The 2000 Miyakejima dike injection: the mechanics of dike and faulting

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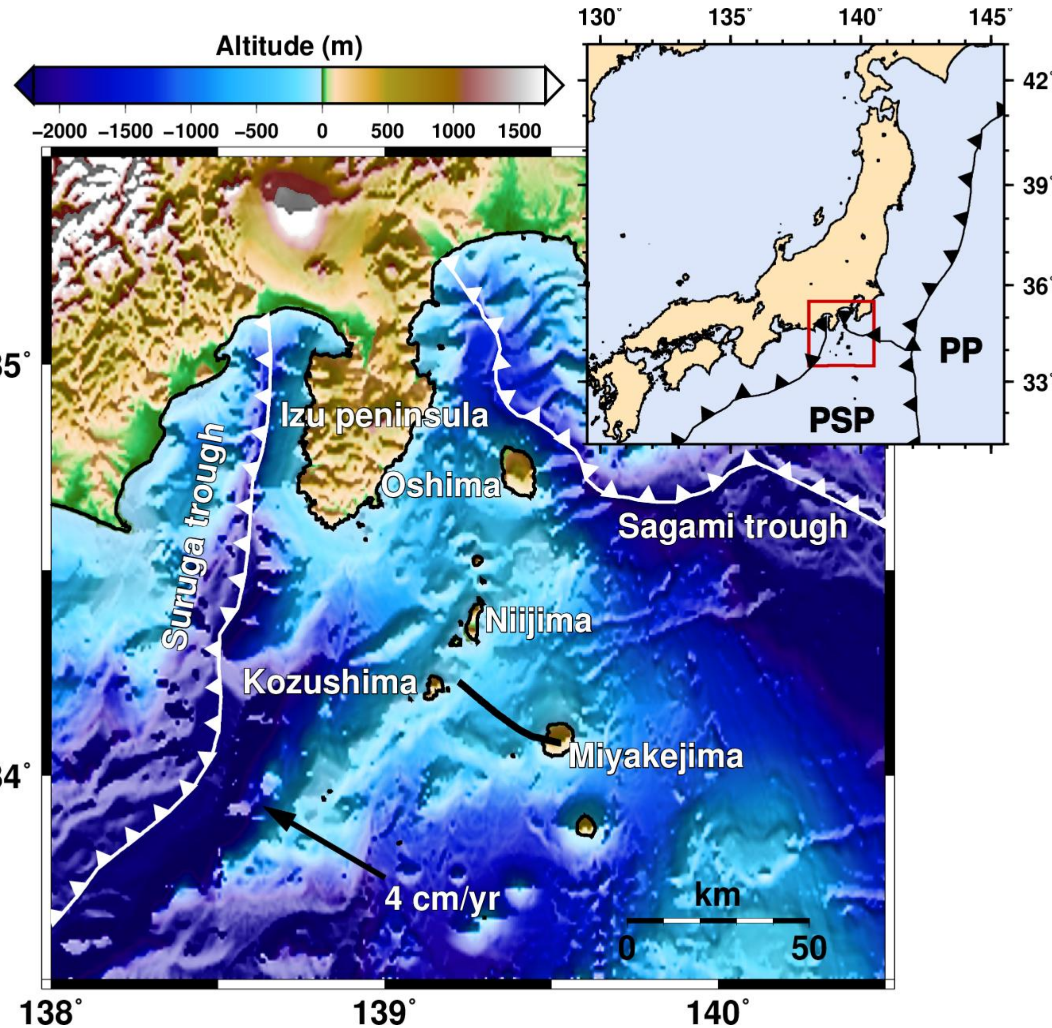
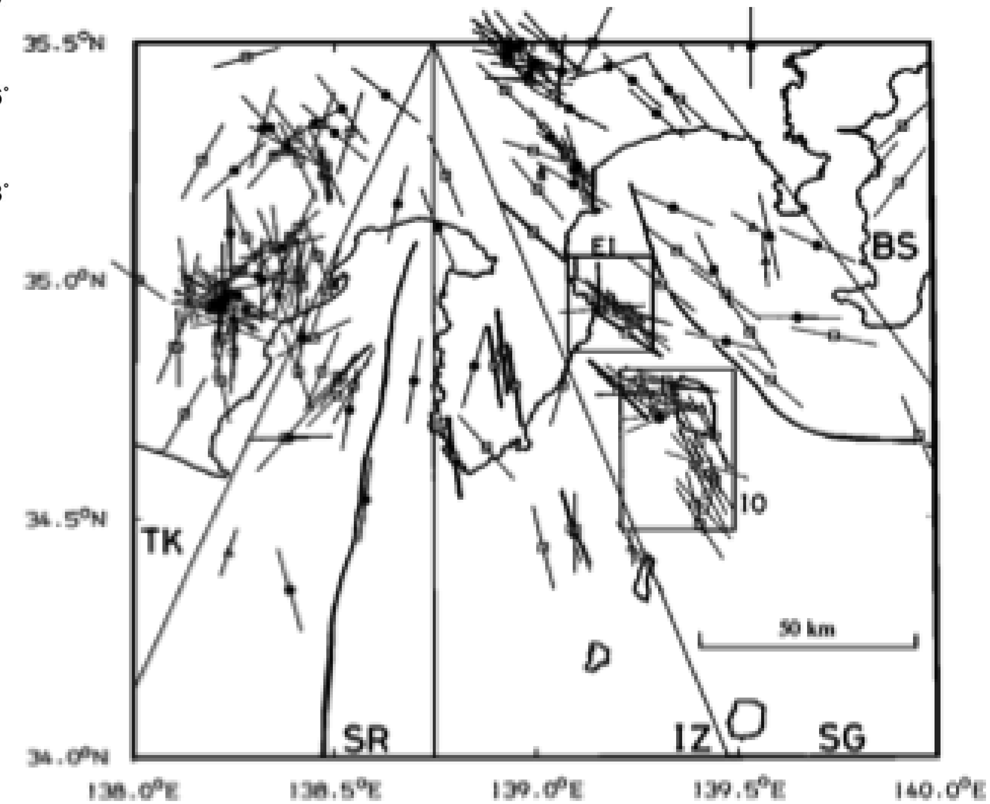
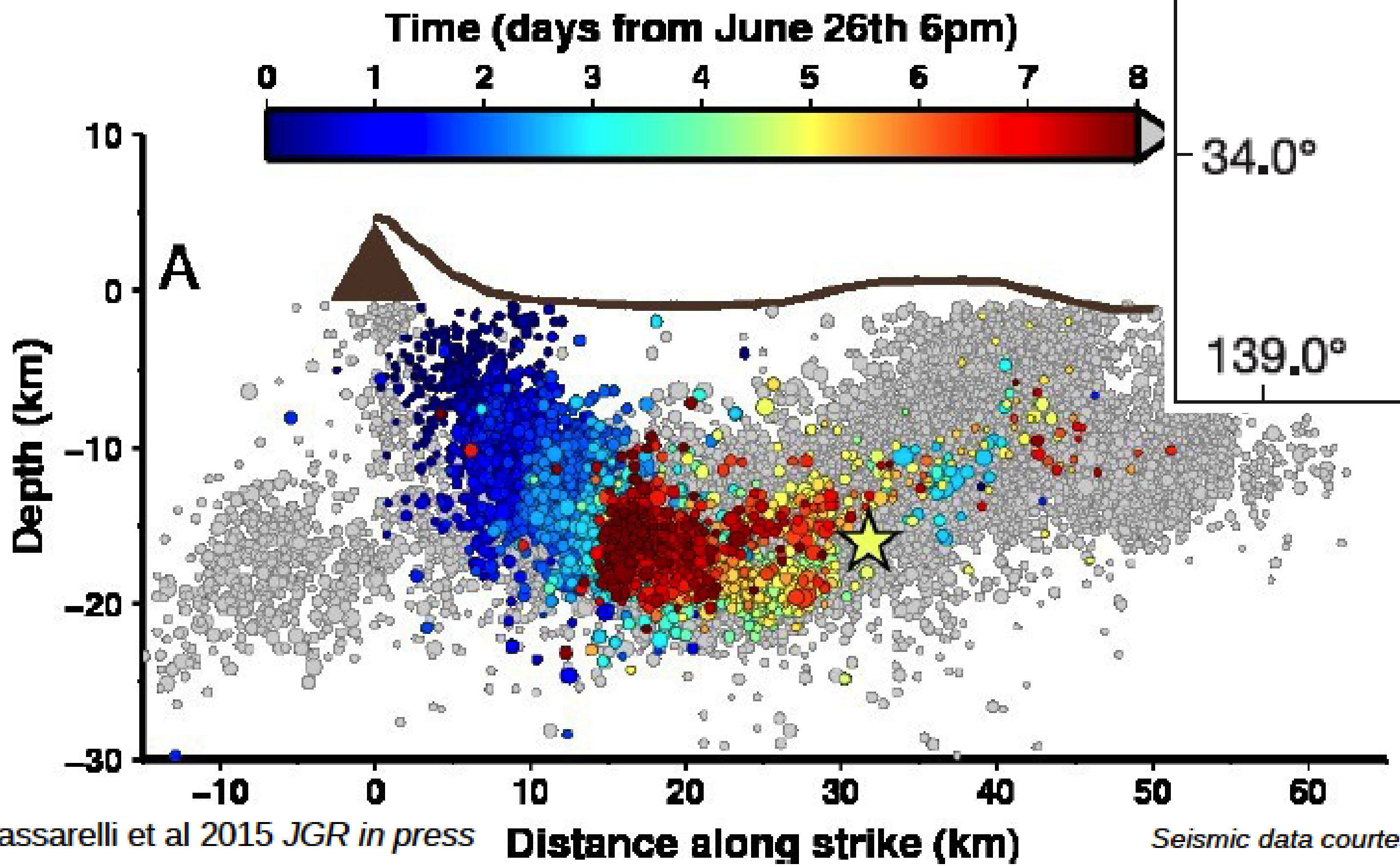
The 2000 Miyakejima dike





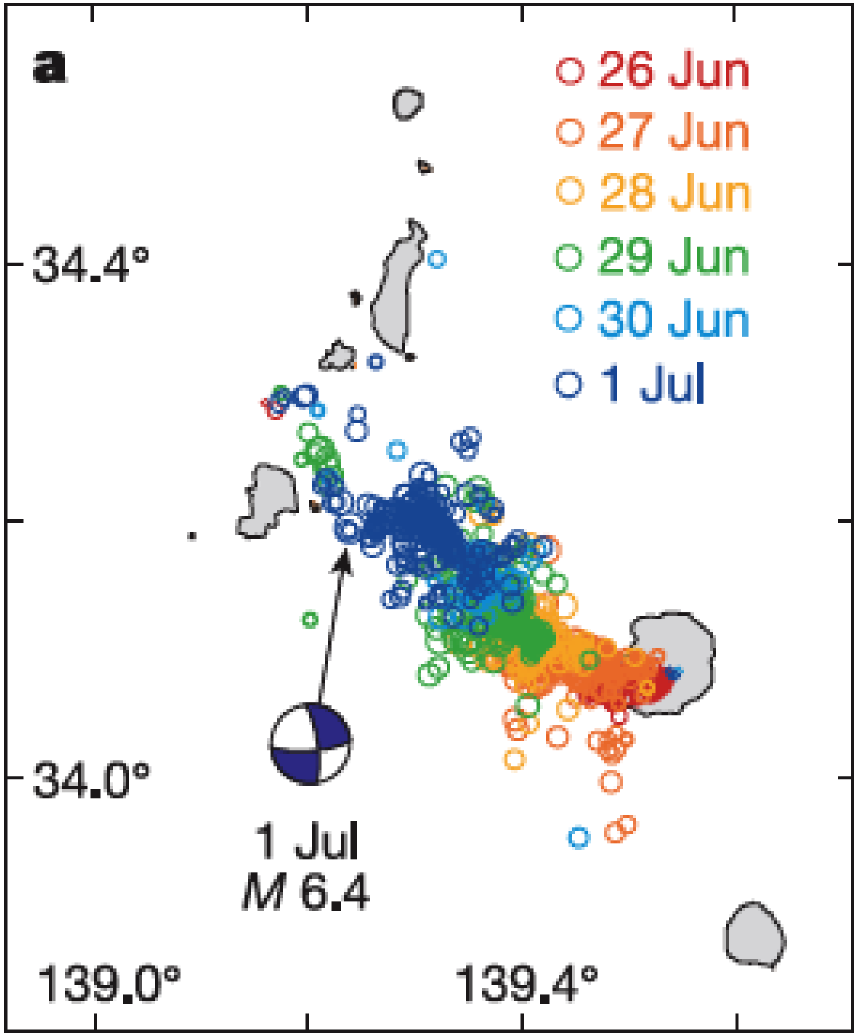
Ukawa, 1991

The 2000 Miyakejima dyke



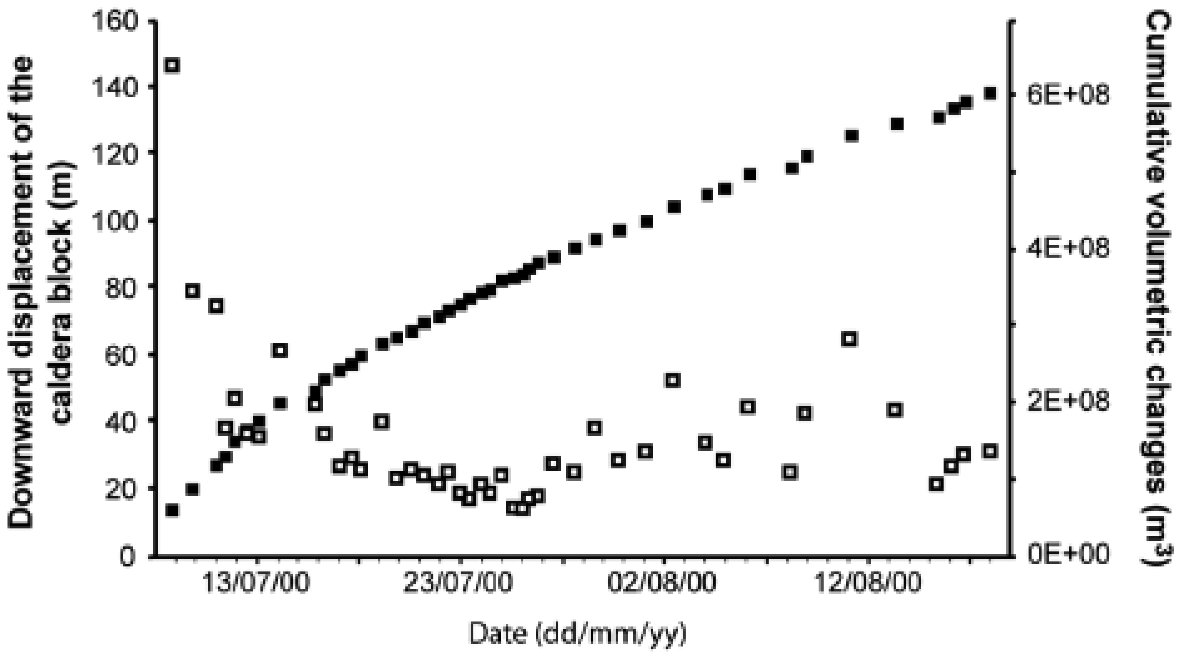
Passarelli et al 2015 *JGR in press*

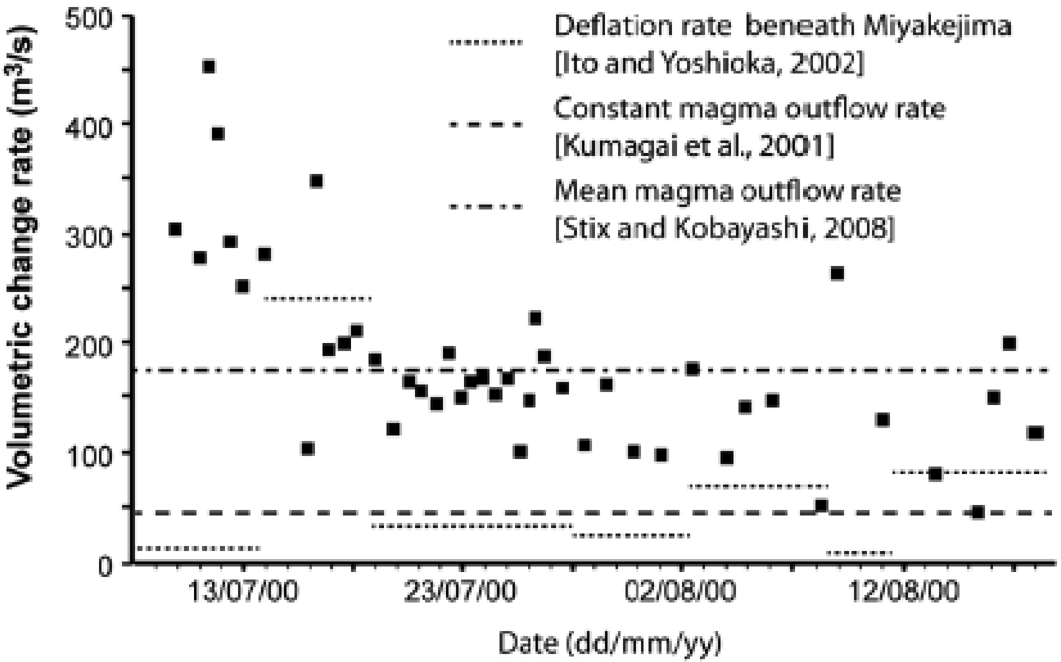
Seismic data courtesy of JMA



Toda et al., 2002

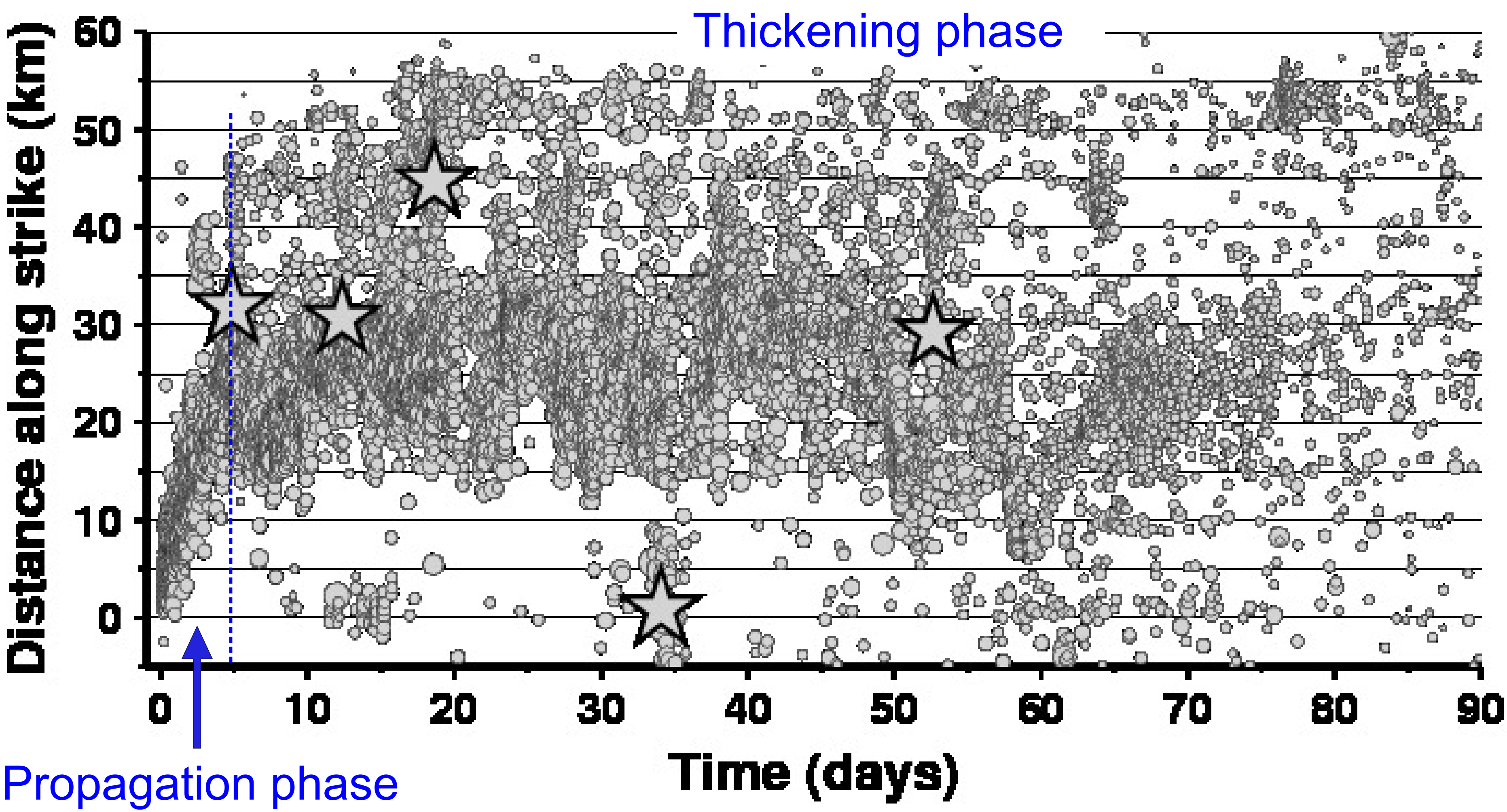
The dynamics of the caldera





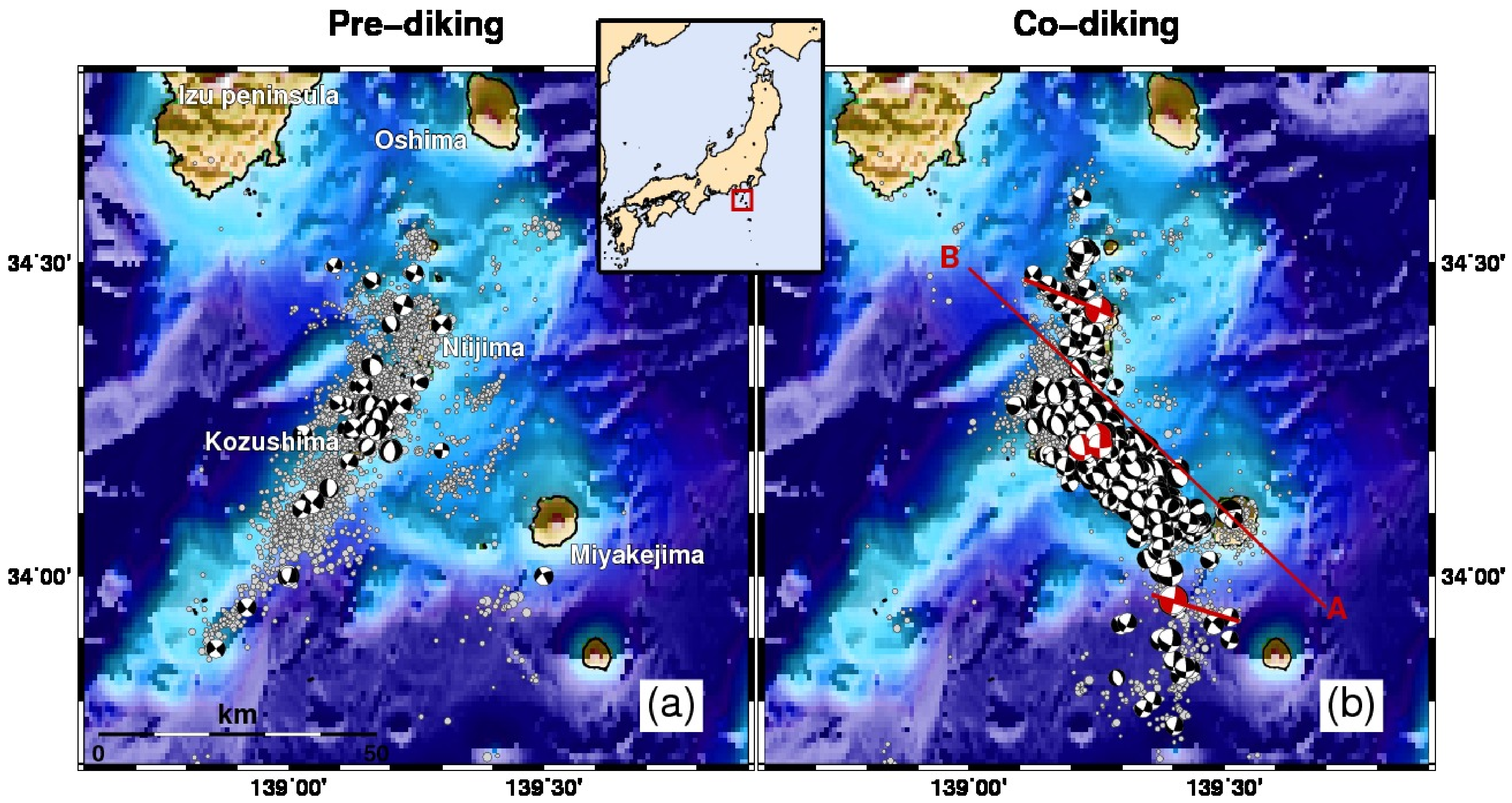
Michon et al., 2011

Motivation: dyke dynamics



- The dike became arrested and did not resume propagation in spite of being abundantly fed. Why?
- What consequences did this have onto the mechanics strain release?

Motivation: faulting patterns



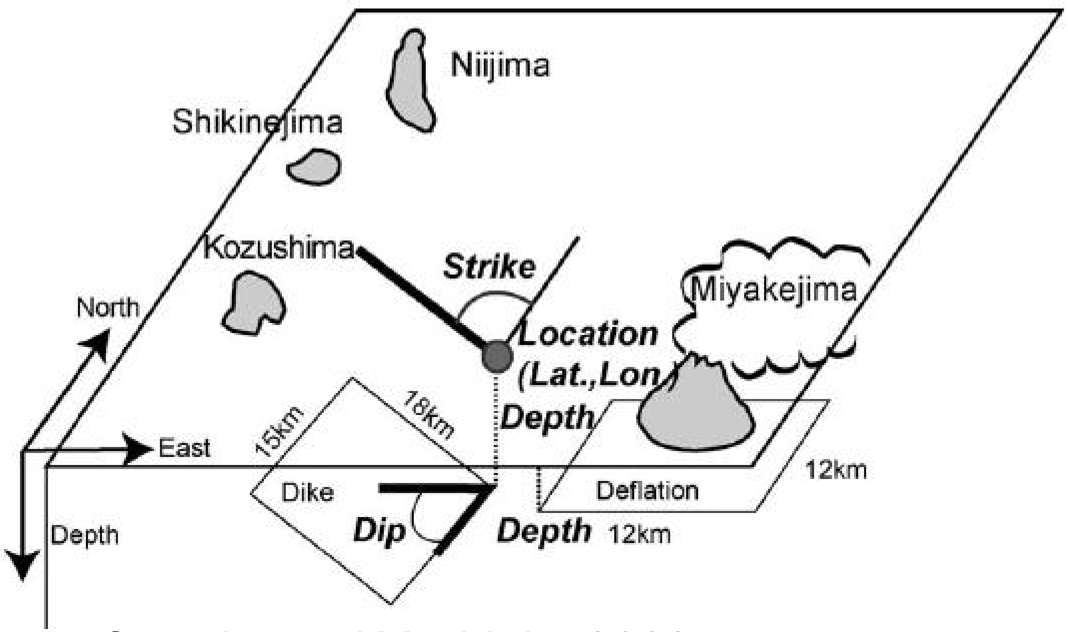
From *Passarelli et al., 2015*. Hypocenters by JMA, M_l>1.5, FMs by NIED, M_w>3

- The co-diking FMs show variability of fault plane orientation. Why?

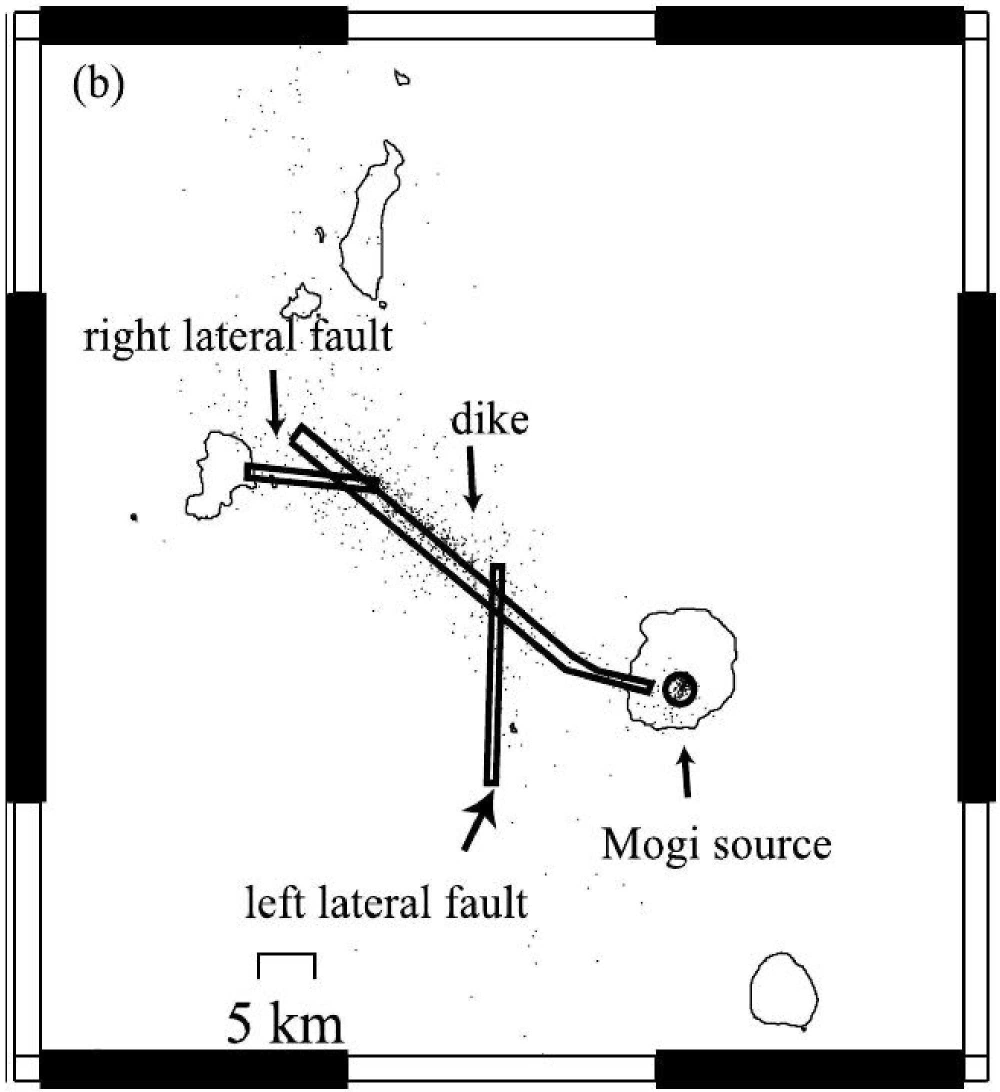
Motivation: deformation

Deformation models span from simple to complex geometries

- Multiple 'slowly moving' shear sources are needed

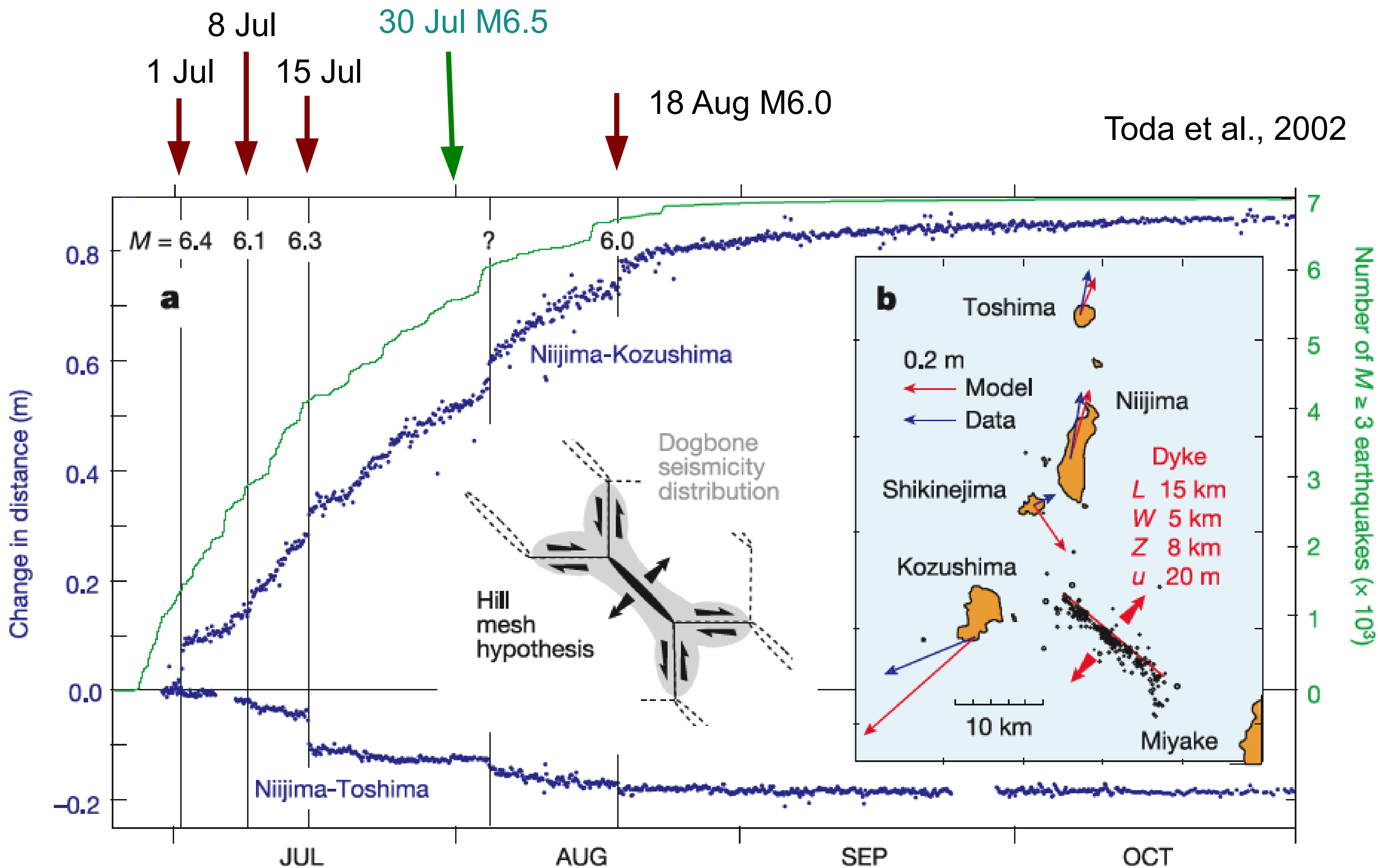


from *Ito and Yoshioka 2002*.

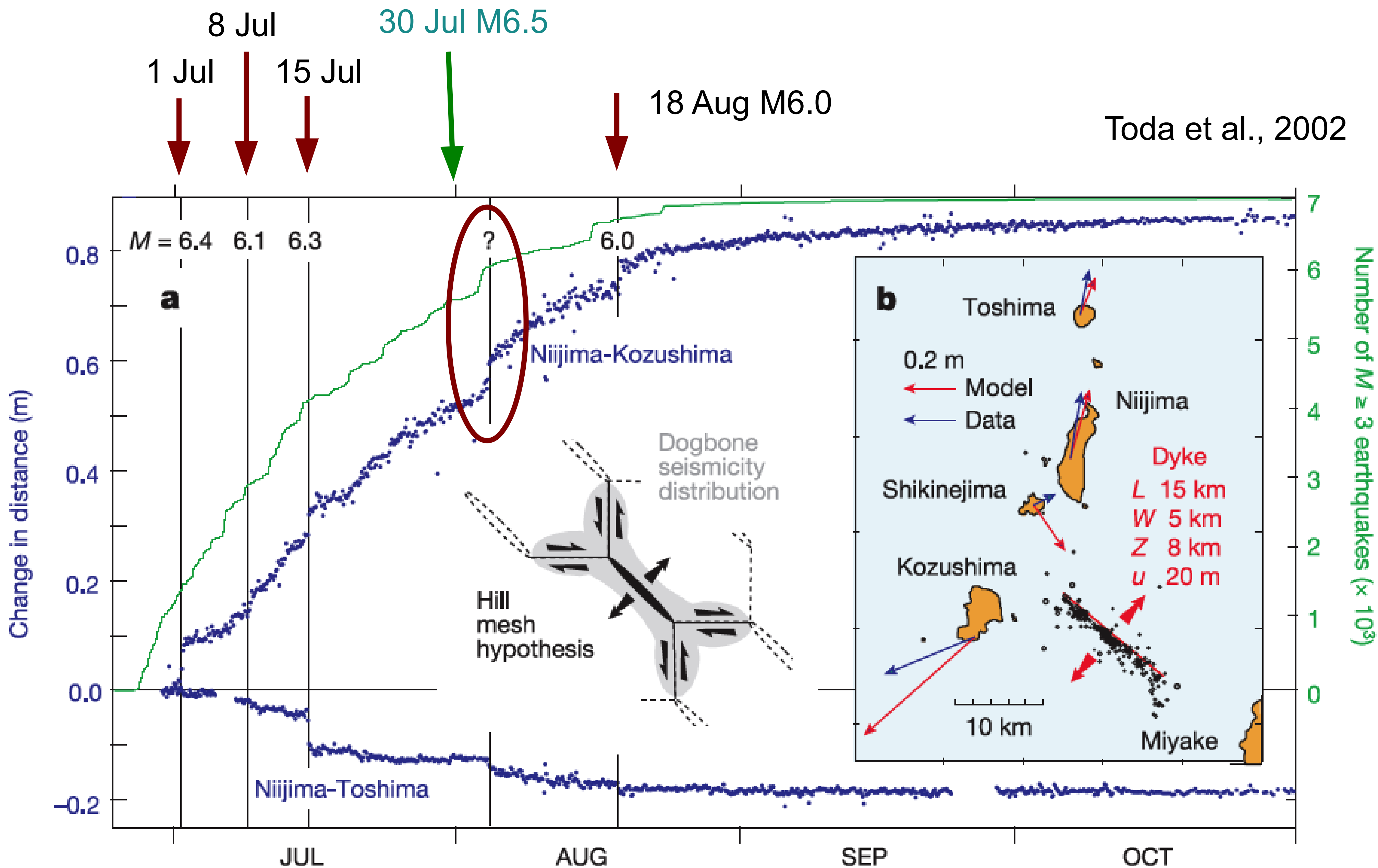


from Ozawa et al., *2004*.

Motivation: deformation and seismicity



- The deformation shows unexplained jumps. What is that?



Talk outline

Explore fault-dike interaction for the 2000 Miyakejima dyke

by means of:

1) Numerical and analog mechanical models

2) Statistics

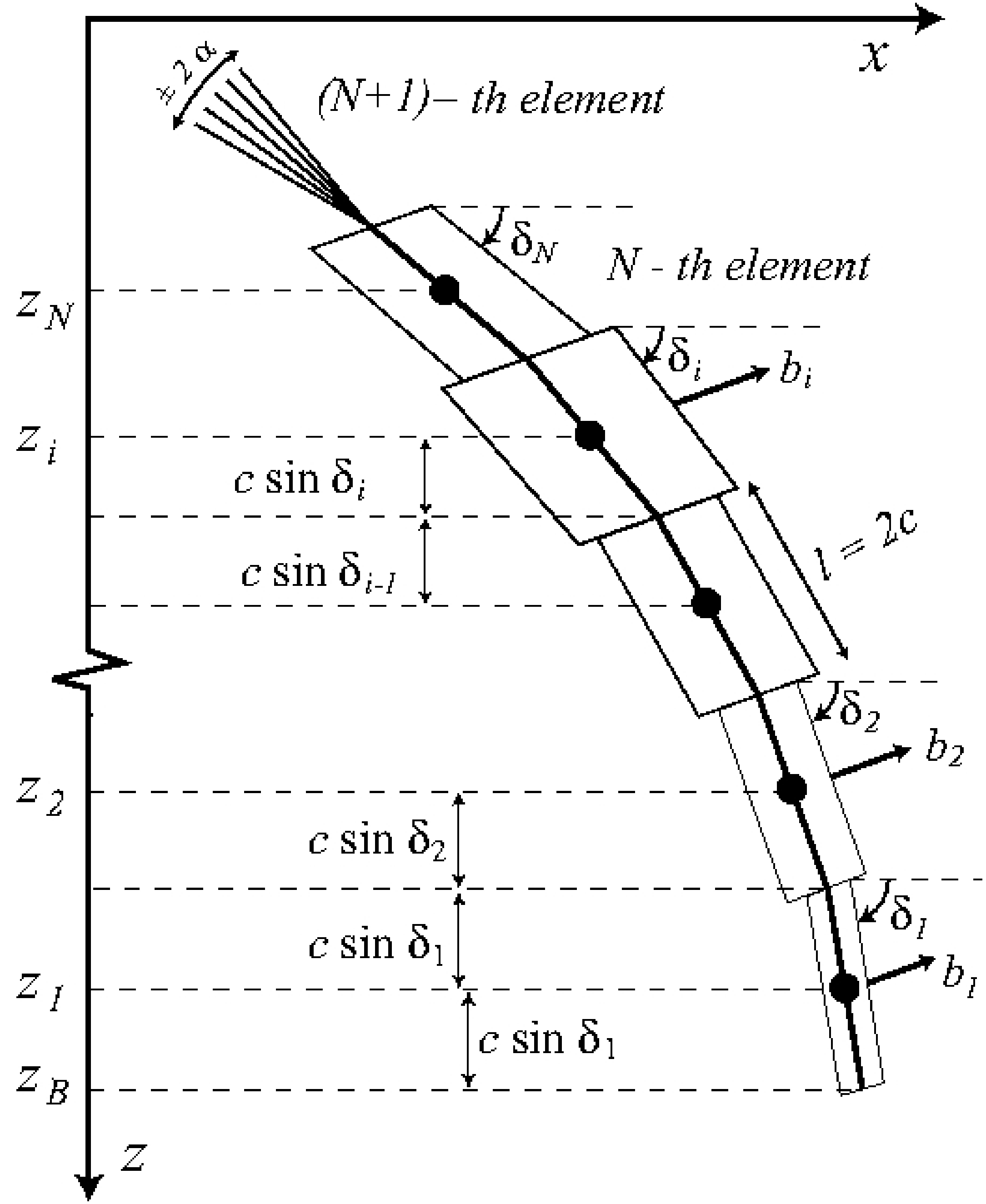
Questions:

1) What arrested the dike?

2) How was the strain released during this dike intrusion?

Numerical model

- *Boundary elements (Displacement discontinuity method)*;
- The *dike propagation* is realized by adding a dislocation element at the tip of the crack and checking if energy release E> fracture energy Ec (if E<Ec -> stop);
- The direction that *maximizes* the total *energy release* is chosen;



Dahm 2000, Maccaferri, et al., 2010 and 2011

Numerical model: Set-up and assumptions

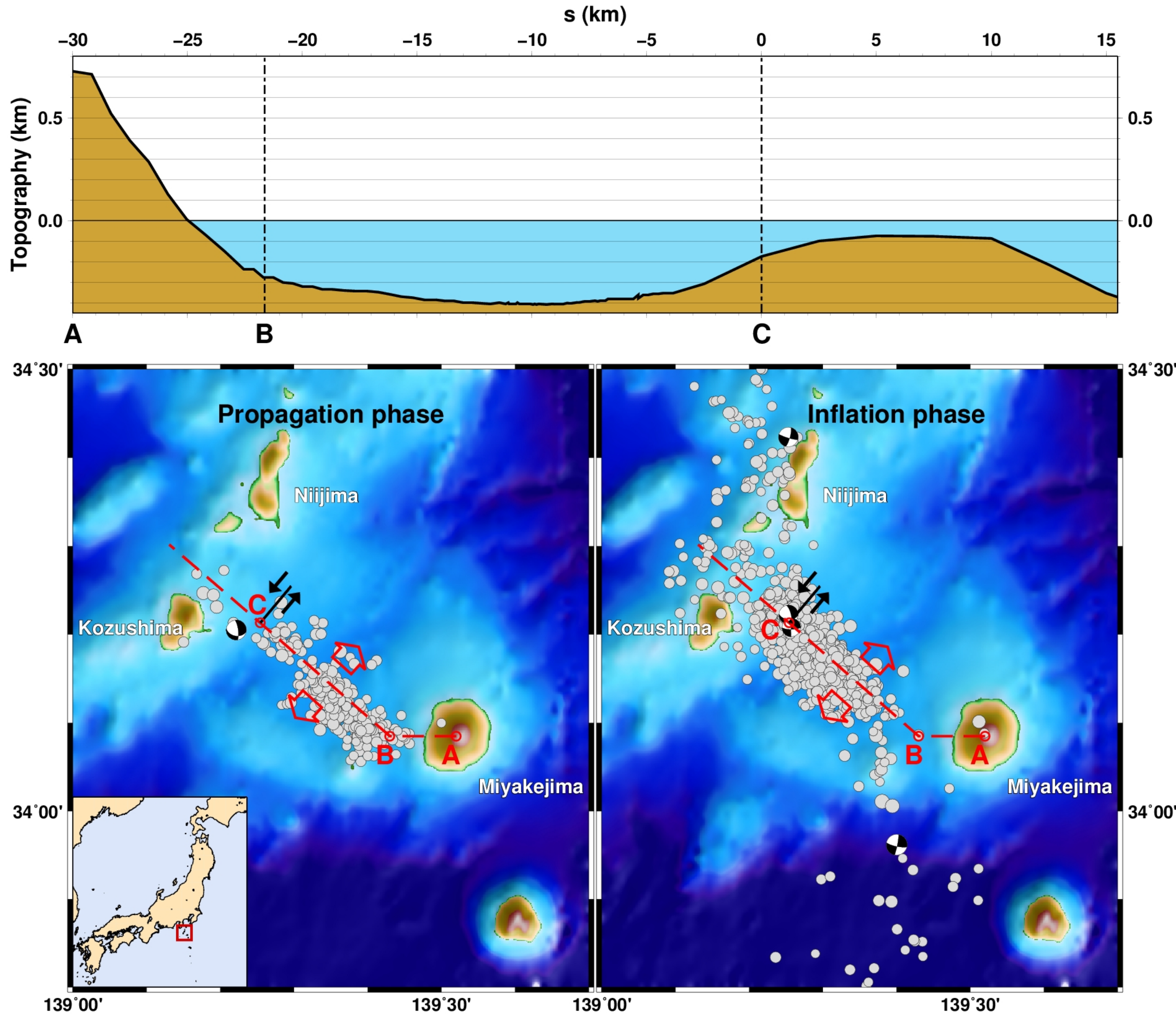
We simulate three scenarios:

1) stress gradient due to topographic load only,

2) dike-faulting interaction only,

3) 1) + 2)

We simulate magma influx by incrementing the dyke volume at each model step.



Numerical model: Parameters and constraints

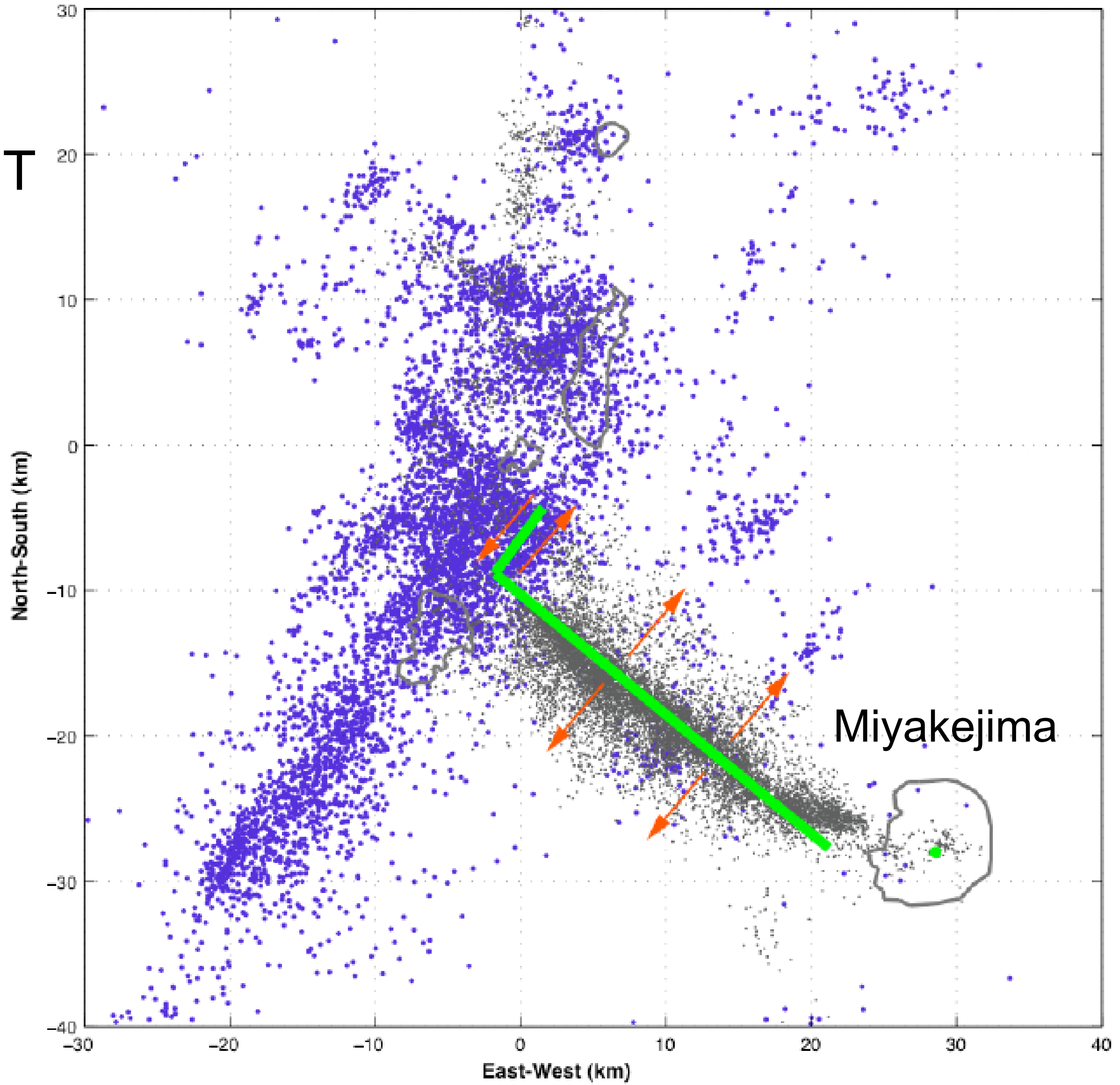
From *Hughes G. R., 2010, PhD thesis*.

• MECHANICALLY CONSISTENT DIKE – FAULT GEOMETRY

• INVERTED OPENING & SLIP:

End of propagation phase
- DIKE OPENING = 0.82 m
- FAULT SLIP = 0.39 m

End of inflation phase
- DIKE OPENING = 3.4 m
- FAULT SLIP = 4.4 m



Numerical model: Procedure

For each scenario:

• At every model step, feed dike, add one dislocation element, calculate dike shape and energy release -> if E>Ec accept increment.

•By trial and error, calibrate Ec, (constant) so that the opening at the end of propagation phase is Du=0.82 m (Hughes, 2010).

• For scenarios 2) and 3), we constrain the interacting dike and fault to have Du=0.82 m and slip=0.39 m -> set shear stress pre-loaded on the fault

• Continue to feed the dyke. Check propagation. Stop simulation when either the dike reaches the final opening (3.4 m) or is way beyond the final point.

• For scenarios 2) and 3), obtain shear stress rate for the fault to have a final fault slip of 4.4 m

Numerical model: Model output

For a given set of parameter values, the model tells us, for each position of the propagating tip:

• How much areal volume has flown into the dyke

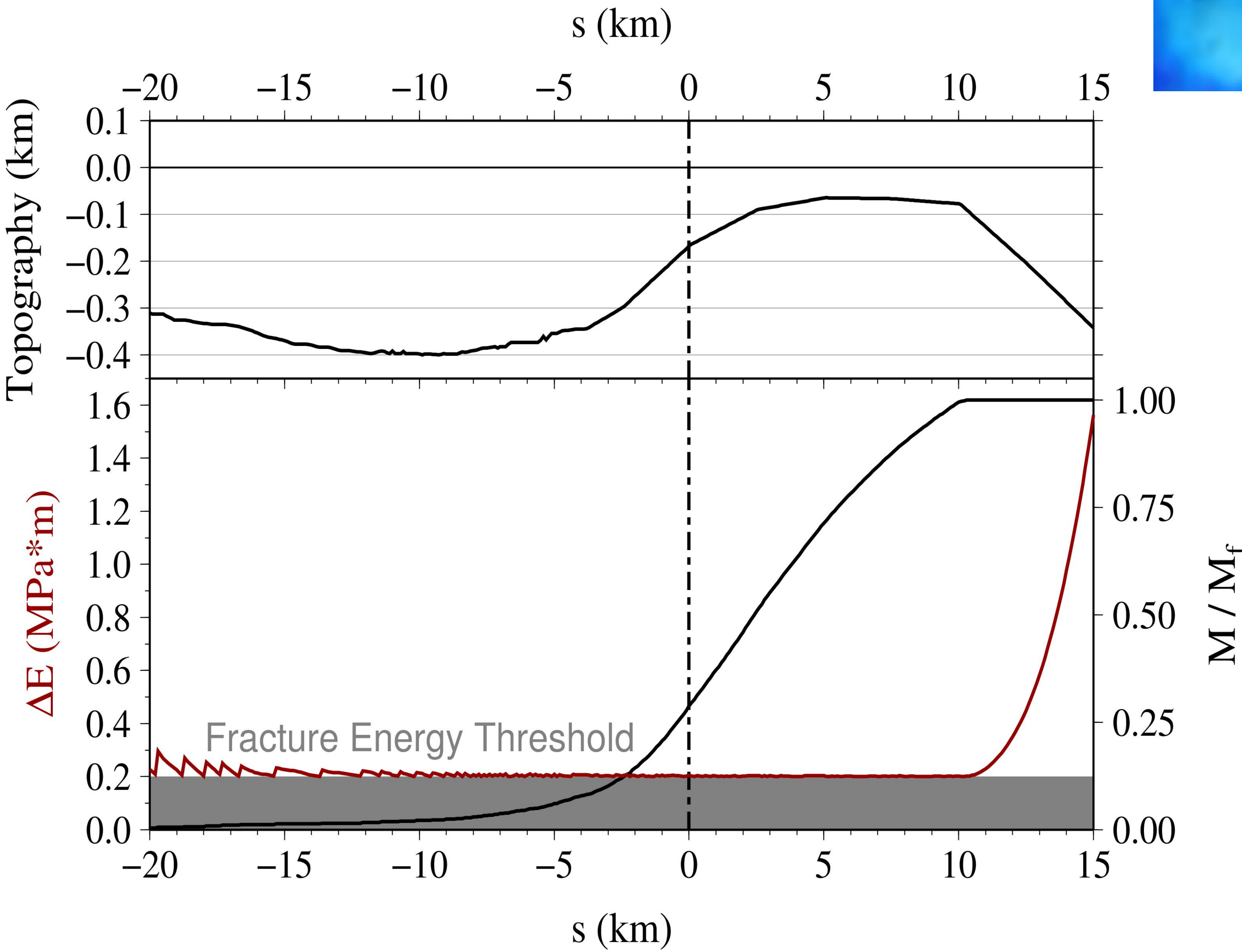
• The cross-sectional shape of the dike (and of the distributed fault displacement)

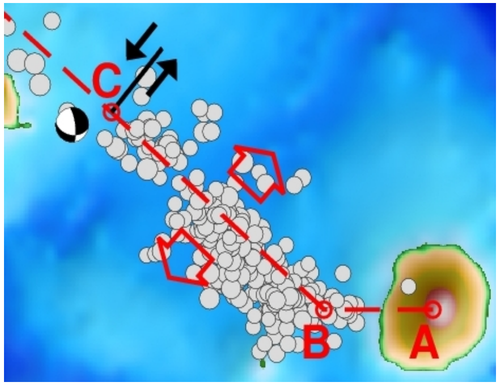
• The stress drop on dyke and fault

• Once the propagation phase has been calibrated, the model reveals if the dyke is going to propagate further or stay arrested.

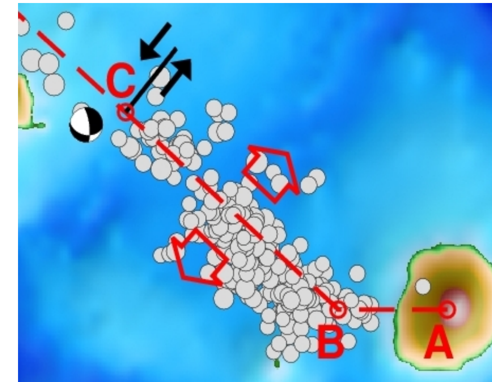
-> If the model was 3D (future work) we could use the magma influx obtained from the published analyses of the caldera floor dynamics to convert the model steps into time steps. Moreover, we could calculate the expected induced seismicity and deformation.

1) Only topographic load: Results

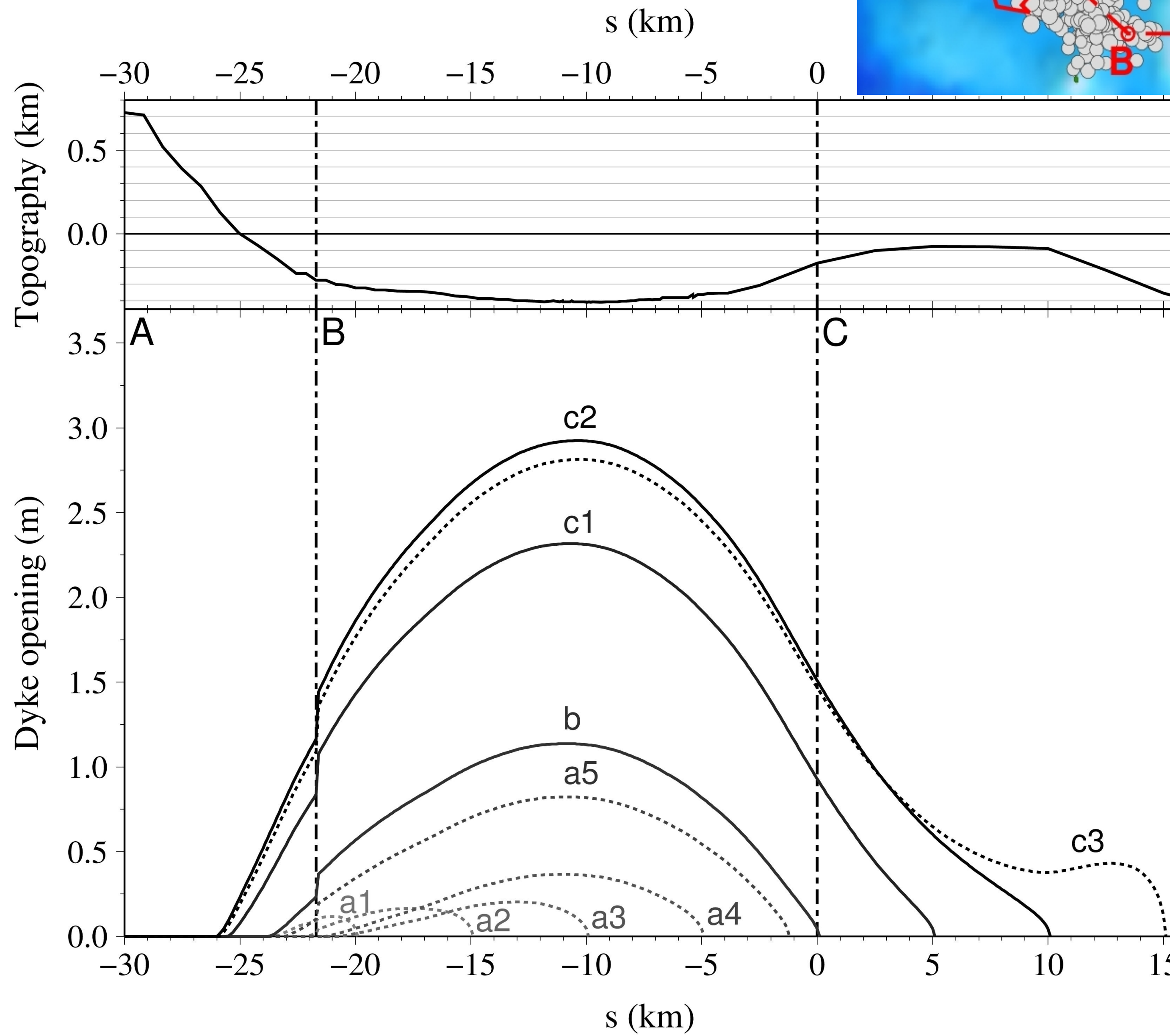




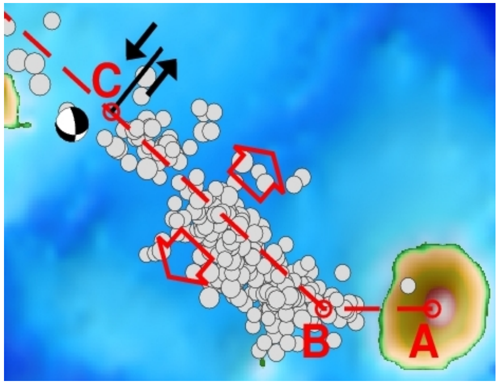
1) Only topographic load: Results



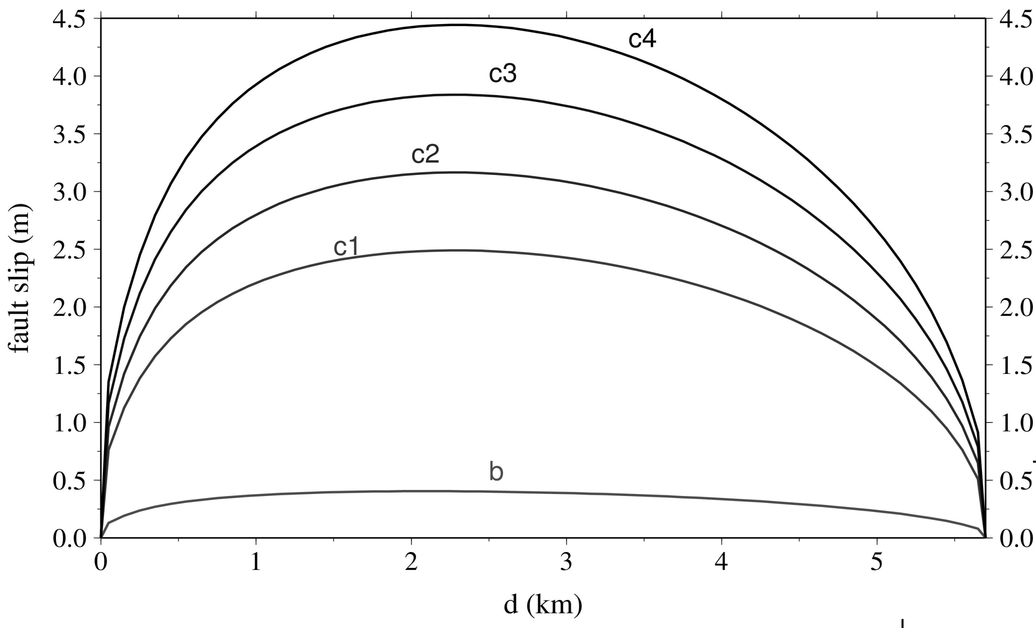
- Dike tip does not stop in C (s=0)
- Dike opening does not reach 3.4 m (max opening = 2.9 m)



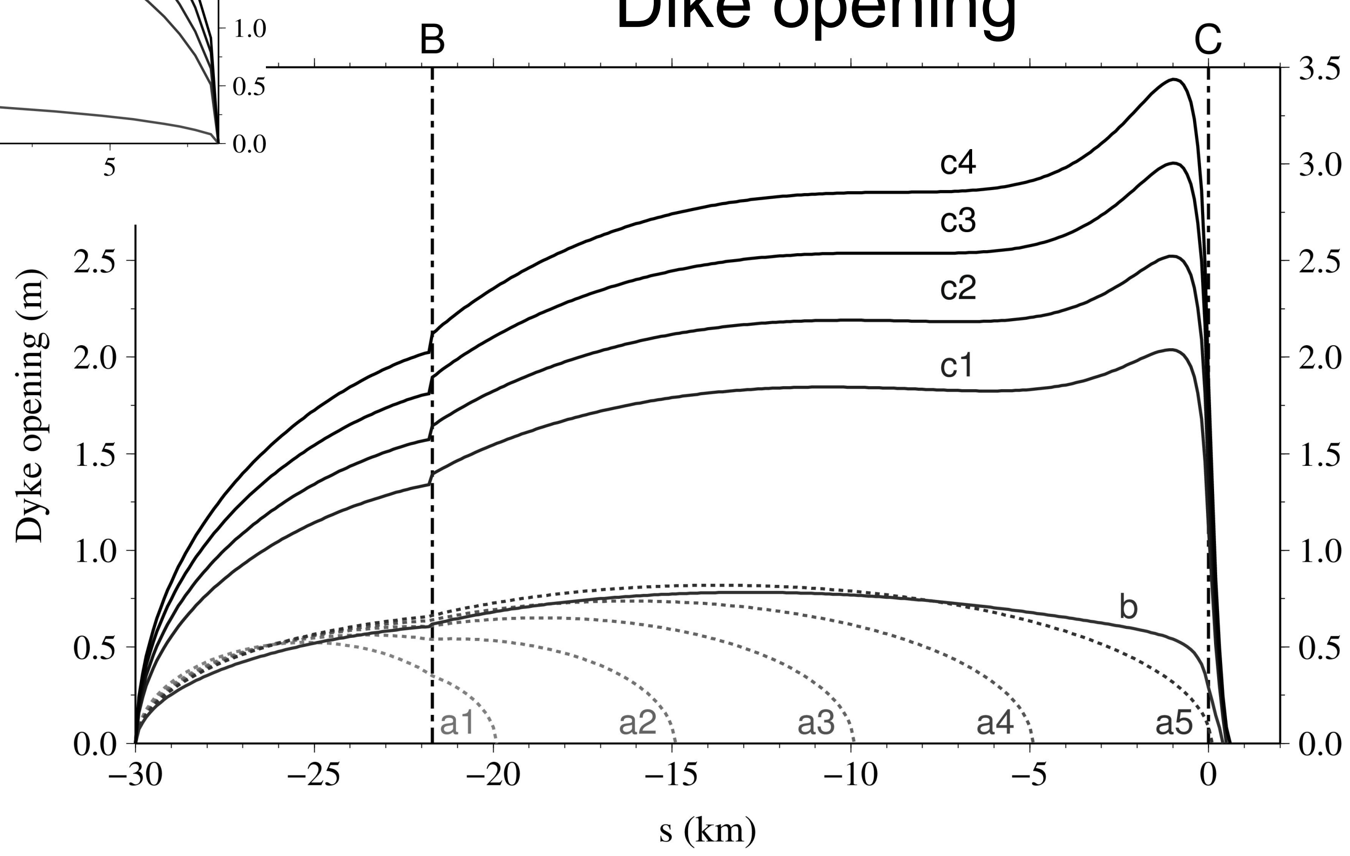
2) Only dike-fault interaction: Results



Fault slip



Dike opening



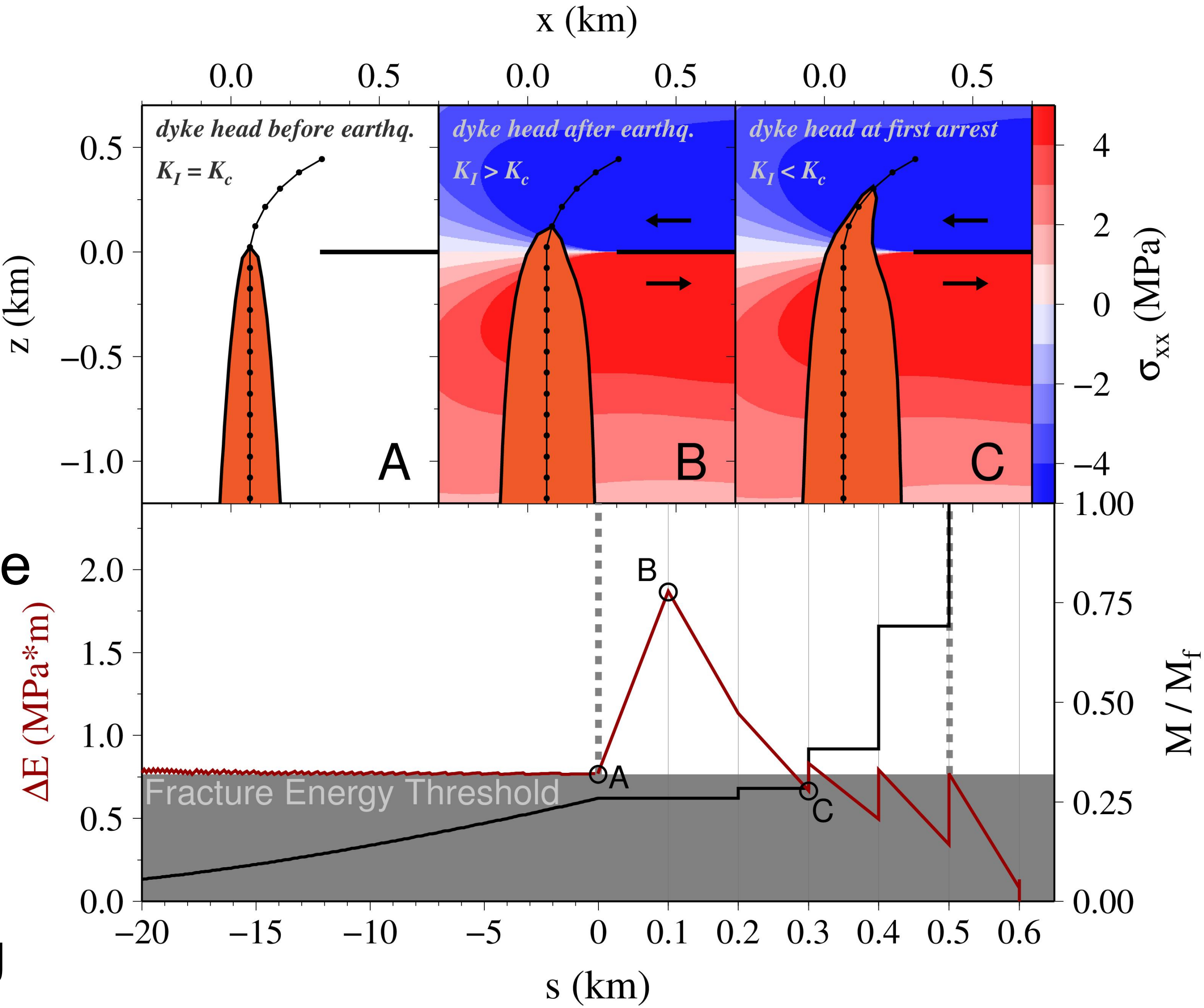
- Dyke reaches 3.4 m opening without resuming propagation.
- Dyke inflates along the whole segment.

• Dike propagation with $K=K_r$ (K_r=175 MPa*m½).

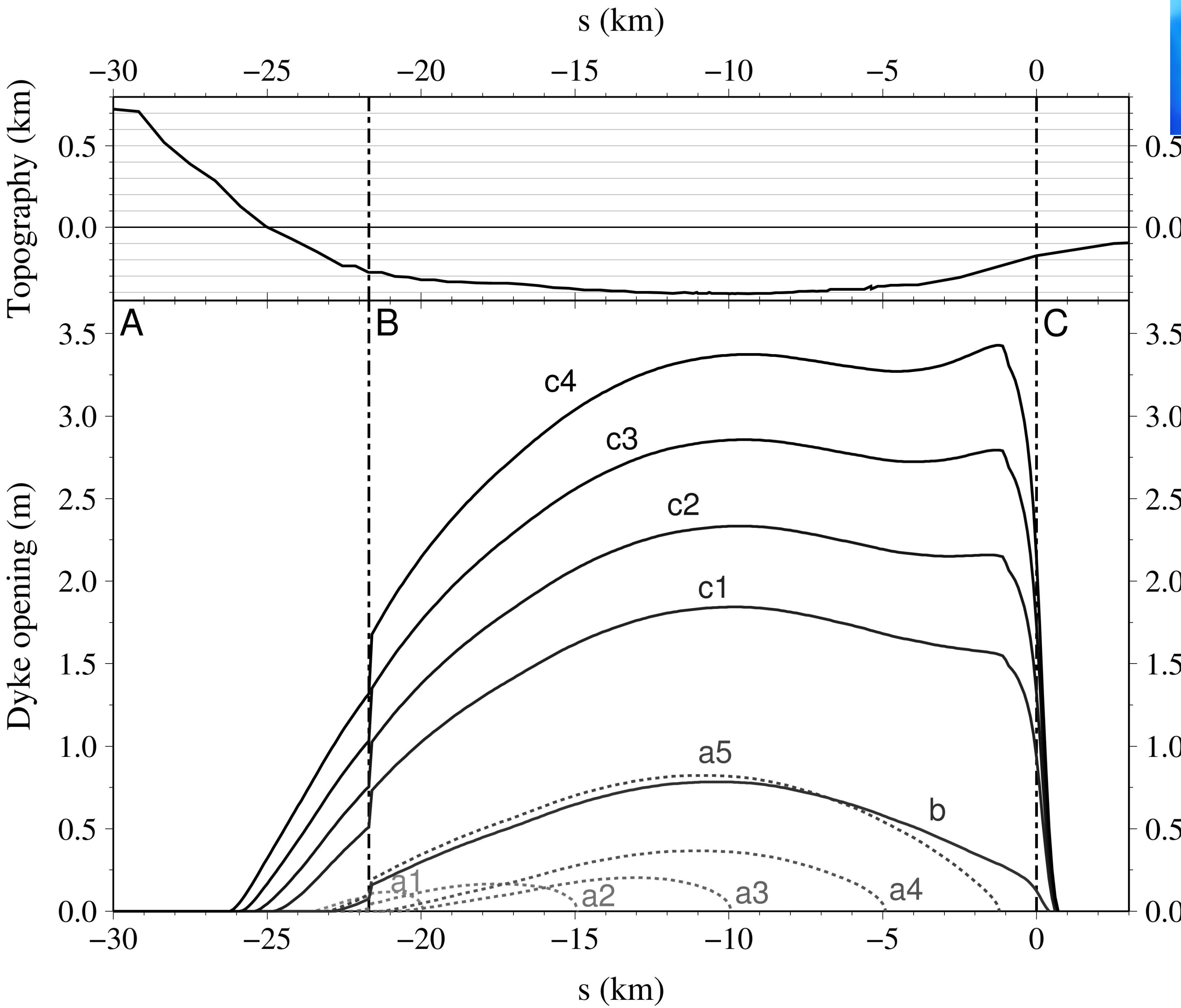
• Dike tip stops close to point C (s=0.5).

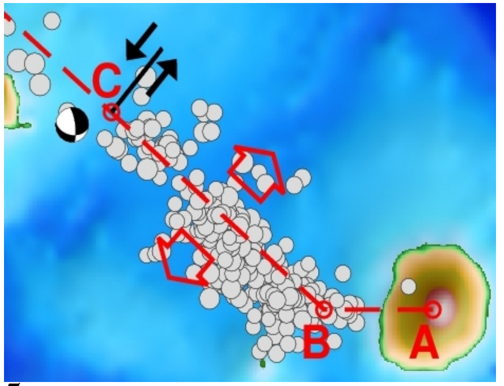
• Dike reach 3.4 m opening.

• Dike inflates along the whole segment.



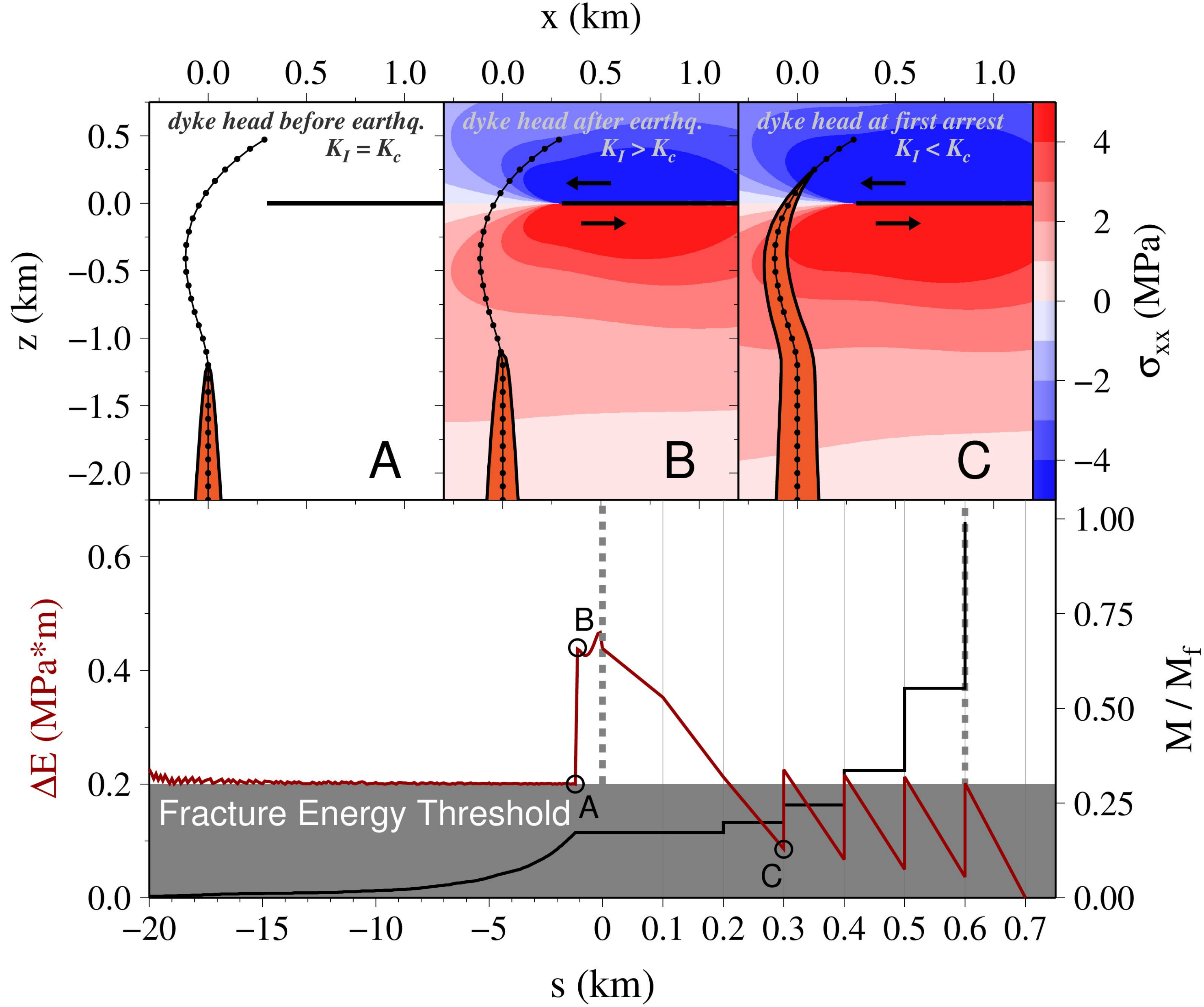
3) Topography and dike-fault interaction





3) Topography and dike-fault interaction

- Dike tip stops close to point C (s=0)
- Dike inflates and reaches 3.4 m opening without rem=suming propagation
- Dike opening concentrates on B-C



Rubin, 1995

lens cap) (photo courtesy of P Delaney). In (*b*), magma front (*arrow*) extends slightly beyond the intersection of the fault zone with the dike; crack followed by magma continues beyond top of photo. A small amount of magmatic material has infiltrated the fracture zone. (Lens cap has been moved to the opposite side of the dike.)

Mechanical model: conclusions

• The numerical model shows that interaction with the pre-existing fault system explains efficient dyke arrest provided that:

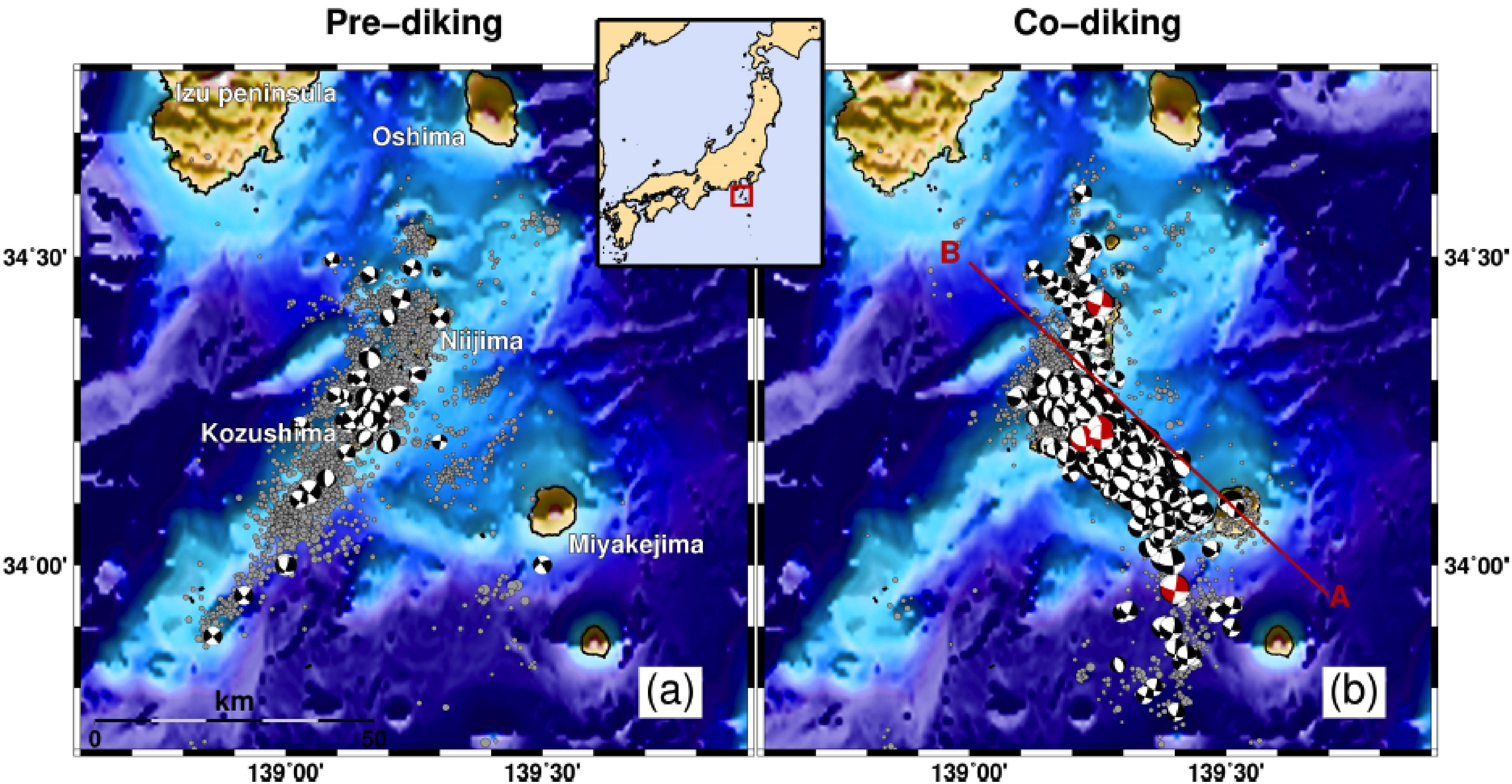
1) The fault was pre-loaded (-> a dyke does not get itself arrested by inducing faulting)

2) A shear stress rate was active on the fault (-> additional pre-loaded faults and asperities breaking one after another)

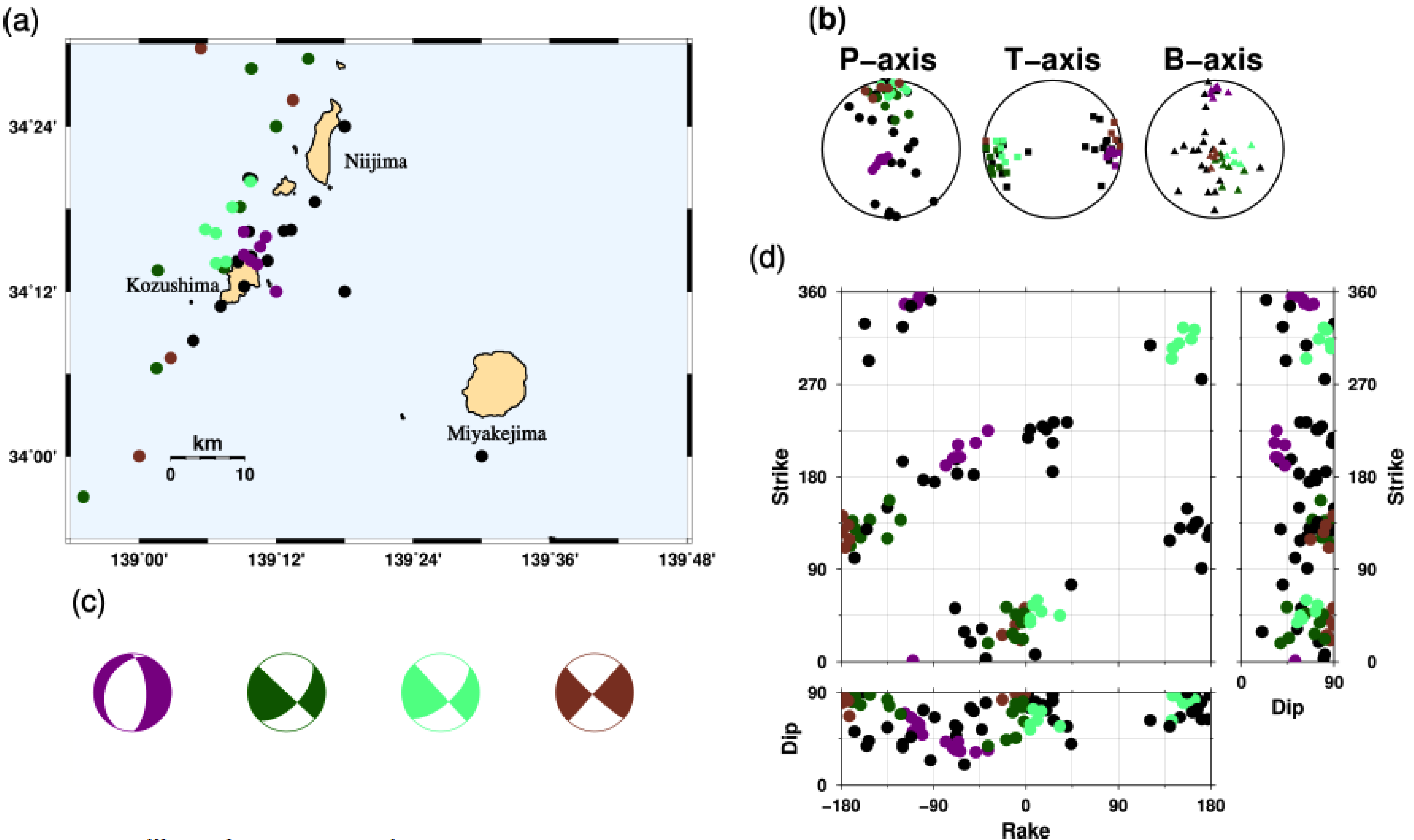
3) The topographic load is necessary to explain the 'confined' opening of the dike, and the propagating cloud of seismicity

4) Fracture energy values ~0.2-1 MJ m^(-2) (equivalent to ~100-200 Pa m^(1/2)) and areal inflow rate ~ are consistent with the other parameters

Focal mechanisms

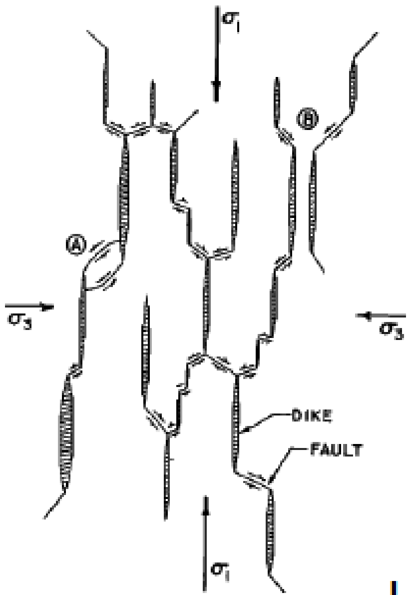


Focal mechanisms: pre-diking

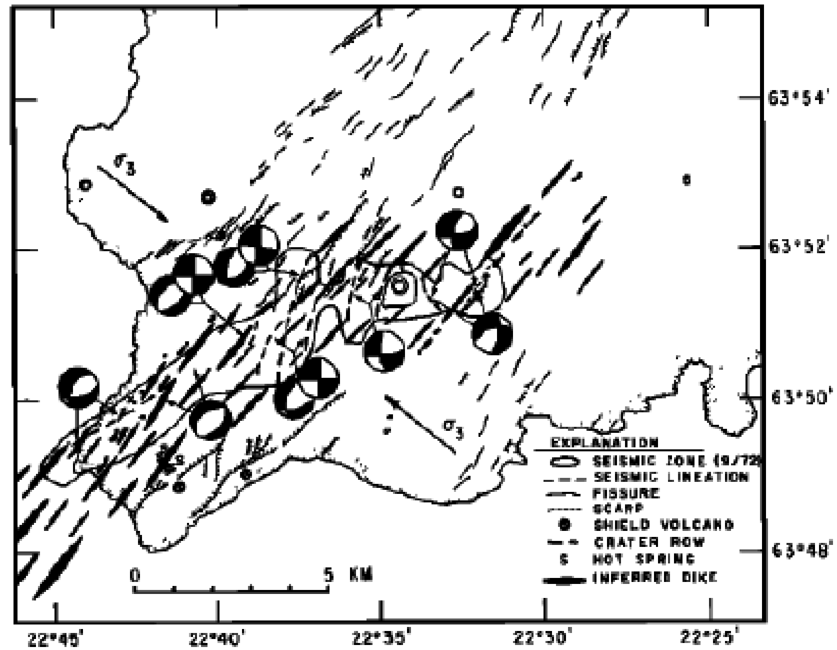


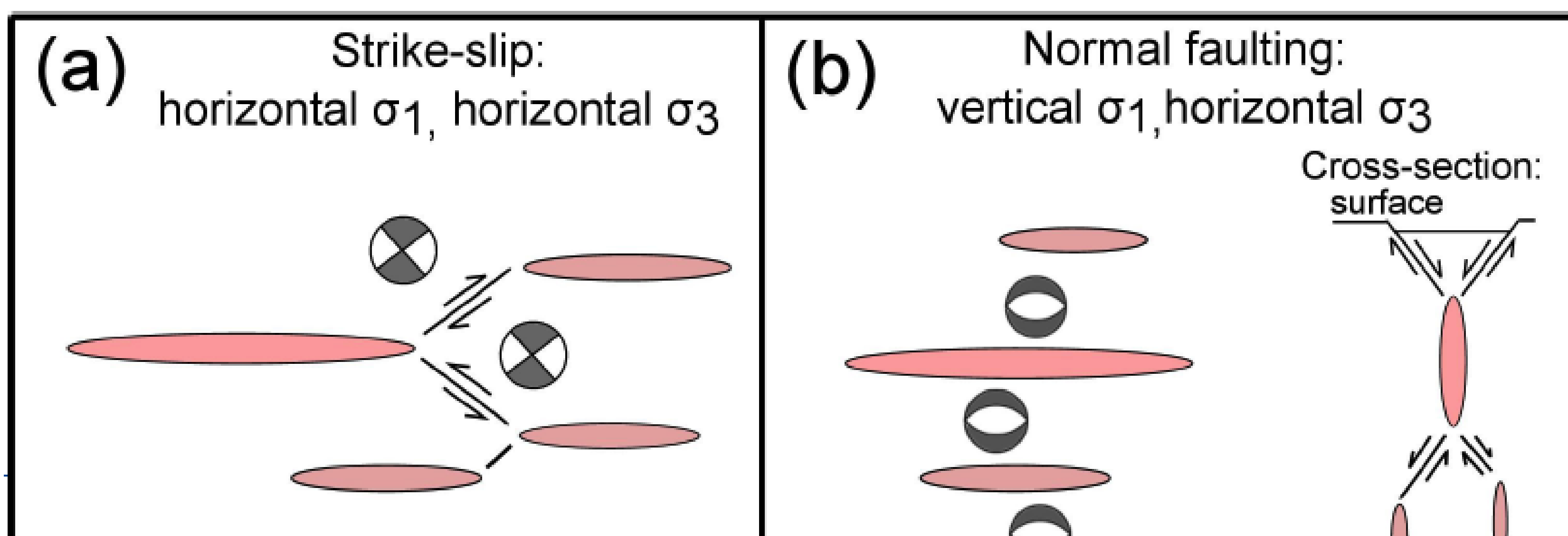
Passarelli et al 2015 *JGR in press*

Focal mechanisms: previous models



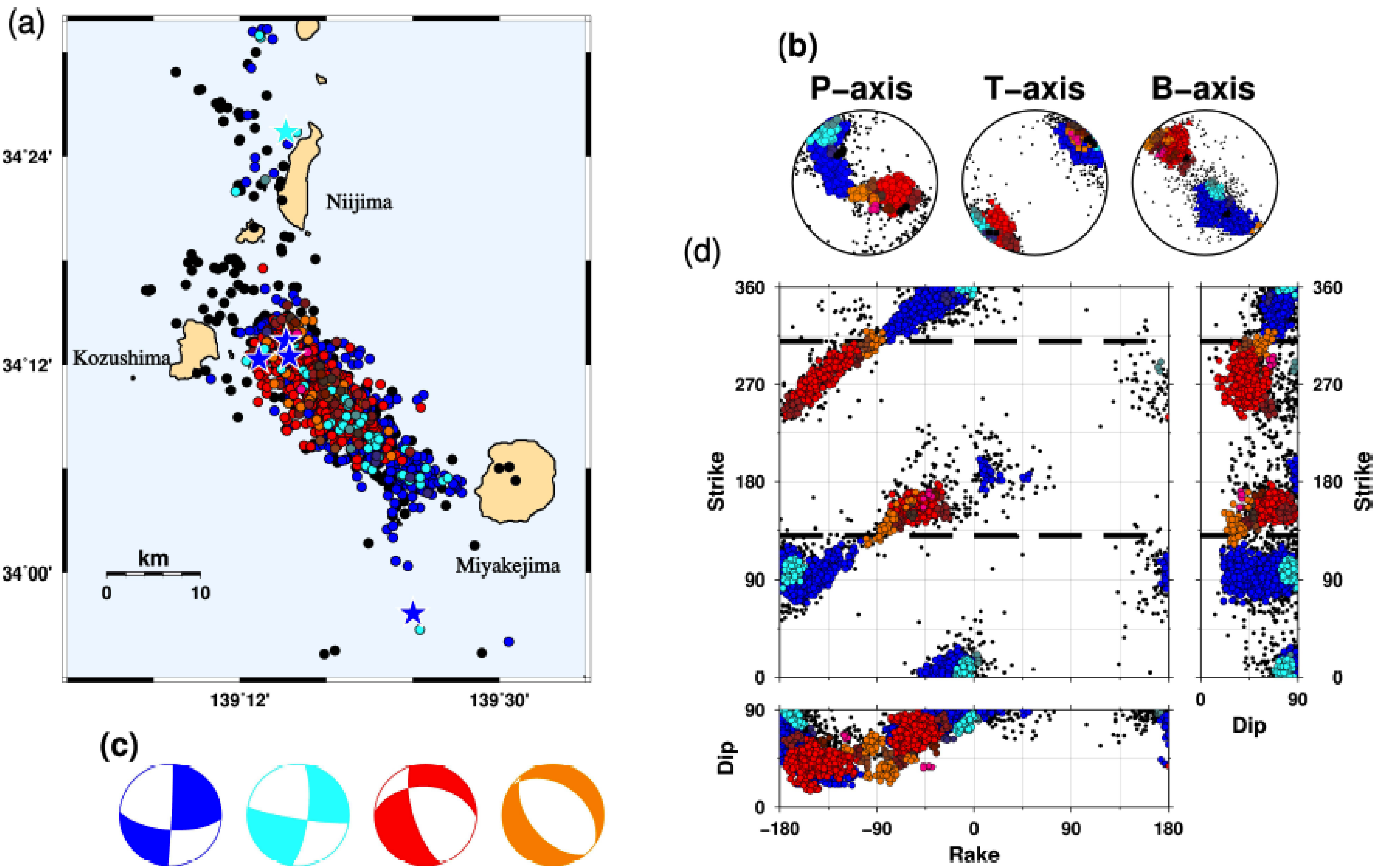
Hill, 1977



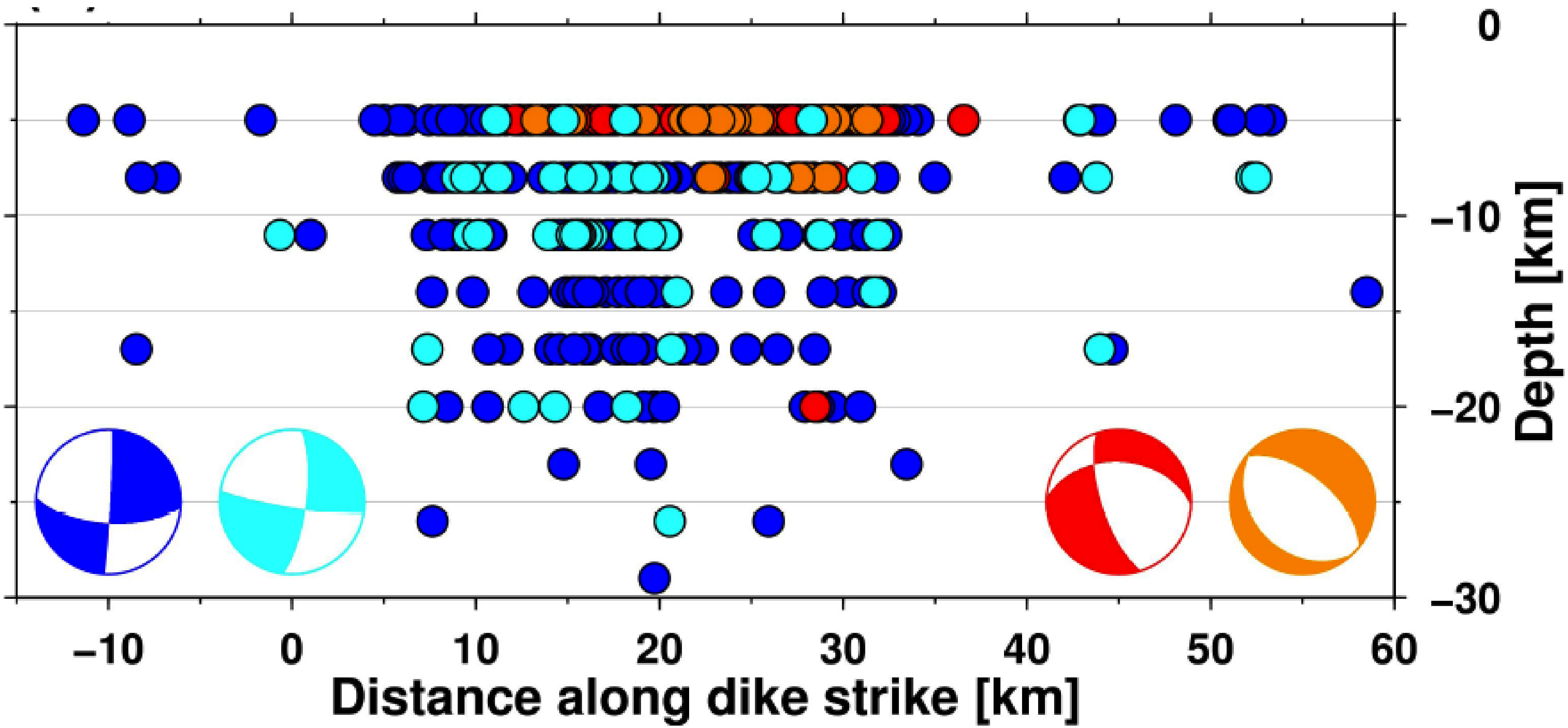


Passarelli et al 2015 submitted JGR

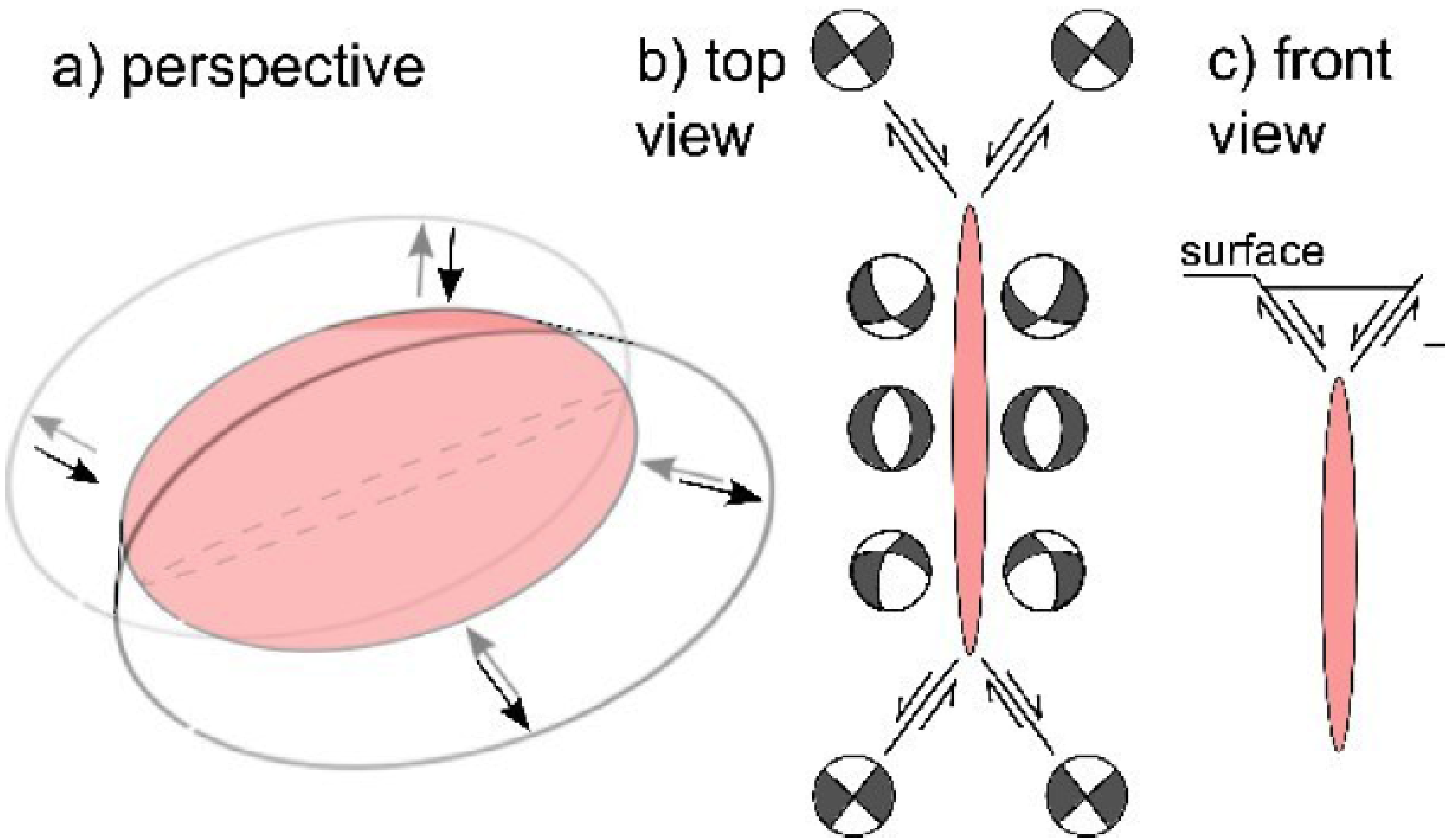
Focal mechanisms: co-diking



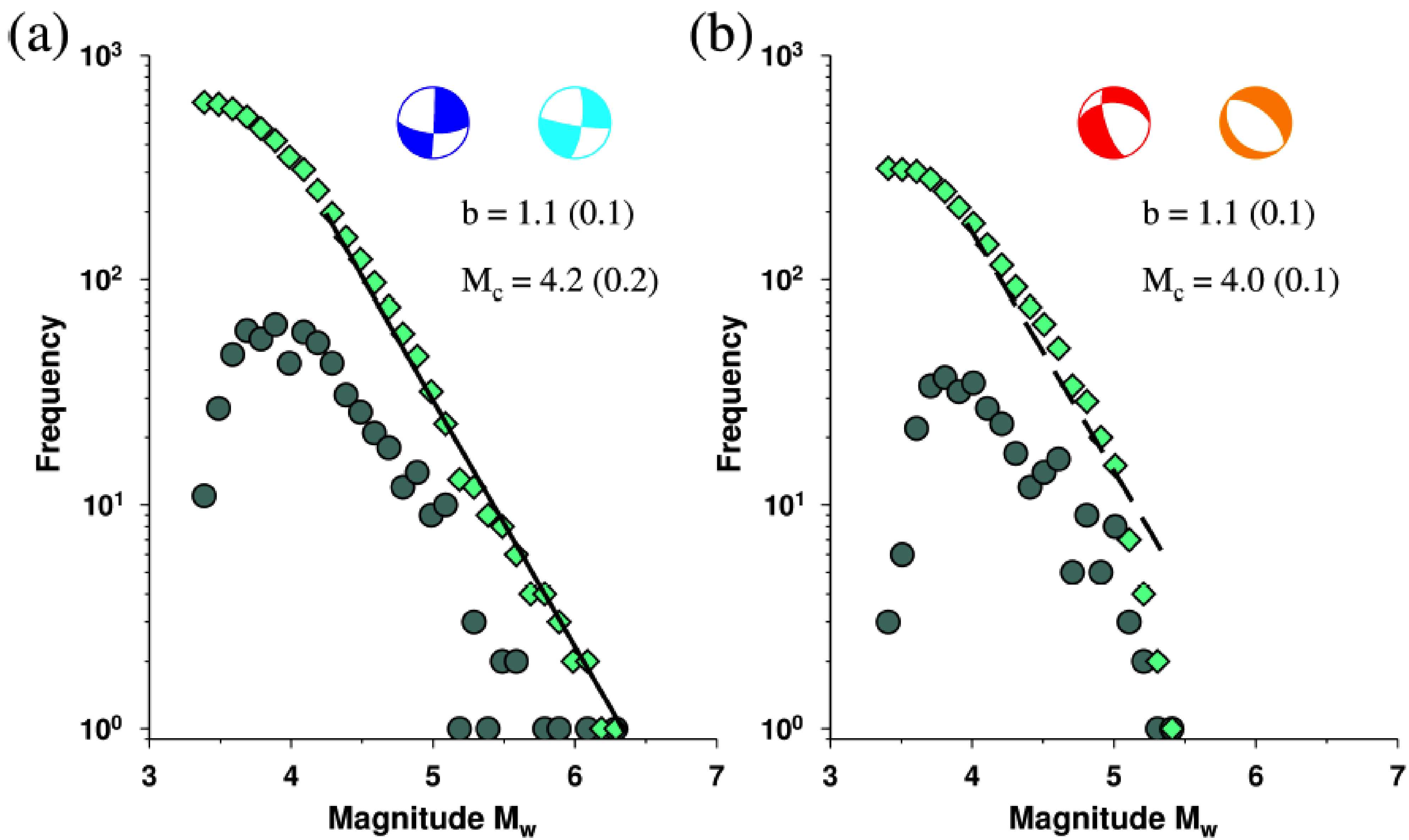
Focal mechanisms: depth



Focal mechanisms: depth



Focal mechanisms: statistics



Focal mechanisms: statistics

Seismic *b*-values in volcanic areas have large variability.

Influenced by:

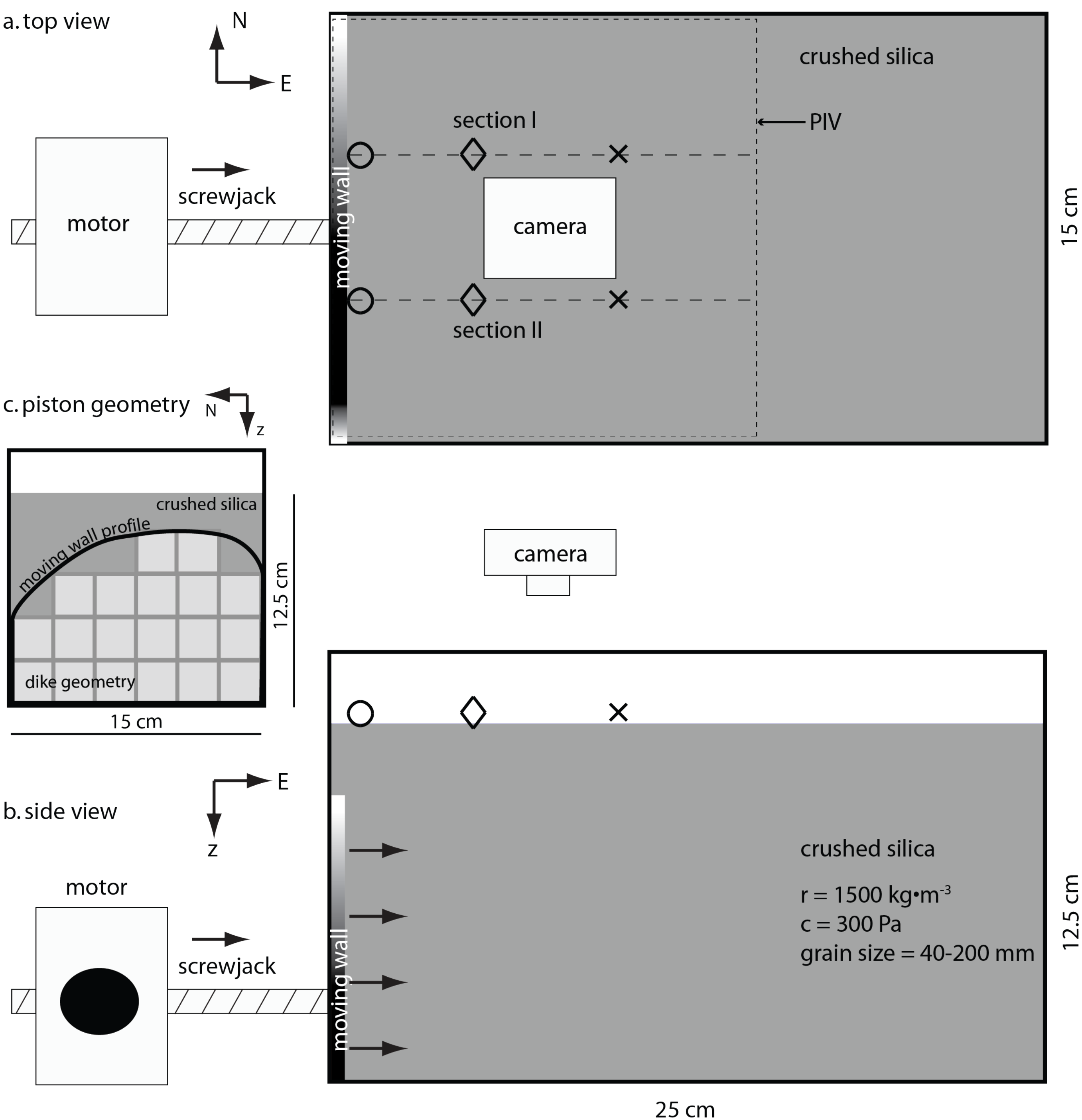
State of stress:

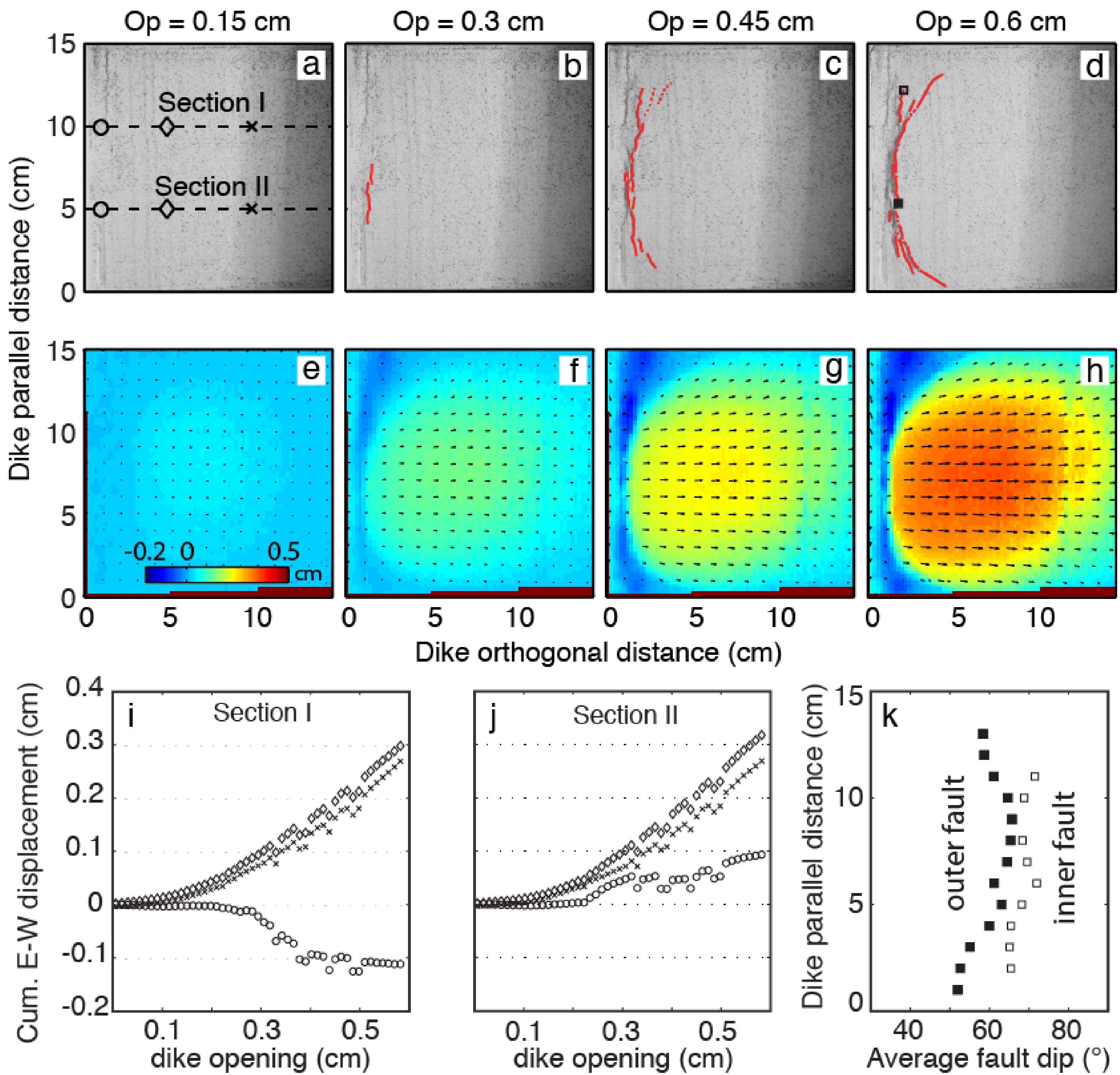
- Stress (Scholz, 1968, Schorlemmer, 2005),
- Thermal stresses
- Pore pressure (Wyss, 1973)

Material heterogeneities:

- Fracture density (Mogi, 1962)
- Material rheology (Amitrano, 2003, Bean et al., 2013)
- Limited thickness of competent rock layers (Becker et al., 2012)

Analog model





Op = 0.15 cm
Op = 0.3 cm
Op = 0.45 cm
Op = 0.6 cm
a
b
c
d
Section I
Section II
e
f
g
h
-0.2 0 0.5
cm
Dike parallel distance (cm)
Dike orthogonal distance (cm)
i
Section I
j
Section II
k
outer fault
inner fault
Cum. E-W displacement (cm)
dike opening (cm)
dike opening (cm)
Dike parallel distance (cm)
Average fault dip (°)