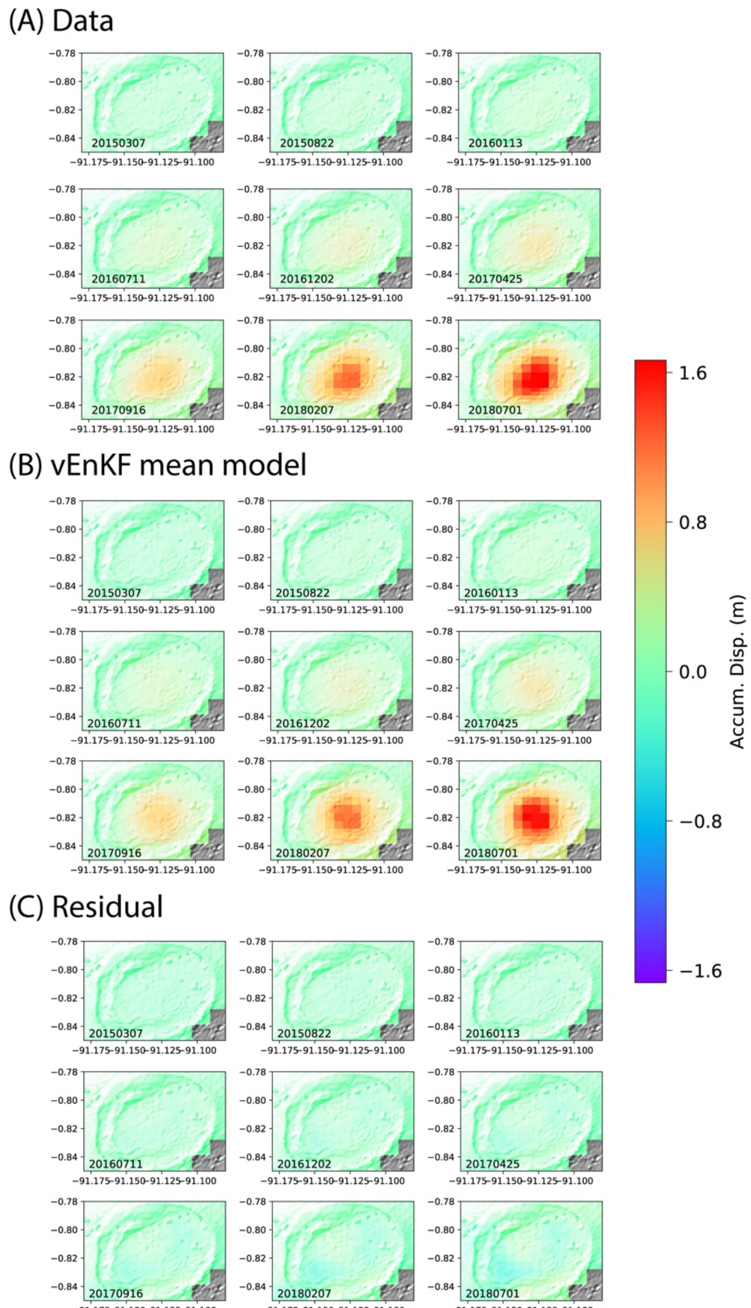

Fig. S6. EnKF Temperature-dependent hindcast (Tot), model-data comparison for select time steps. (A) InSAR derived accumulated displacement used as observational input for the EnKF. (B) EnKF modeled accumulated displacement. Model result is shown for the best-fit EnKF ensemble member. (C) The residual between the InSAR derived displacement and the best-fit EnKF ensemble member. The hindcast utilized all available InSAR observations up to the June 26, 2018 eruption (Figure S5).

Table S1. Model Parameters

Parameter	Description	Value
A_D	Dorn parameter, Pa s	10^9
C_P	Specific heat capacity, J kg^{-1} K^{-1}	1250
E_A	Activation energy, J mol^{-1}	1e5
E_0	Initial Young's modulus, GPa	50
E_m	Minimum Young's modulus, GPa	5
f	Angle of internal friction, °	25
g	Gravitational acceleration, m s^{-2}	9.81
k	Thermal conductivity, W m^{-1} K^{-1}	3
μ_f	Apparent friction coefficient	0.25
υ	Poisson's ratio	0.25
R_g	Universal gas constant, J mol^{-1} K^{-1}	8.3114
ρ_r	Host rock density, kg m^{-3}	2700
T_{geo}	Geothermal gradient, K km^{-1}	30
T_m	Initial magma chamber temperature, °C	1100
T_s	Surface temperature, °C	0

Table S2. Model Variables

Variable	Description
A^a	EnKF analysis ensemble
A	EnKF forecast ensemble
A_f	Fault area, m^2
ΔCFF	Coulomb stress change, bars
C	Cohesion, MPa
C_d	EnKF measurement covarience matrix
D	EnKF measurement matrix
dP	Pressure change, MPa
E_{td}	Temperature-dependent Young's modulus, Pa
ε	Strain
ϕ	Reservoir source strike, °
G	Shear modulus, Pa
H	EnKF model operator matrix
K	Bulk modulus, Pa
M_0	Seismic moment, dyne cm
M_w	Moment magnitude
θ	Reservoir source dip, °
S	Fault slip, m
R_1	Vertical half-width, m
R_2	Vertical half-height, m
σ	Stress, Pa
σ_n	Normal stress, Pa
σ_{ts}	Tensile stress in the r-z plane, Pa
σ_{ij}	Stress tensor, Einstein notation, Pa
$\Delta\sigma$	Change in normal stress, Coulomb stress calculation, bars
$\Delta\tau$	Change in shear stress, Coulomb stress calculation, bars
T	Temperature, K
Tc	Tensile failure criterion
t	Time
τ	Shear stress, Pa
u_x	Horizontal displacement, m
u_z	Vertical displacement, m
X	EnKF ensemble covariance matrix
x, y	Horizontal distance, Cartesian coordinate system, m
z	Depth, positive up, m

Table S3. EnKF model set up and run time

Forecast	Td Hindcast & Tot Hindcast	nTd Hindcast
Ensembles: 240 *Iterations per step:* 6 *Number of time steps:* 67 *Compute Time:* 1680 core hours	*Ensembles:* 240 *Iterations per step:* 6 *Number of time steps:* 98 *Compute Time:* 3000 core hours	*Ensembles:* 240 *Iterations per step:* 6 *Number of time steps:* 98 *Compute Time:* 2460 core hours
Initial Values D = -8000 to -2000 [m] X & Y = -5000 to 5000 [m] R1 = 200 to 1000 [m] R2 = [0.1 to 10] * R1 [m] Φ = 0° to 90° Θ = 0° to 360° dP = -10e6 to 10e6 [Pa]	*Initial Values* D = -8000 to -2000 [m] X & Y = -5000 to 5000 [m] R1 = 200 to 1000 [m] R2 = [0.1 to 10] * R1 [m] Φ = 0° to 90° Θ = 0° to 360° dP = -10e6 to 10e6 [Pa]	*Initial Values* D = -8000 to -2000 [m] X & Y = -5000 to 5000 [m] R1 = 200 to 1000 [m] R2 = [0.1 to 10] * R1 [m] Φ = 0° to 90° Θ = 0° to 360° dP = -10e6 to 10e6 [Pa]