

Granite Transport and Emplacement: a Review

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There has been considerable discussion about the transport mechanism of felsic magmas through the crust. Diapirism has been discredited as an efficient transport mechanism partly because diapirs rise slowly and are thought to freeze early and close to the magma source, and partly because it has recently been shown that *sufficiently wide* dykes (2 to 20 m wide) are able to rapidly transport felsic magmas through the crust without freezing. Several authors now consider that felsic plutons are fed by dykes and that the observed ductile structures around plutons result from the pushing aside of the heated wall rocks by expanding magma chambers (ballooning plutons, Clemens and Mawer, 1992, Petford et al., 2000). However, there are remarkably few recognised feeder dykes to granitic plutons, and it remains thus far unclear how felsic dykes grow to the metric to decametric widths required for their survival. It may ultimately be the ability of dykes to grow within the magma source area that controls whether or not dykes will be the preferred transport mechanism.

Within a partially molten source, magma may reside in a range of structures with a wide range of shapes, sizes and degrees of connectivity. Whereas the growth of an individual dyke within a partially molten zone, and the self-propagation of wide dykes into subsolidus crust, have both been studied in some detail, little attention has been given to the crucial intermediate step of the growth of a network of dykes in the source, capable of feeding wide, crustal-scale transporting dykes. The rarity of granite dyke swarms suggests that, if dyking is the preferred magma transport mechanism, felsic magmas sources produce only a few major transporting dykes during their lifetime. Alternatively dyking is not an important mechanism.

Weinberg and Podladchikov (1994) demonstrated that, contrary to previous work, diapirism may be an efficient way of transporting viscous magma through the crust. These authors used the power-law rheology (stress-dependent viscosity) of crustal rocks and the buoyancy stress of diapirs to calculate the effective viscosity of crustal rocks. This approach contrasts with previous works which had used an estimate of crustal viscosity to calculate diapir velocity and cooling (the hot Stokes models of the 1980s). The high buoyancy stress of diapirs causes the power-law crust to respond with much lower viscosities than those previously estimated, allowing rapid diapir ascent and late magma freezing.

In contrast to dykes, diapiric ascent of magmas imposes a convective flow pattern in the crust with two important consequences: a) upward flow of the wall rocks may cause decompression melting of the hot aureole around the diapir, adding magma and buoyancy to the diapir; b) downward crustal flow to replace the rising diapiric mass provides the source area with fresh, potentially fertile rocks that may undergo melting and give rise to another diapir, resulting in a sequence of diapirs using the same crustal path. Whereas source renewal is a direct result of diapirism, dyking leads to the accumulation of refractory restite in the source preventing further melting. Through decompression melting and source renewal diapirs are capable of recycling and fractionating large crustal volumes.

Rubin (1993a,b) suggested that the response of the crust to applied magmatic stresses may be a combination of elastic (dyking) and viscous (diapirism) behaviour, in which the rapidly applied stresses at the propagating tip of a dyke cause an elastic response in the form of propagating cracks, whereas the continued stresses on the wall rocks along the main dyke body causes viscous deformation and outward bulging of the dyke's walls. Weinberg (1996) applied Rubin's results to study the conditions in which dykes can successfully propagate from the top of a diapir. He found that in the lower crust dykes will freeze as they leave the diapir, whereas in the upper crust, conditions are more favourable for dykes to propagate successfully away from and drain the diapir. Thus, diapirs may be the preferred mechanism of magma transport in the lower crust, while dykes may take over in the upper crust.

An alternative mode of transport characteristic of hot crustal regions, close to the magma source, is pervasive flow. Pervasive magma flow leads to magma sheets emplaced preferentially parallel to the foliation or shear zones. Four mechanisms act locally to promote magma migration and these are: a) local dyking; b) overpressure related to volatile exsolution; c) tectonic pumping; d) magmatic wedging. The latter two are driven by local, tectonically-driven mean pressure gradients. Pervasive magma migration requires hot crust, and makes use of the fact that the solidus temperature of partial melts is generally lower than that of the source rock. This implies that above the magma source there are solid rocks which themselves are not undergoing melting but that are above the solidus of partial melts produced below. Within these solid rocks, the melts are freed from the constraints of freezing and may intrude them pervasively. Magmas rising pervasively may gradually migrate to form a large magma body which may then rise diapirically, produce dykes or simply freeze as a pluton overlying an injection migmatite such as those in Shuswap, Canada (Vanderhaeghe and Teysier, 1997) and Pangong, India (Weinberg and Searle, 1998).

Field evidence and inheritance patterns of zircons in the 600-km long, Andean-type calc-alkaline, pre-continental collision, Ladakh Batholith, in the Indian Himalayas, suggest that older mantle-derived batholithic rocks were remelted within a few million years of their crystallization to give rise to younger batholithic magmas. This suggests that magma fractionation and ascent took place over a series of cycles of intrusion, solidification, remelting, and ascent. In each cycle older, more primitive magmatic rocks remelted to give rise to younger, more fractionated rocks. A dynamic environment is envisaged in which mantle-derived magmas underplate and intraplate the crust, maintaining high crustal temperatures for several tens of millions of years. Local temperatures and pressures constantly fluctuate in this environment and early igneous intrusion may remain close to its solidus for a long time, melting and remelting. Partial melts segregate and rise through dyking, diapirism, and pervasive flow, all of which may act in parallel or sequentially leading to a vertical fractionation of the batholith. If this cycling documented through zircons in Ladakh is a general feature of Andean-type batholiths, it explains the origin of voluminous granodioritic magmas from mantle-derived melts, with little or no involvement of felsic crustal material.

Considerable evidence world-wide suggests that shear zones play a significant role in the transport and emplacement of plutons. However, the relationship between magma transport/emplacement and regional scale transcurrent shear zones has been a topic of recent controversy. In the Brasiliano-age (Panafrican) Borborema Province, NE Brazil, pre-tectonic plutons are elliptical or irregular in shape, and generally crop out away from late-developed regional shear zones. By contrast, syn-tectonic plutons generally have *en cornue* or blister shapes, characteristic of transcurrent terranes. These plutons were emplaced preferentially at the margins of 1-km to 10-km wide, regional scale transcurrent shear zones and the largest

plutons were emplaced where shear zones cut across major terrane or lithological boundaries, defining a regional triple point. The sympathetic relationship between syn-tectonic plutons and shear zones, particularly regional triple points, suggests shear zone control of pluton emplacement.

As has often been argued in the literature, shear zones provide favourable pathways to granitic melts. If this is so, why are the syn-tectonic plutons commonly emplaced at shear zone shoulders rather than within shear zones? The intriguing relationship between plutons and regional triple points in the Borborema Province suggests that the combination of shearing and regional rheological changes could play a role in pluton emplacement, through the development of regions of strain incompatibility. In order to investigate this hypothesis, numerical models were designed to explore the nature of deformation and stress distribution in such triple points during shearing. Models reveal that triple points are important regions of crustal weakness, where the combination of low mean stress and high differential stress, leads to intense brittle or ductile dilational strain. For magma emplacement, these low-mean-stresses, fragile triple points act as magma sinks, because magmas migrate towards areas of low mean stress. Once magma intrudes into and pond at the triple points, the stress gradient may be partly equilibrated but heating and weakening of the country rocks, associated with continued straining may lead to pluton ballooning. It is concluded that emplacement of granite magmas in transcurrent terranes is controlled by the development of low mean pressure magma traps at the shoulders of shear zones as a result strain incompatibility caused by changes in rheological properties.

In summary, a single transport mechanism is incapable of explaining the variety of features related to felsic intrusions. Magma transport and emplacement are most likely controlled by a number of alternative mechanisms acting in parallel or in sequence. The preferred mechanism at any time results from the interaction of a number of controlling variables, from the interconnectivity of small magma batches in the source, to crustal rheology and temperature profile.

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DD controversy
Pervasive melt migration
Role of shear zones





How do magmas rise through cold crust?

Pilbara





*Syn-magmatic mafic dyke in granite at
Bingie Bingie Point, NSW*



*Syn-magmatic granite diapir in granite,
Borborema Province, Brazil (Weinberg et al., 2001)*

Intrusion shapes



Mafic magmas

dyke swarms

sills

Felsic magmas

elliptical plutons

foliation-parallel sheets

shear zone control

dykes in upper crust



***How do magmas rise
through cold crust?***

***heat up the crust
high speed
large volumes***



How do magmas rise through cold crust?

heat up the crust: pervasive migration
high speed: dyking
large volumes: diapirs



Dyking versus diapirism

Dyking:

elastic response

favoured by low viscosity

magma and stiff crust

Diapirism:

viscous response

favoured by voluminous, buoyant

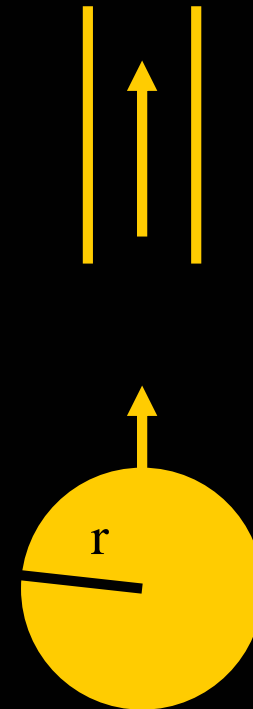
magma and soft

(hot) crust

Transport velocity

Dyking: $V \sim d^2 / \mu_{\text{magma}}$

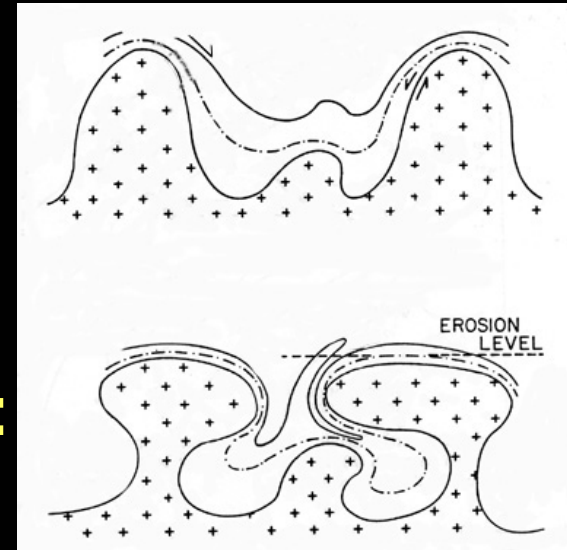
Diapirism: $V \sim r^2 / \mu_{\text{crust}}$



Dyking x diapirism

Until late 1980s (eg Ramberg):
Granite diapirism

Late 1980s early 90s:
*Diapirs: too slow, early
freezing*
Dykes very efficient

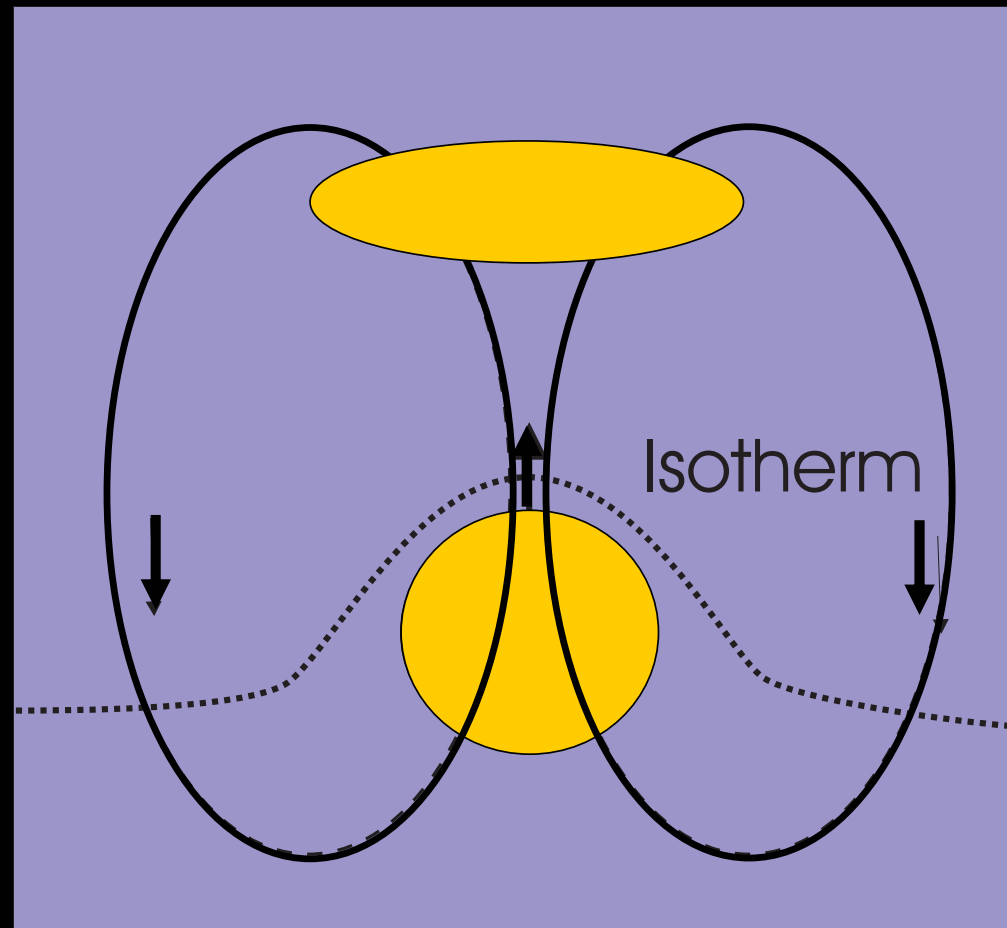


Diapirs

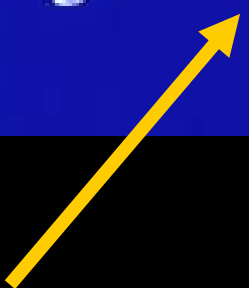
**forced crustal
convection**

**emplacement/
transport**

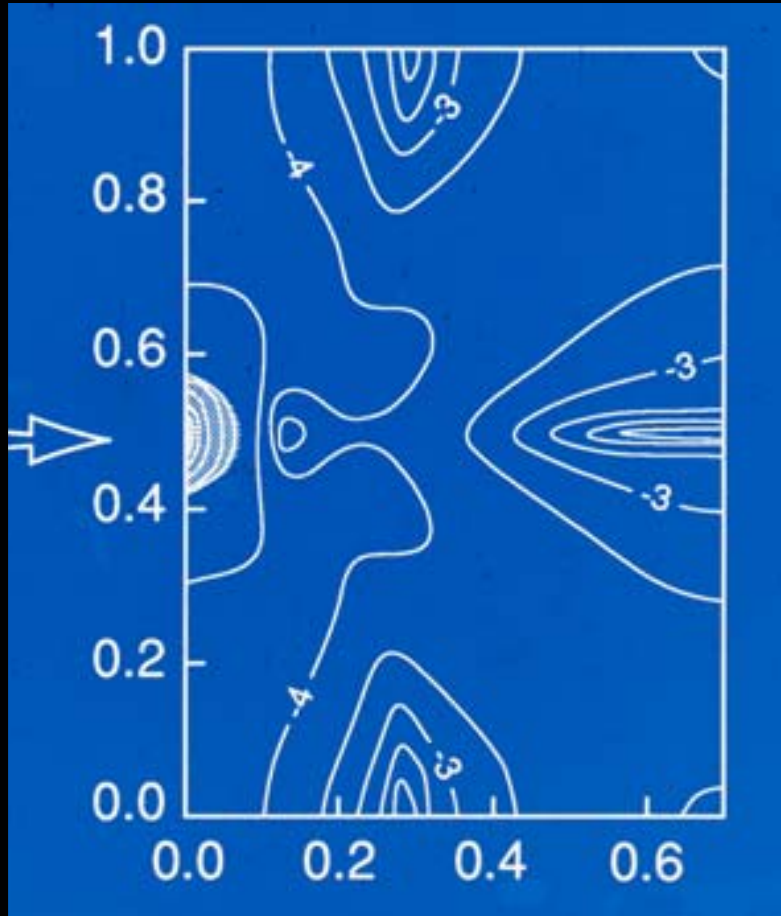
**magma cools/
differentiates in
transit**



Diapirs: Stokes Equation

$$V = \frac{1}{3} \frac{\Delta\rho g r^2}{\mu} \left(\frac{\mu + \mu_{\text{sph}}}{\mu + \frac{3}{2}\mu_{\text{sph}}} \right)$$


Diapirs in power-law rocks



**stress-dependant
viscosity**

**high stress=low
viscosity**

$$V = \frac{1}{3} \frac{\Delta\rho g r^2}{\mu} \left(\frac{\mu + \mu_{\text{sph}}}{\mu + \frac{3}{2}\mu_{\text{sph}}} \right)$$

Arguments against diapirs:

rapid magma
migration:
xenoliths
(yield strength)

diapir pathways
not recorded



Goscombe, 1992

Dykes:

propagation controlled by magma viscosity

**felsic dykes require critical widths > 2 -
20m (Petford et al. 1993)**

Difficulties:

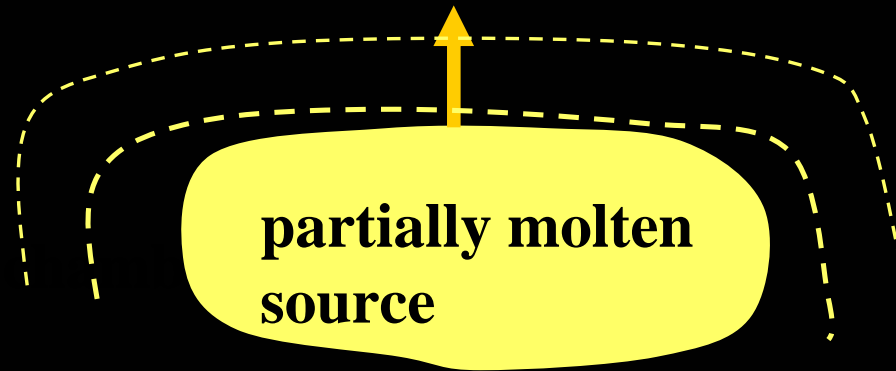
**dyking must reach critical widths
dyking requires an emplacement
mechanism: ballooning,
stoping, roof uplifting,
floor downwarping**



Rarity of felsic dyke swarms

dyking is a *rare* event:
very efficient??

cooling + melt
interconnectivity



birth of dykes:

We know:

- a) magmas segregate within the source
to produce sheets and pods
- b) wide dykes can successfully
propagate across the crust

We do not know how a) links to b) ?
time scale, the dynamics and the geometry
of melt segregation??

Pervasive Migration

**Injection complexes
capped by plutons,
sheets**

Typical of hot crust





Pervasive Migration

foliation-parallel sheets

blisters

**viscous system with
preferential weakness planes**





Nuptse, Himalaya

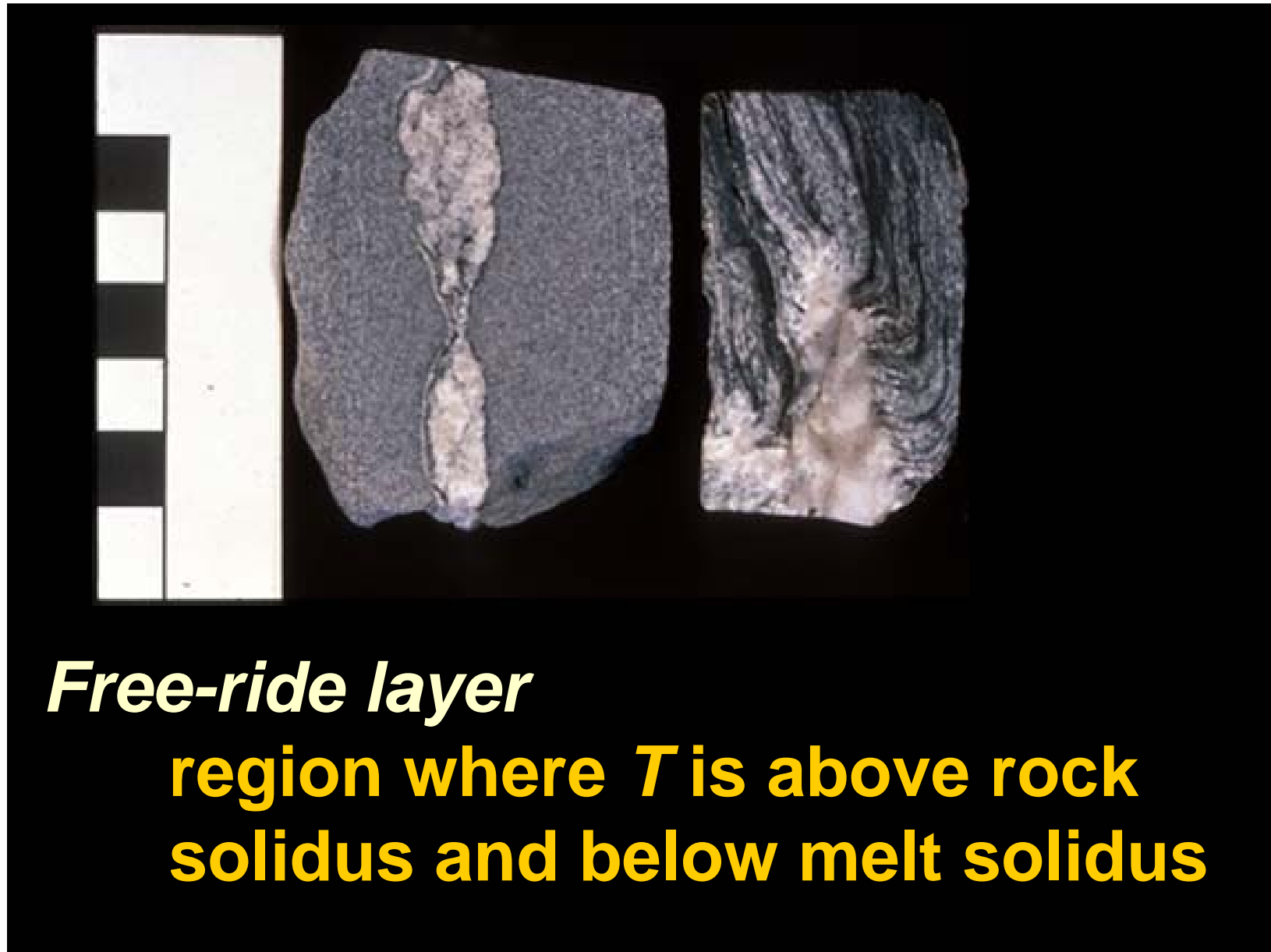
Pervasive Migration (Weinberg & Leitch, EPSL 2002)

Segregated melt pods: lower solidus than source rock

Melt migrates freely into solid rocks above melt source



Ladakh, Himalaya



Pervasive Migration



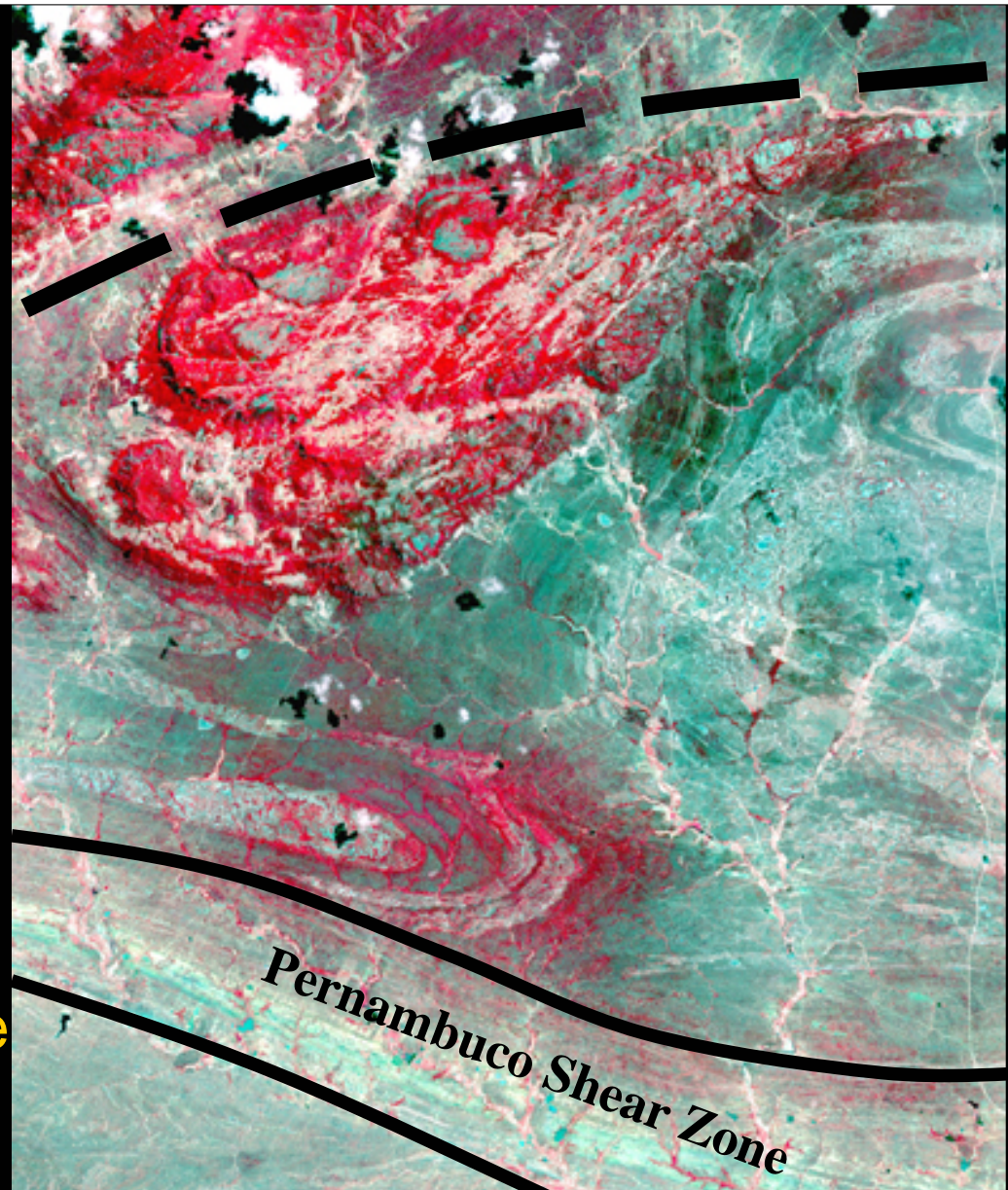
early stages of migration within the free-ride layer will set the melt up for later migration:

interconnected systems may feed a dyke

large magma bodies may rise diapirically

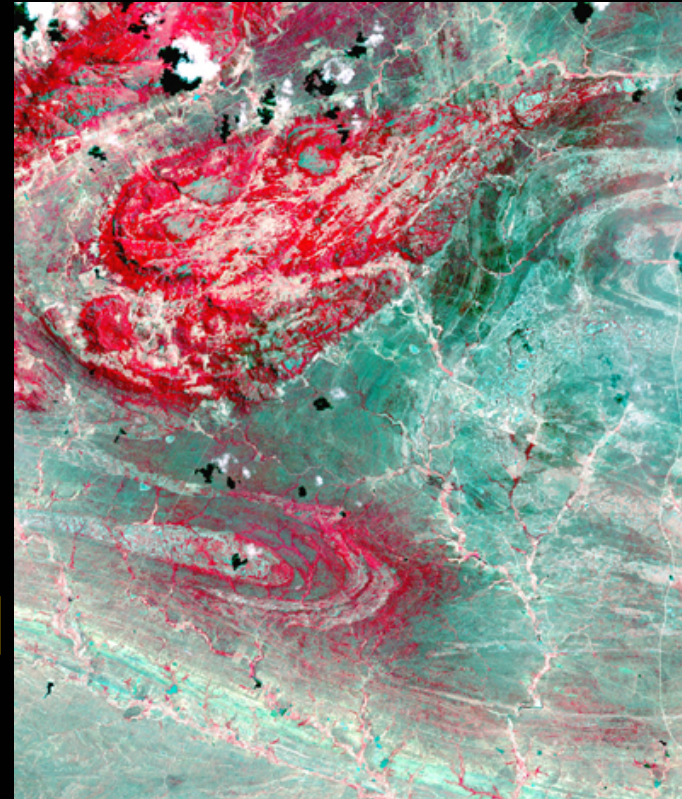
Plutons and shear zones

Borborema Province
NE Brazil

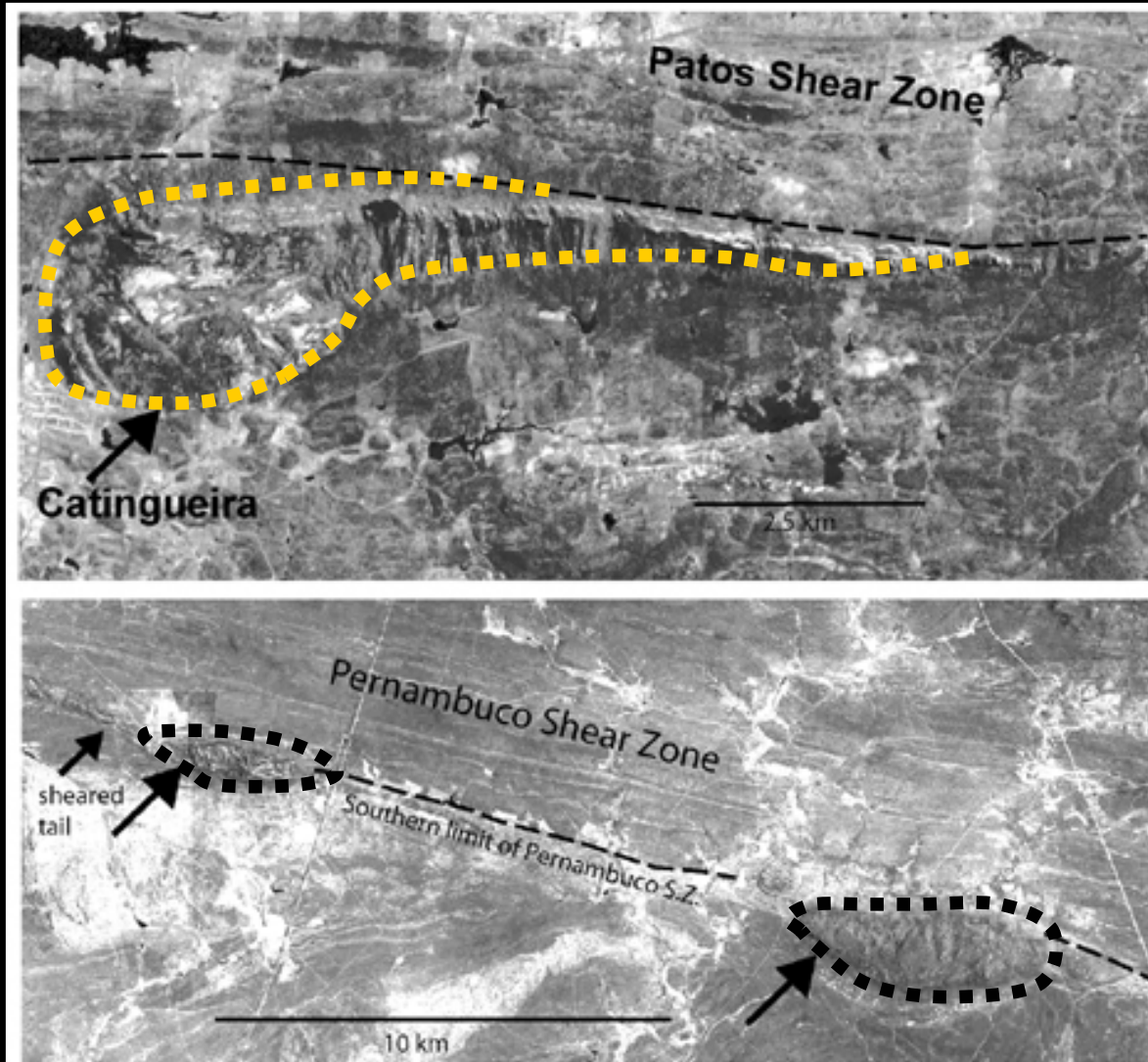


Plutons and shear zones:

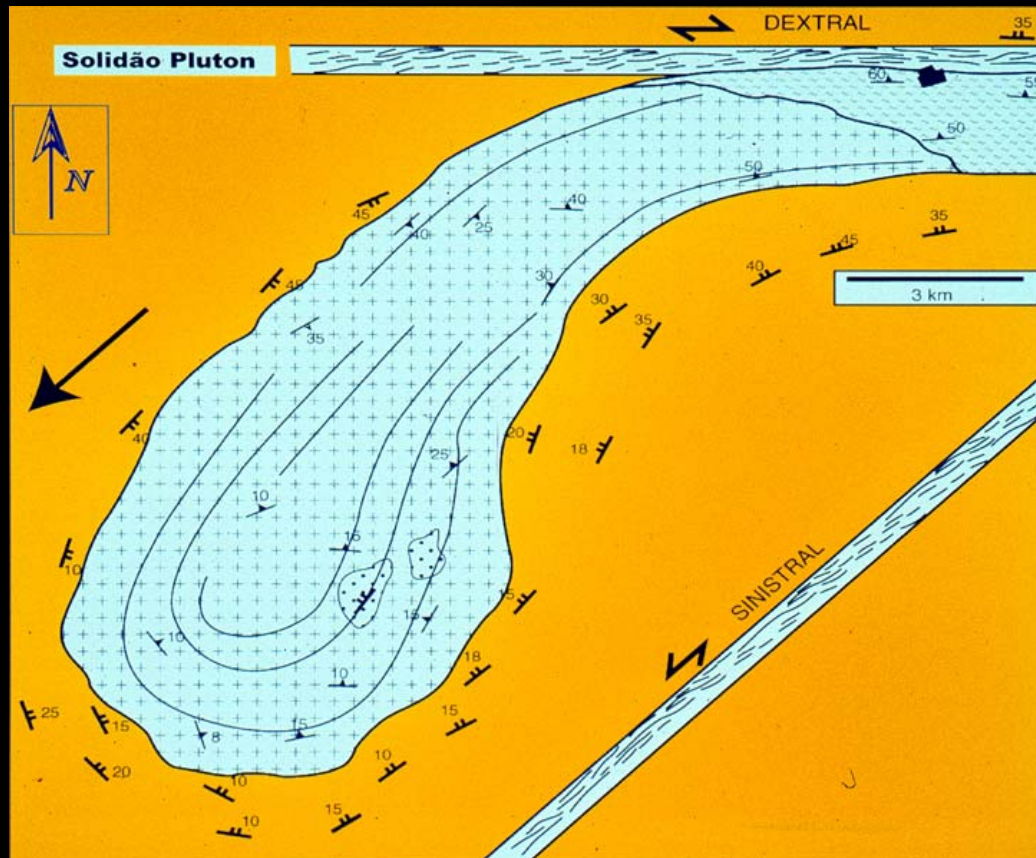
- weakness plane
- feedback: straining, shear heating, intrusion
- melt enhancement and focusing at the source



Borborema Province



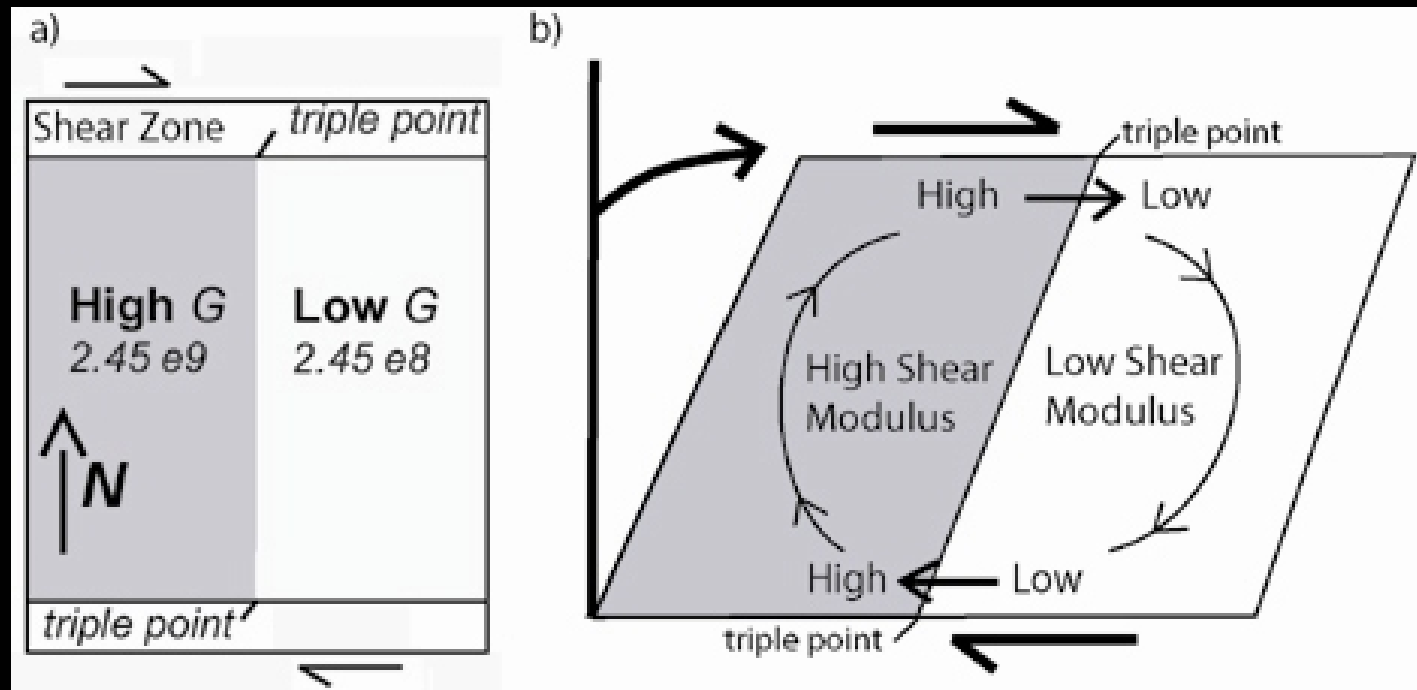
Pluton emplacement



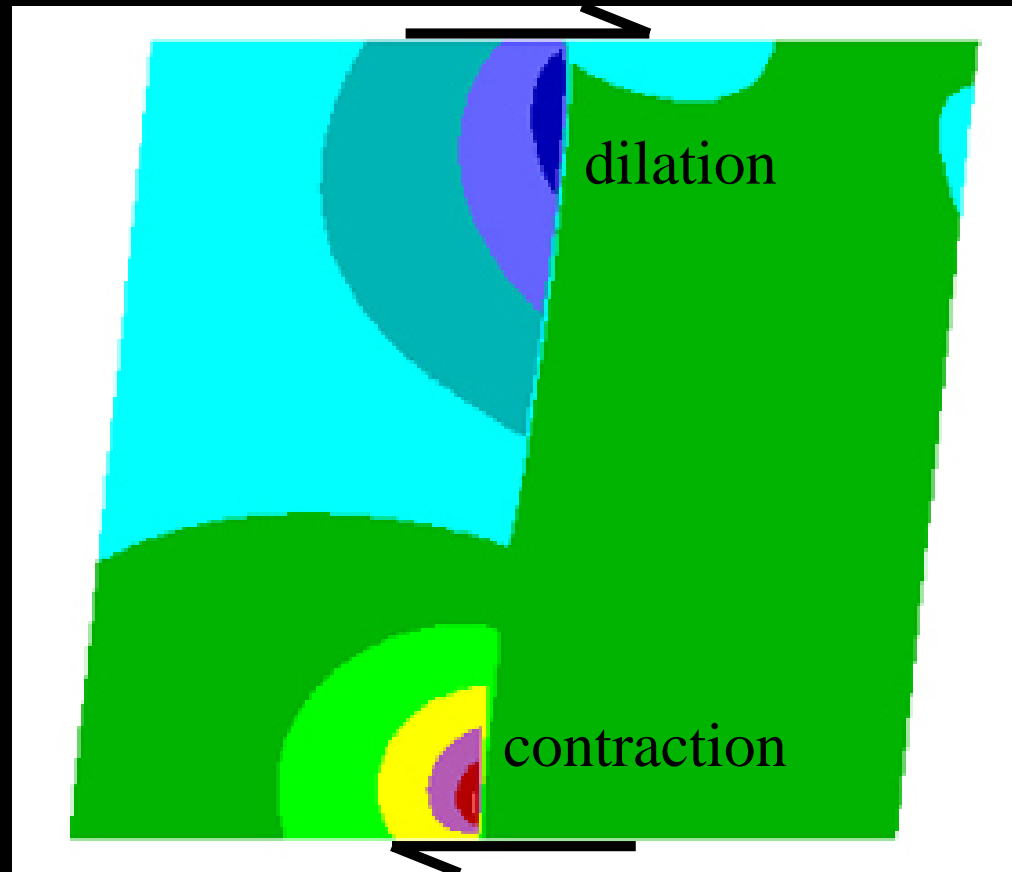
Conjugate shear zone intersection

Largest plutons at intersection between shear zone and terrane boundaries

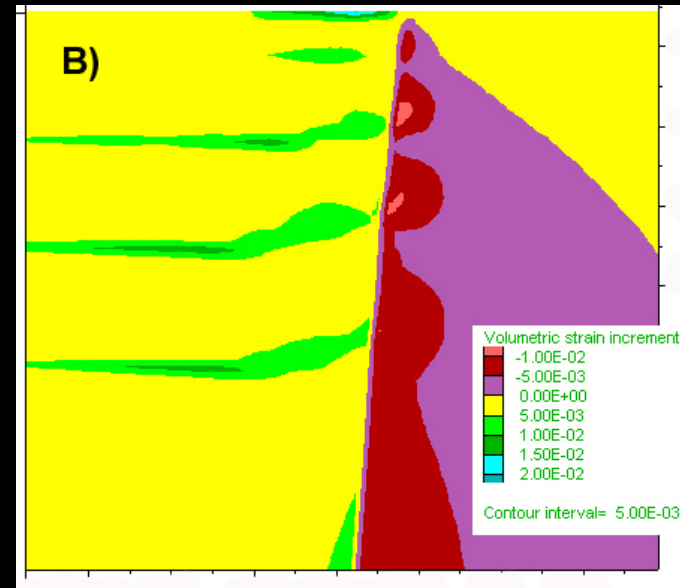
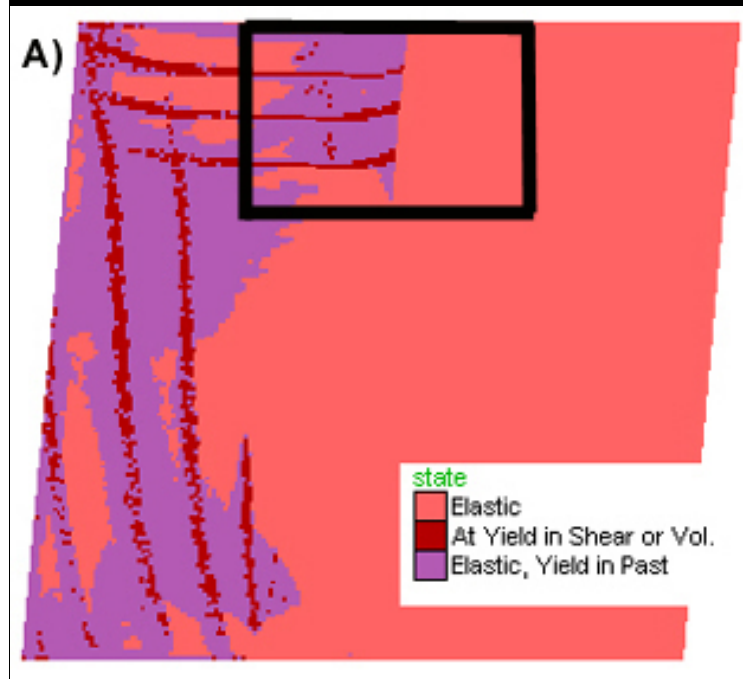
Model set-up (FLAC)



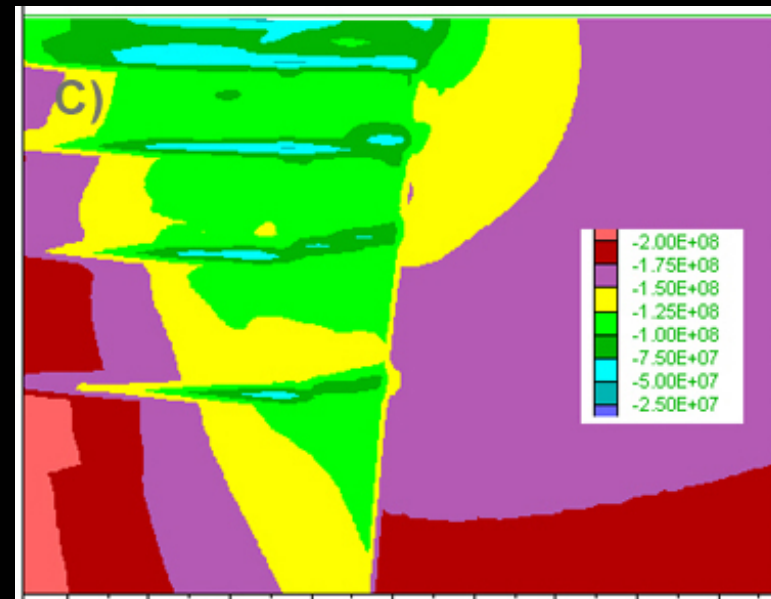
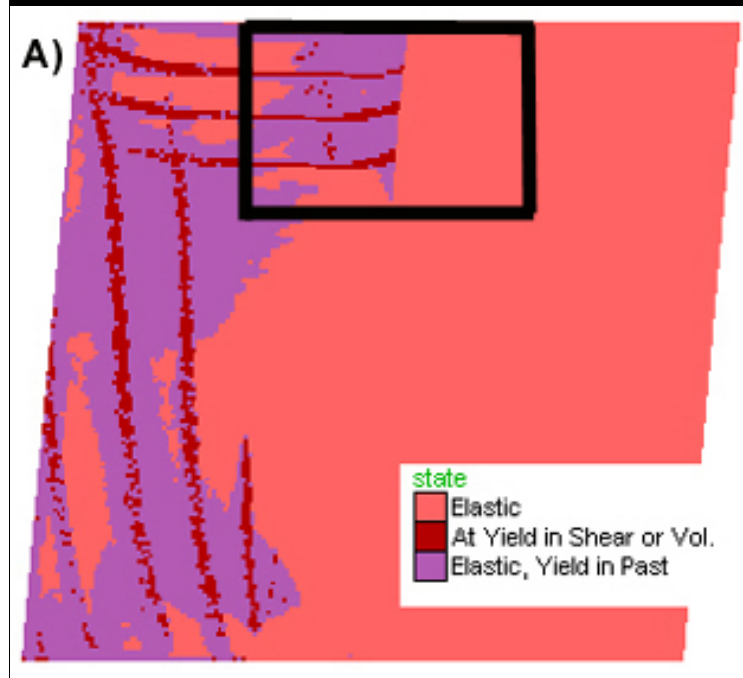
Elastic deformation



Plastic deformation: fracturing and dilation



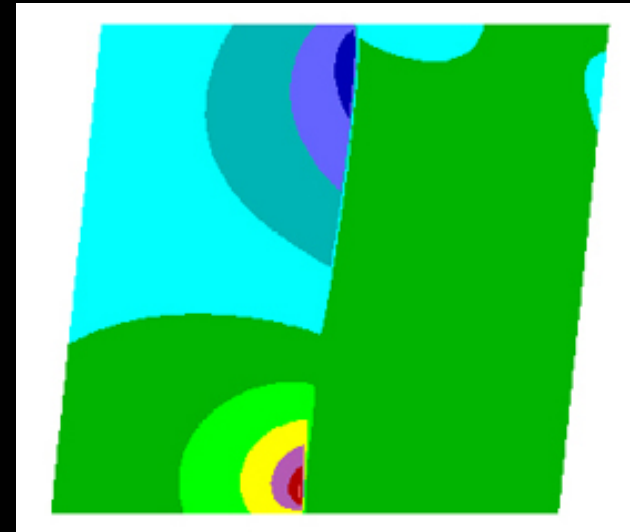
Plastic deformation: fracturing and mean stress



Model Conclusions

Shearing of heterogeneous crust: low and high mean pressure sites

Low mean pressure sites: *dilational and fragile*, favouring magma ponding and emplacement



Personal view:



1. Processes at the source (melt connectivity) and close to the source (free-ride layer) control the destiny of felsic magmas

2. Rare felsic dyke swarms:

large-scale dyking is rare and inefficient in extracting felsic magma from the source



3. Shear zones: stress distribution along shoulders control emplacement/ponding

