HAROKOPIO UNIVERSITY

esa

→ 4th ADVANCED TRAINING COURSE IN LAND REMOTE SENSING

Terrain Motion 2: Volcano Deformation, Models and Examples

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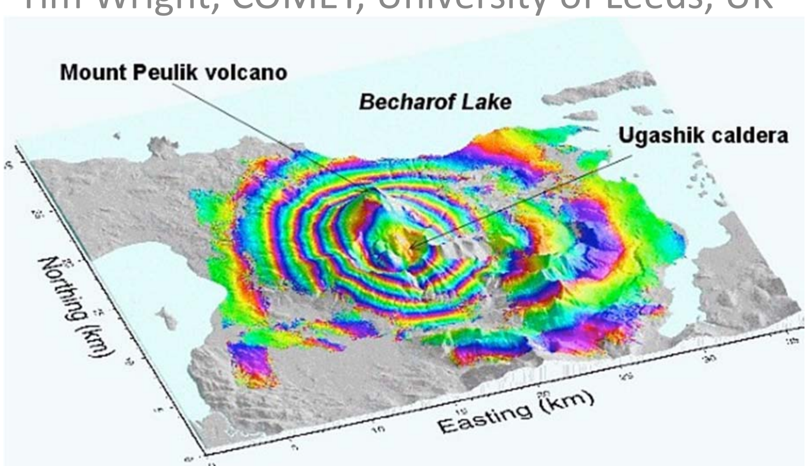
COMET, School of Earth and Environment, University of Leeds, UK

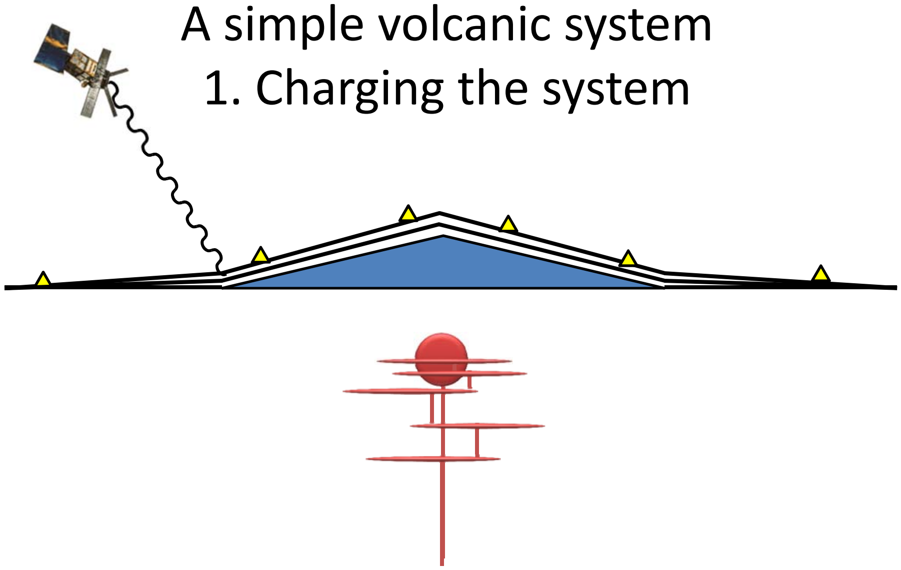
1–5 July 2013 | Harokopio University | Athens, Greece

Volcano Deformation – Models and Examples

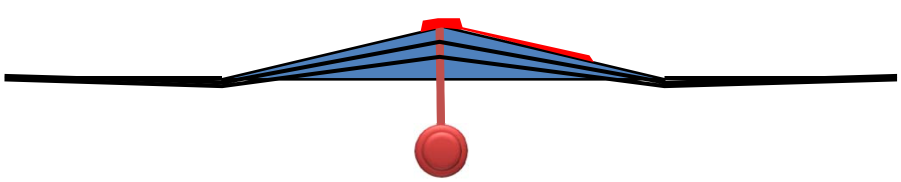
Tim Wright, COMET, University of Leeds, UK



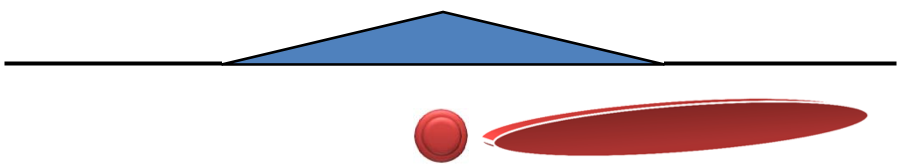
A simple volcanic system
1. Charging the system



A simple volcanic system
1. Discharging the system
(a. eruptions)



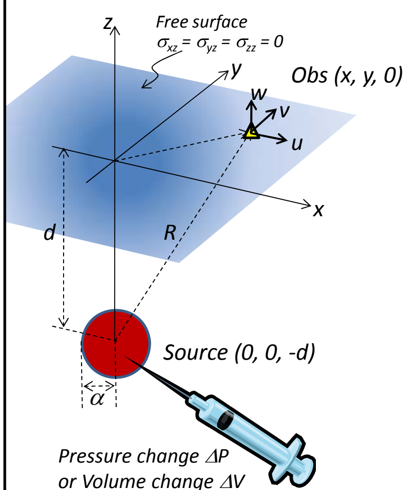
A simple volcanic system
1. Discharging the system
(b. intrusions)



Outline

- Simple volcanic deformation sources
  - Point Pressure (‘Mogi’ Model for magma chambers)
  - Elastic Dislocations (‘Okada’ model for Dykes and Sills)
  - Penny-shaped crack (for sills)
  - Other models
- Limitations of Volcanic Geodesy
- How to interpret volcanic deformation
- Comparison of InSAR and GPS
- Science vs Monitoring

Simple Sources: 1. The Mogi Model



Assumptions

1. Isotropic elastic half space
   (Poission's ratio ν; Shear modulus μ)
2. $\alpha << d$ (i.e. spherical point source)
3. Incompressible magma

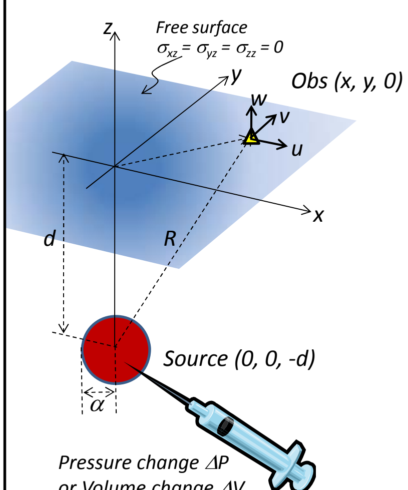
$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \alpha^3 \Delta P \frac{(1-\nu)}{\mu} \begin{pmatrix} x/R^3 \\ y/R^3 \\ d/R^3 \end{pmatrix}$$

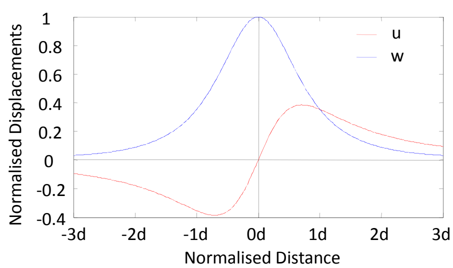
But $\Delta V \approx \frac{\Delta P}{\mu} \pi \alpha^3$ so

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \Delta V \frac{(1-\nu)}{\pi} \begin{pmatrix} x/R^3 \\ y/R^3 \\ d/R^3 \end{pmatrix}$$

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Mogi, K. (1958), *Bull. Earthq. Inst. U. Tokyo*, 36, 99-134
Delaney, P., McTigue, D.(1994) Bull. Volcanology, 56 417-424

Simple Sources: 1. The Mogi Model





$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \Delta V \frac{(1-\nu)}{\pi} \begin{pmatrix} x/R^3 \\ y/R^3 \\ z/R^3 \end{pmatrix}$$

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Mogi, K. (1958), *Bull. Earthq. Inst. U. Tokyo*, 36, 99-134
Delaney, P., McTigue, D.(1994) Bull. Volcanology, 56 417-424

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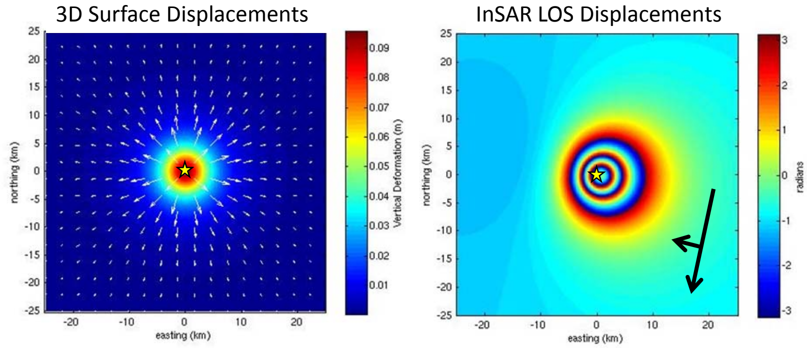
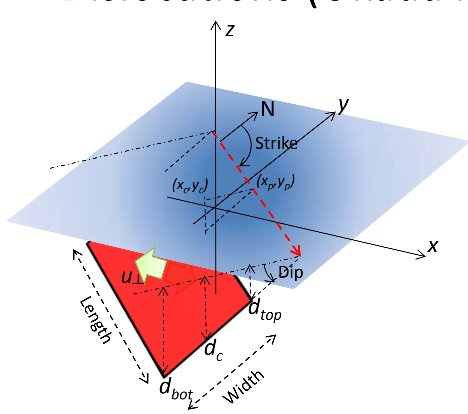


Source Depth = 5 km; Volume = 10^7 m^3
Maximum uplift ≈ 95 mm

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Mogi, K. (1958), *Bull. Earthq. Inst. U. Tokyo*, 36, 99-134
Delaney, P., McTigue, D.(1994) Bull. Volcanology, 56 417-424

Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or dykes)



Assumptions

1. Isotropic elastic half space
2. Uniform opening (for dykes/sills) on rectangular dislocation

Parameters

8 parameters needed to define dislocation:

Strike, *Dip*	[2]
Location (x_c, y_c) or (x_p, y_p)	[2]
d_c and *Width* (or d_{top}, d_{bot})	[2]
Length	[1]
Opening ($u_\perp$)	[1]

Can simplify
e.g. *Length* = *Width* for sills;
Dip = 0 for sills, 90 for dykes

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

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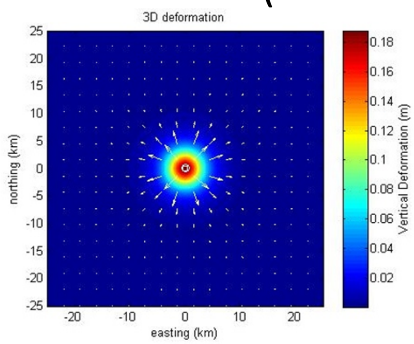

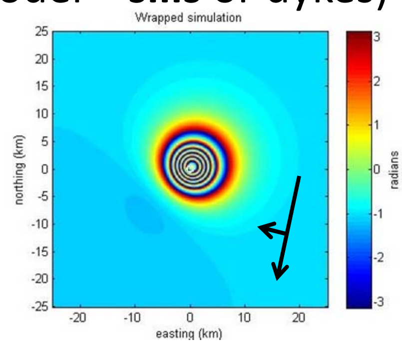

Sill 1: Dip = 0, Strike =0, x=y=0, d_c = 5 km
Length=Width=1 km
Opening = 10 m [Volume = 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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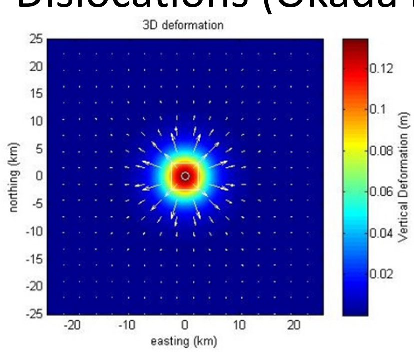
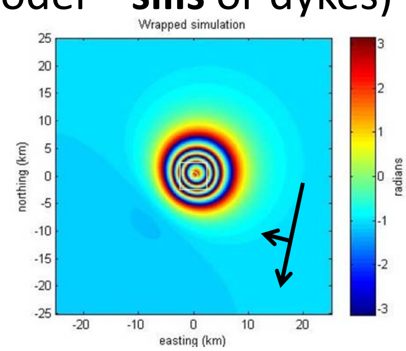
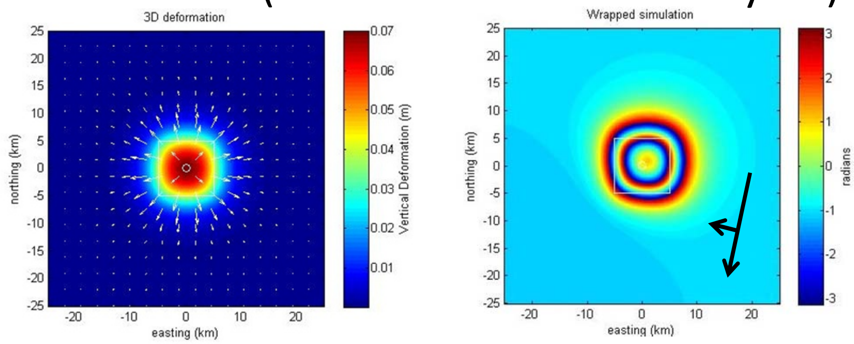




Sill 2: Dip = 0, Strike =0, x=y=0, d_c = 5 km
Length=Width=5 km
Opening = 0.4m [Volume = 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

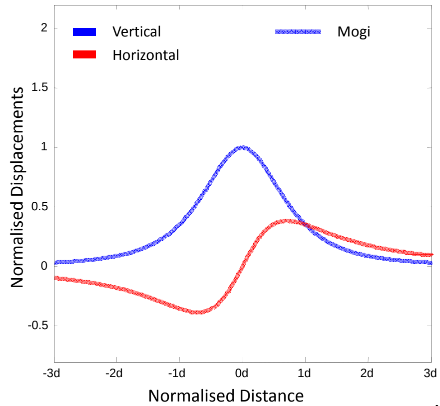
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – **sills** or dykes)



Sill 3: Dip = 0, Strike =0, x=y=0, d_c = 5 km
Length=Width=10 km
Opening = 0.1 m [Volume = 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

Simple Sources: 2. Tensile Elastic Dislocations (Okada model – **sills** or dykes)



- Vertical deformation normalised by Mogi uplift
- Distance normalised by depth of source

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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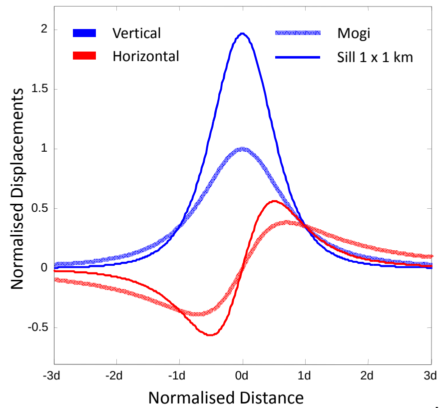
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – **sills** or dykes)



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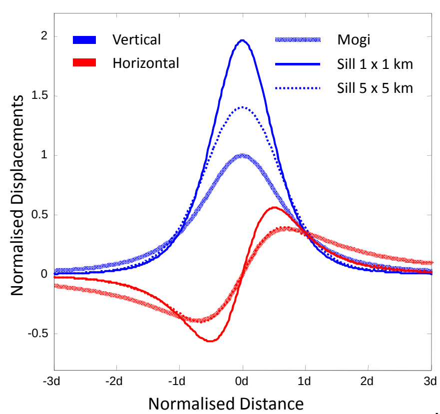
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – **sills** or dykes)



- Vertical deformation normalised by Mogi uplift
- Distance normalised by depth of source

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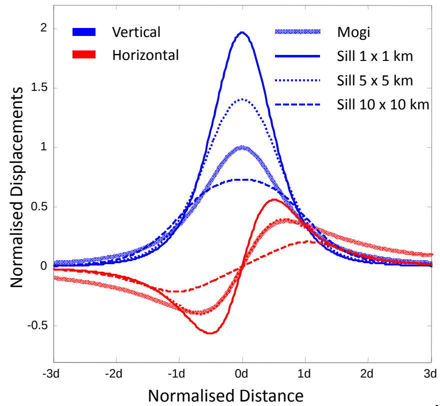

- Vertical deformation normalised by Mogi uplift
- Distance normalised by depth of source

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Source volume vs uplift volume

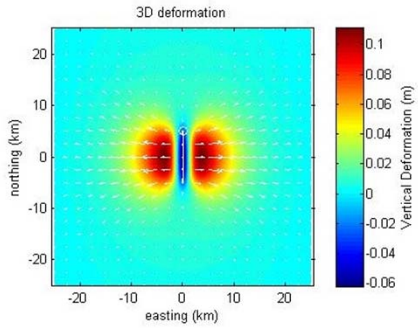
Delaney and McTigue (1994) showed:

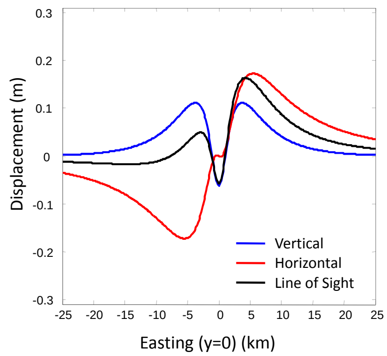
1. For sills, source volume change = surface uplift volume
2. For Mogi, source volume change = surface uplift volume / 2(1-ν)
   e.g. For ν = 0.25, source volume = (2/3) * surface uplift volume

These relationships are only true if the Magma is incompressible. See Johnson et al (2000), Rivalta and Segall, (2008) for details

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Johnsson, D (2000), Bull. Volcanol., 61, 491-493
Rivalta, E. and P. Segall (2008), GRL

Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 1: Dip = 90, Strike =0, x=y=0

d_{top} = 2 km, d_{bot} = 8 km

Length= 10 km

Opening = 1 m [Volume = 6 x 10^7 m^3]

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Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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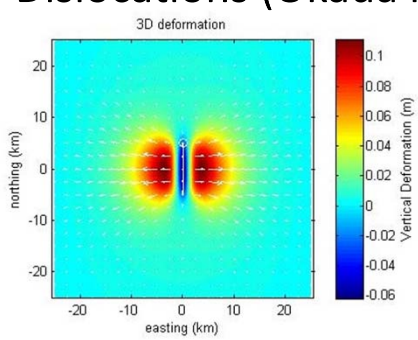

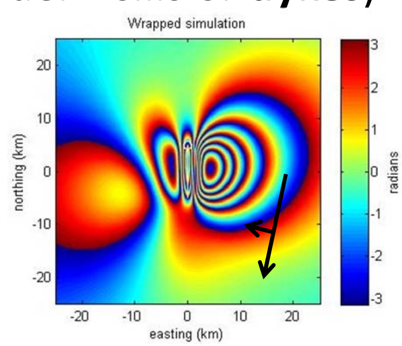

Dyke 1: Dip = 90, Strike =0, x=y=0

d_{top} = 2 km, d_{bot} = 8 km

Length= 10 km

Opening = 1 m [Volume = 6 x 10^7 m^3]

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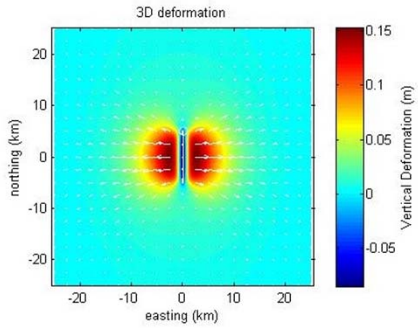
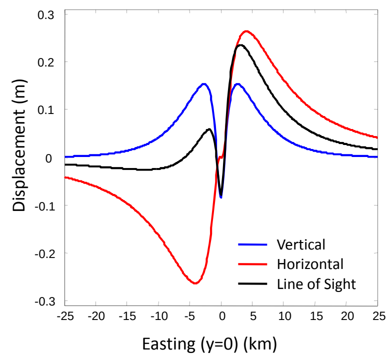
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 2: Dip = 90, Strike =0, x=y=0

d_{top} = 1 km, d_{bot} = 8 km

Length= 10 km

Opening = 1 m [Volume = 7 x 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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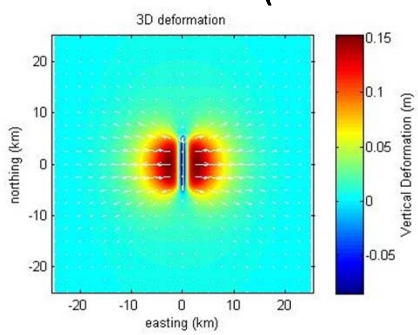
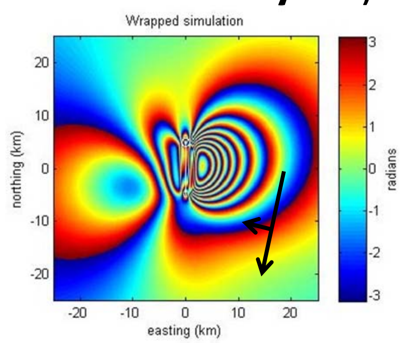
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 2: Dip = 90, Strike =0, x=y=0

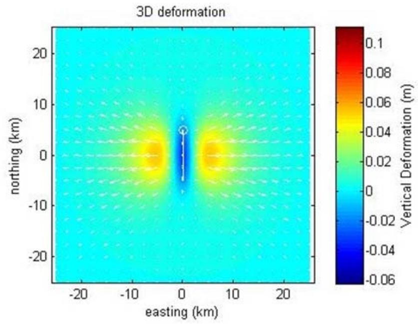
d_{top} = 1 km, d_{bot} = 8 km

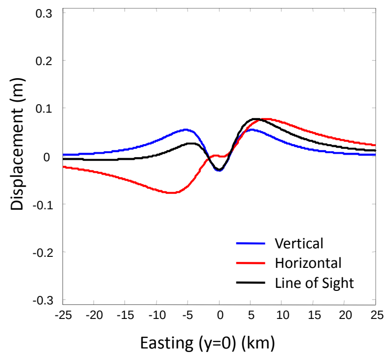
Length= 10 km

Opening = 1 m [Volume = 7 x 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 3: Dip = 90, Strike =0, x=y=0

d_{top} = 4 km, d_{bot} = 8 km

Length= 10 km

Opening = 1 m [Volume = 4 x 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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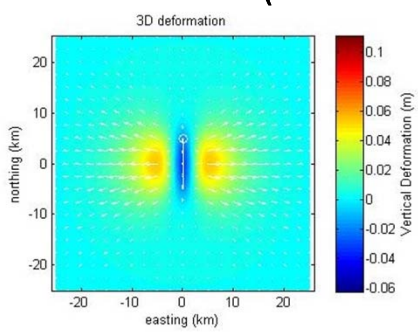
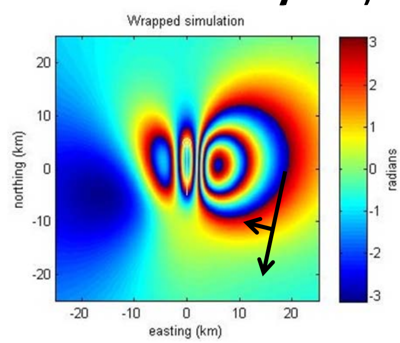
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 3: Dip = 90, Strike =0, x=y=0

d_{top} = 4 km, d_{bot} = 8 km

Length= 10 km

Opening = 1 m [Volume = 4 x 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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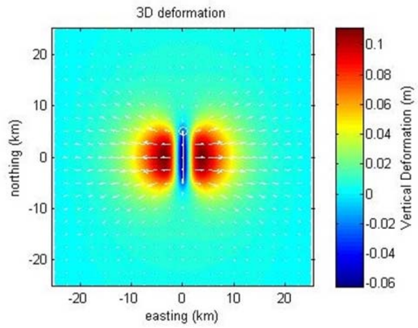
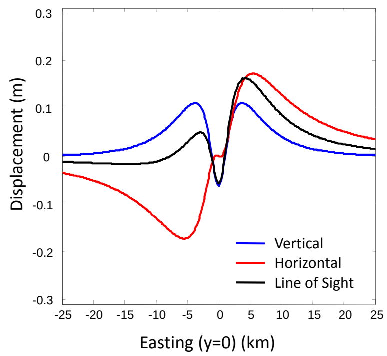
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 1: Dip = 90, Strike =0, x=y=0
d_{top} = 2 km, d_{bot} = 8 km
Length= 10 km
Opening = 1 m [Volume = 6 x 10^7 m^3]

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Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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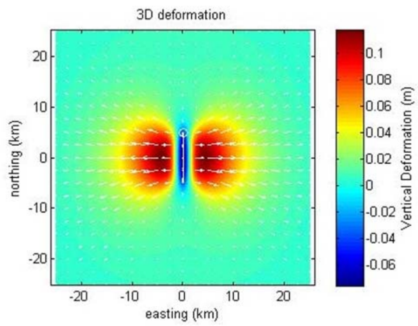
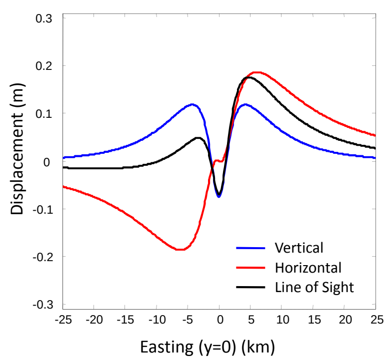
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 4: Dip = 90, Strike =0, x=y=0
d_{top} = 2 km, d_{bot} = 12 km
Length= 10 km
Opening = 1 m [Volume = 10 x 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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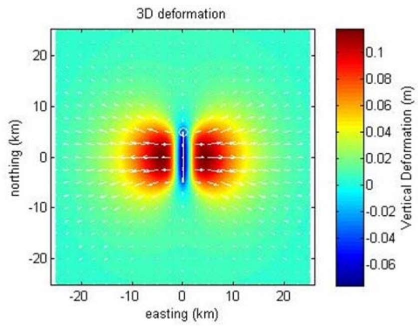
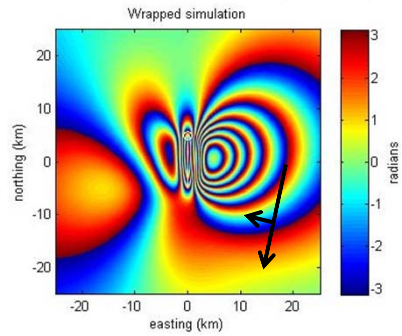
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)





Dyke 4: Dip = 90, Strike =0, x=y=0

d_{top} = 2 km, d_{bot} = 12 km

Length= 10 km

Opening = 1 m   [Volume = 10 x 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
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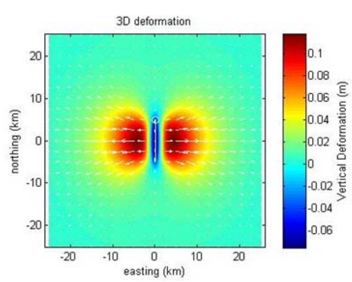
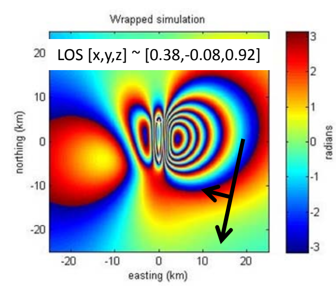
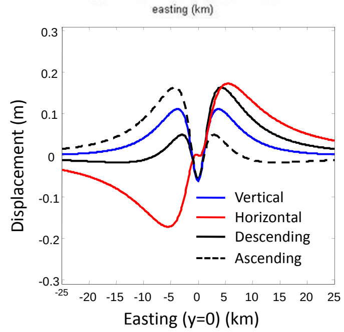
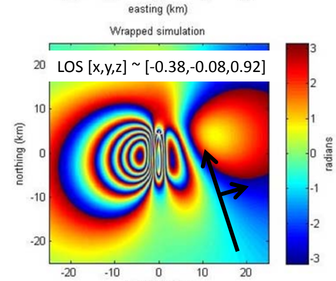
Ascending vs Descending

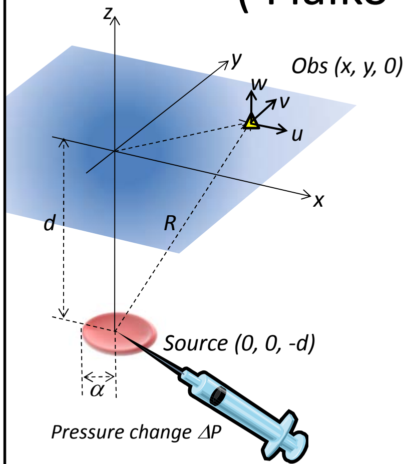








Simple Sources: 3. Penny-shaped crack (‘Fialko’ model for sills)



Assumptions

1. Isotropic elastic half space (Poission’s ratio ν; Shear modulus μ)
2. Uniformly pressurized horizontal crack

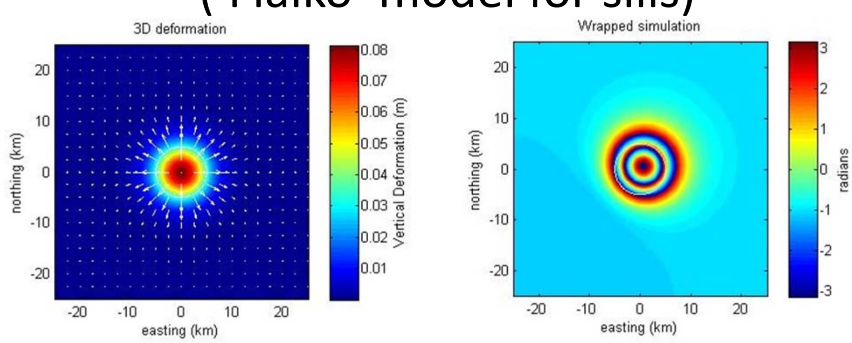
Parameters

1. Depth
2. Radius of source
3. Pressure

For full equations see Fialko et al., 2001.

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190

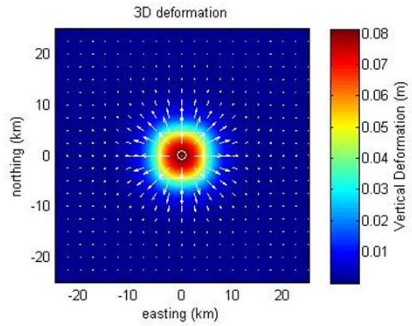
Simple Sources: 3. Penny-shaped crack (‘Fialko’ model for sills)

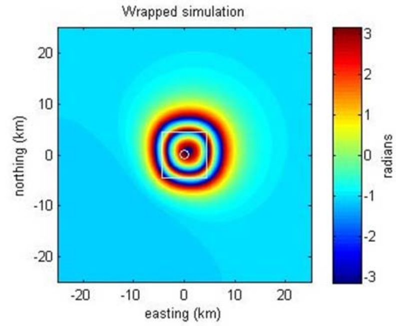


Penny Sill: Source Depth = 5 km; Radius = 5 km;
Pressure = 0.77 MPa

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190

Simple Sources: 3. Penny-shaped crack (‘Fialko’ model for sills)

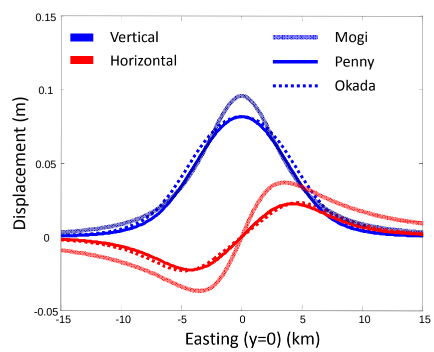




Penny Sill: Source Depth = 5 km; Radius = 5 km;
Pressure = 0.77 MPa
Okada Sill: Source Depth = 5 km; Length = Width = 8.86 km (= $\sqrt{\pi 5^2}$)
Opening = 0.13 m (= $10/(\pi 5^2)$) [Volume = 10^7 m^3]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190

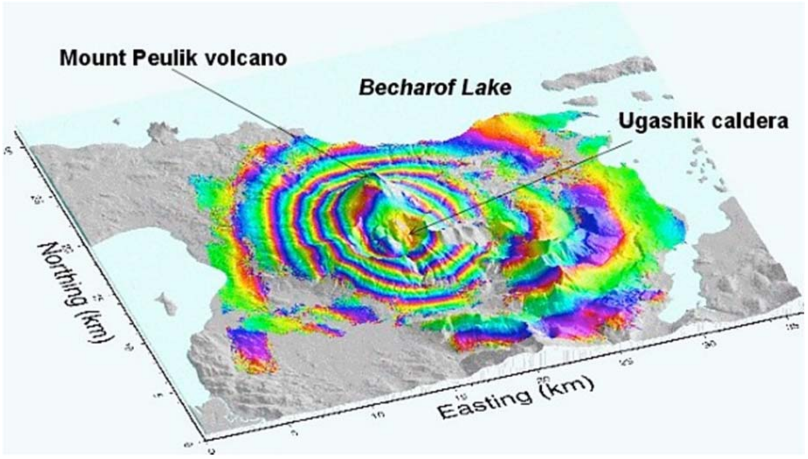
Simple Sources: 3. Penny-shaped crack (‘Fialko’ model for sills)



Penny Sill: Source Depth = 5 km; Radius = 5 km;
Pressure = 0.77 MPa
Okada Sill: Source Depth = 5 km; Length = Width = 8.86 km (= $\sqrt{\pi 5^2}$)
Opening = 0.13 m (= $10/(\pi 5^2)$) [Volume = 10^7 m^3]
Mogi Point: Source Depth = 5 km; Volume Change = 10^7 m^3

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190

Mt Peulik. Dormant Stratovolcano: Last eruption:1852



Mount Peulik volcano inflated 0.051 ± 0.005km^3 between October 1996 and September 1998.

Zhong Lu, Chuck Wicks, USGS

Limitations of Simple Models used in Volcano Geodesy

- Ambiguity of source geometries
- Isotropic, Elastic Half-Space Assumption
- Volumes/Pressures dependent on assumptions about geometries or magma/rock properties
- Models are purely kinematic
- Magma is hot → visco-elastic effects?
- How to interpret signals?

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
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InSAR vs GPS for geohazards

	InSAR	GPS
Frequency of Observation	Every 10-40 days for each satellite.	Up to 50 Hz. Typically get daily positions for continuous sites.
Spatial coverage	Continuous (in coherent areas)	Points
Dimensionality	1D (Line of Sight) Displacement	3D Displacements
Cost	Data is cheap/free for most satellites	Cost of instruments vary
Field requirements	None	Installation and servicing on the ground
Accuracy	~1 cm for single interferogram. Better for time-series/stacks	~1mm/yr for continuous sites

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190