The Abdus Salam
International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

2053-43

Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa

17 - 28 August 2009

Volcano Deformation - models and examples

Tim Wright
University of Leeds
U.K.

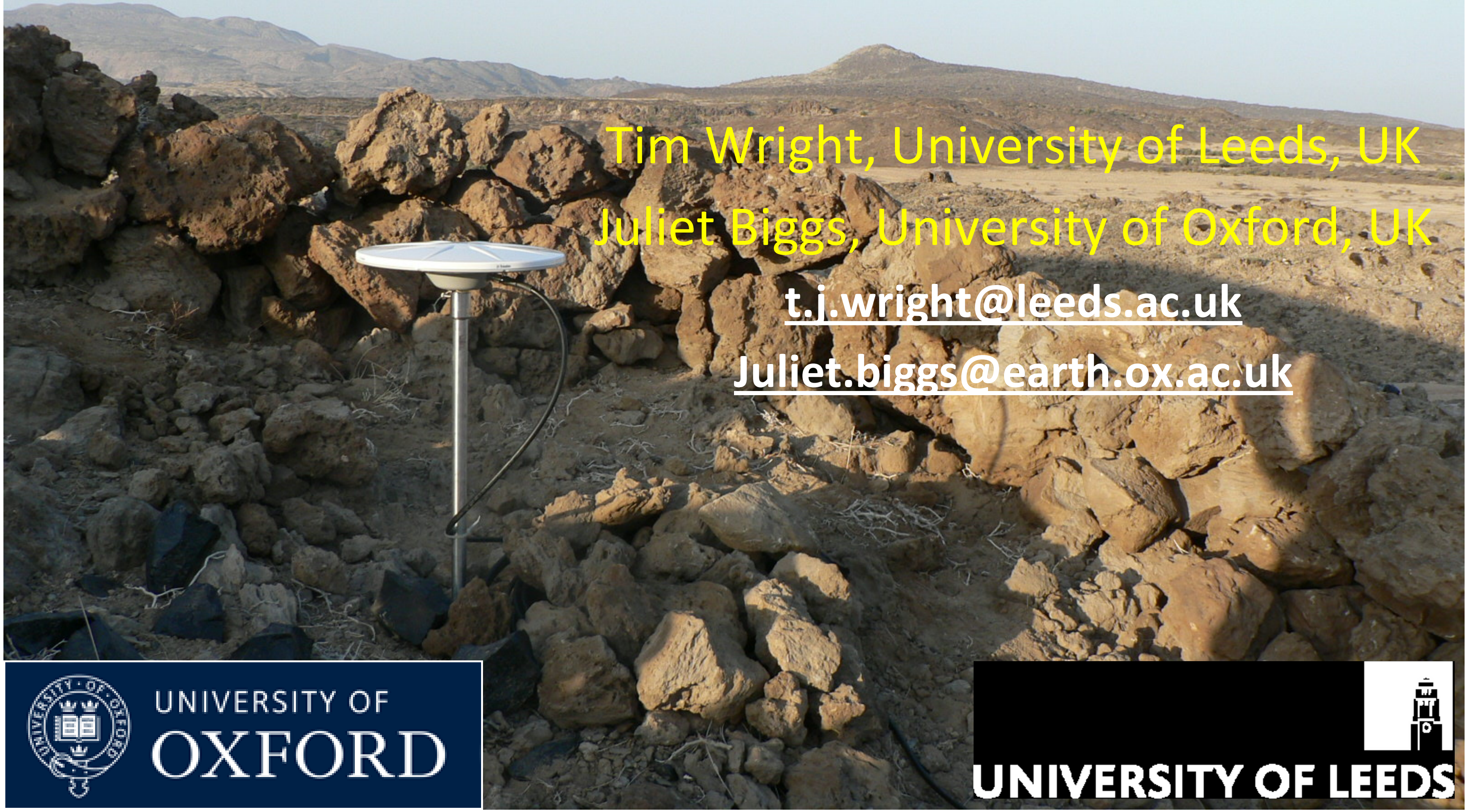
Volcano Deformation – Models and Examples

Tim Wright, University of Leeds, UK

Juliet Biggs, University of Oxford, UK

t.j.wright@leeds.ac.uk

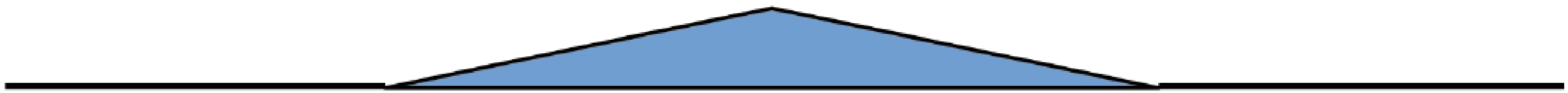
Juliet.biggs@earth.ox.ac.uk



UNIVERSITY OF OXFORD

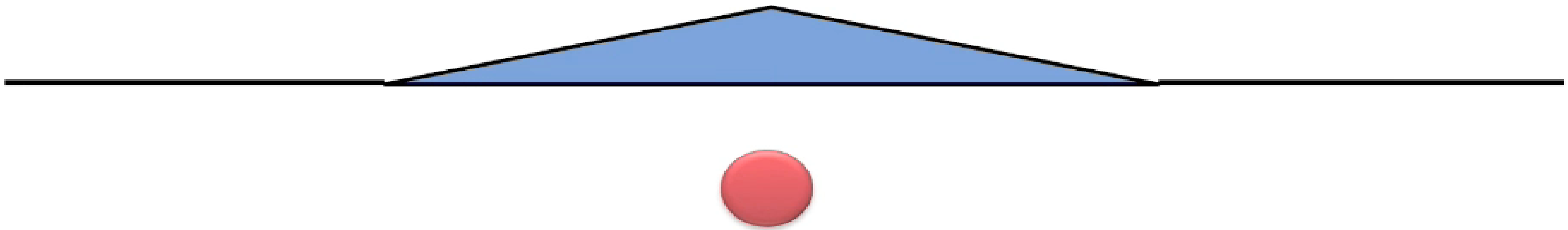
UNIVERSITY OF LEEDS

A simple volcanic system
1. Charging the system



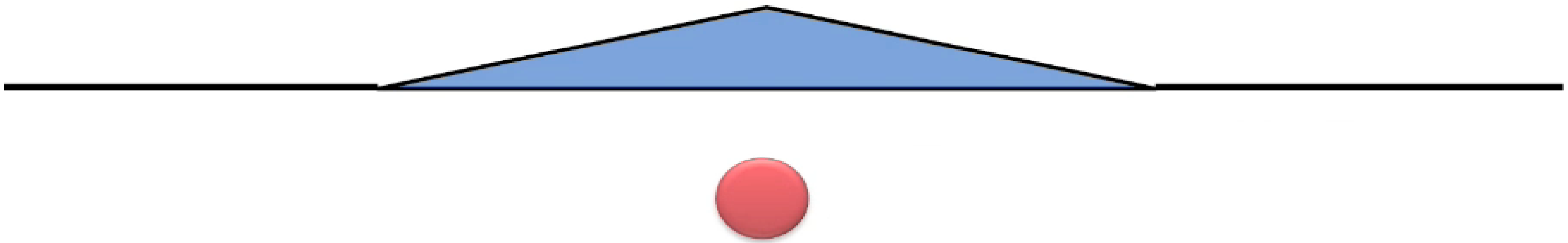
movie

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



movie

A simple volcanic system
1. Discharging the system

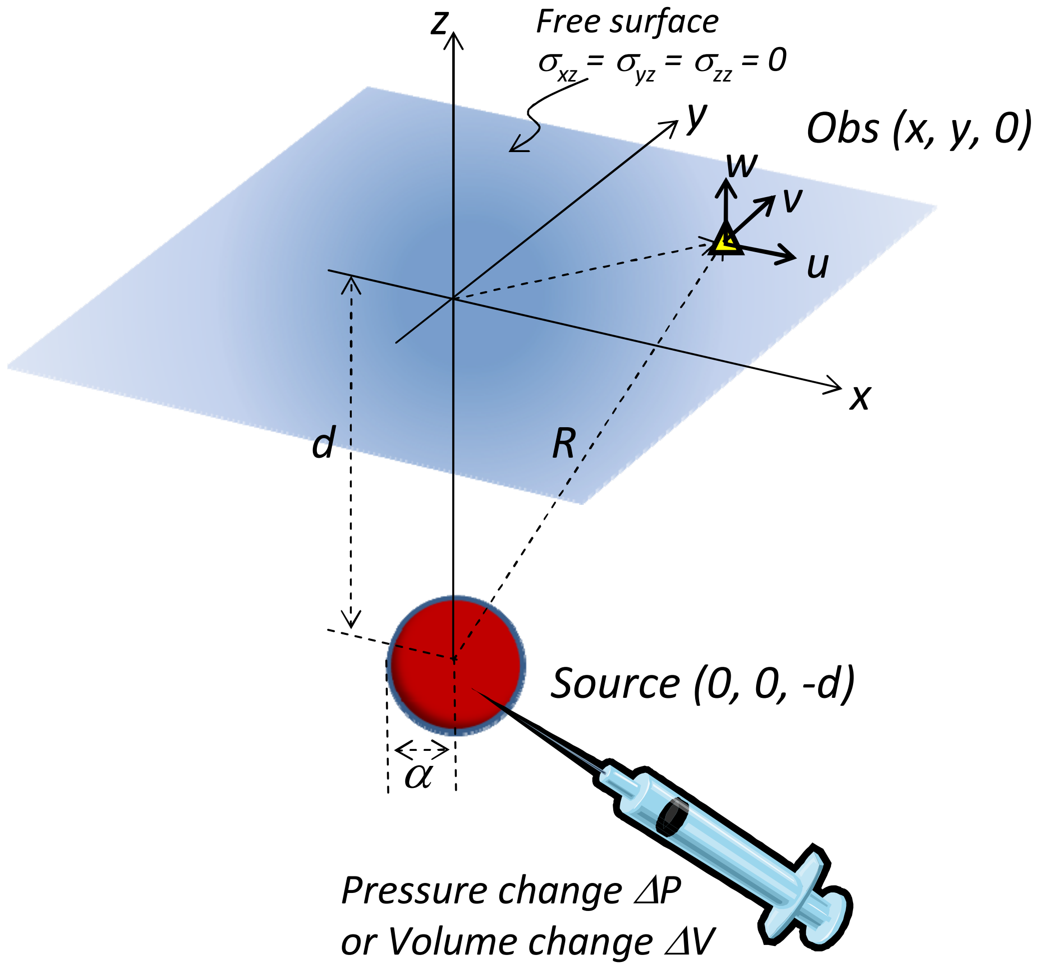


movie

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
- Comparison of InSAR and GPS
- Alaskan Case Study

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

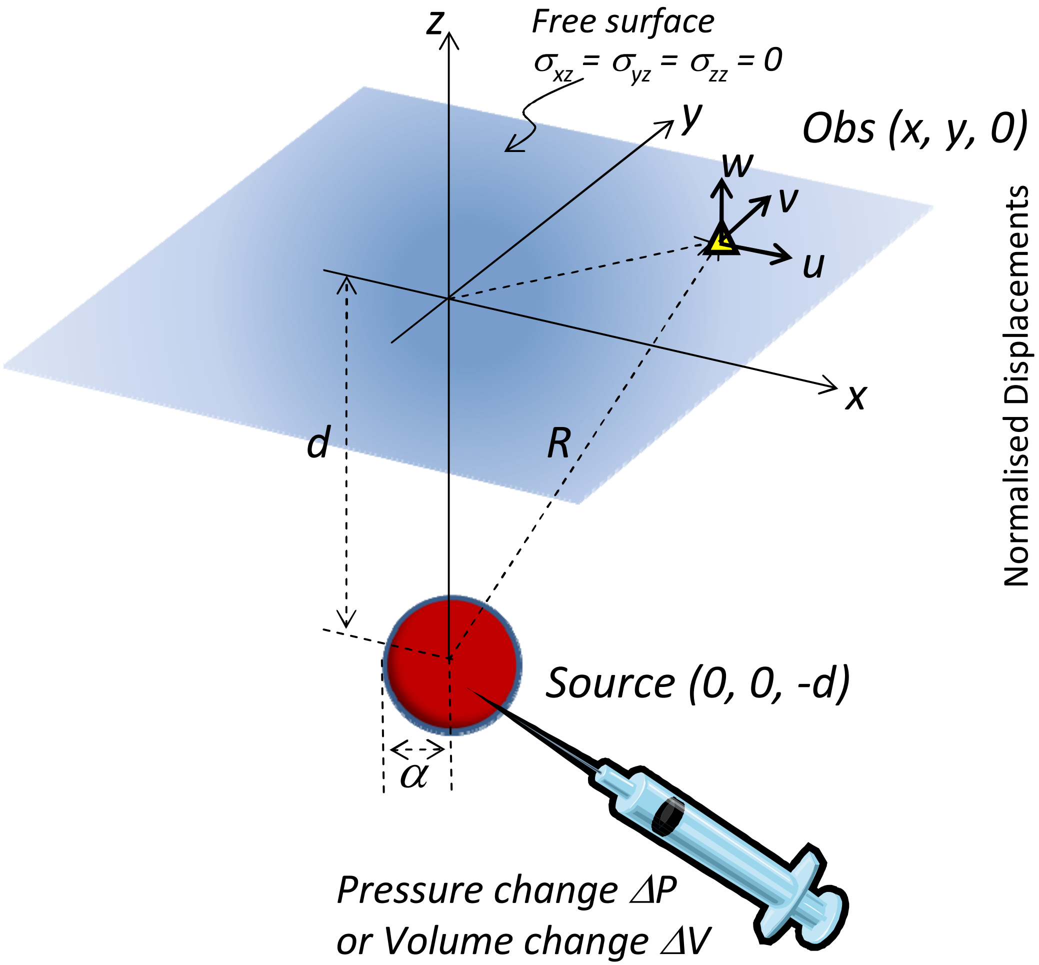
$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \alpha^3 \Delta P \frac{(1-\nu)}{\mu} \begin{pmatrix} x/R^3 \\ y/R^3 \\ z/R^3 \end{pmatrix}$$

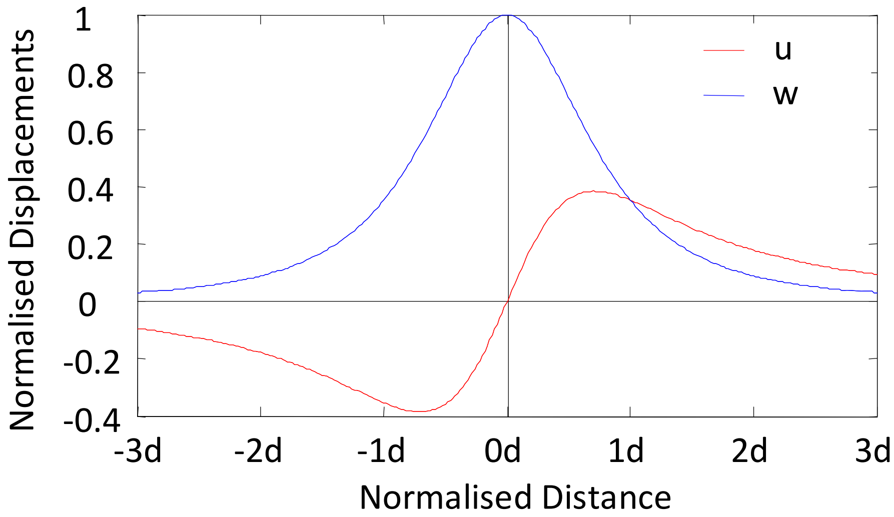
But $\Delta V \approx \dfrac{\Delta P}{\mu} \pi \alpha^3$ so

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

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

Simple Sources: 1. The Mogi Model

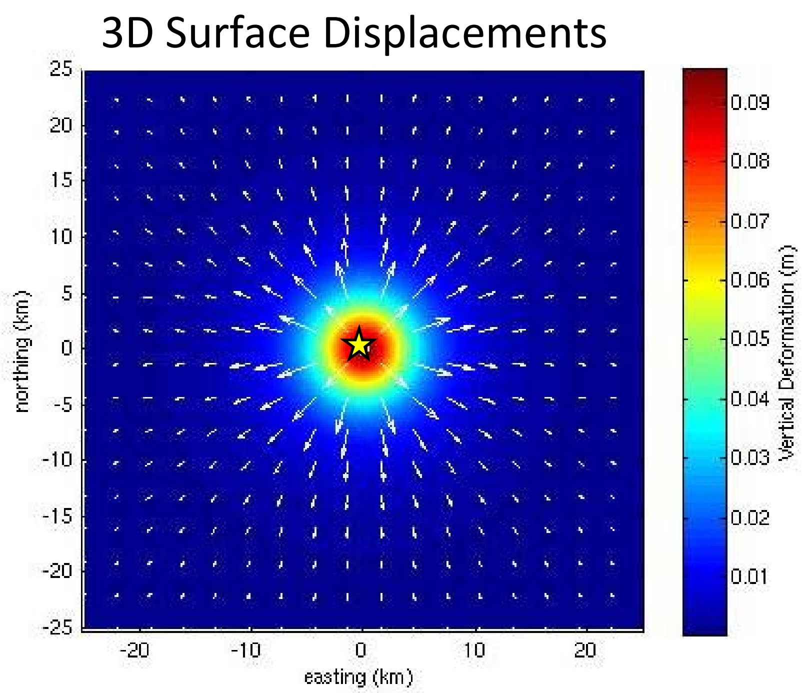


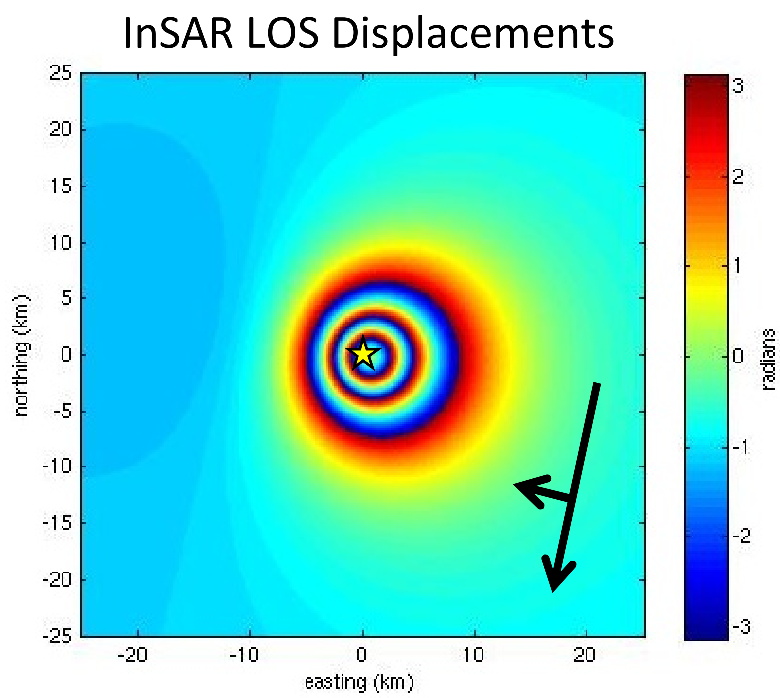


Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Mogi, K. (1958), *Bull. Earthq. Inst. U. Tokyo*, 36, 99-134
Delaney, P., McTigue, D.(1994) Bull. Volcanology, 56 417-424

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

Simple Sources: 1. The Mogi Model

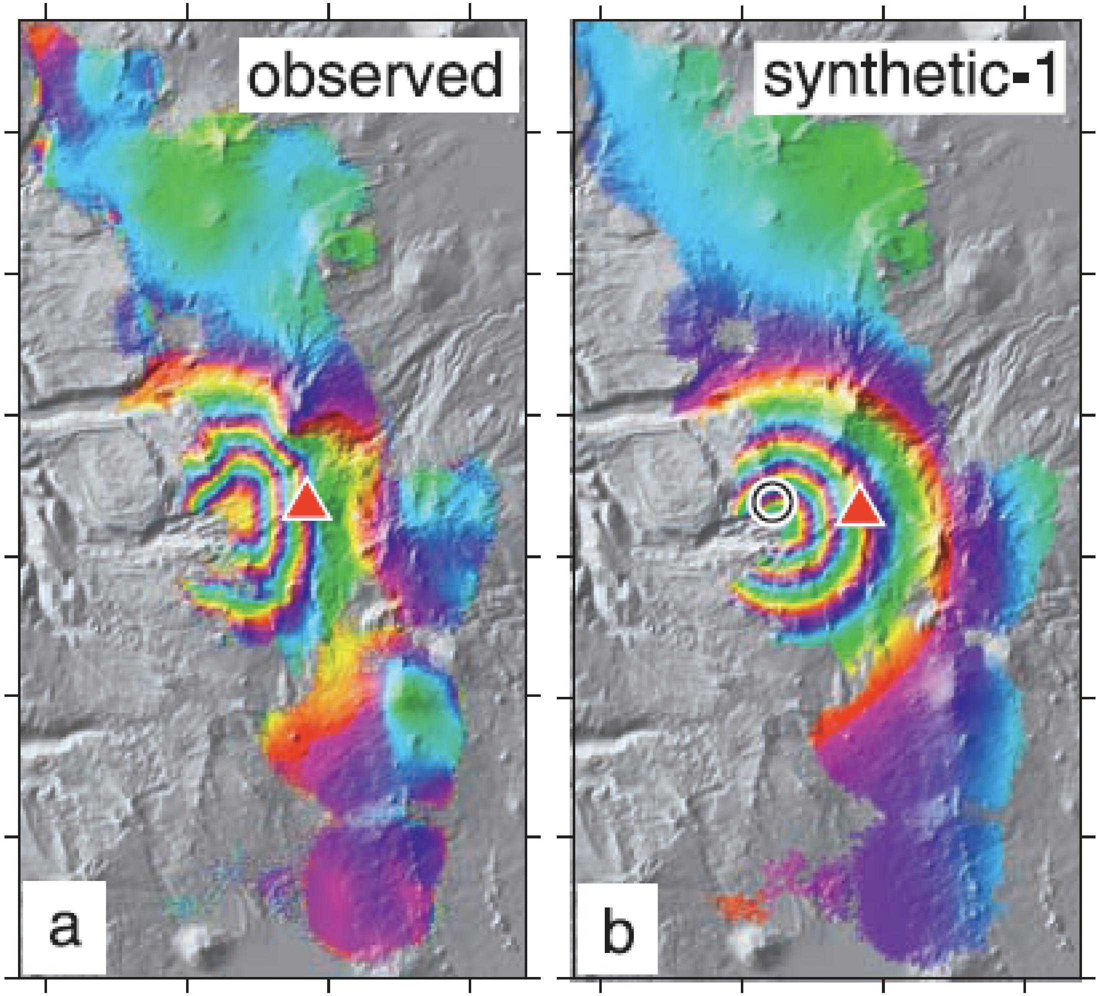




Source Depth = 5 km; Volume = 10^7 m^3
Maximum uplift ≈ 95 mm

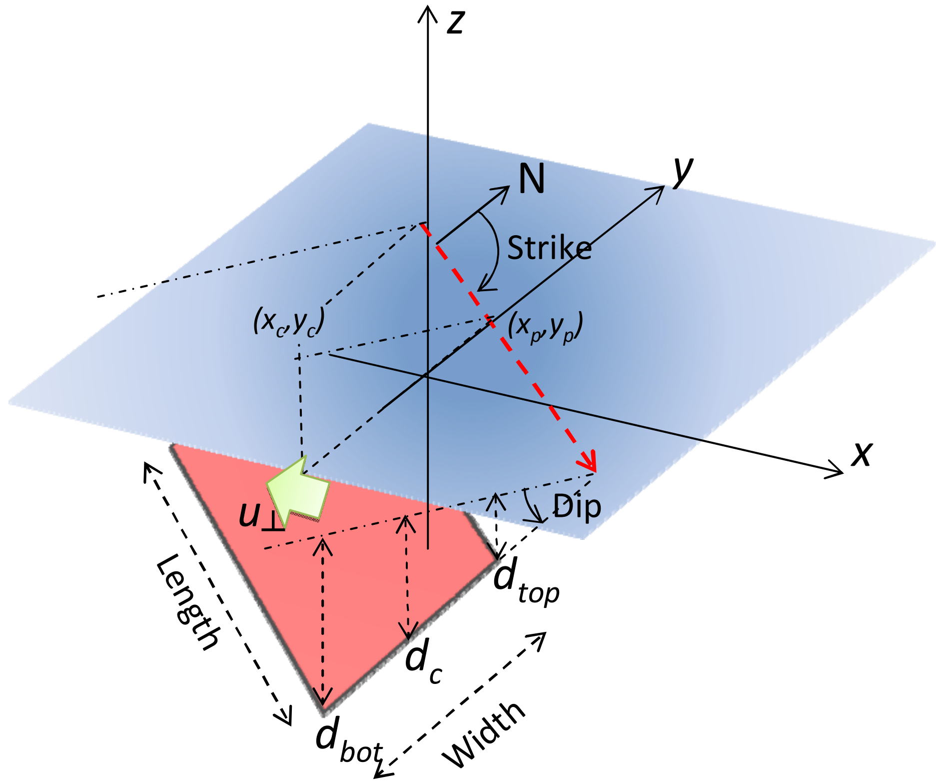
Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques*.
Mogi, K. (1958), *Bull. Earthq. Inst. U. Tokyo*, 36, 99-134
Delaney, P., McTigue, D.(1994) Bull. Volcanology, 56 417-424

Simple Sources: 1. The Mogi Model



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
Wicks, C., Dzurisin, D. et al (2002), GRL, 27.

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;

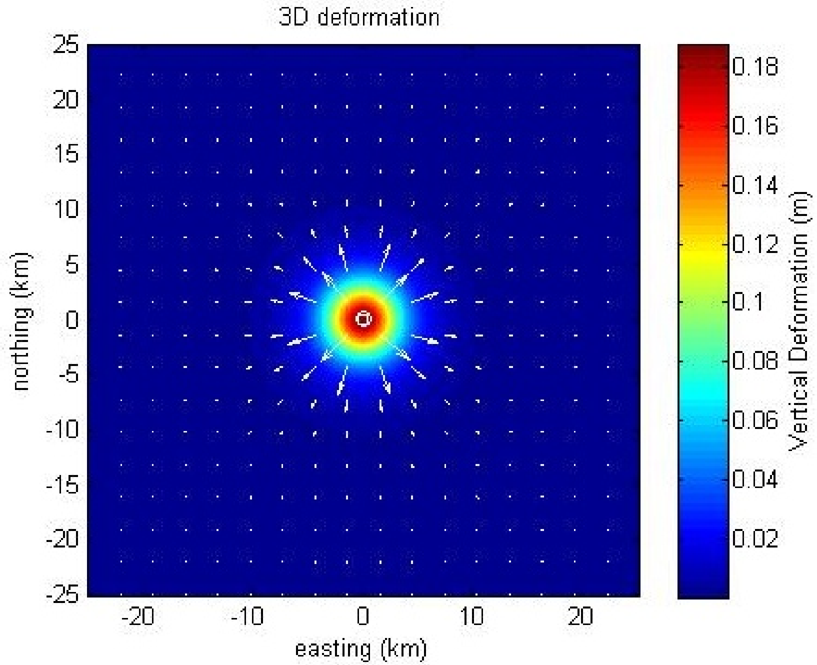
Dip = 0 for sills, 90 for dykes

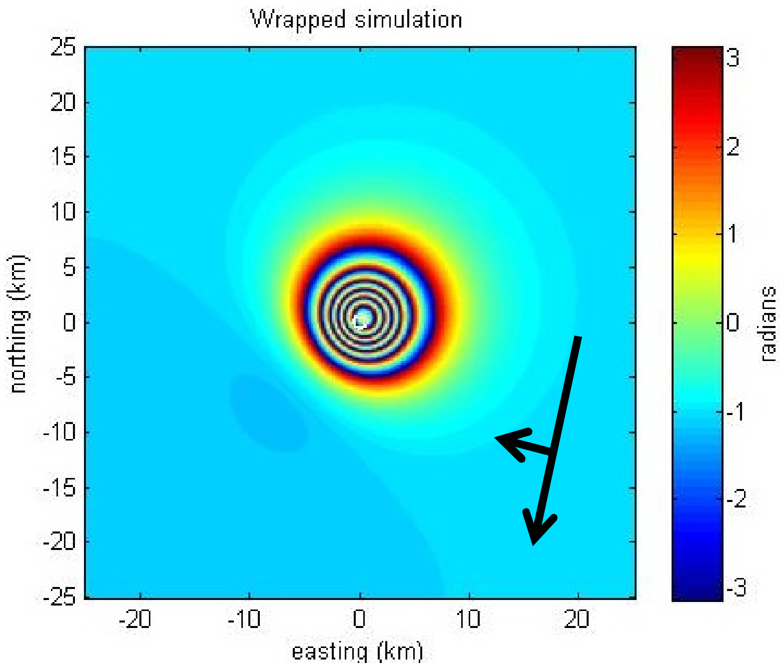
Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*

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]

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

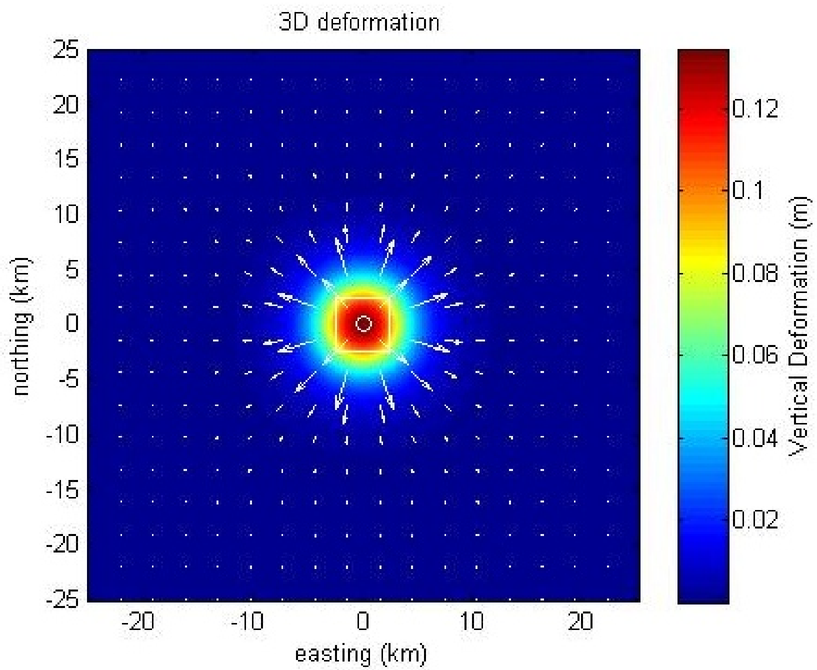


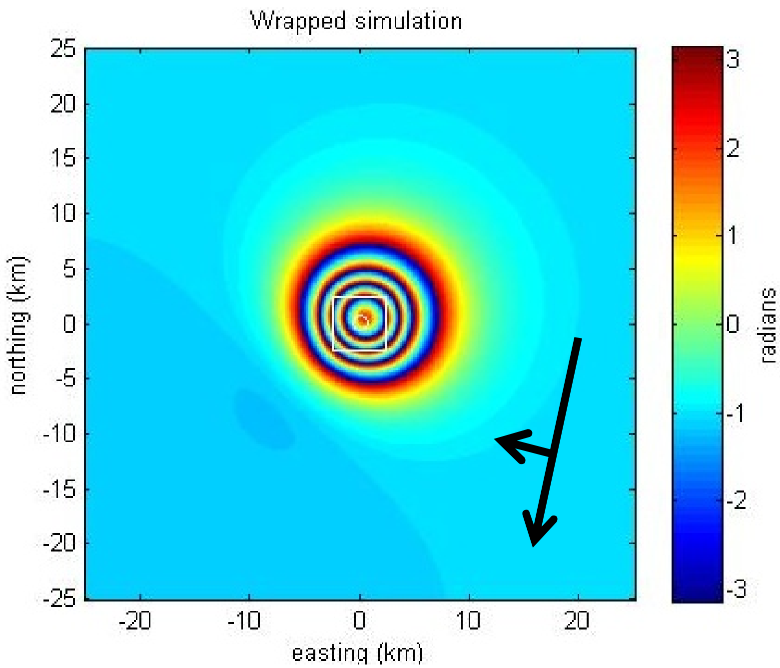


Sill 1: Dip = 0, Strike =0, x=y=0, d_c = 5 km
Length=Width=1 km
Opening = 10 m [Volume = 10^7 m^3]

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

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

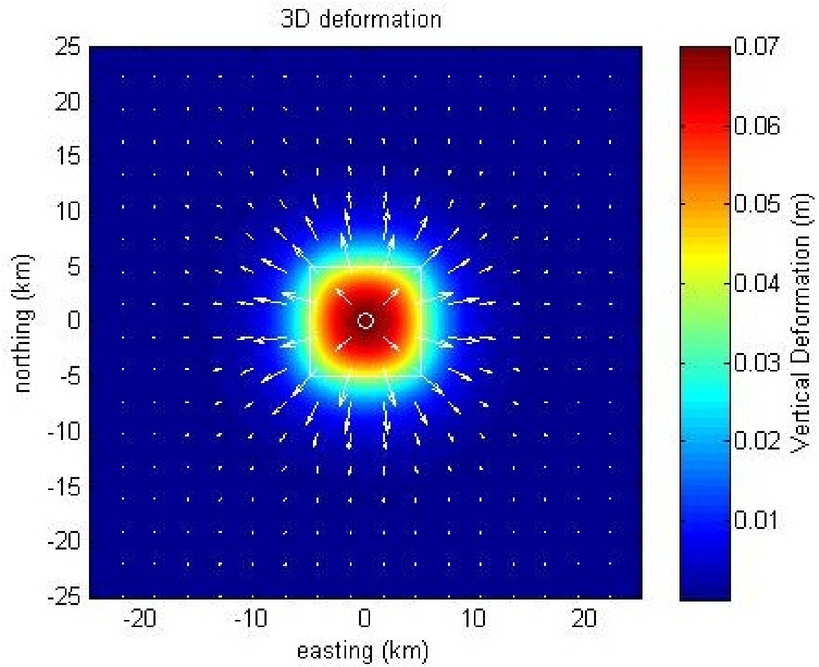


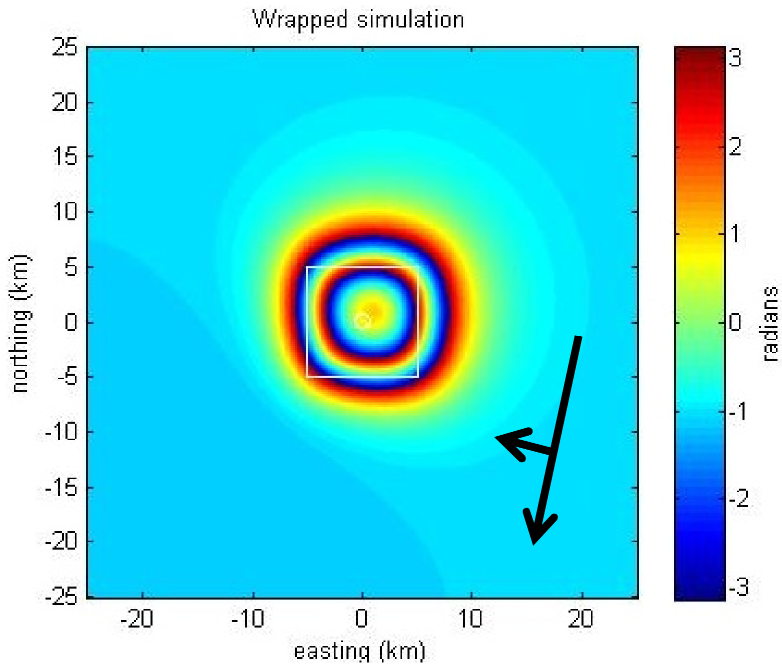


Sill 2: Dip = 0, Strike =0, x=y=0, d_c = 5 km
Length=Width=5 km
Opening = 0.4m [Volume = 10^7 m^3]

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)

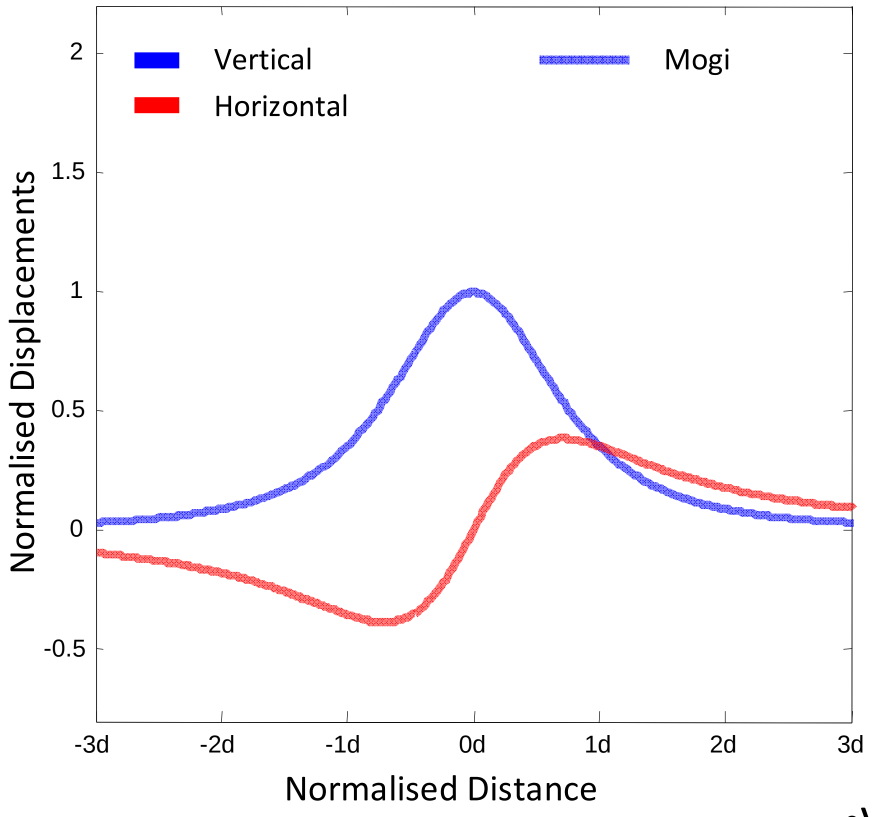




Sill 3: Dip = 0, Strike =0, x=y=0, d_c = 5 km
Length=Width=10 km
Opening = 0.1 m [Volume = 10^7 m^3]

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]

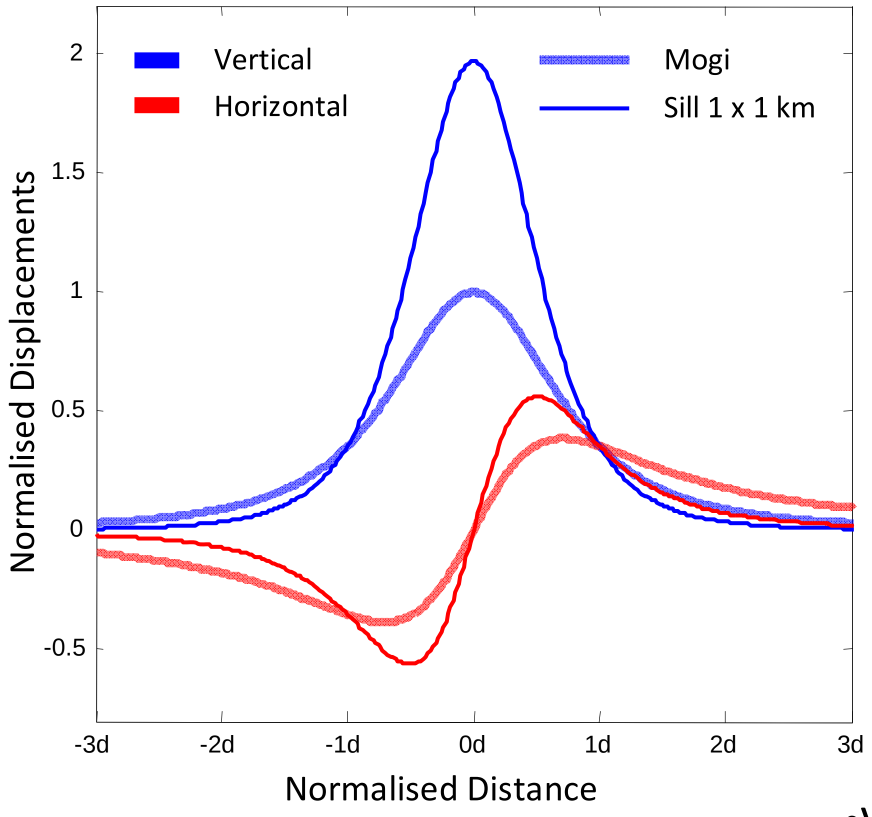
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – **sills** or dykes)



•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]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

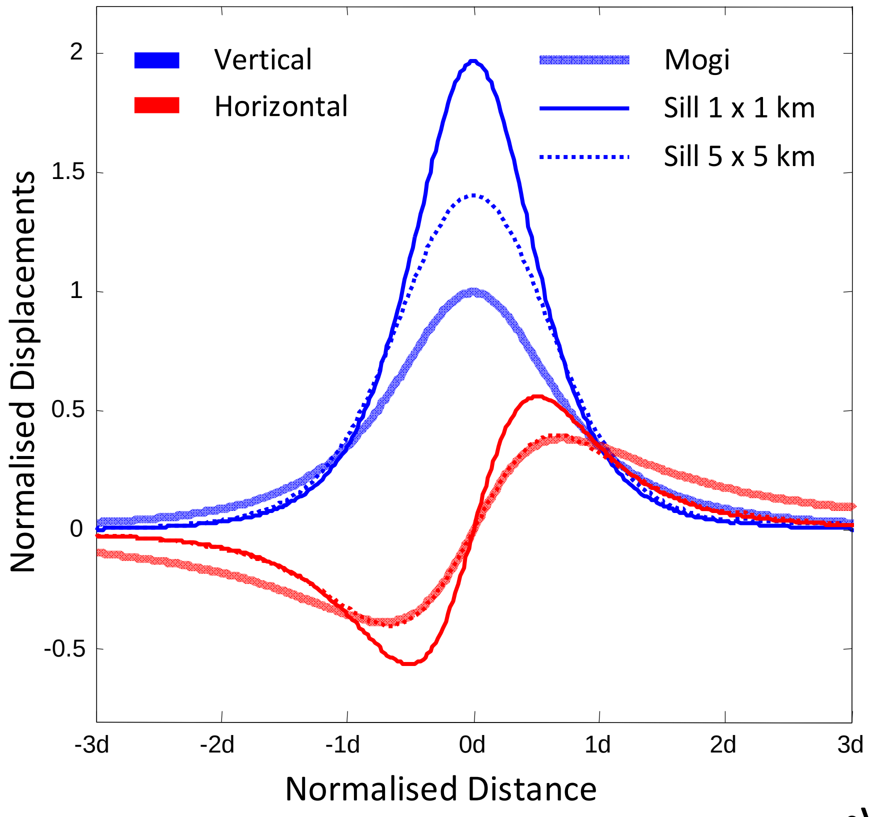
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – **sills** or dykes)



- 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]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

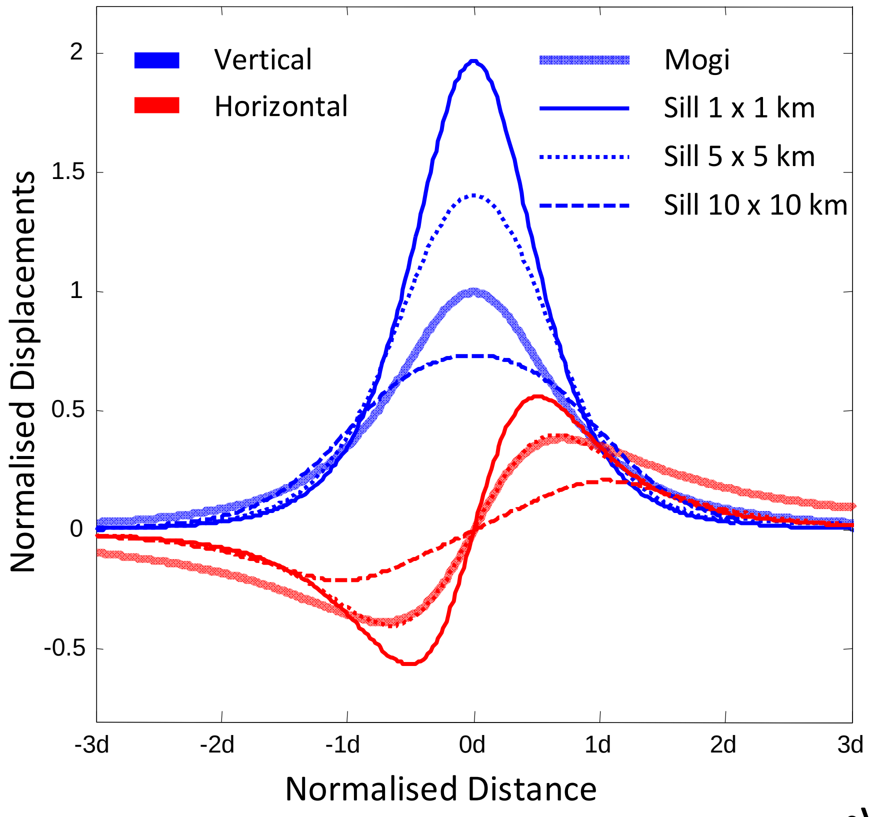
Simple Sources: 2. Tensile Elastic Dislocations (Okada model – **sills** or dykes)



- 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]
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]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

Source volume vs uplift volume

Delaney and McTigue (1994) showed:

1. For sills, source volume change = surface uplift volume

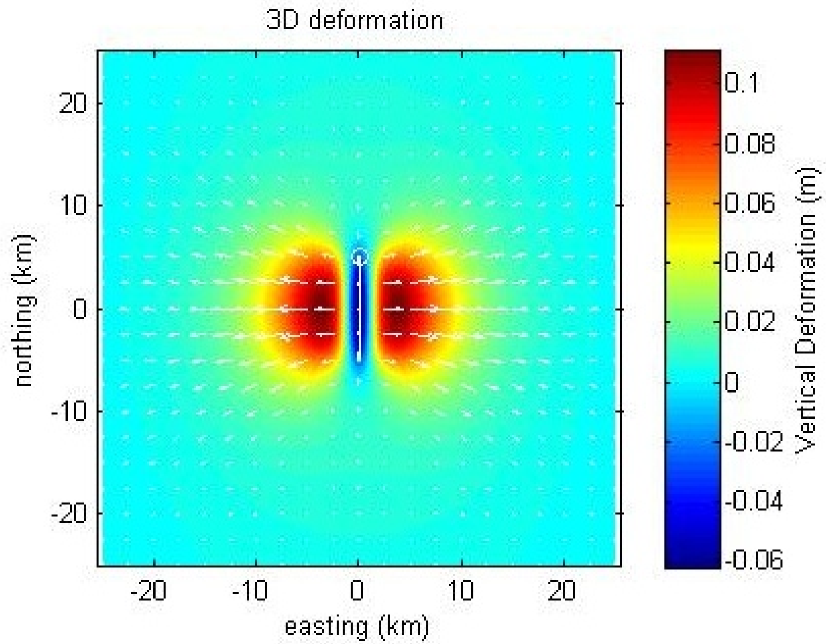
2. For Mogi, source volume change = surface uplift volume / $2(1-\nu)$

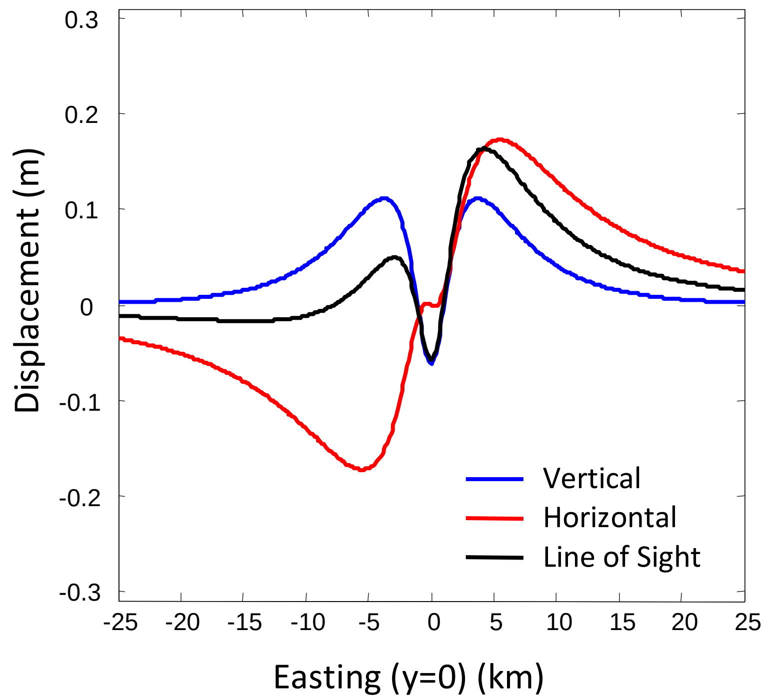
   e.g. For $\nu = 0.25$, source volume = (2/3) * surface uplift volume

These relationships are only true if the Magma is incompressible. See Johnson et al (2000) for details [also summarised in Dzurisin (2007)]

Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Johnsson, D (2000), Bull. Volcanol., 61, 491-493

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





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

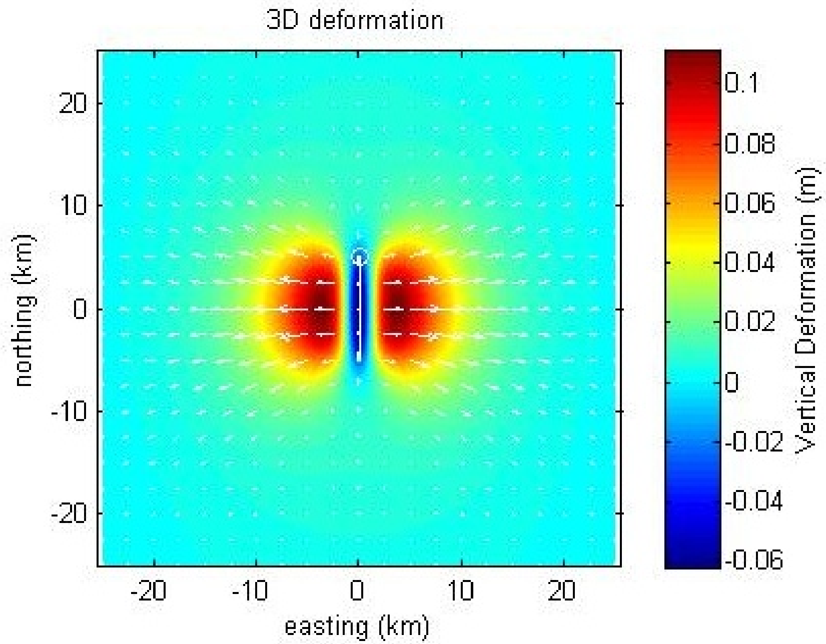
d_{top} = 2 km, d_{bot} = 8 km

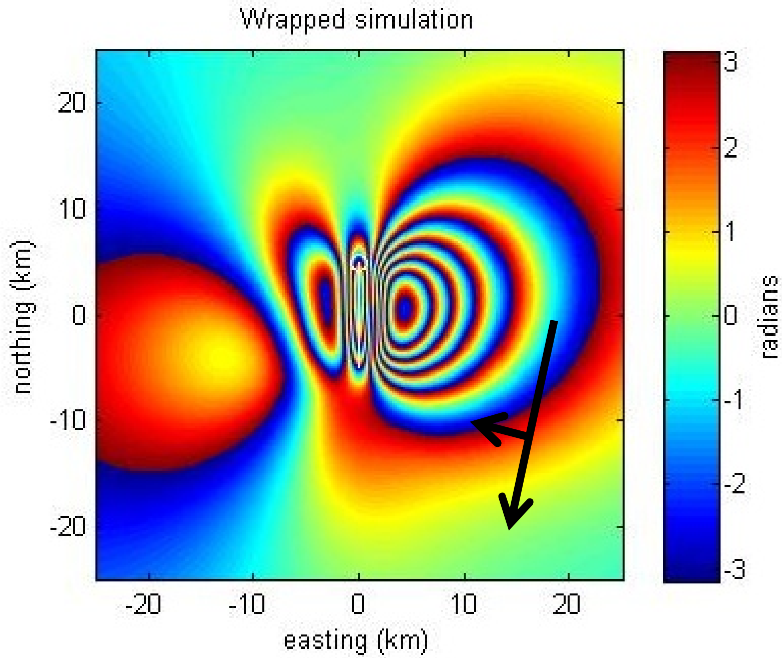
Length= 10 km

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

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

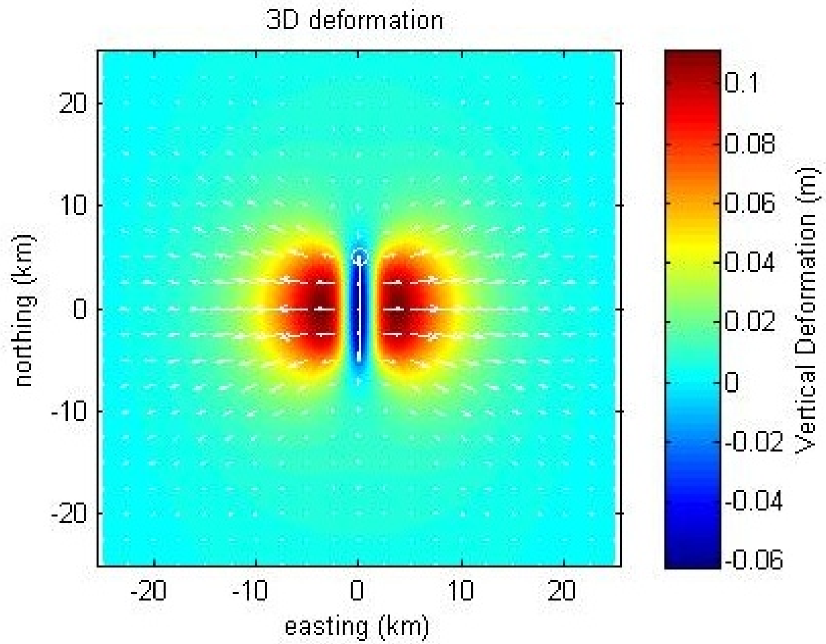
d_{top} = 2 km, d_{bot} = 8 km

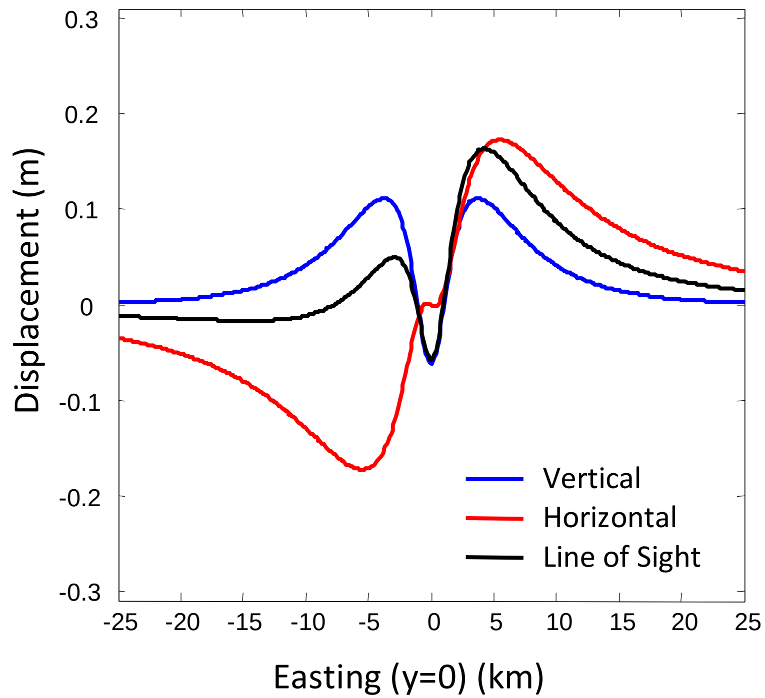
Length= 10 km

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

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

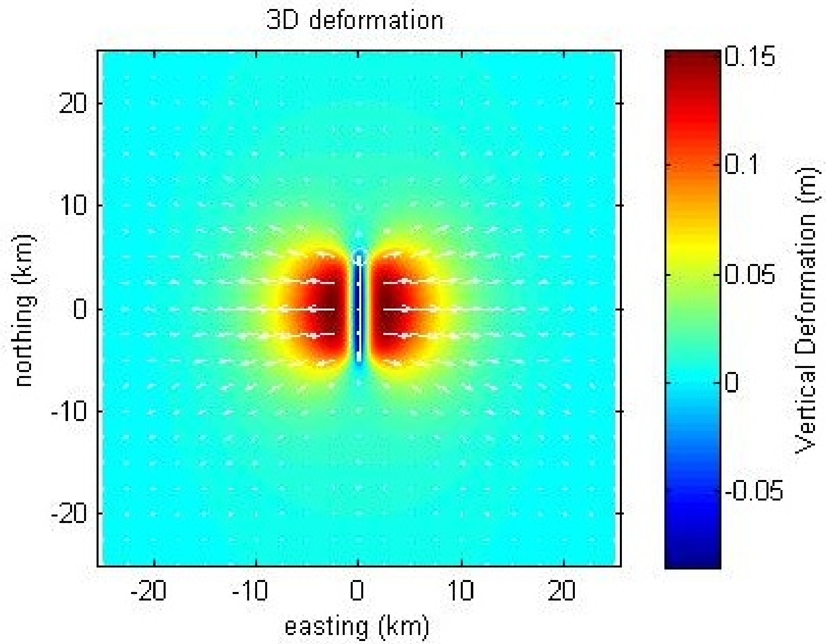
d_{top} = 2 km, d_{bot} = 8 km

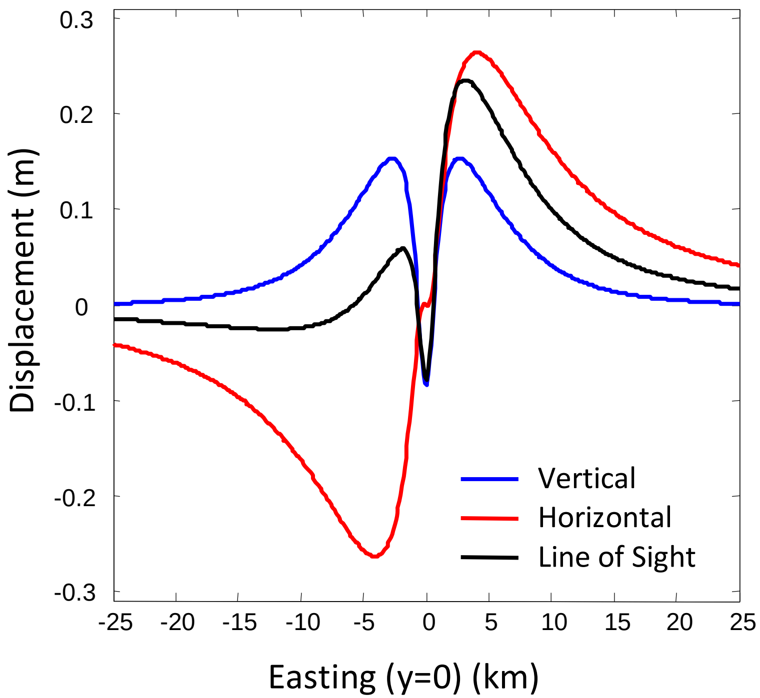
Length= 10 km

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

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

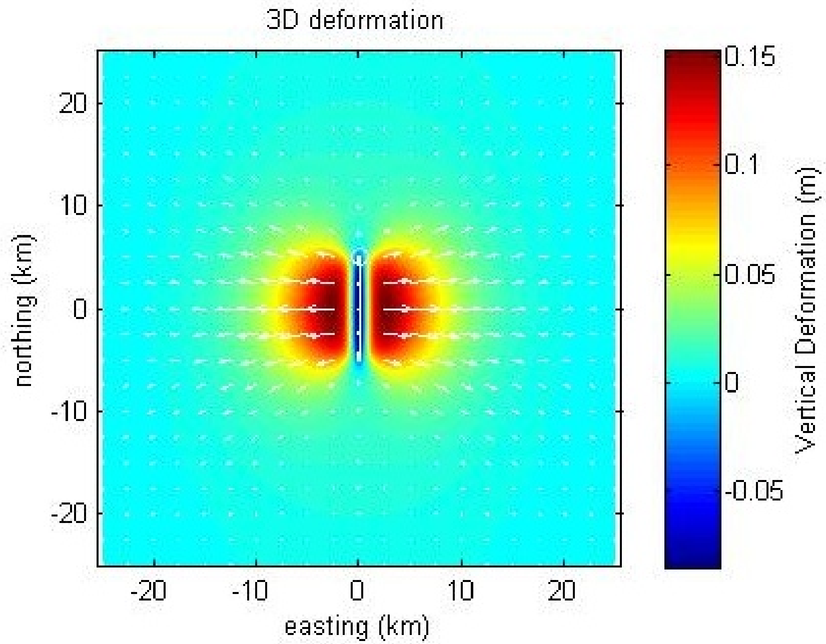
d_{top} = 1 km, d_{bot} = 8 km

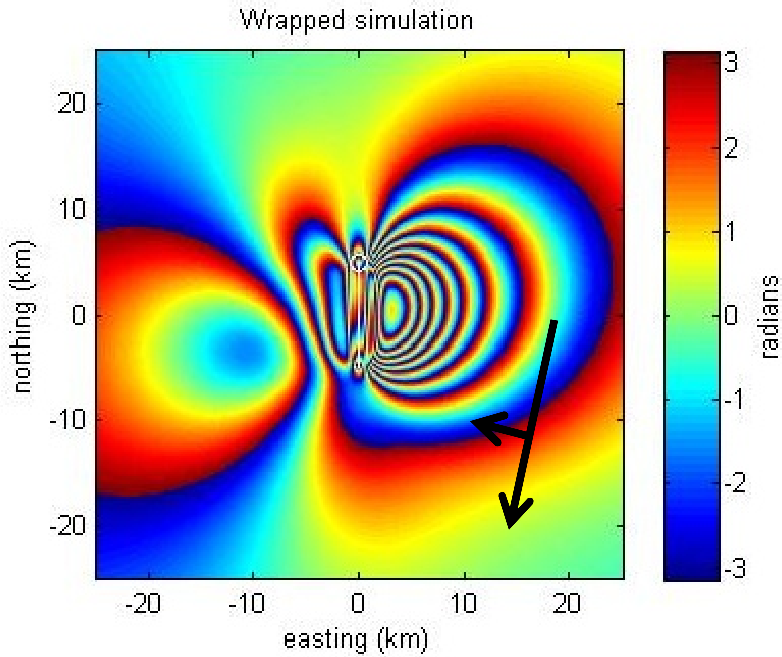
Length= 10 km

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

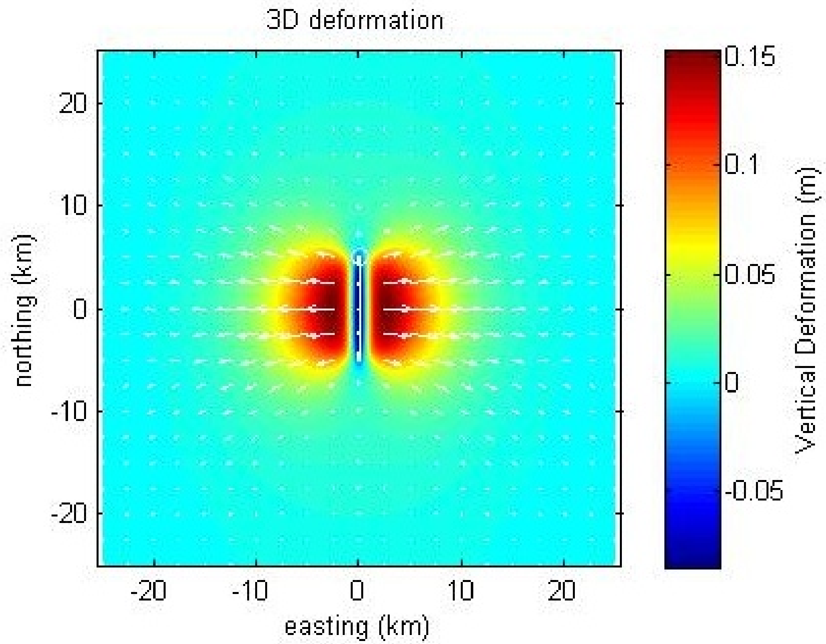
d_{top} = 1 km, d_{bot} = 8 km

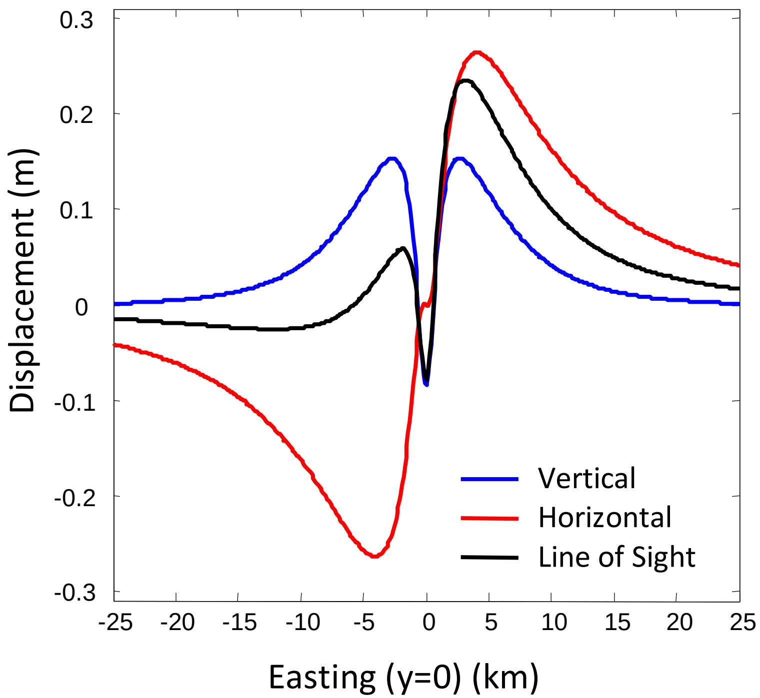
Length= 10 km

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

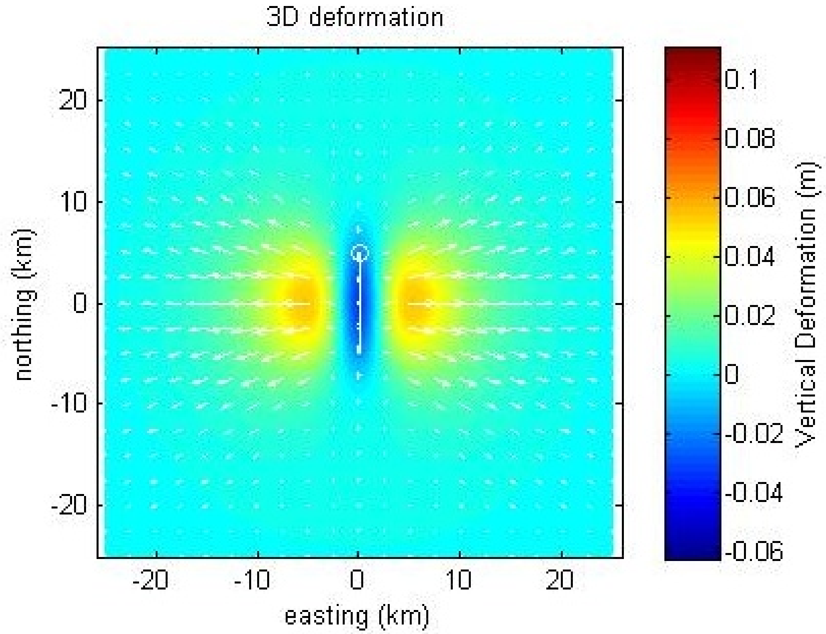
d_{top} = 1 km, d_{bot} = 8 km

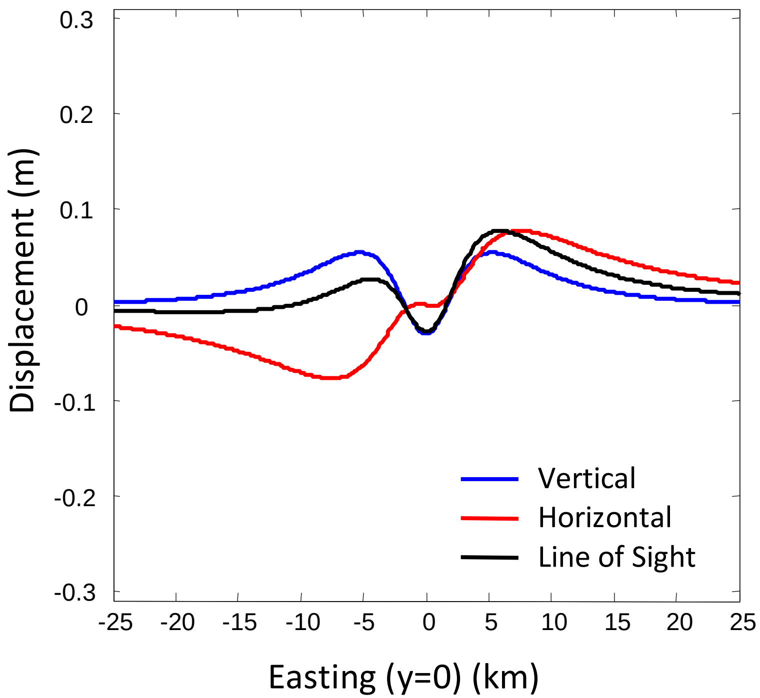
Length= 10 km

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

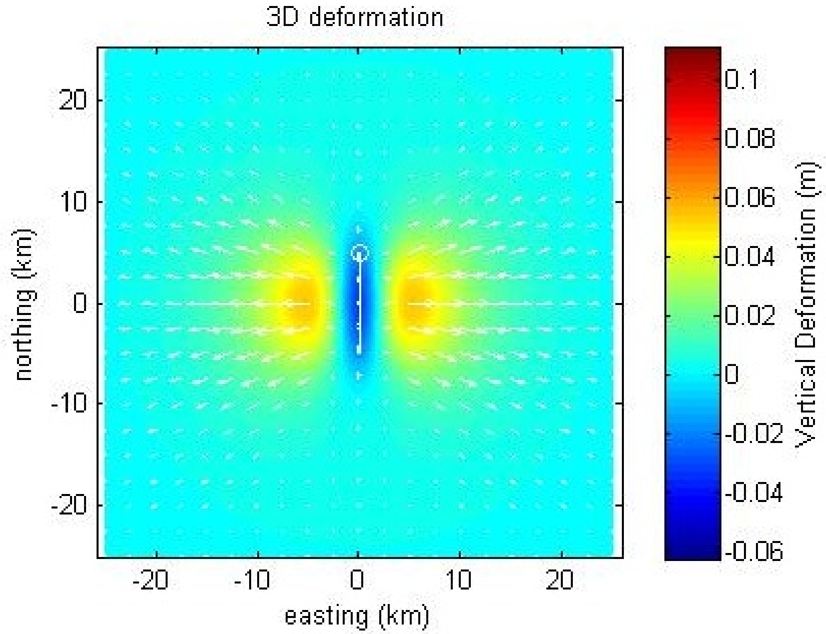
d_{top} = 4 km, d_{bot} = 8 km

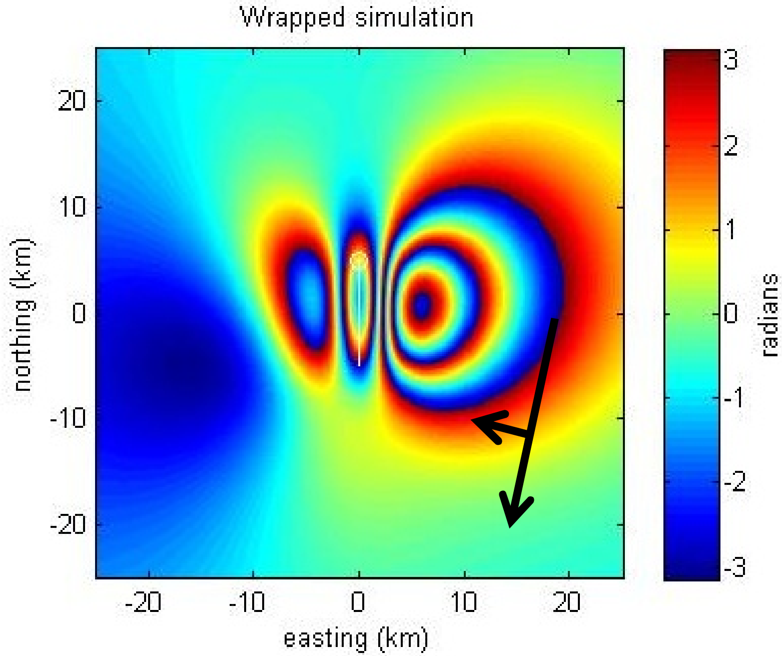
Length= 10 km

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]
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

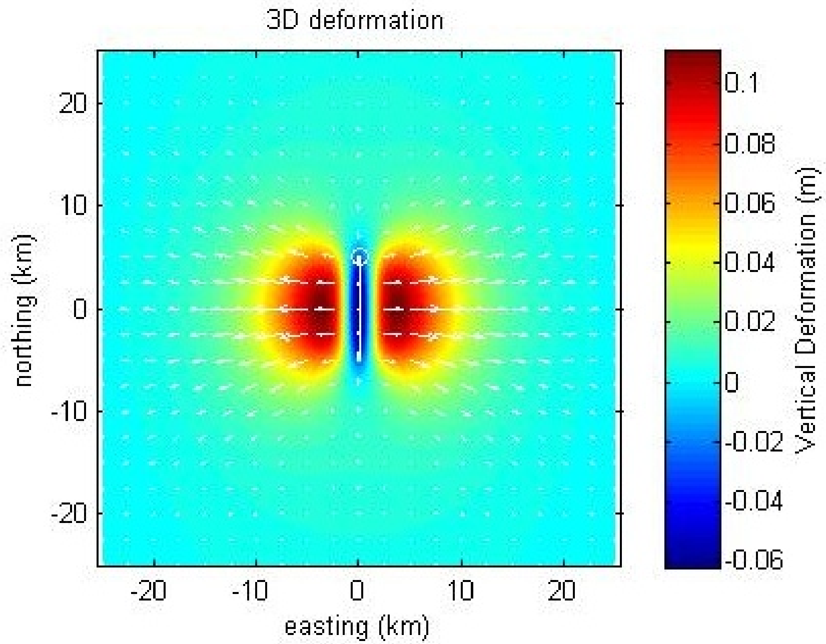
d_{top} = 4 km, d_{bot} = 8 km

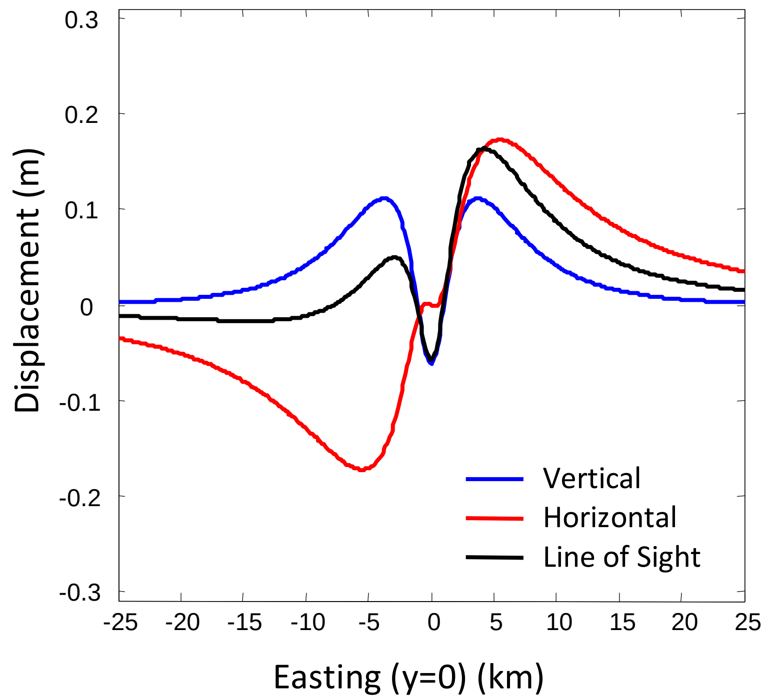
Length= 10 km

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

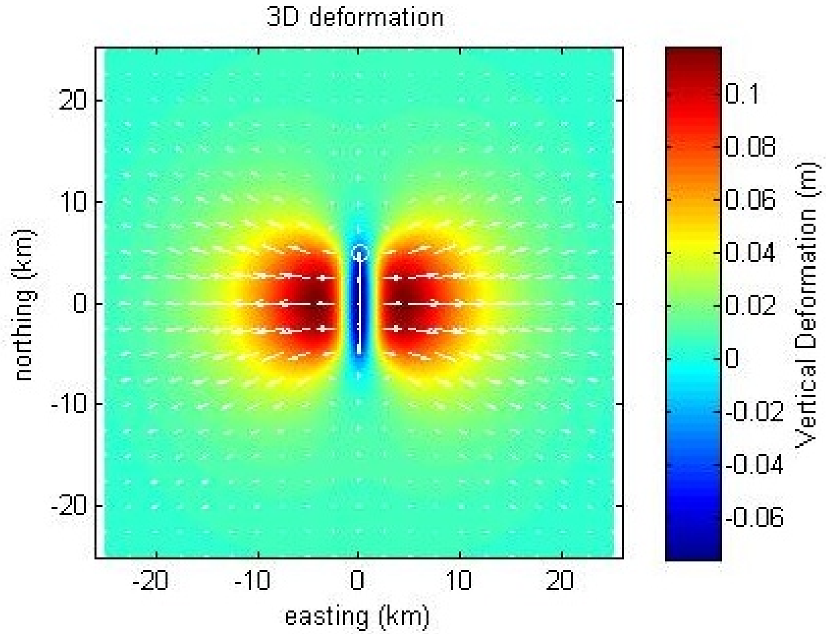
d_{top} = 2 km, d_{bot} = 8 km

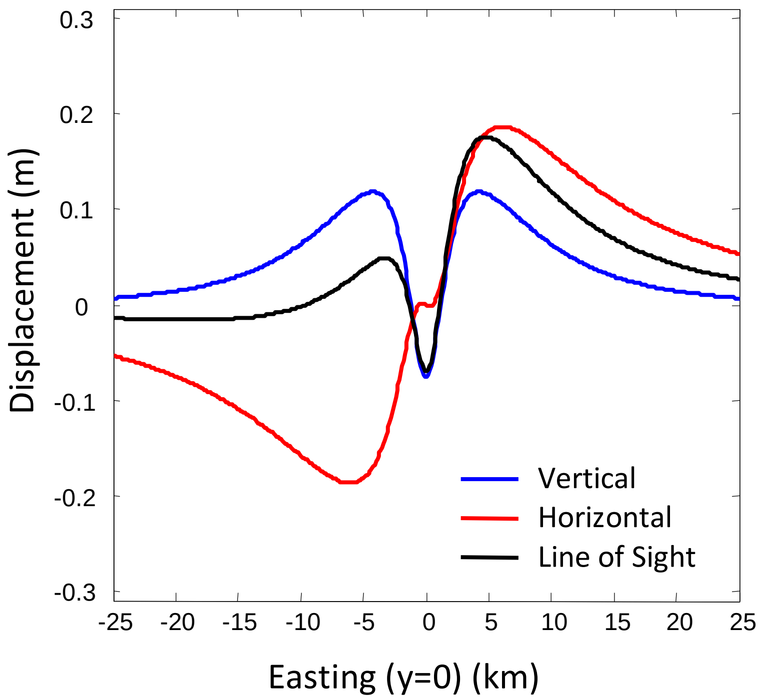
Length= 10 km

Opening = 1 m [Volume = 6×10^7 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**)

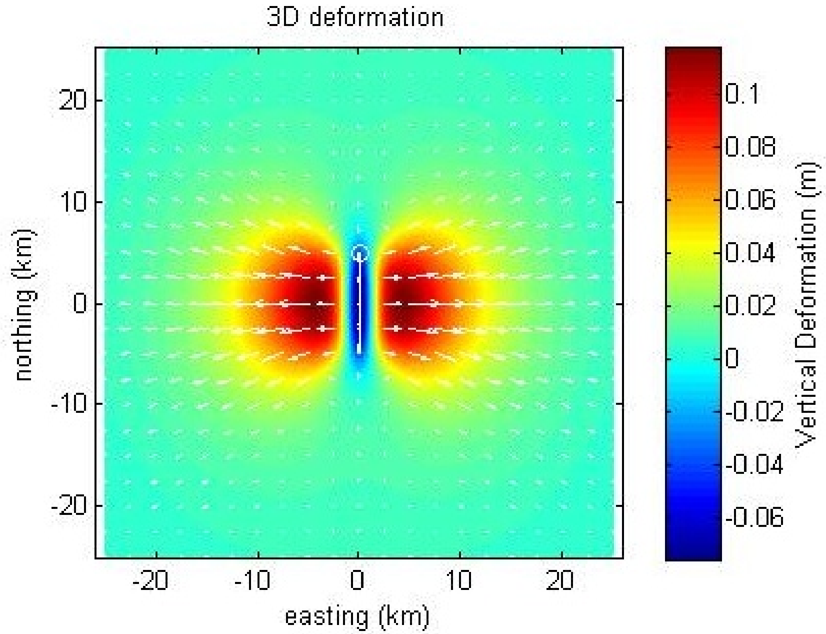


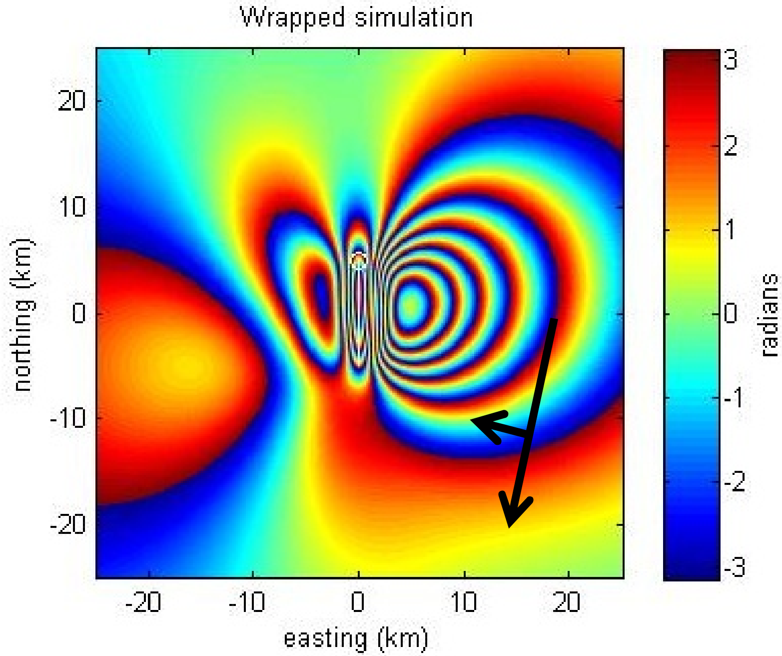


Dyke 4: Dip = 90, Strike =0, x=y=0
d_{top} = 2 km, d_{bot} = 12 km
Length= 10 km
Opening = 1 m [Volume = 10 x 10^7 m^3]

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

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

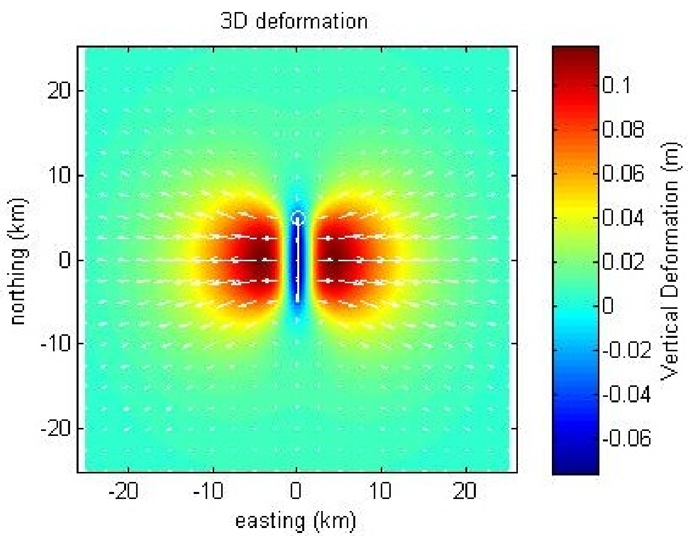


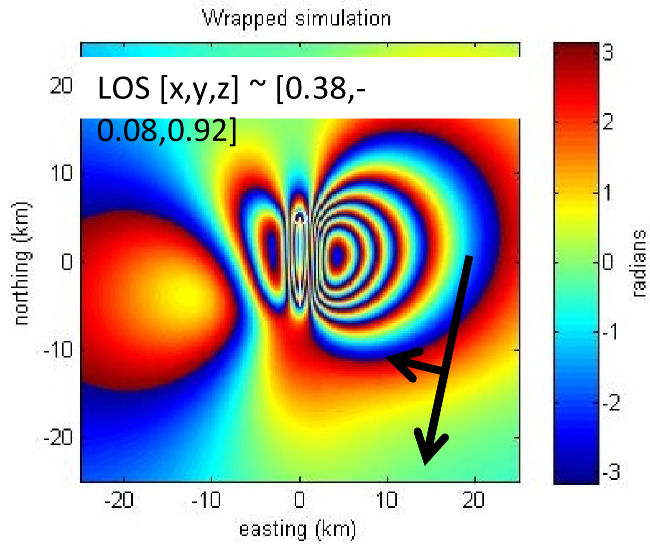


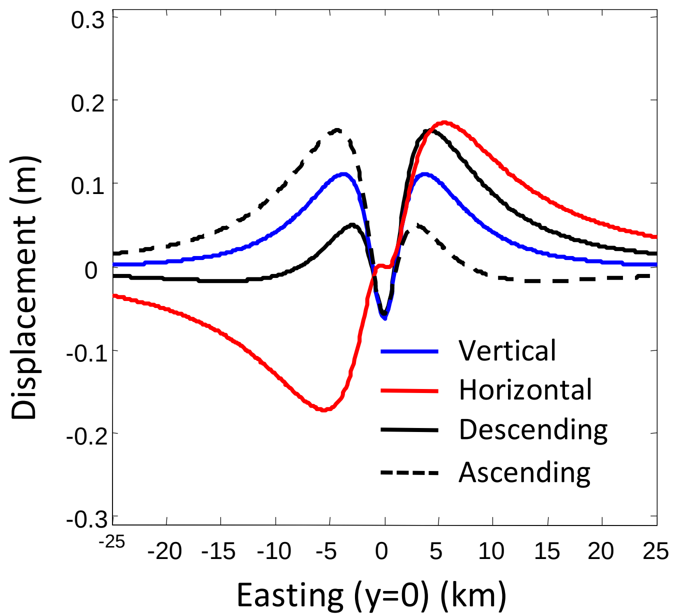
Dyke 4: Dip = 90, Strike =0, x=y=0
d_{top} = 2 km, d_{bot} = 12 km
Length= 10 km
Opening = 1 m [Volume = 10 x 10^7 m^3]

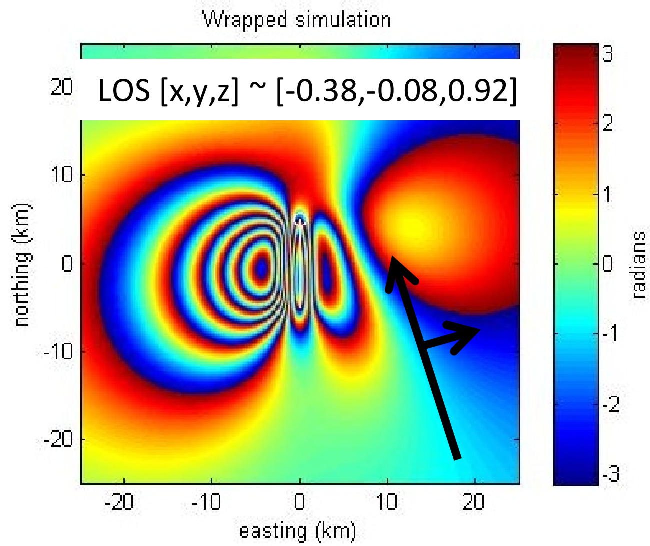
Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Okada, Y. (1985). Bull. Seis. Society of America 75 (4), 1135-1154 [surface]
Okada, Y. (1992). Bull. Seis. Society of America 82 (2), 1018-1040 [internal]

Ascending vs Descending

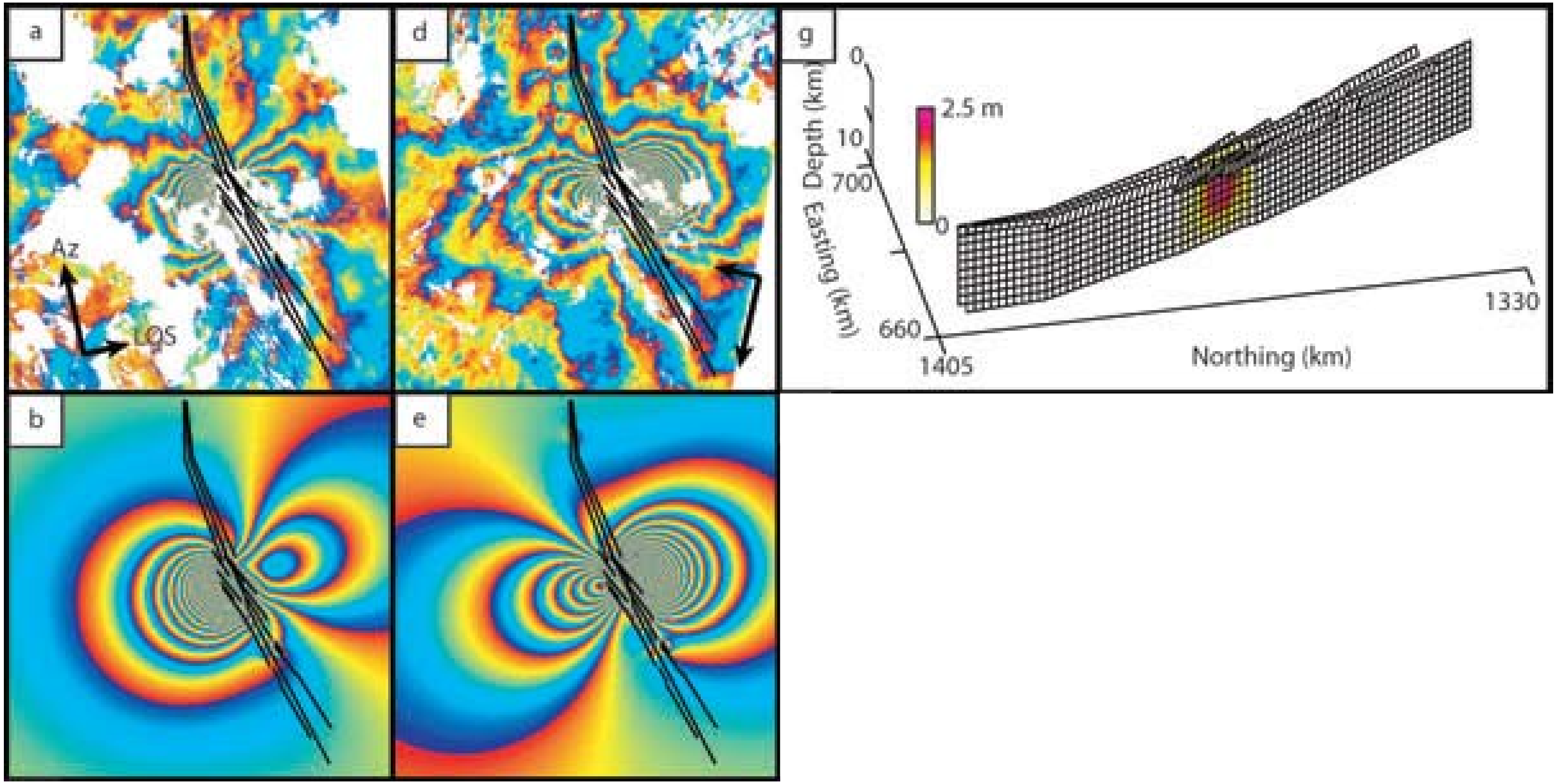






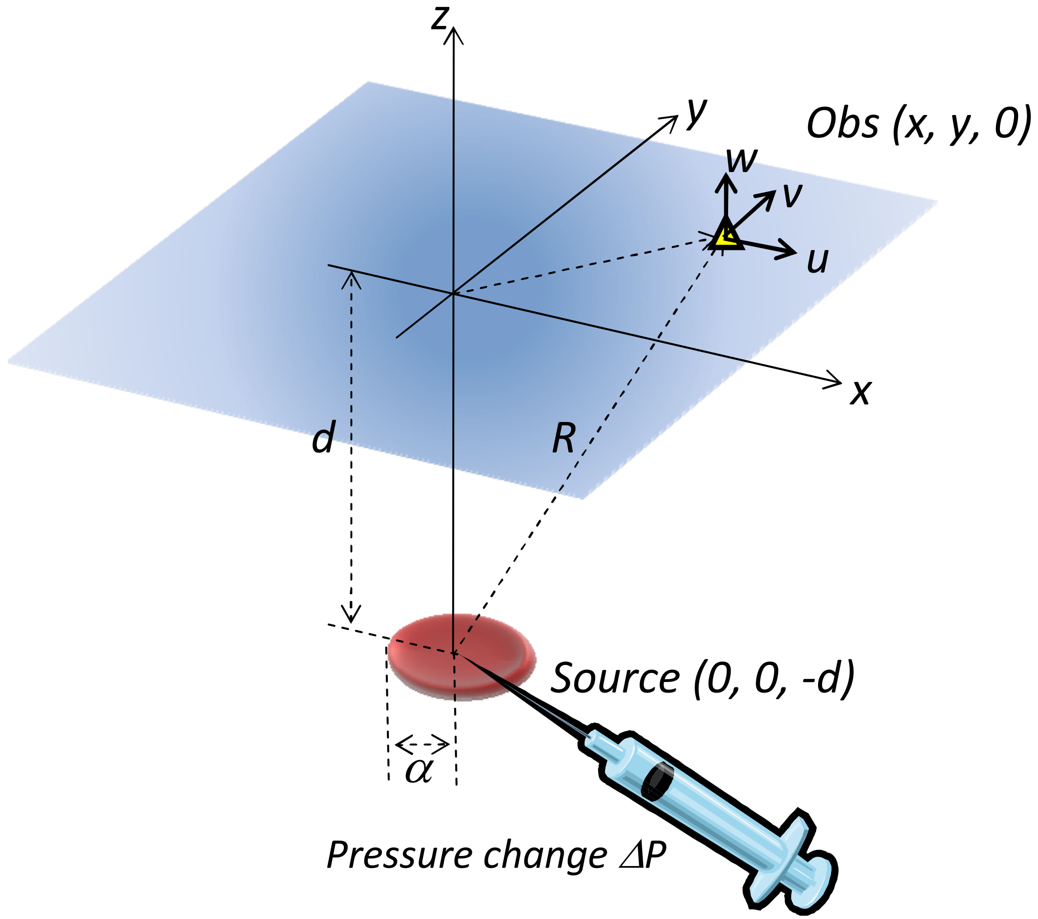


Simple Sources: 2. Tensile Elastic Dislocations (Okada model – sills or **dykes**)



June 2006 Dyke, Afar, Ethiopia. Hamling et al. (2009), Geophysical J. Int.

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

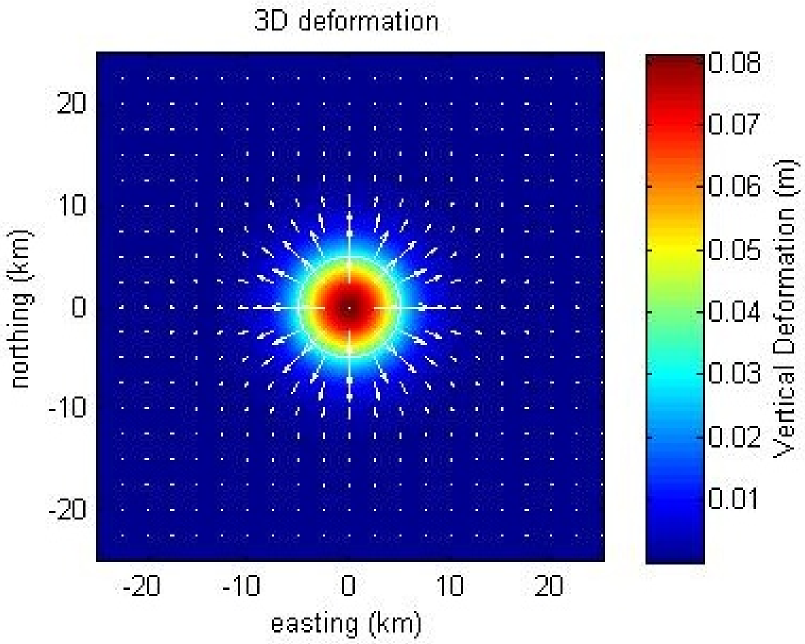
Parameters

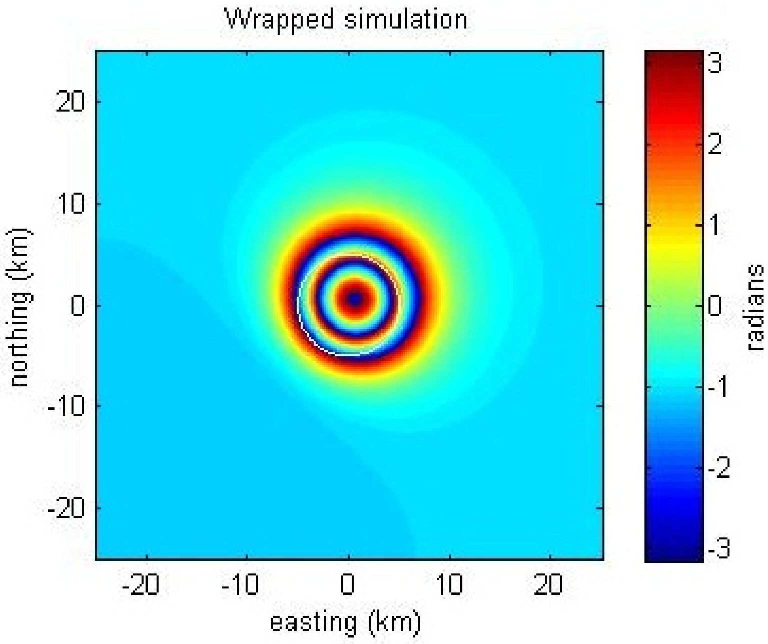
1. Depth
2. Radius of source
3. Pressure

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)

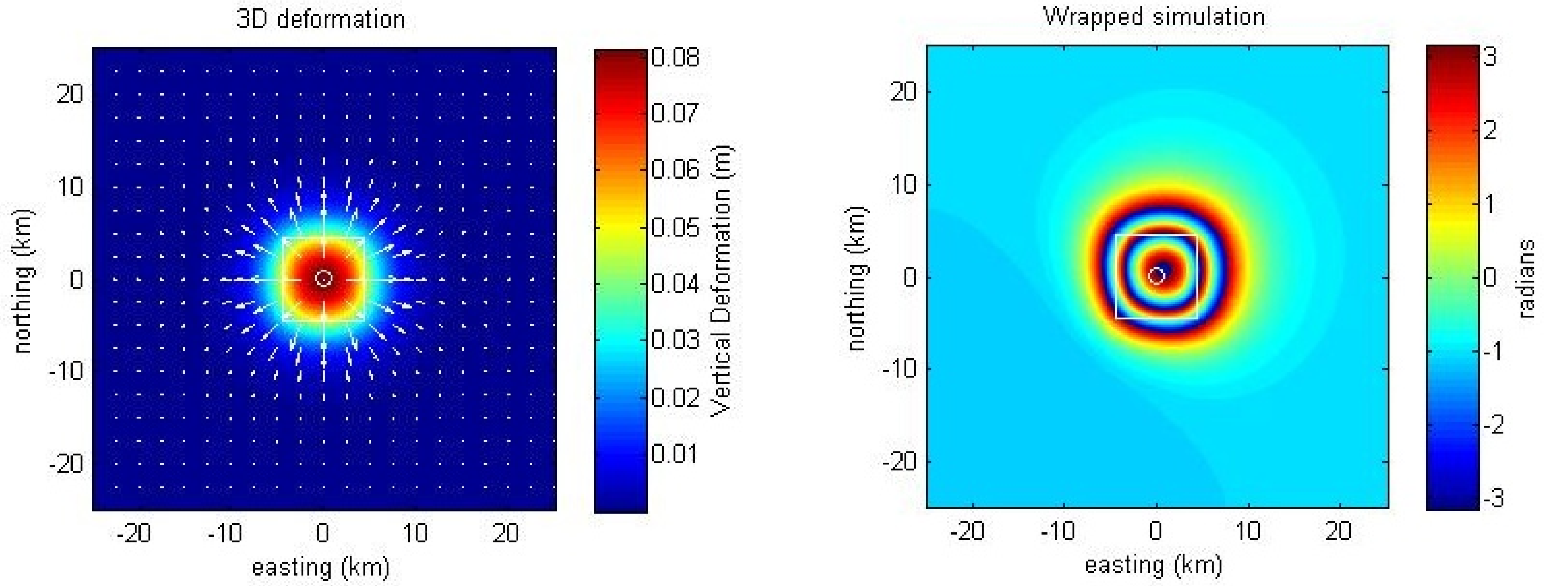




Penny Sill: Source Depth = 5 km; Radius = 5 km;
Pressure = 0.77 MPa

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)

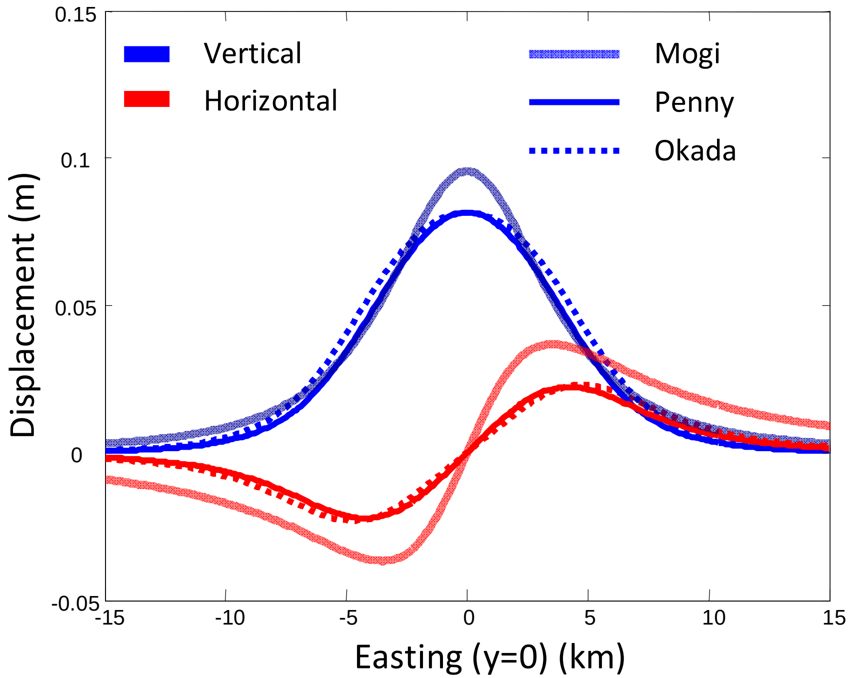


Penny Sill: Source Depth = 5 km; Radius = 5 km;
Pressure = 0.77 MPa

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)



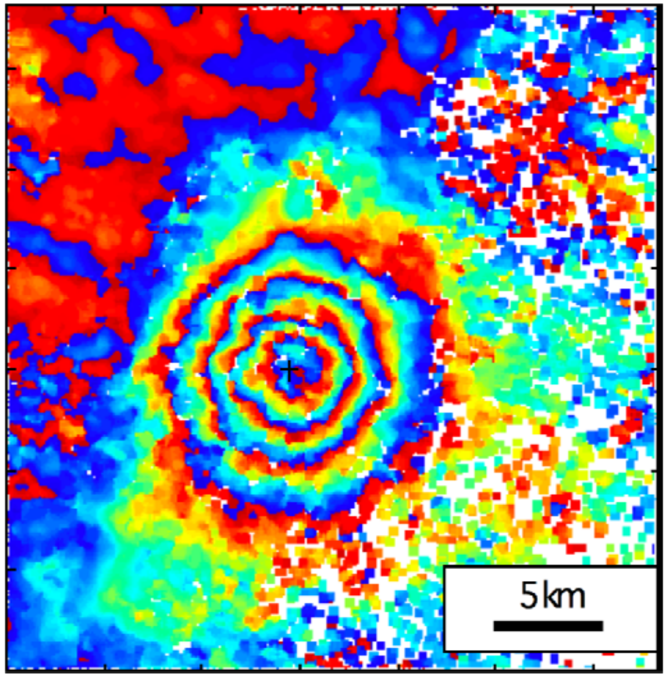
Penny Sill: Source Depth = 5 km; Radius = 5 km;
Pressure = 0.77 MPa

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

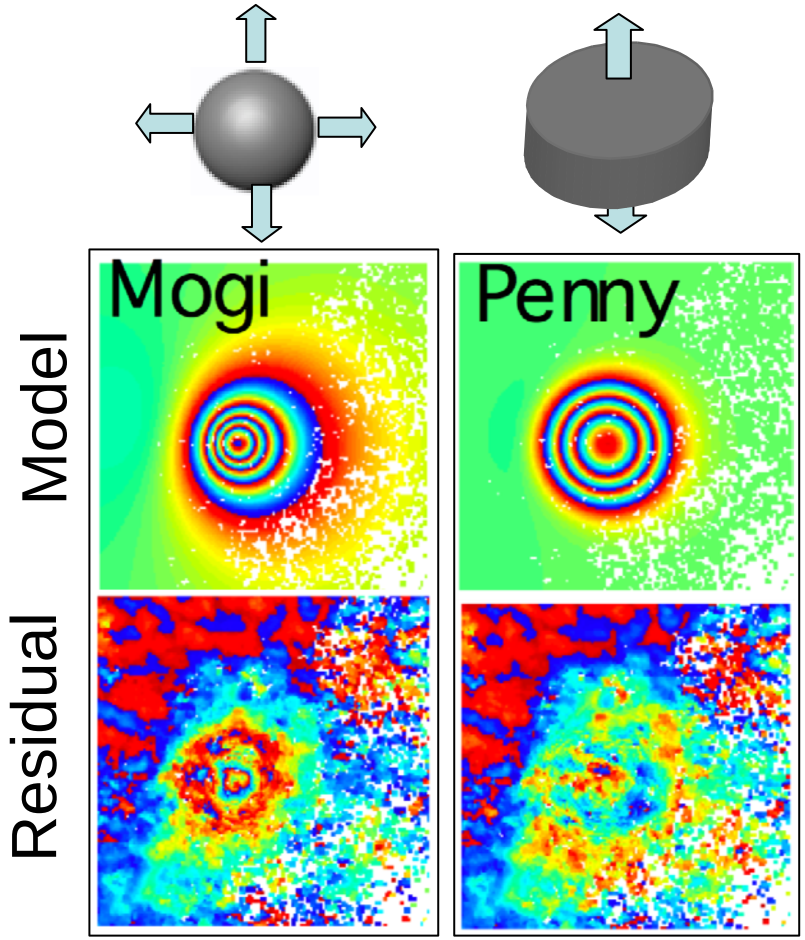
Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190

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



Stack of 5 images

Biggs et al. (2009), Geology, In Press.



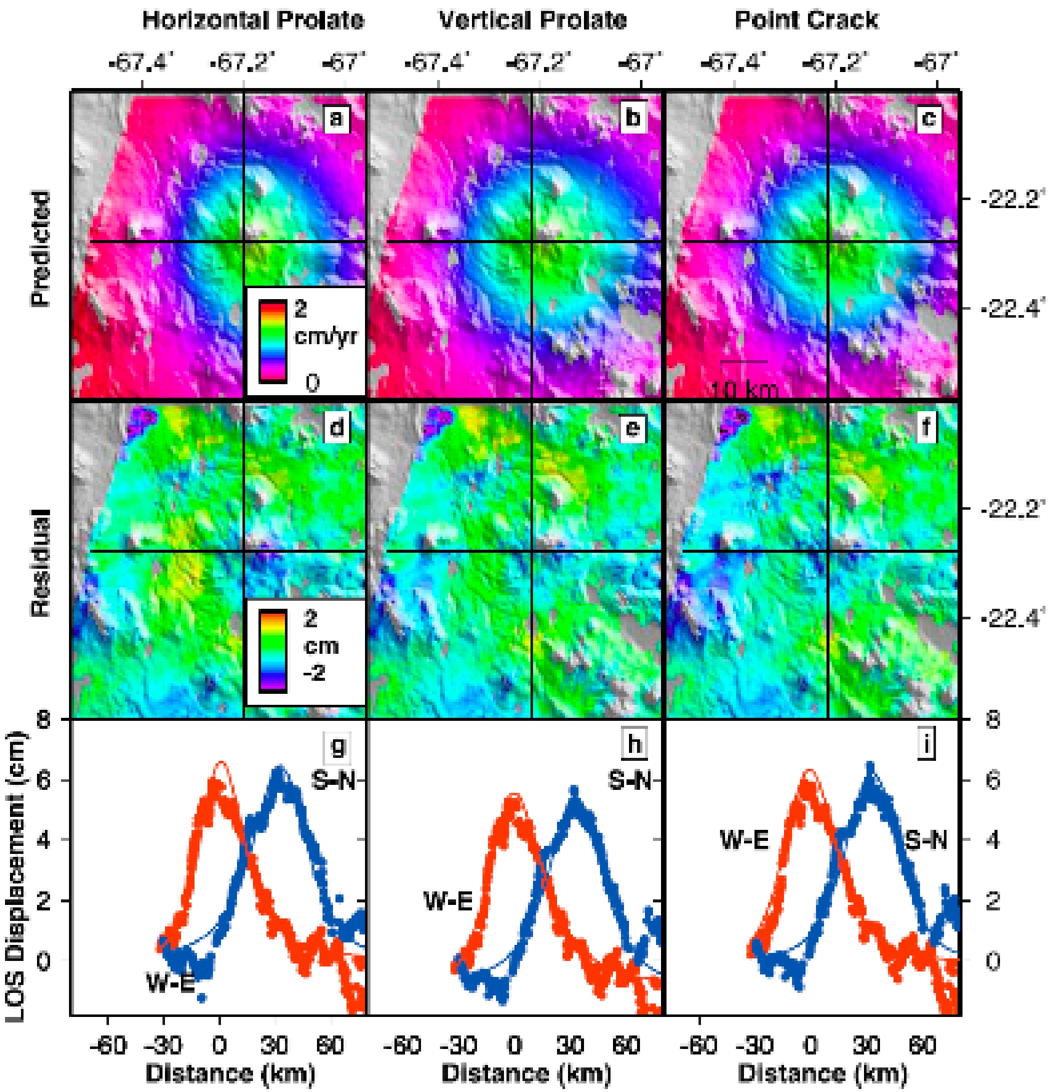
Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190

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?

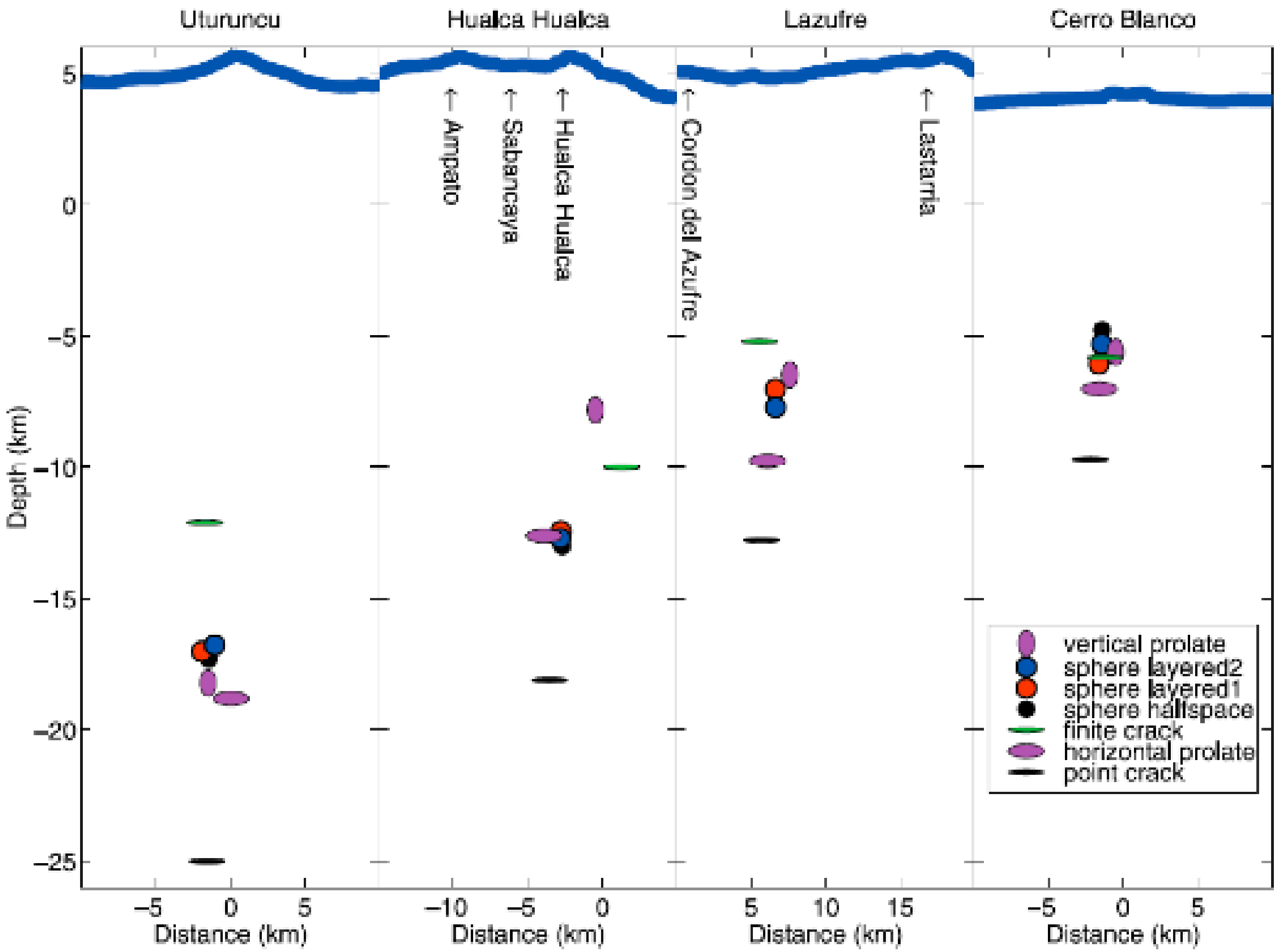
Dzurisin, D. (2007), *Volcano Deformation: Geodetic Monitoring Techniques.*
Fialko, Y. et al. (2001), Geophys. J. Int., 146, 181-190

Source Model Ambiguity: Uturuncu



Pritchard and Simons, 2004, G3

Source Geometry Ambiguity: Effect on Depth Estimates



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