The dynamics of kimberlite magma intrusions: The role of dykes

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Dykes

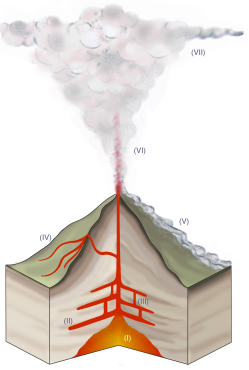
(Photos c/o Louis J. Maher, Jr.)

- Magma-filled fractures that are discordant; Length:thickness ~1000:1
- Idealised as **thin sheets** intruding an **elastic crust**
- **Coupled** magma intrusion and host-rock deformation

Dykes

Feeder dyke: Miyakejima Volcano, Japan
Geshi et al., 2010

Rekyanes Peninsula, Iceland

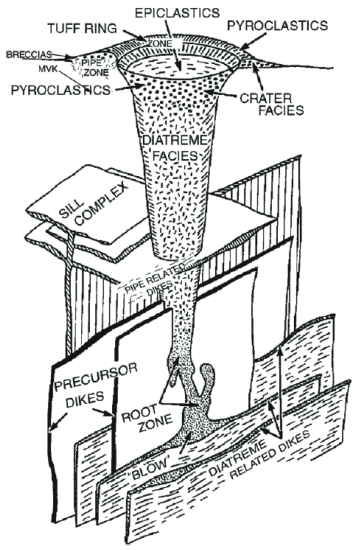


Kavanagh, et al. Accepted. *Solid Earth.*

http://photos.gudmann.is

Structure of a kimberlite volcano?

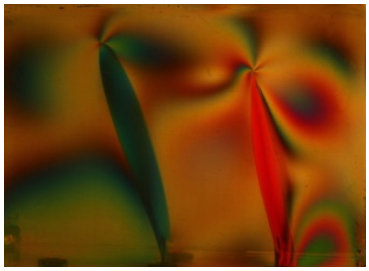
- Maar-diatreme
  - Crater facies
  - Diatreme facies
  - Root zone
- Sheet intrusions transitioning into pipe

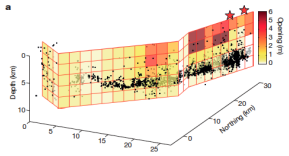


Adapted from Mitchell,1986; see Sparks et al., 2006

How are dykes and sills studied?

1. Field studies – fossil intrusions
2. Scaled analogue experiments
3. Geophysics+Geodesy – magma movement





Problems and questions

Problems

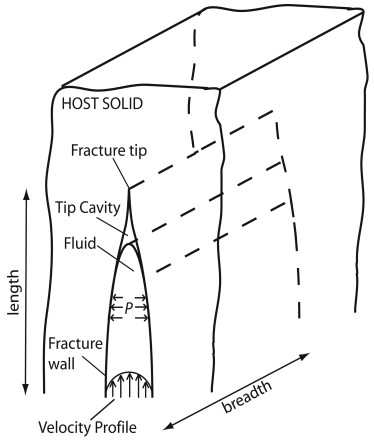
- Indirect observations, limited exposure
- Alteration of deposits
- Magma and host-rock deformation are both important

Questions?

- How do dyke propagate through the crust?
- How are kimberlite dykes different?

Dyke propagation and geometry

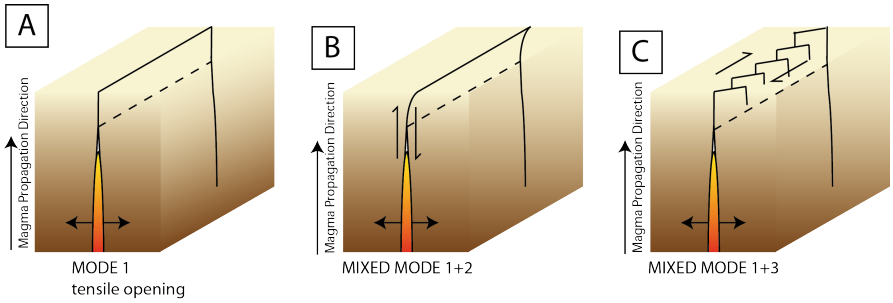
- Idealised as planar sheet intruding an elastic material
  - Thickness to length aspect ratio 1:1000
  - Intrusion time is short
- Pressure scales
  - Driving: elastic pressure, buoyancy pressure
  - Resisting: fracture pressure, viscosity
- Reynolds number



Kavanagh et al., 2006

Dyke emplacement models

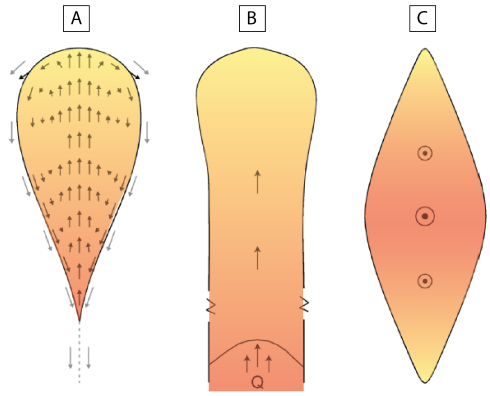
- Hydraulic fracture or viscous indenter?



Kavanagh, 2018. *Volcanic and Igneous Plumbing Systems* (Ed. S. Burchardt), Elsevier.

Dyke emplacement models

- Passive or active intrusion?
- Vertical or lateral propagation?



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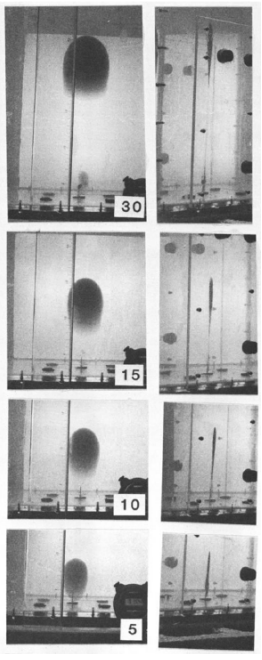
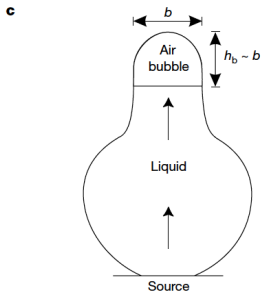


Takada 1990

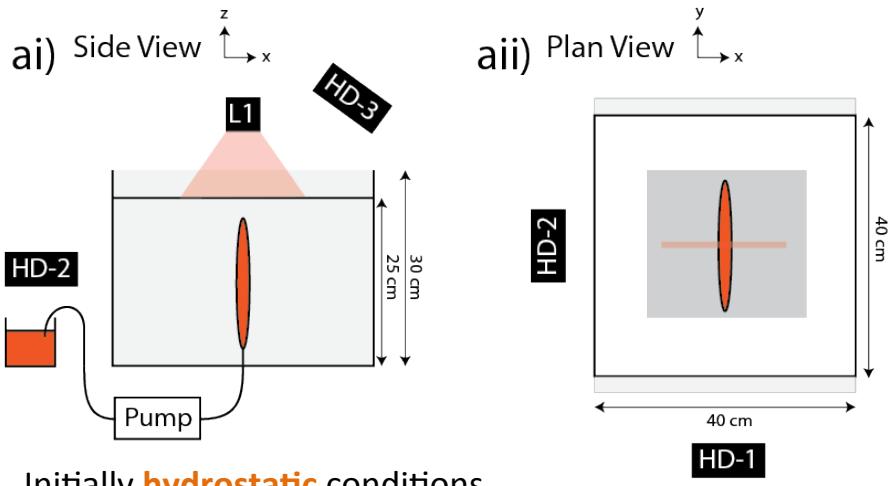
Buoyant dyke ascent

- Gelatine experiments – injecting oil, liquid+air
- Teardrop geometry in cross section
- Dyke narrows in width as buoyant tip accelerates ahead



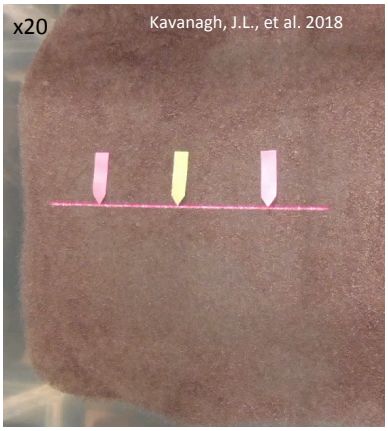
Menand and Tait, 2001

Gelatine analogue experiments



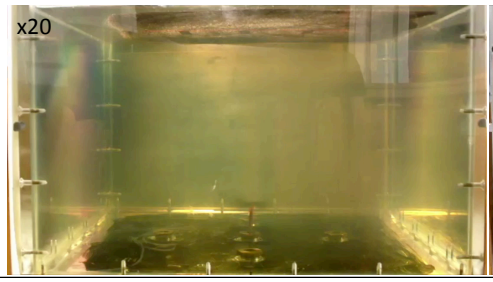
- Initially **hydrostatic** conditions
- **Constant flux** experimental intrusions injected from below

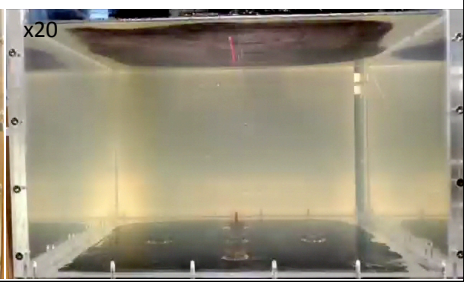
Kavanagh, J.L., et al. In Review

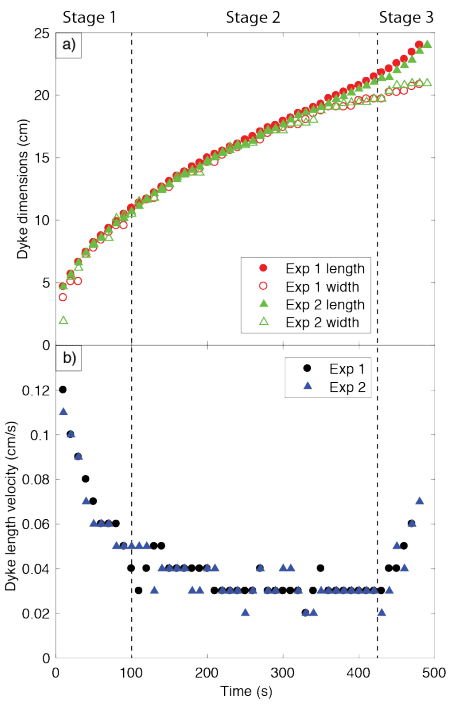


Dike growth and eruption

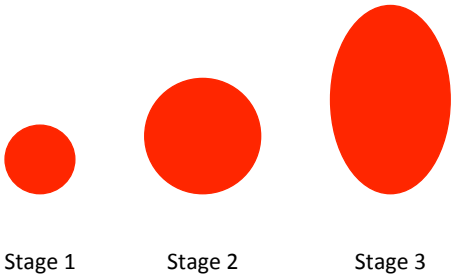
- **Penny-shaped** crack
- '**Bow-tie**' stress distribution
- Surface elevation change is **distributed** and **late**
- Small **fissure** eruption





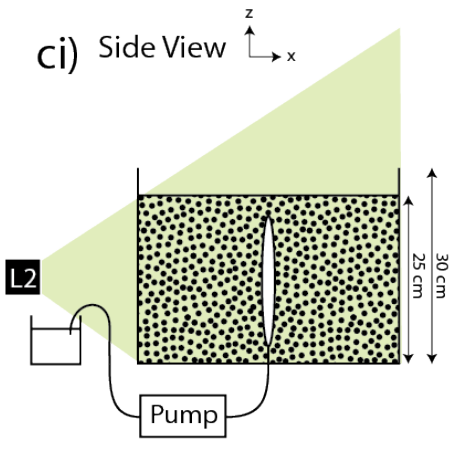


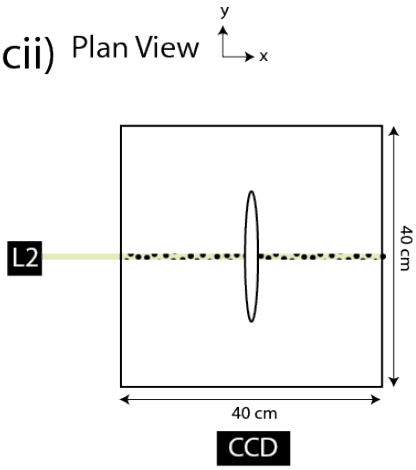
Growth rate and evolving geometry



Kavanagh, J.L., et al. In Review, JVGR

Exp C: Strain evolution





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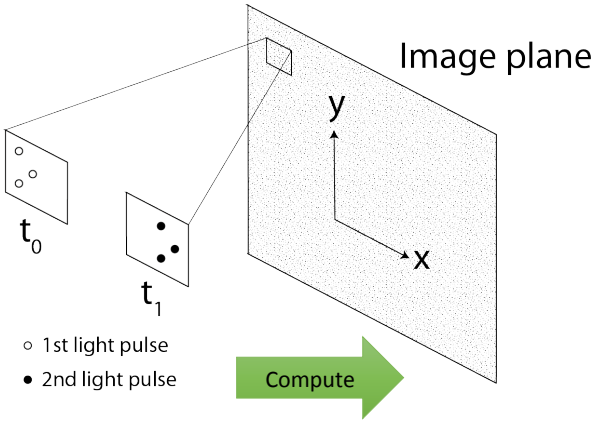
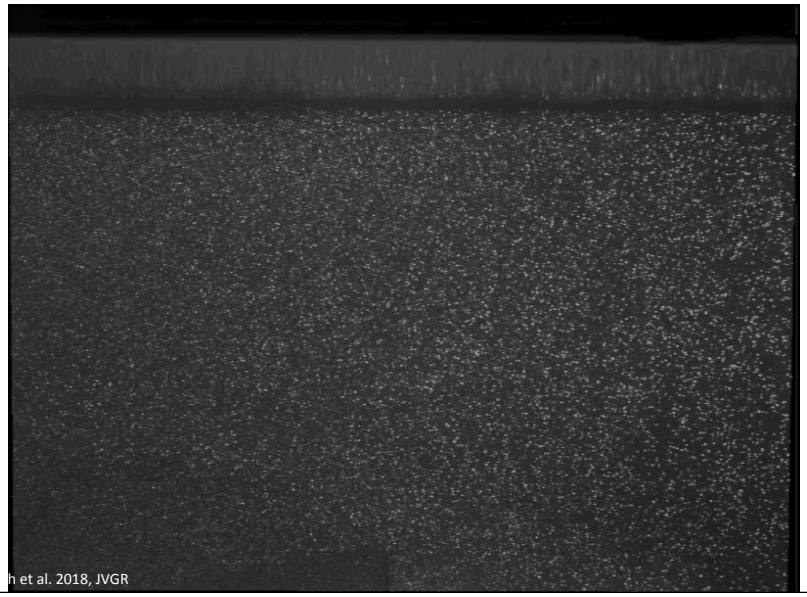
Digital Image Correlation (DIC)



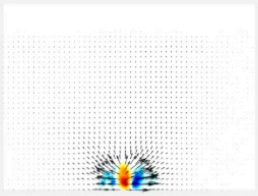
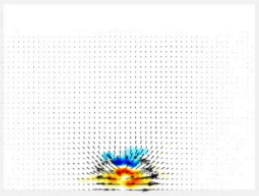
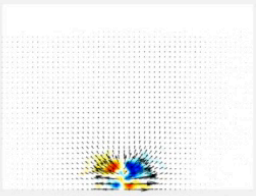
1. Displacements (mm/s)
2. Incremental Strain
   - ε_{xx}
   - ε_{zz}
3. Finite Strain
   - e_{xx}
   - e_{zz}

Modified after Raffel, 2007

Raw experimental images

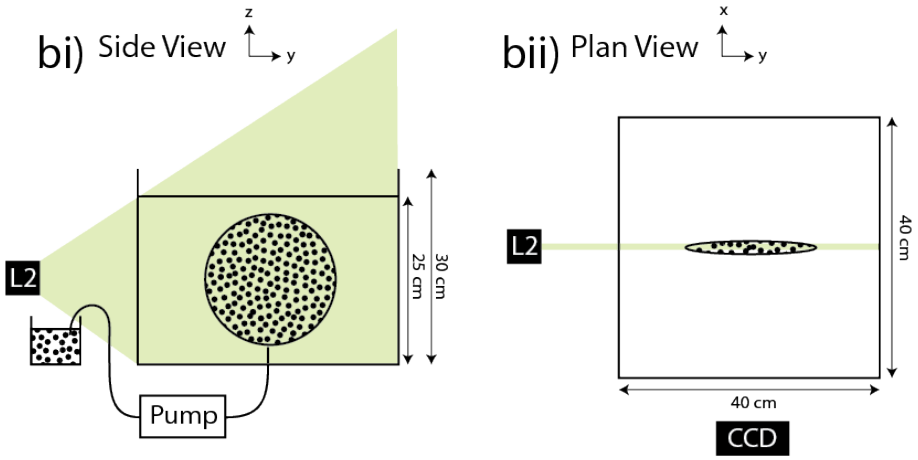


Incremental Strain: Digital Image Correlation

Horizontal	Vertical	Shear
		
ε_{xx}	ε_{zz}	ε_{xz}

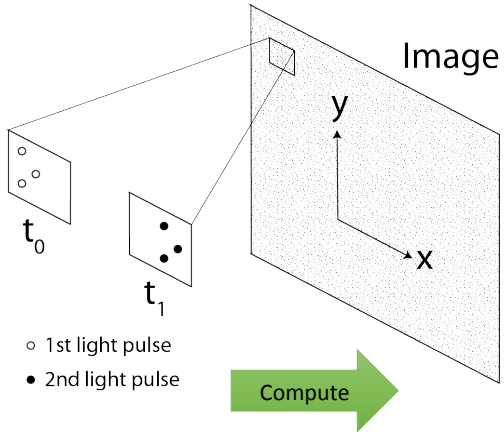
Kavanagh et al. 2018, JVGR

Exp D: Fluid Flow



Kavanagh et al. 2018, JVGR

Particle Image Velocimetry (PIV)

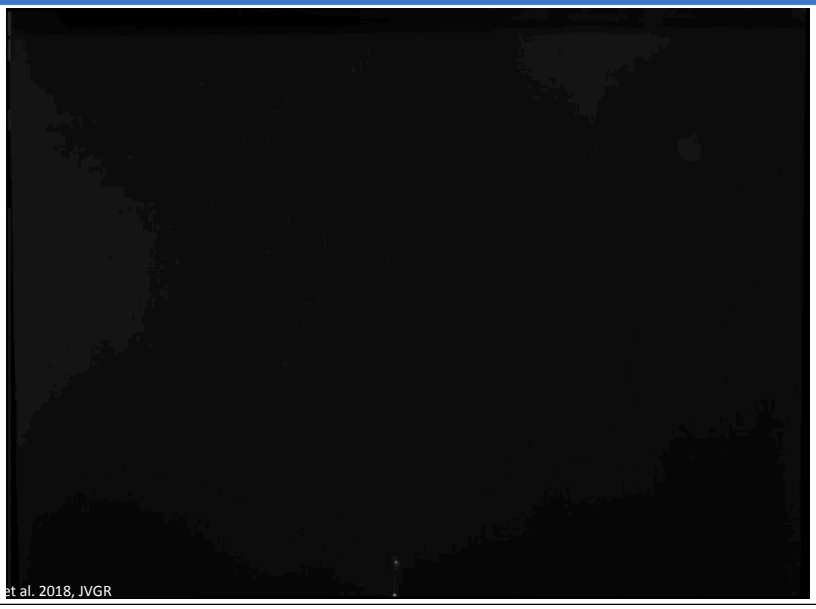


Compute

Vector field mapping fluid flow (mm/s)

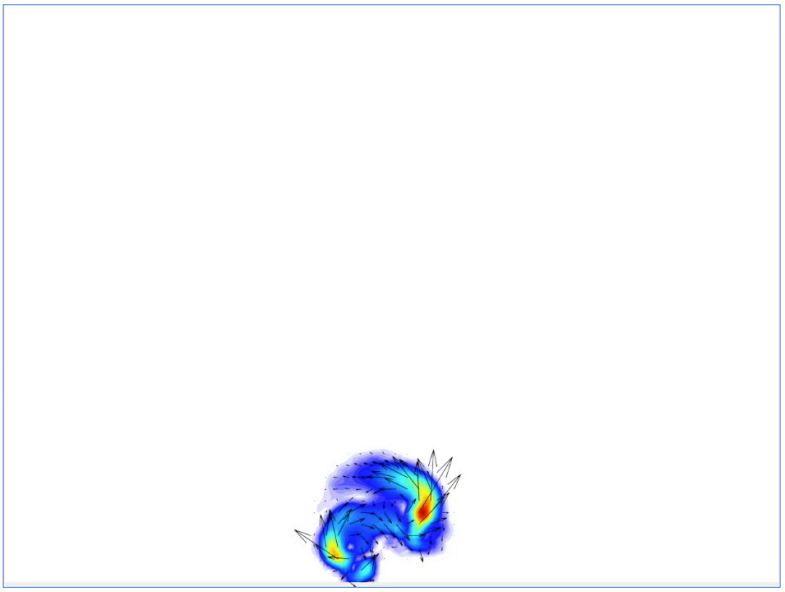
Modified after Raffel, 2007

Raw experimental images



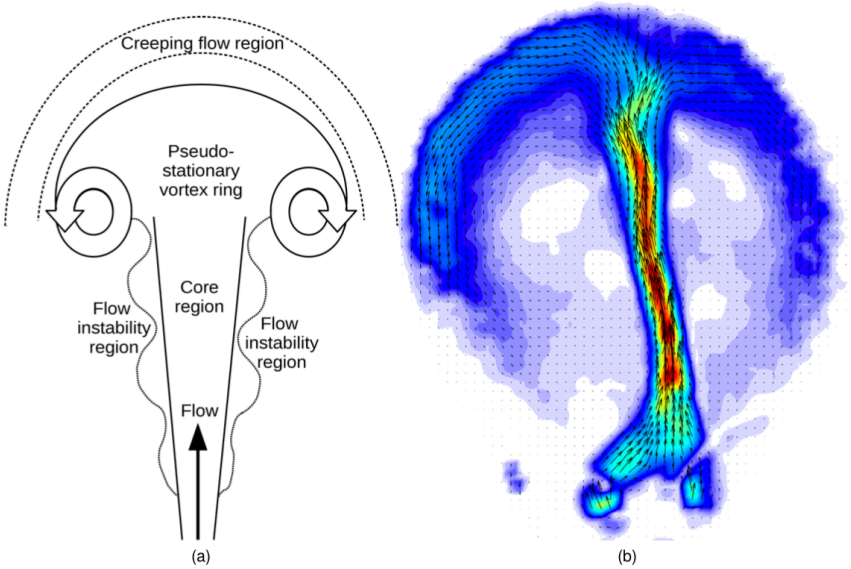
et al. 2018, JVGR

Flow velocity: Particle Image Velocimetry



Kavanagh, et al. 2018, JVGR

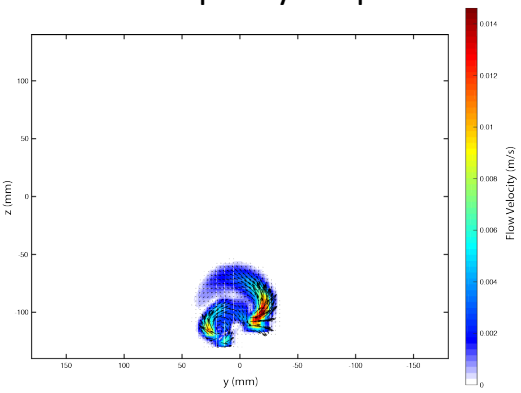
Dyke fluid dynamics (Water)

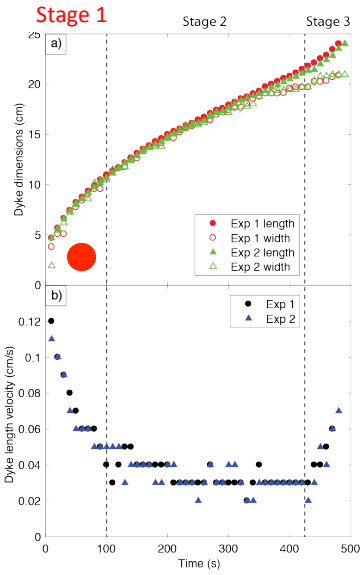


3 Stages of dike emplacement

Stage 1: Early growth

- Two jets circulate
- Length and width grow equally to create penny-shape

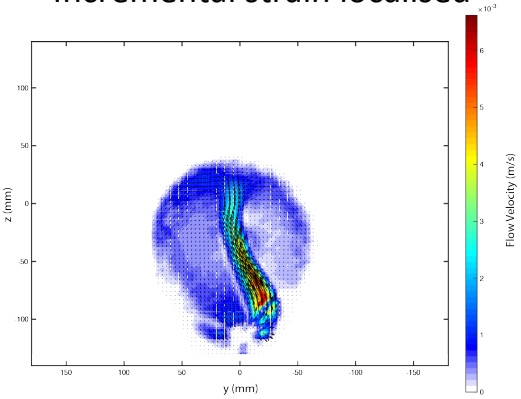


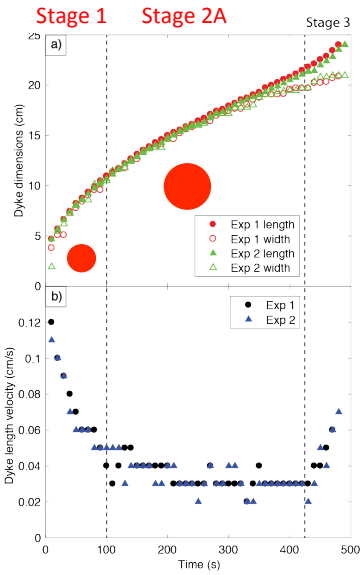


3 Stages of dike emplacement

Stage 2A: Pseudo-steady growth

- Rapid uprising single jet
- Down-welling fluid at margins
- Incremental strain localised





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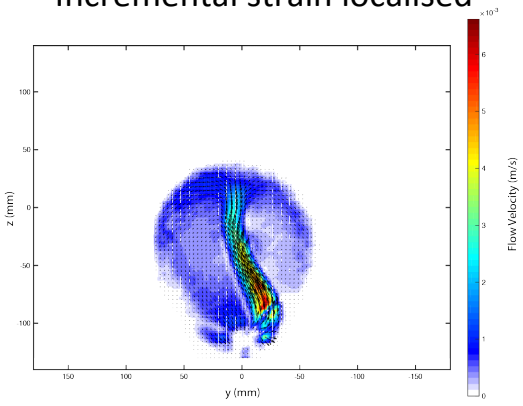
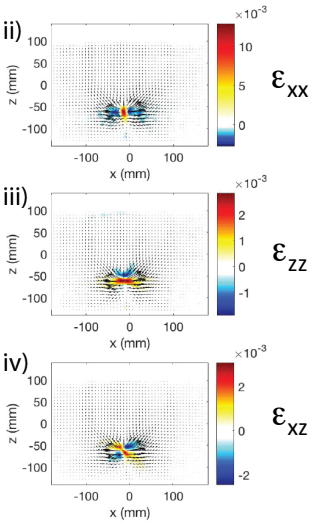
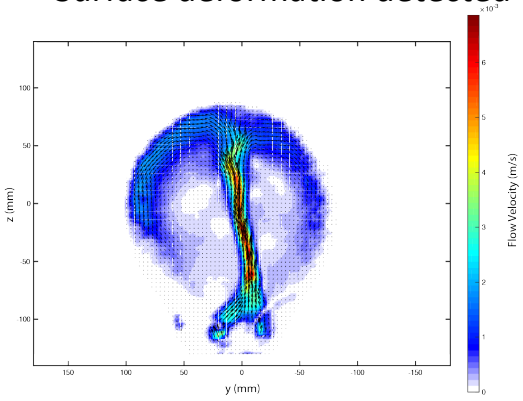


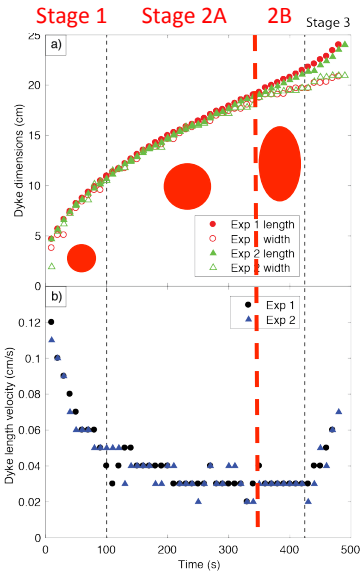


3 Stages of dike emplacement

Stage 2B: Pre-eruption unsteady

- Instability develops, jet meanders
- Tail pinches, negative ε_{xx}
- Surface deformation detected ε_{zz}





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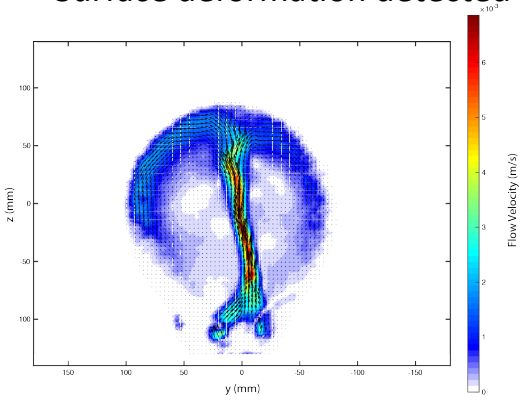
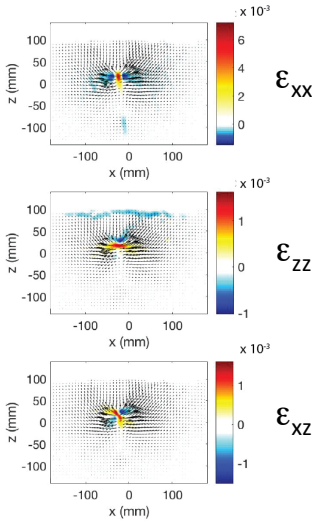
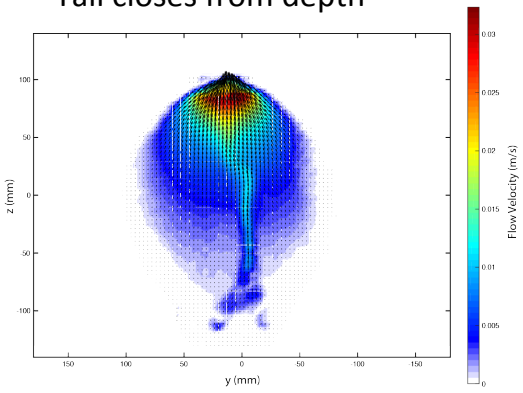


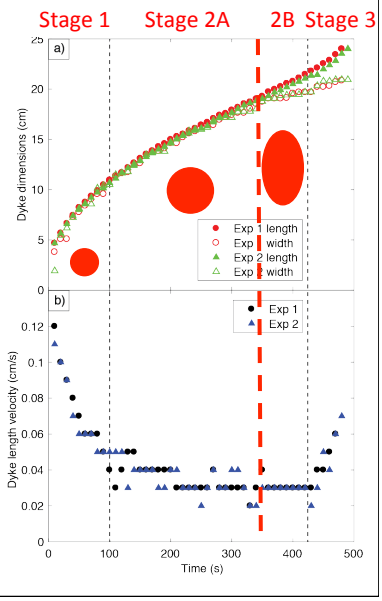


3 Stages of dike emplacement

Stage 3: acceleration to eruption

- Rapid outflow of fluid as fissure forms
- Dike collapses as pressure released
- Tail closes from depth





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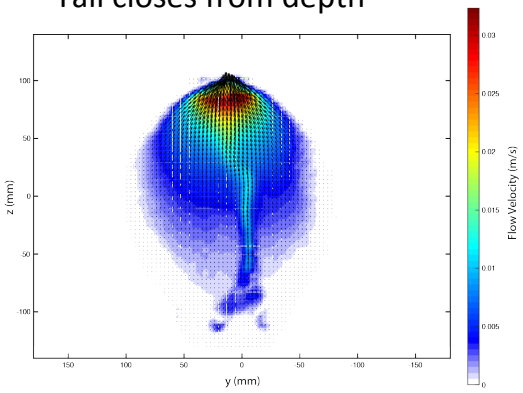
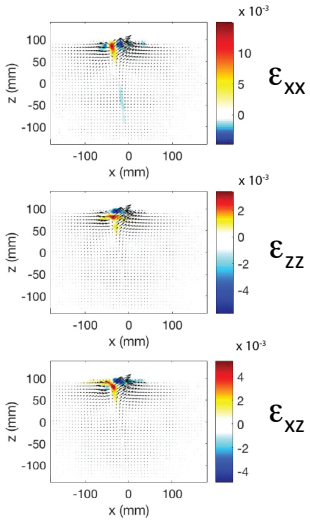




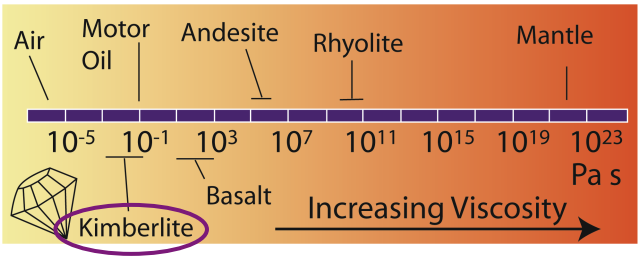
Kimberlite magmas

- There are a lot of unknowns but the composition and physical properties of kimberlite melt are *somewhere* between basalt and carbonatite

Physical properties of kimberlite melts

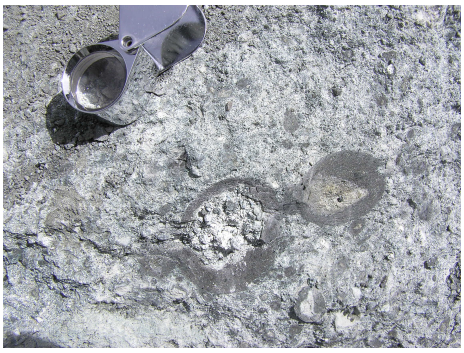
- Low viscosity: 0.1-1 Pa s
- High gas contents
  - ≥5 wt % CO_2
  - ≥5 wt % H_2O
- Highly explosive or effusive eruptions
- Changes during ascent – protokimberlite at depth

Carbonatite lava flow

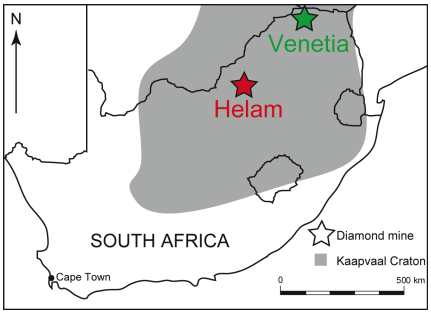


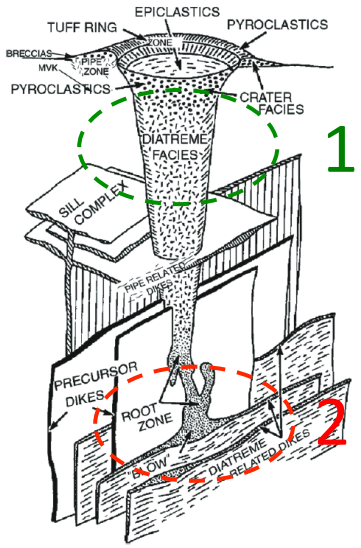
Physical properties of melt

- Dyke stringers (dykelets)
- Magma rims
  (pelletal lapilli)



South African Case Studies





Adapted from Mitchell,1986; see Sparks et al., 2006

Venetia Mine, South Africa

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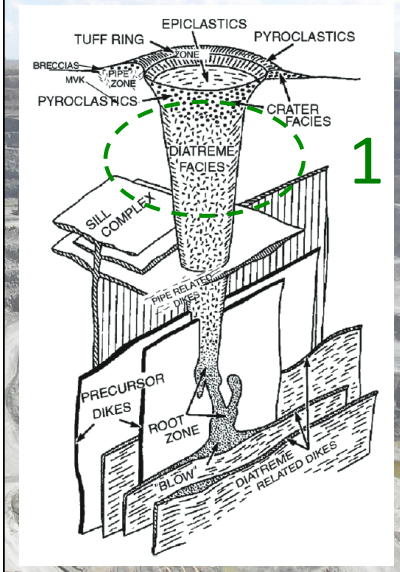
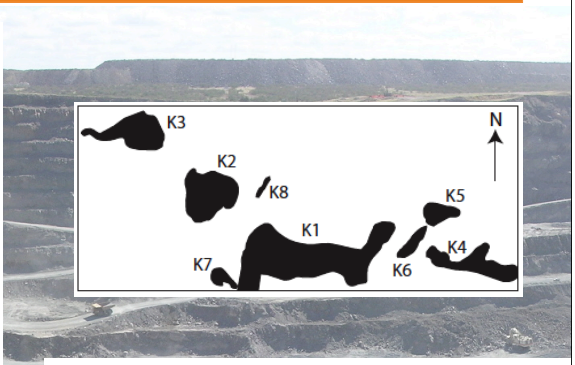
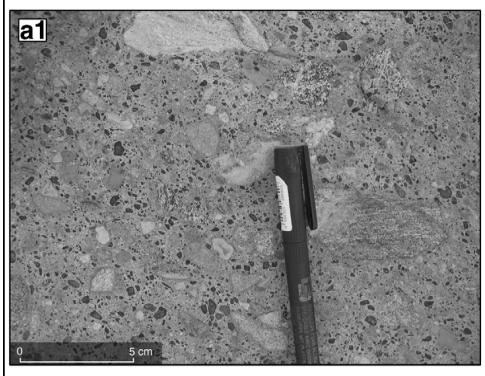


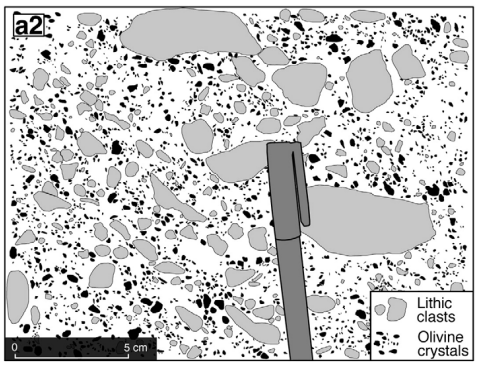


- Venetia kimberlite cluster: 14 bodies intruded ~519 Ma
- Intruded Proterozoic metamorphic basement
- Lithic breccias well exposed in K1 and K2 kimberlite pipes

Adapted from Mitchell,1986; see Sparks et al., 2006

Volcaniclastic kimberlite





Gernon et al., 2009

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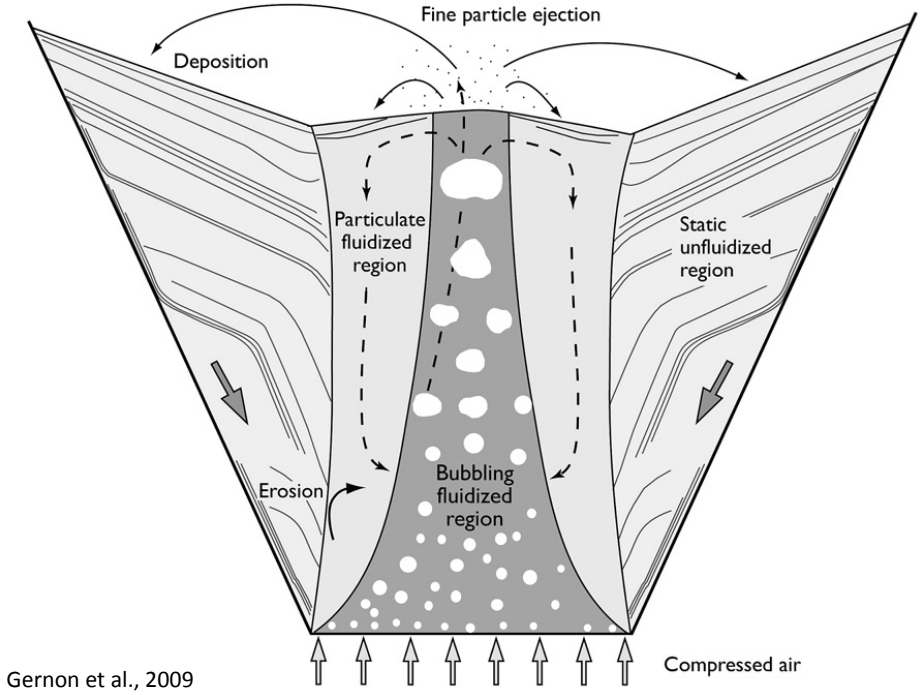


Gernon et al., 2009

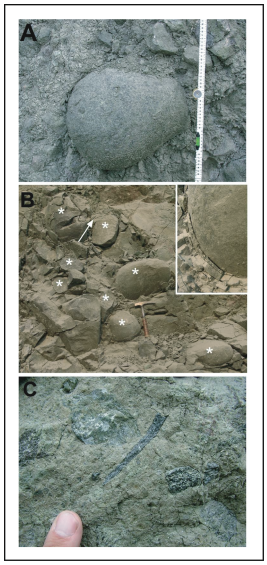
Venetia Mine, South Africa

Venetia Mine, South Africa

Venetia Mine, South Africa

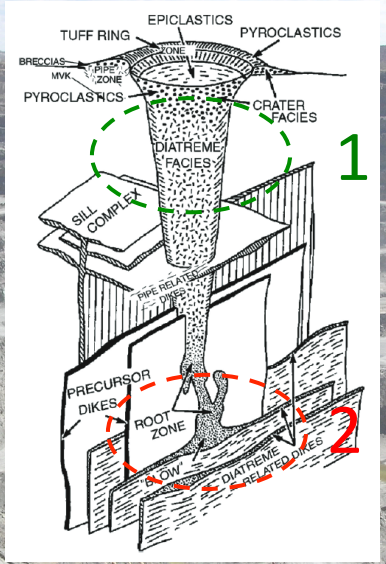
Venetia Mine, South Africa

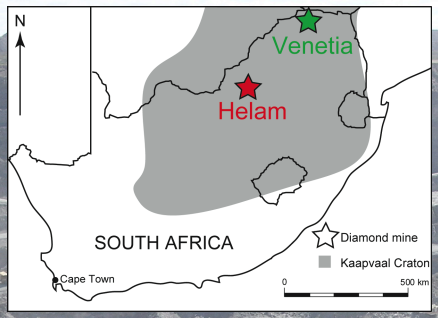
- Extremely well-roundeed, spheroidal lithic clasts
- 5-15% of lithic clast population, ~5cm - 3m
- Fresh cores, surrounded concentric shells
- Detached platy clasts from broken-up shells occur in breccia matrix



Brown et al., 2007

Magma ascent processes?

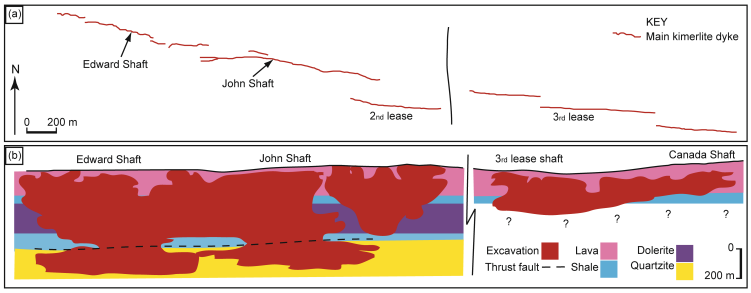




Adapted from Mitchell,1986; see Sparks et al., 2006

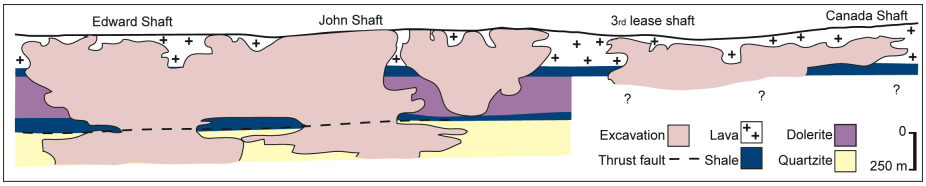
Helam Mine

- 3 dykes: 2 kimberlite, 1 lamprophyre.
- Intruded in close succession at end of Jurassic (Gurney&Kirkley, 1996)
- 7km length array (Basson&Viola, 1997)
- Anastomosing, *en echelon* segments each several hundreds metres long
- Geometry: Erratic in shale, more continuous within dolerite and quartzite



Brown et al., 2007

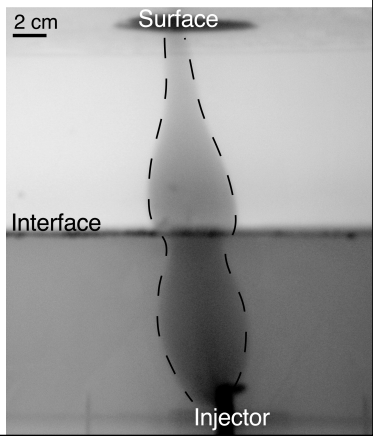
Helam Mine



Brown et al., (2007)

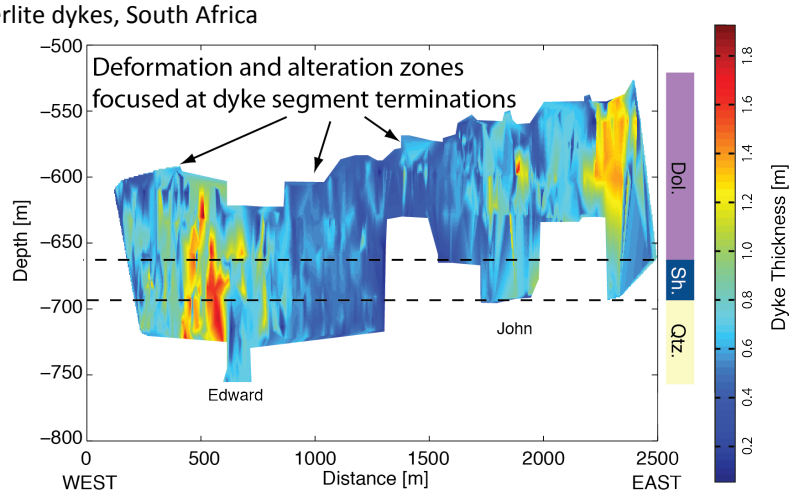
- Propagation of water (magma analogue) in solid gelatine (crust analogue)
- Upper layer less rigid
- Narrowing / "Pinching" at interface

Kavanagh et al. (2006)



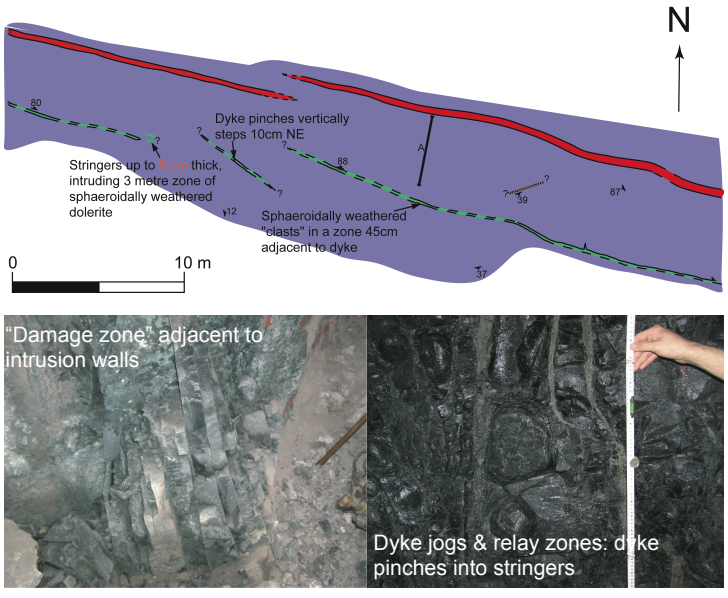
Swartruggens dyke thickness

Kimberlite dykes, South Africa

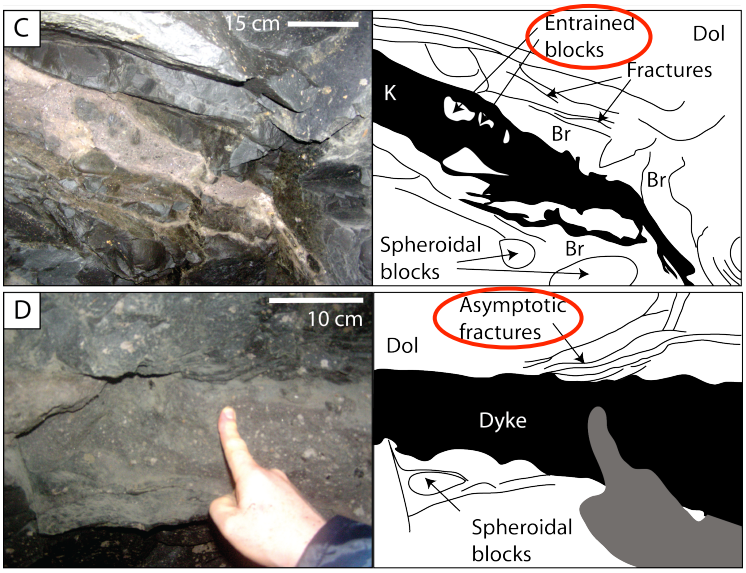


Kavanagh & Sparks, 2011

Helam Mine, RSA



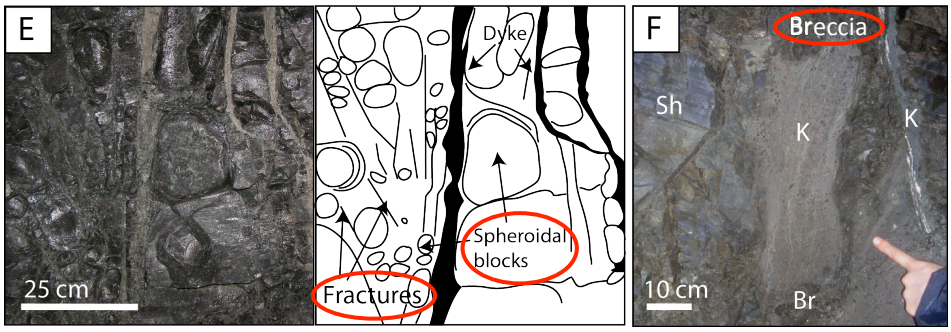
Kimberlite dykes



Kavanagh & Sparks, 2011

Kimberlite dykes

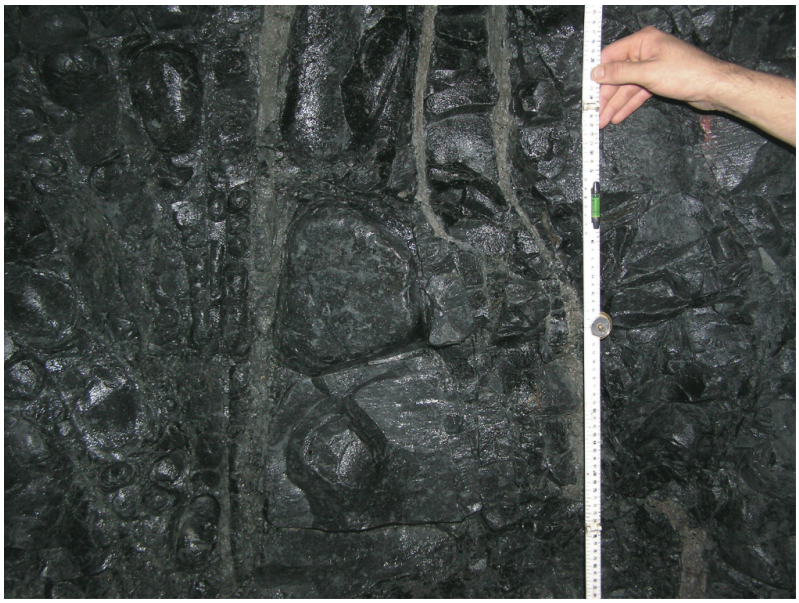
Kimberlite and lamprophyre dykes, South Africa



Kavanagh & Sparks, 2011

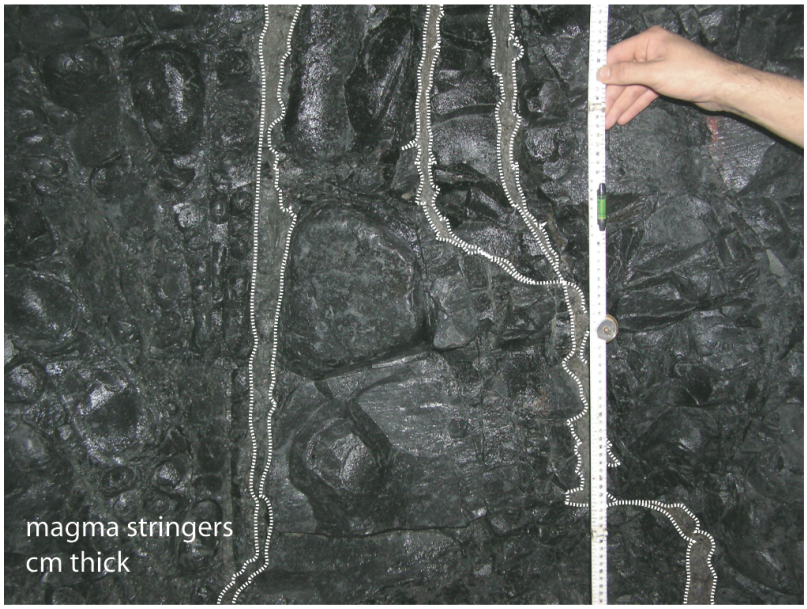
- Kimberlite magma: Low viscosity, volatile-rich, buoyant
- Physical properties intermediate between basalt and carbonatite (Sparks, 2013)

Kimberlite dyke – damage zone + preconditioning

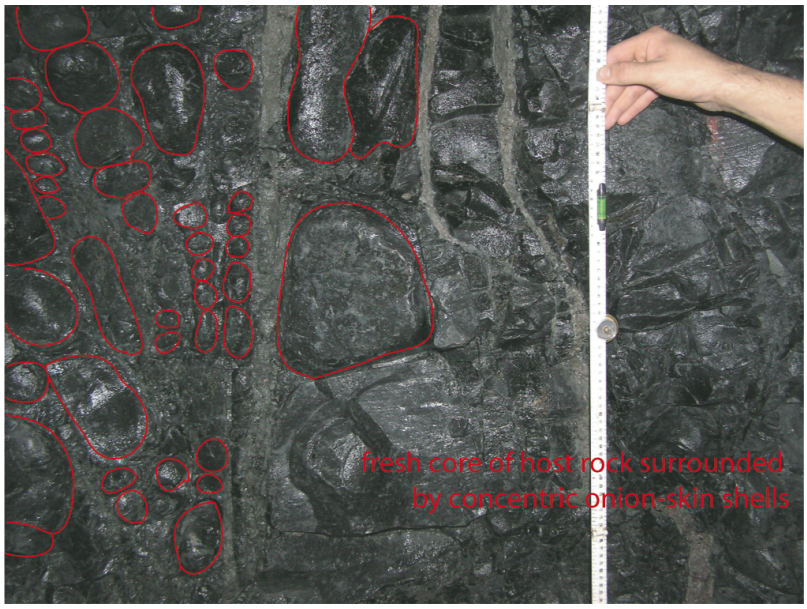


Brown et al., 2007

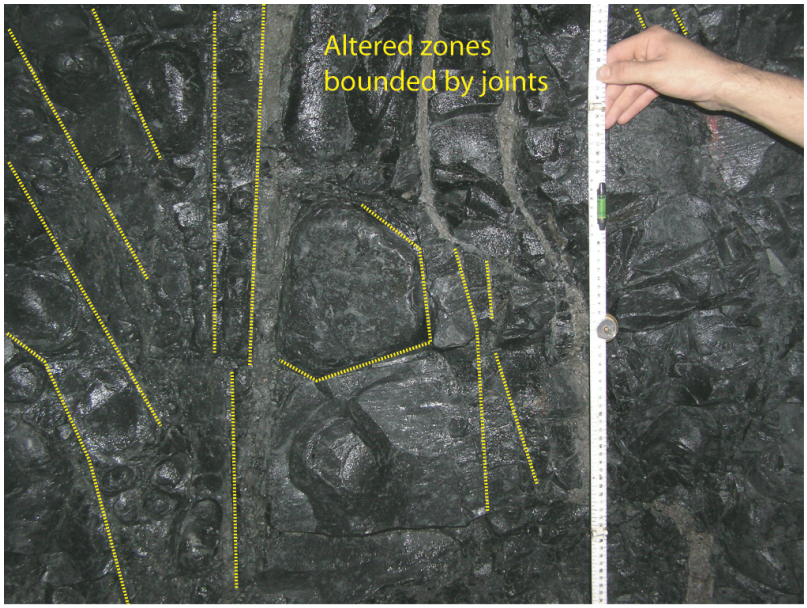
Kimberlite dyke – damage zone + preconditioning



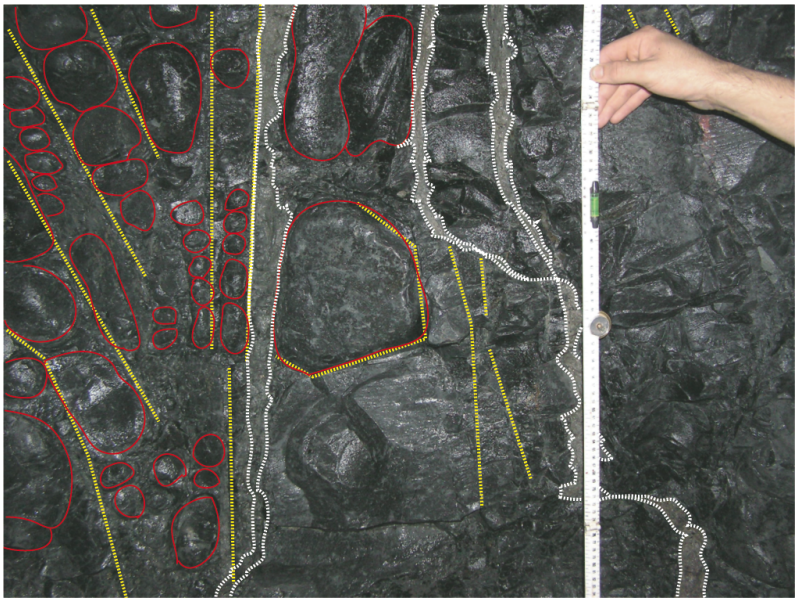
Kimberlite dyke – damage zone + preconditioning



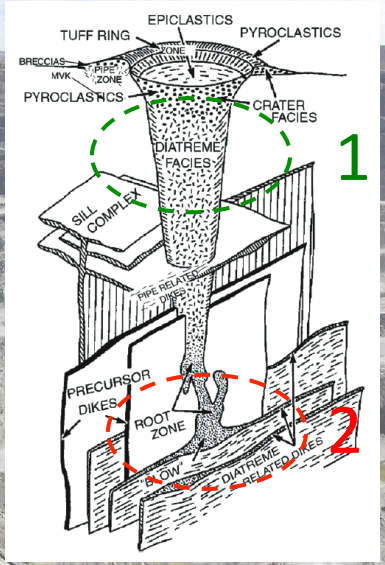
Kimberlite dyke – damage zone + preconditioning

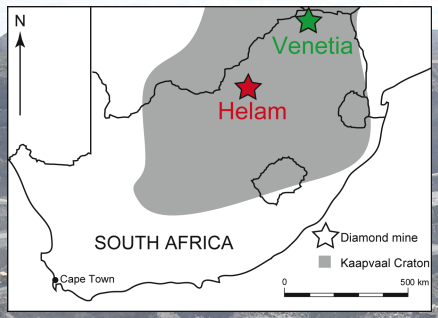


Kimberlite dyke – damage zone + preconditioning



Kimberlite dyke ascent processes?

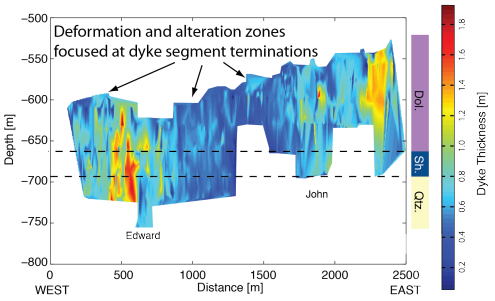




Adapted from Mitchell,1986; see Sparks et al., 2006

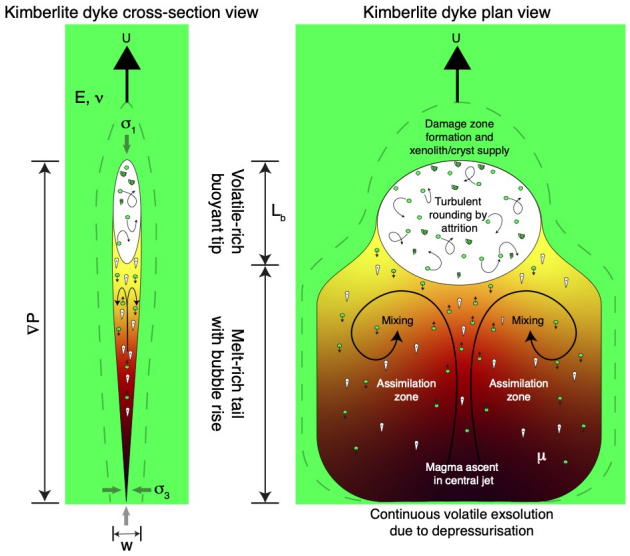
Kimberlite dykes – key features

- Low viscosity magma
- High volatile content
- Buoyant ascent
- Host-rock preconditioning
  - Damage (brecciation, toping)
  - Alteration (volatiles)
- Host rock assimilation

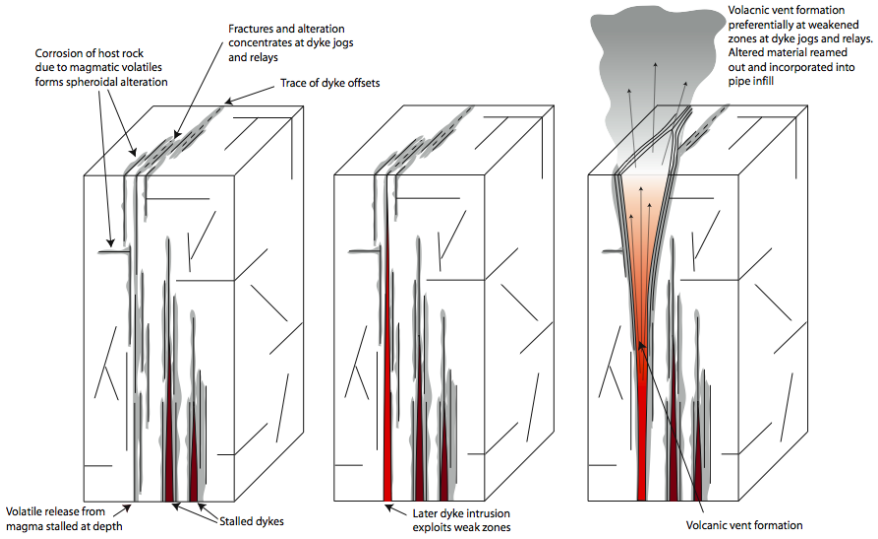


Kavanagh & Sparks, 2011

Kimberlite dyke ascent model



Focused activity: vent formation



Brown et al., 2007

Implications & Conclusions

- Kimberlite dykes have some interesting dynamics with **important consequences** - diamond transport and preservation
- **Low viscosity**, **buoyant** and likely **turbulent** ascent
- Host rock (crust and mantle) is **damaged mechanically** and chemically by the dyke growing
- Magma exsolves volatiles and buoyant volatile-rich tip **ascends ahead** of the magma-filled crack
- **Tear-drop** geometry enhances damage
- Damaged material **incorporated physically & chemically**
- High velocity **magma jet** transports & **recirculates** crystal cargo
- Dyke dynamics **fundamental** to the kimberlite volcanic system