



Weald Basin 2018

Earthquake Cluster Analysis

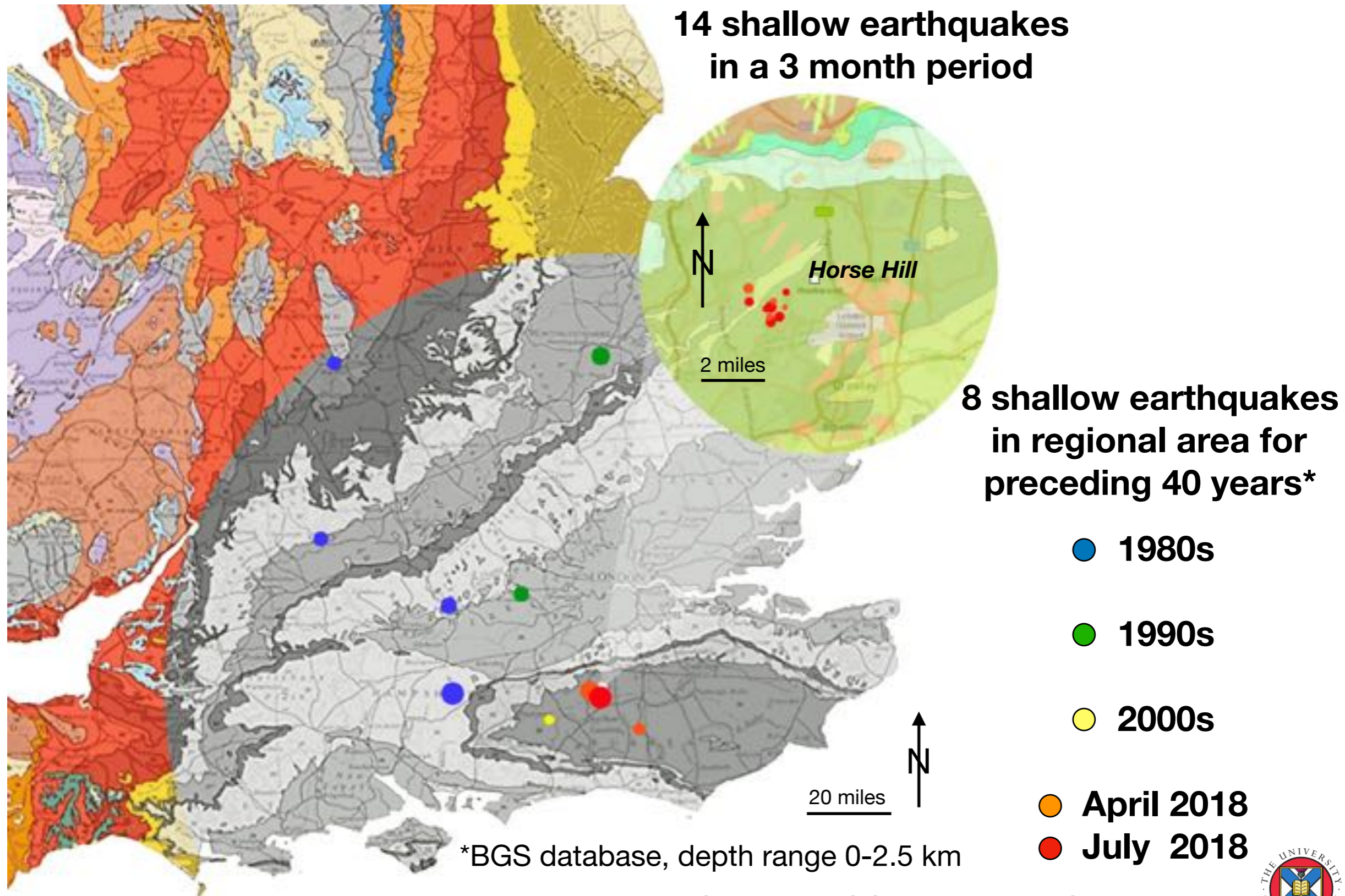
Does Horse Hill meet Davis & Frohlich (1993) criteria for induced earthquakes?

Stuart Haszeldine & Andrew Cavanagh
University of Edinburgh

Davis & Frohlich (1993) Criteria:

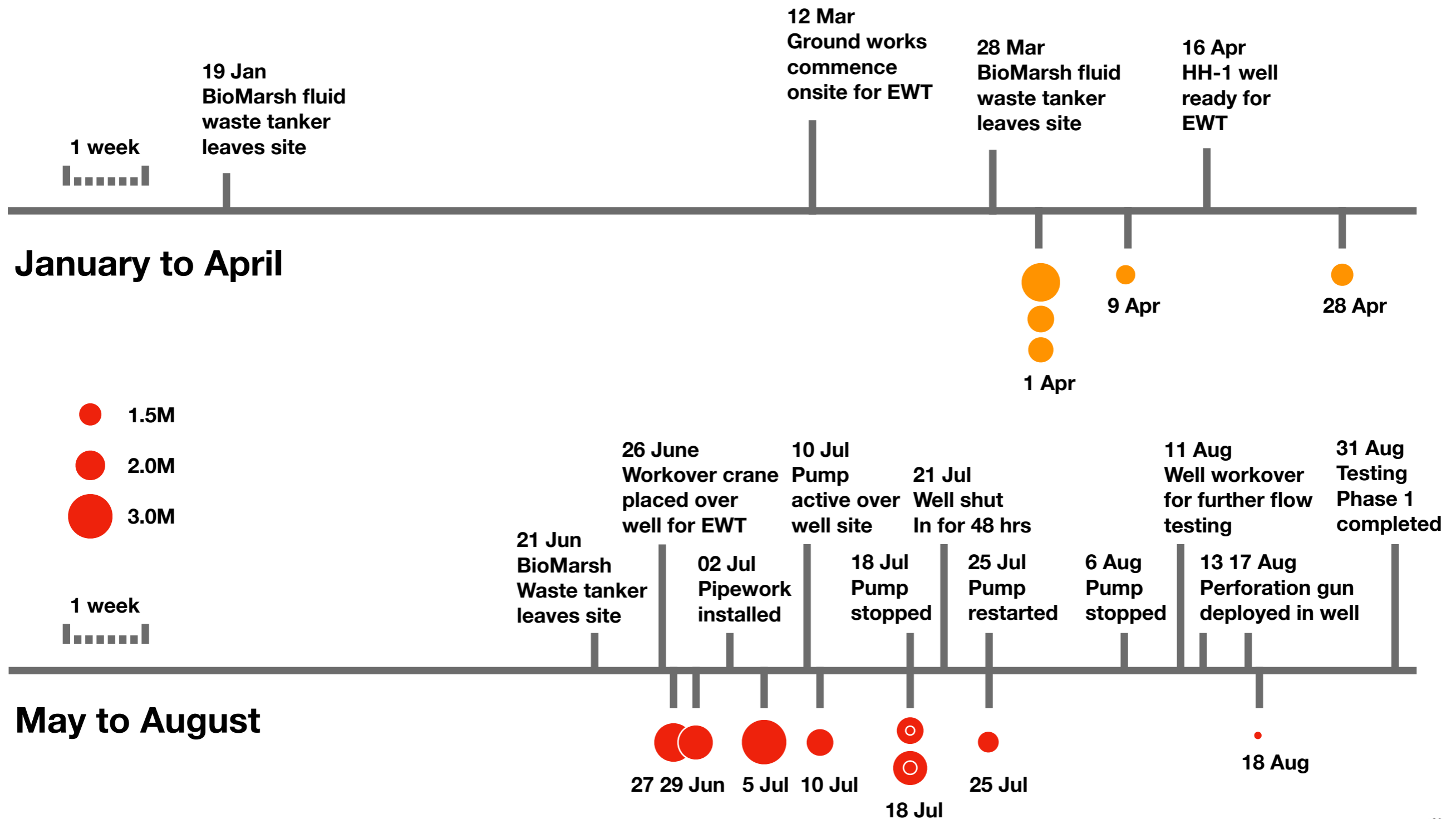
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Yes... without precedent for the Weald Basin.
2. Is there a correlation with HH-1 operations?
Yes... the Horse Hill timeline is compelling.
3. Are the earthquakes close (5 km) to the HH-1 well location?
Yes... the cluster and M3 event are only 3 km away.
4. Do the seismic events occur near HH-1 exploration target depths?
Yes... the target zones are within the range of better-constrained events.
5. Do geological structures connect HH-1 to the cluster?
Yes... a normal fault passes NE-SW through the cluster and well location.
6. Are subsurface changes in fluid pressure sufficient to cause seismicity?
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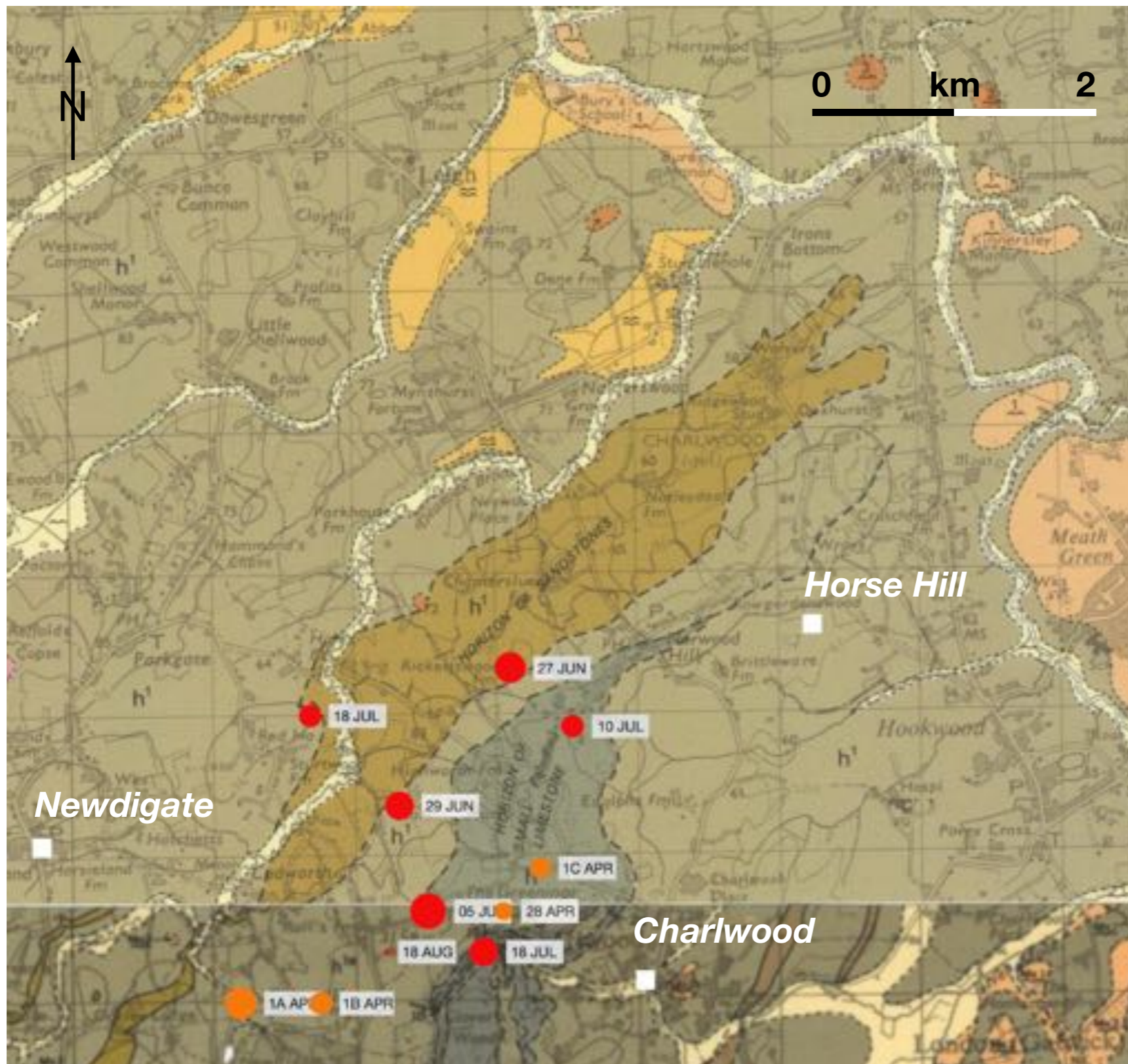


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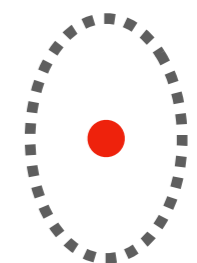
BGS Hypocentres

- April 2018
- July 2018

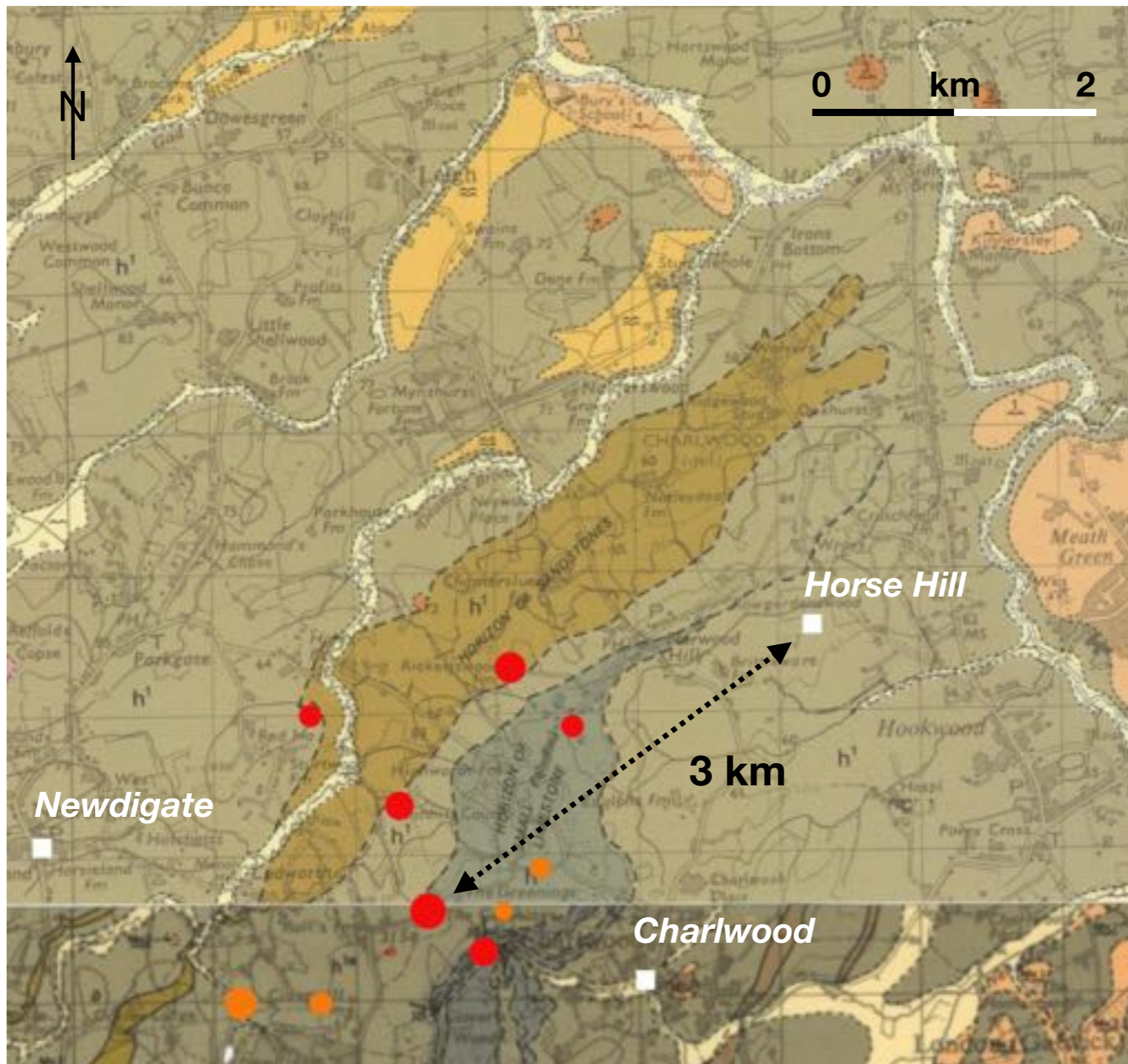
Earthquake magnitude

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Uncertainty ellipse +/- 0.005°



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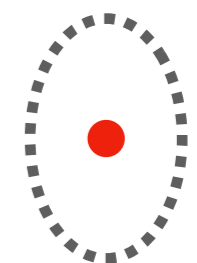
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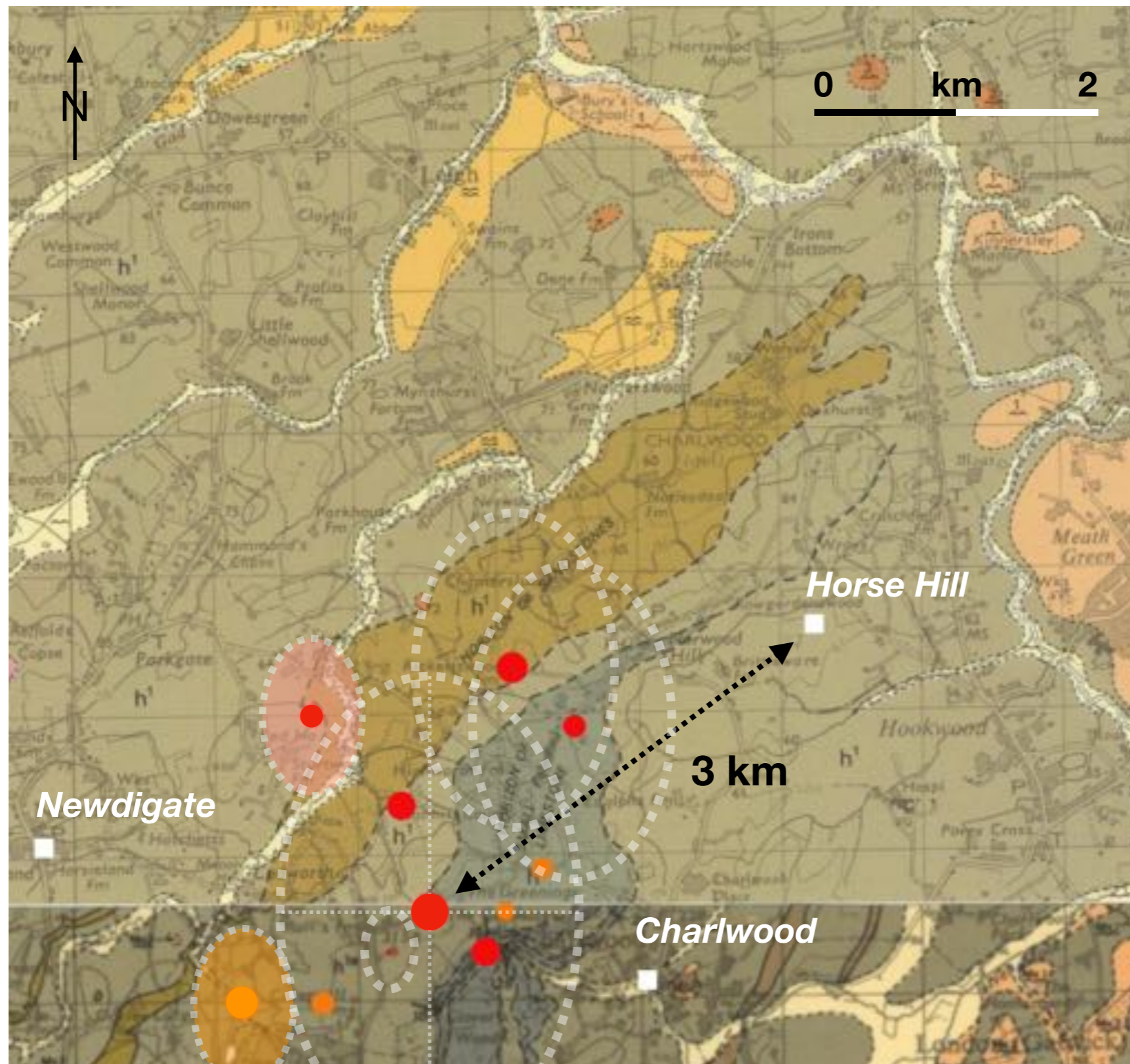
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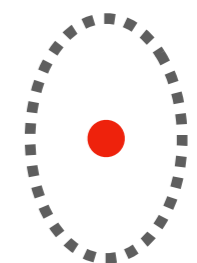
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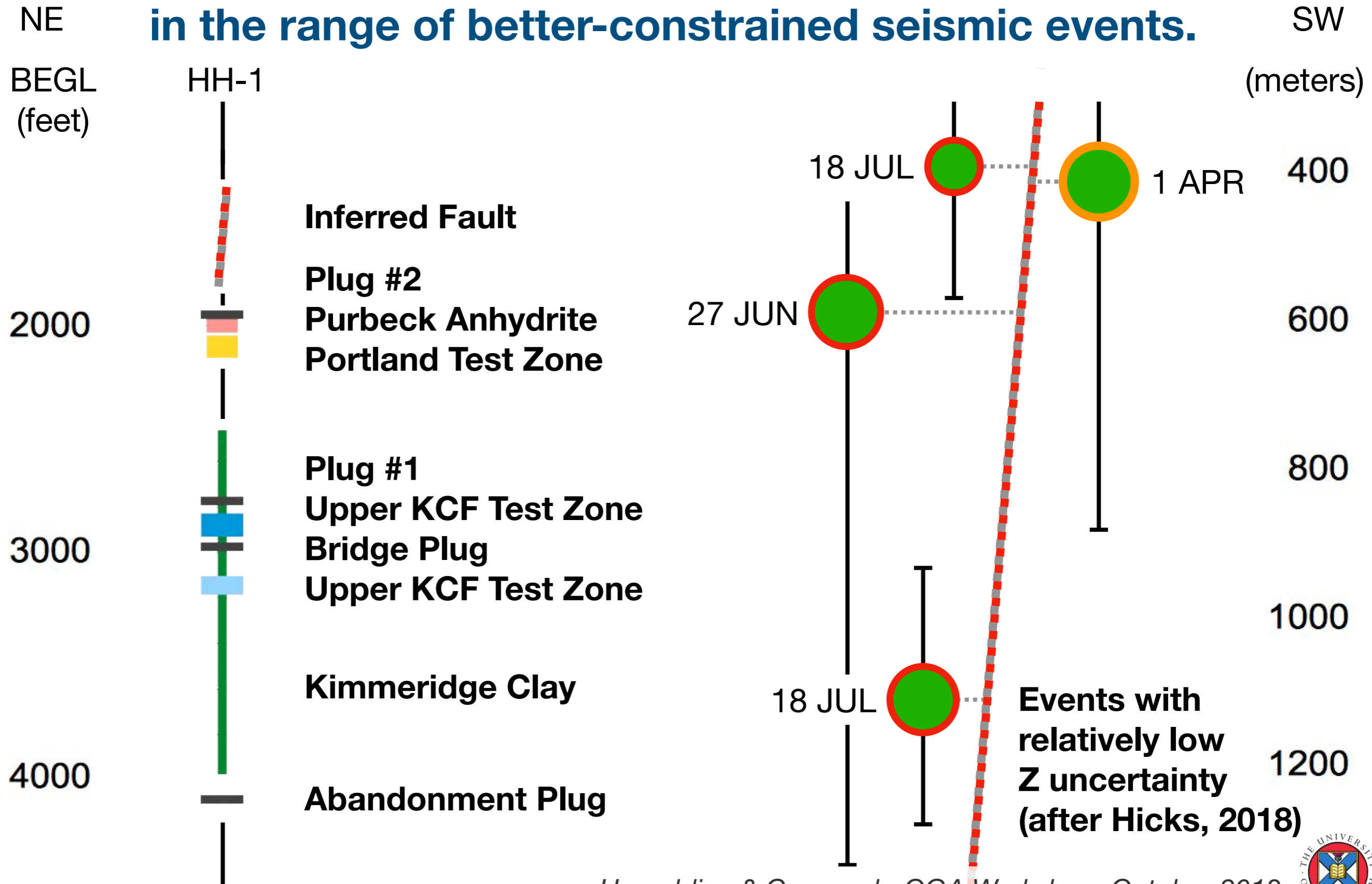
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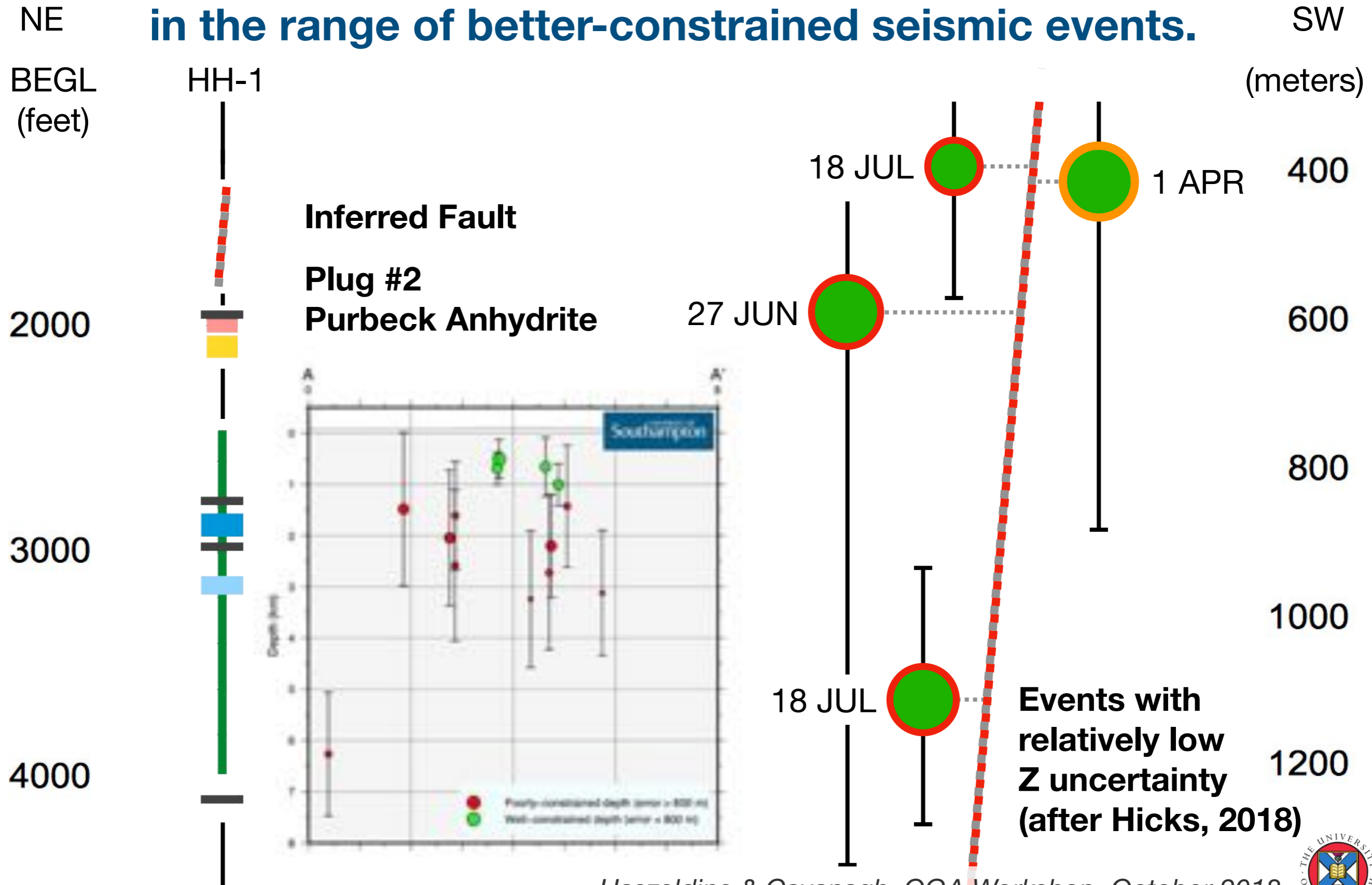
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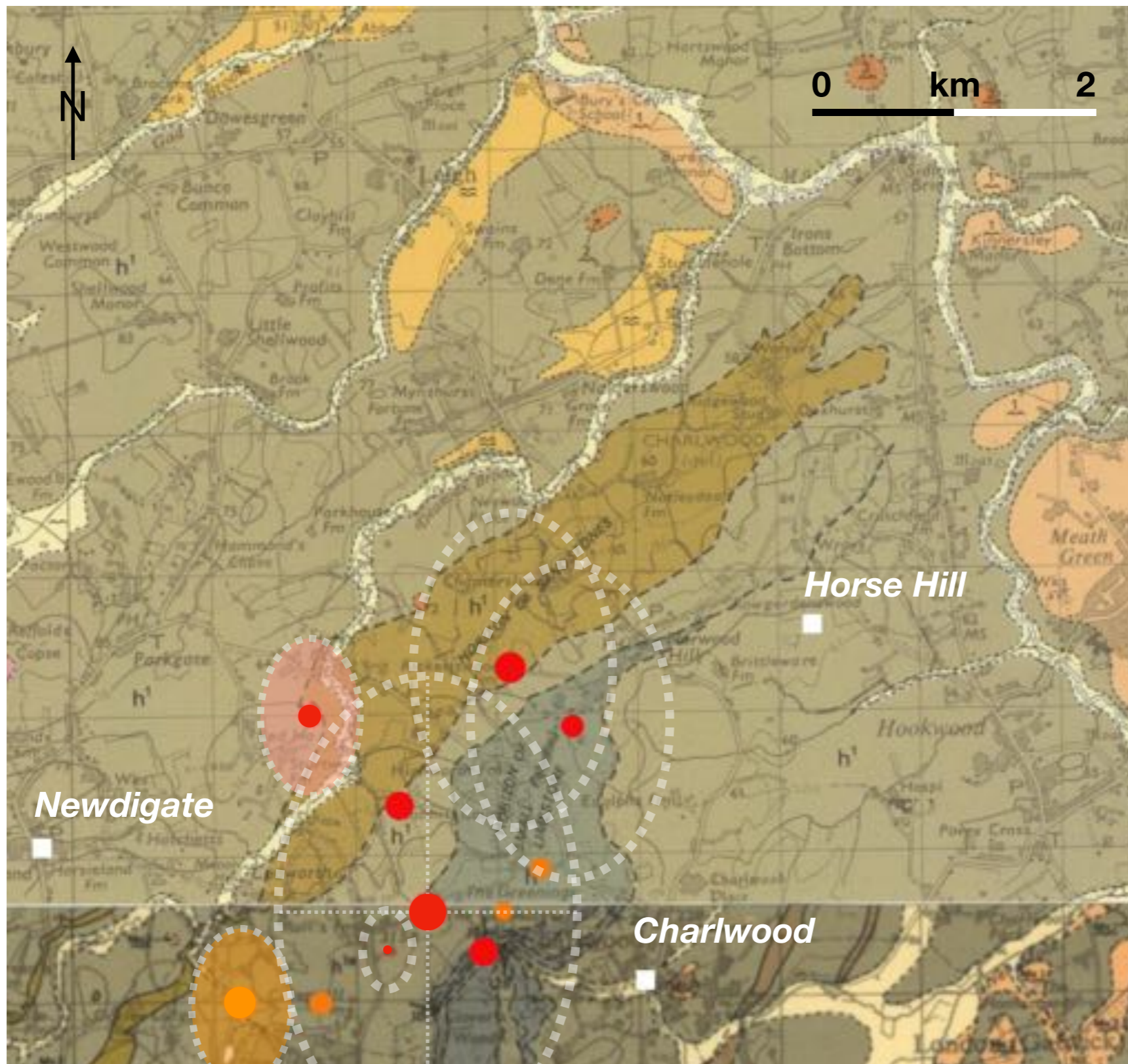


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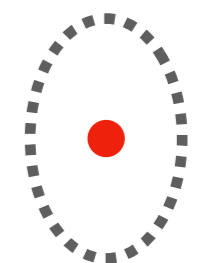
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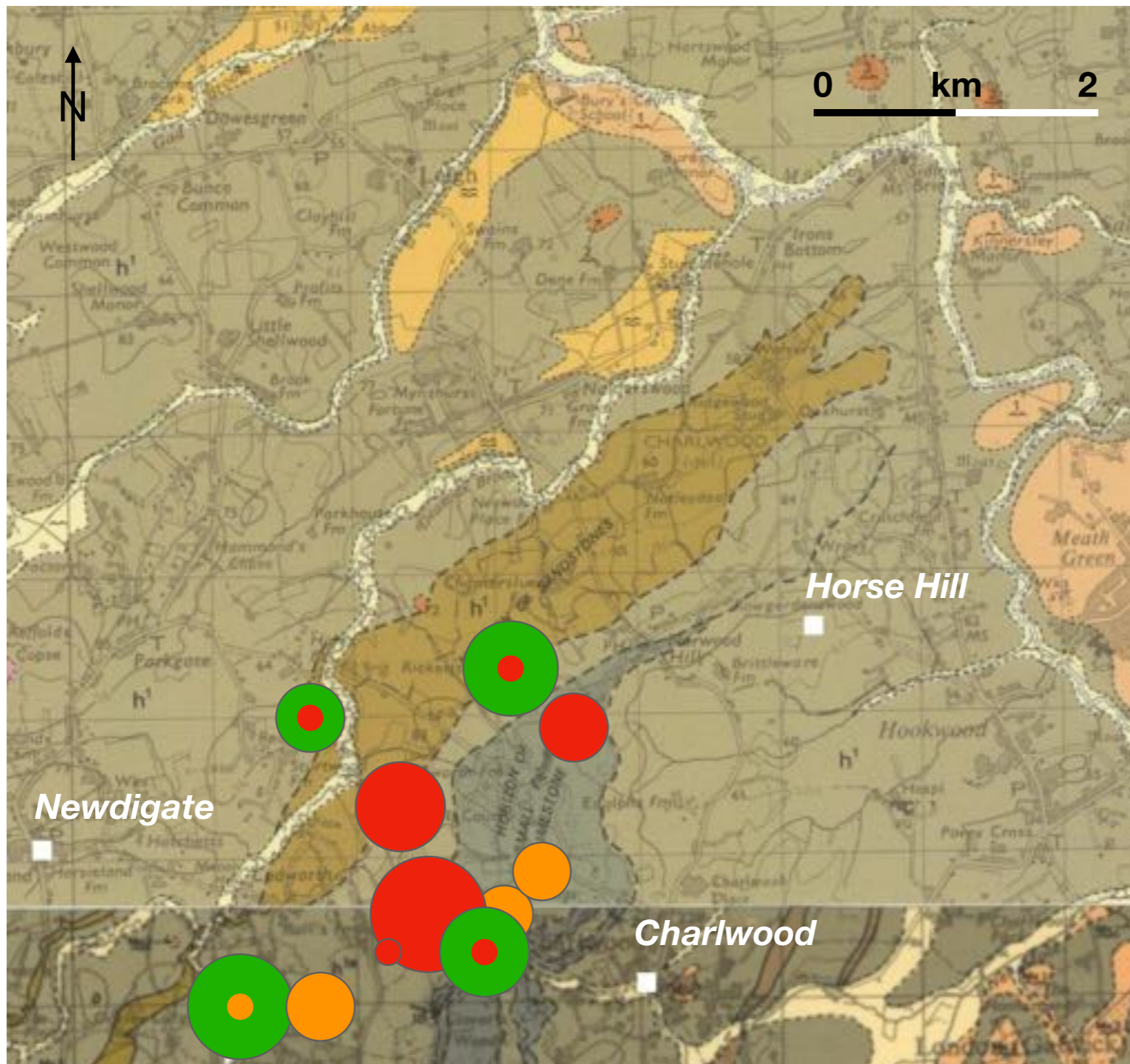
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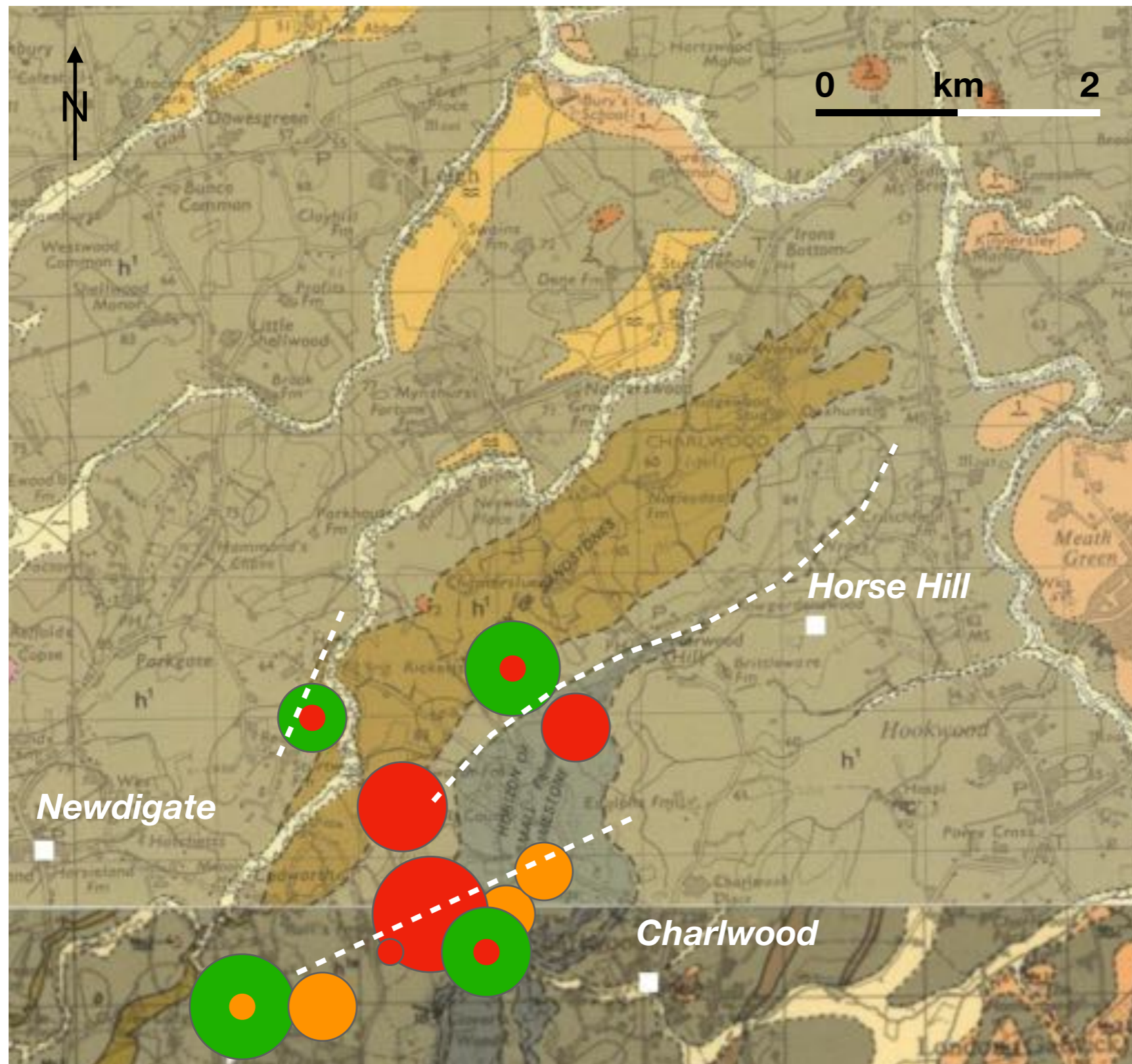
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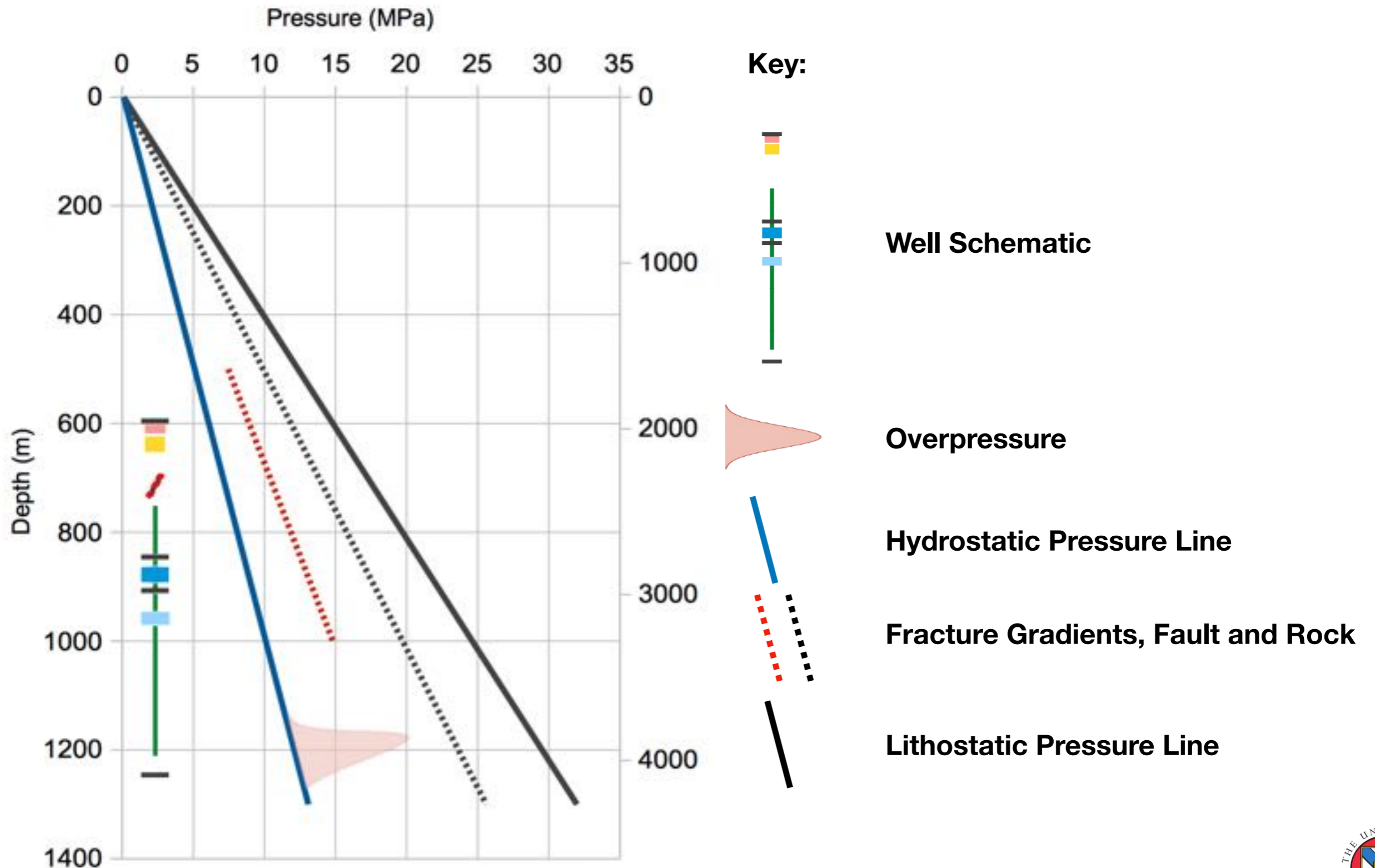
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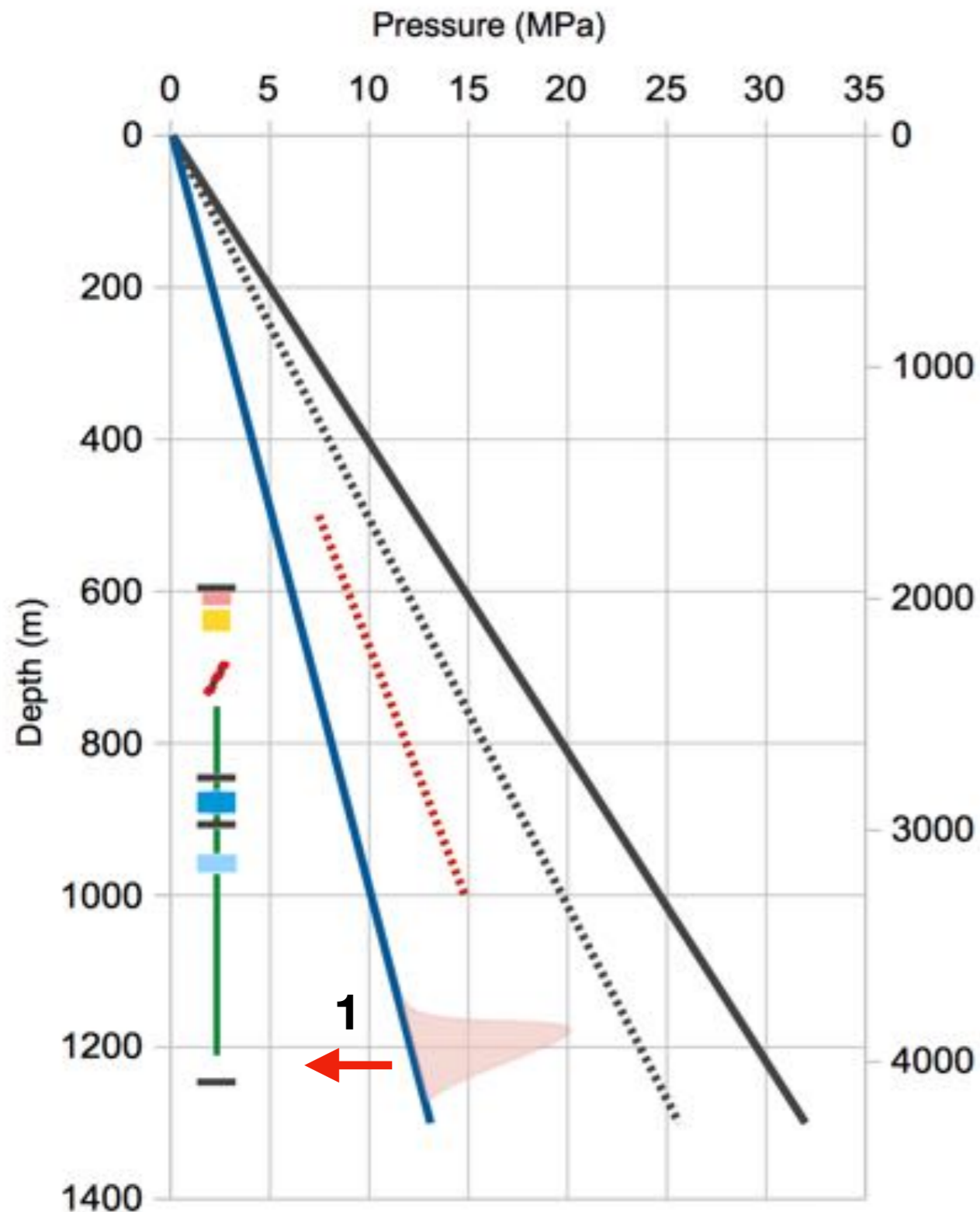
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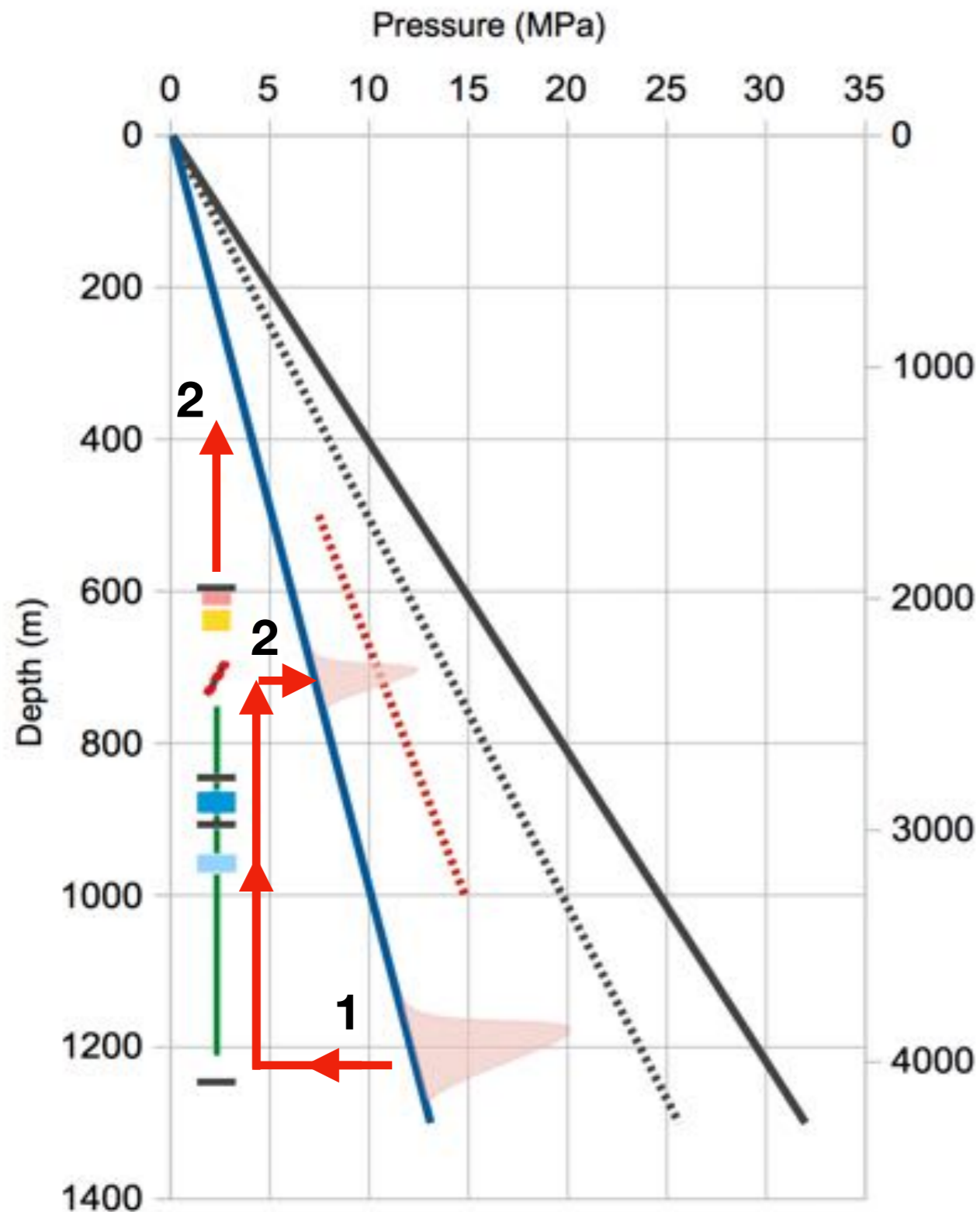
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Gradual Pressurisation

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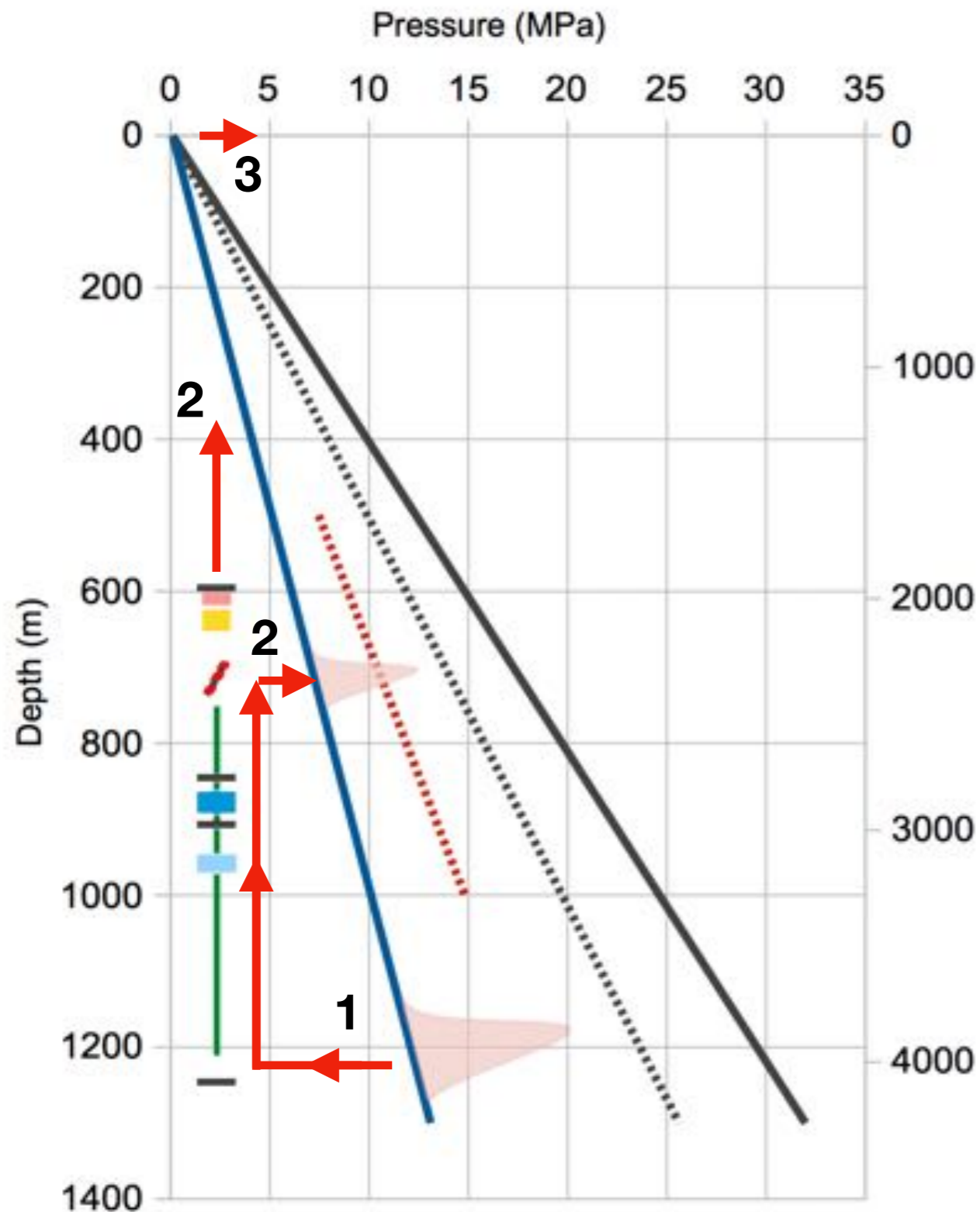
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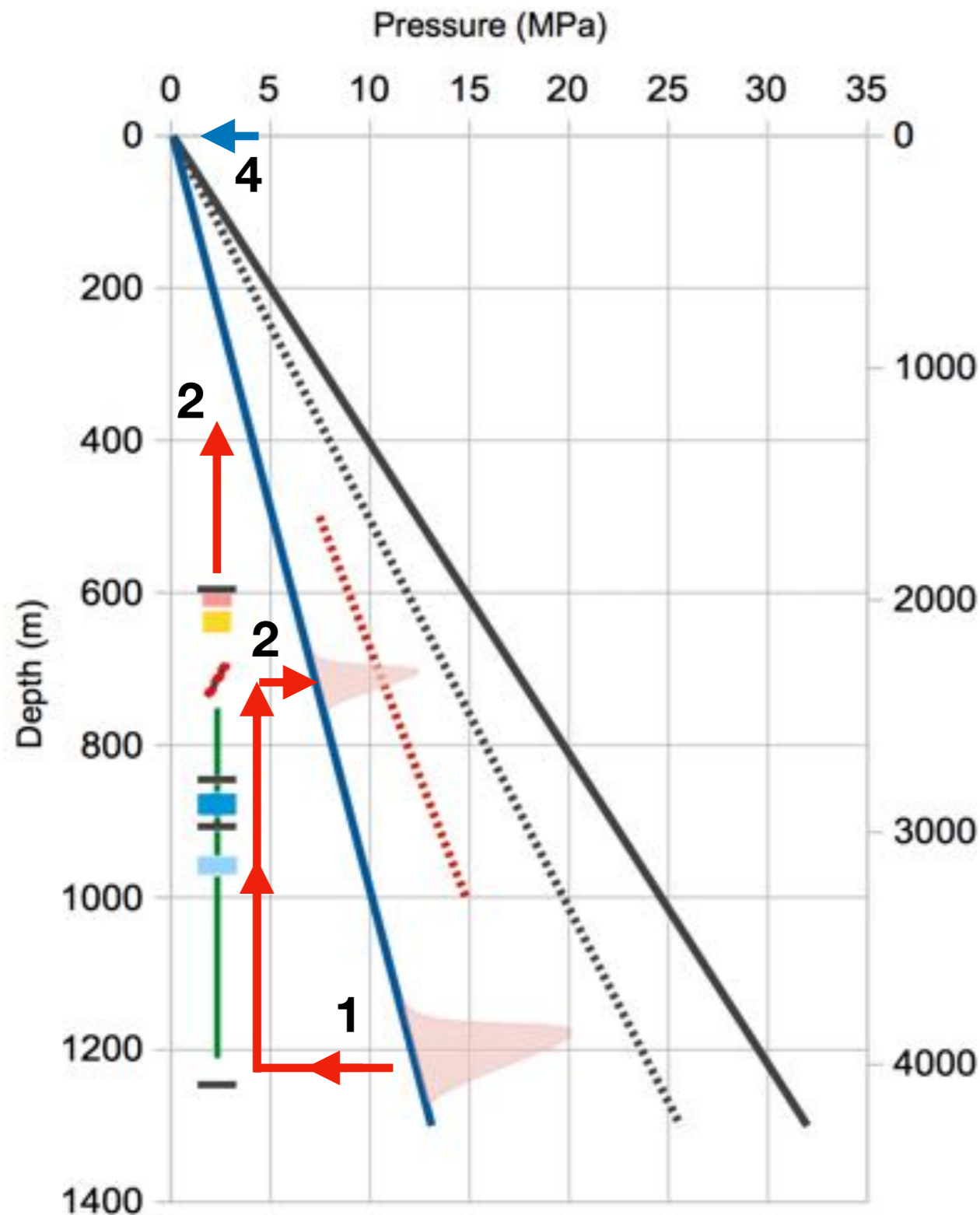
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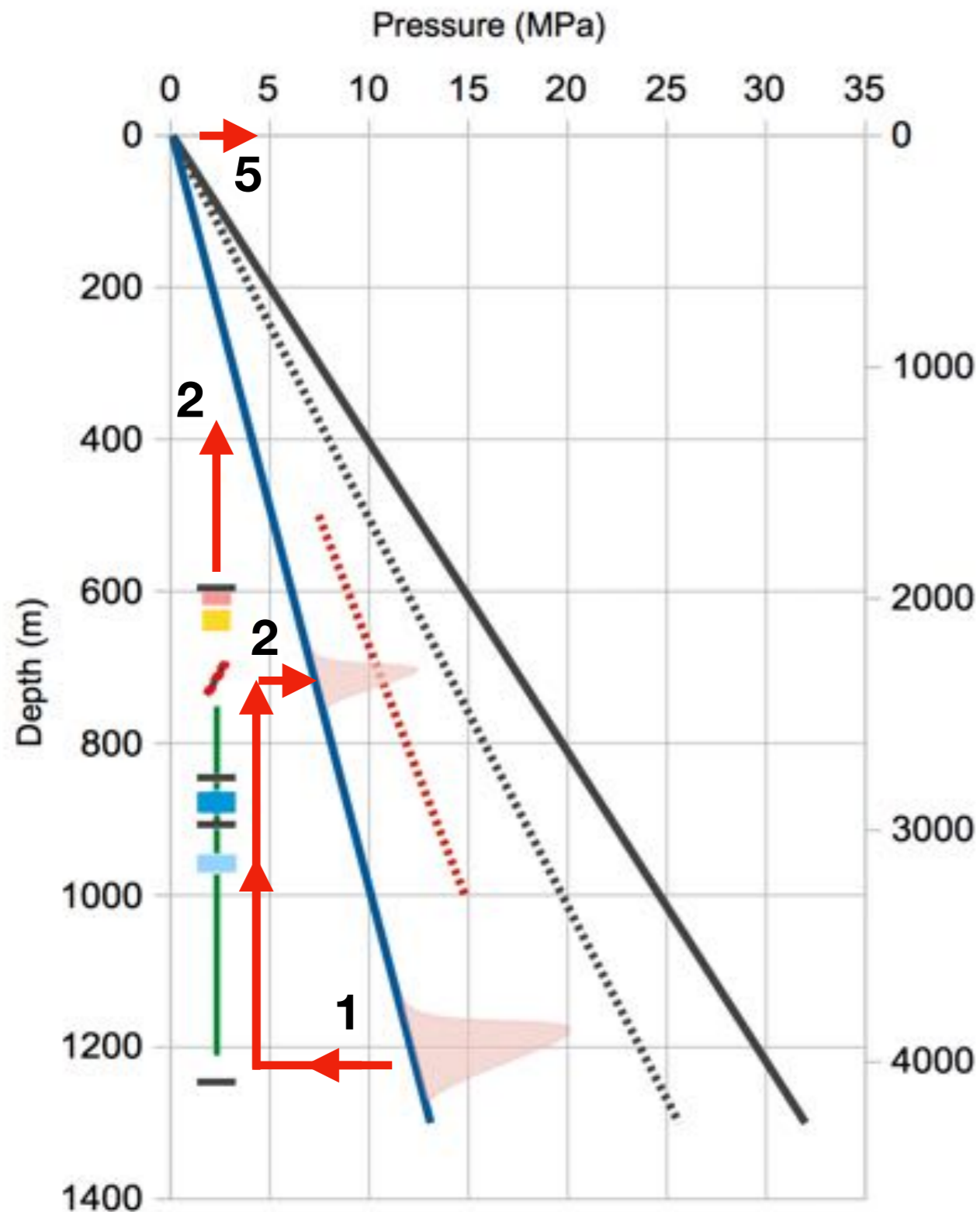
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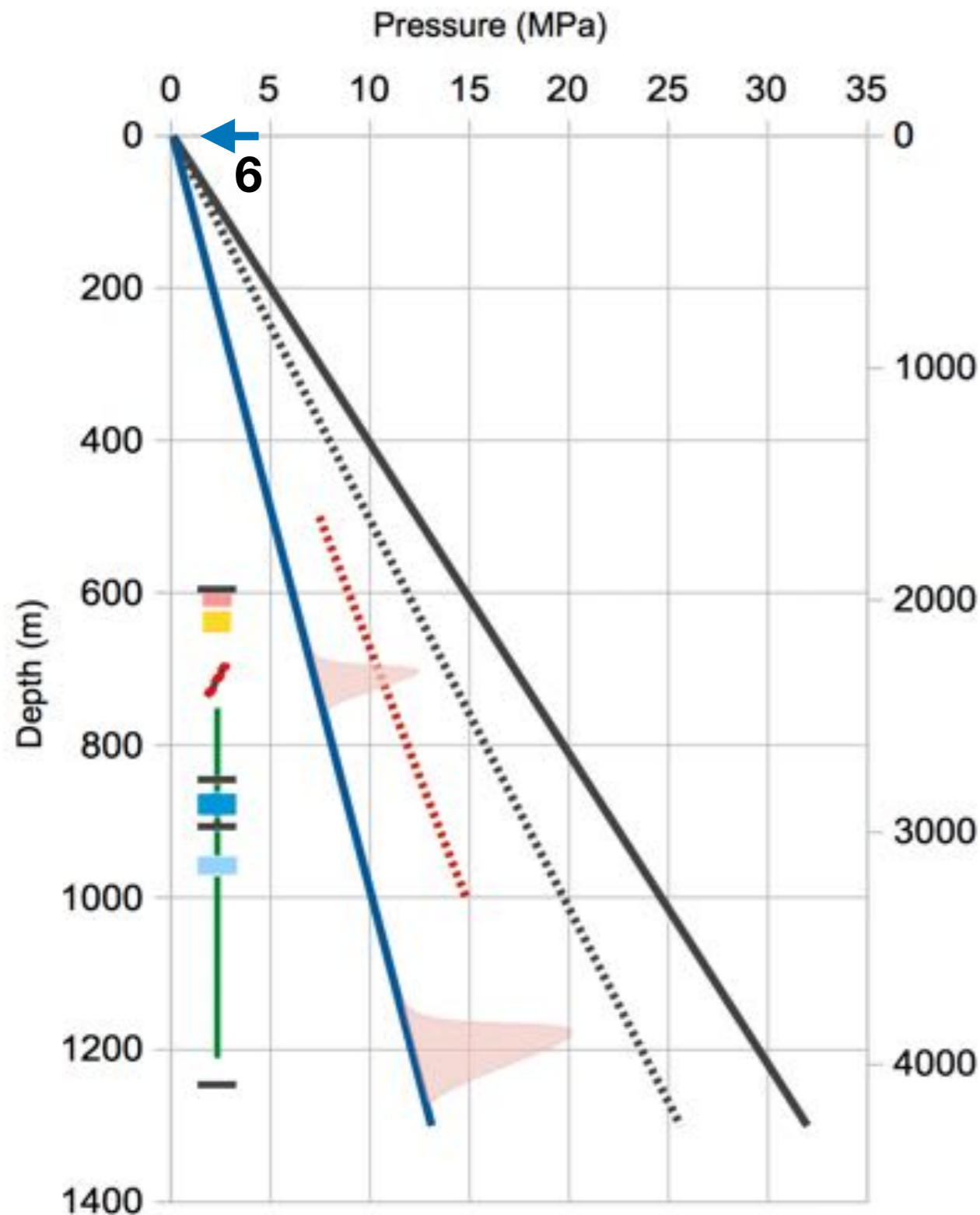
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5. The gas continues to charge the fault zone and annulus during shut-in period (2016-2018).

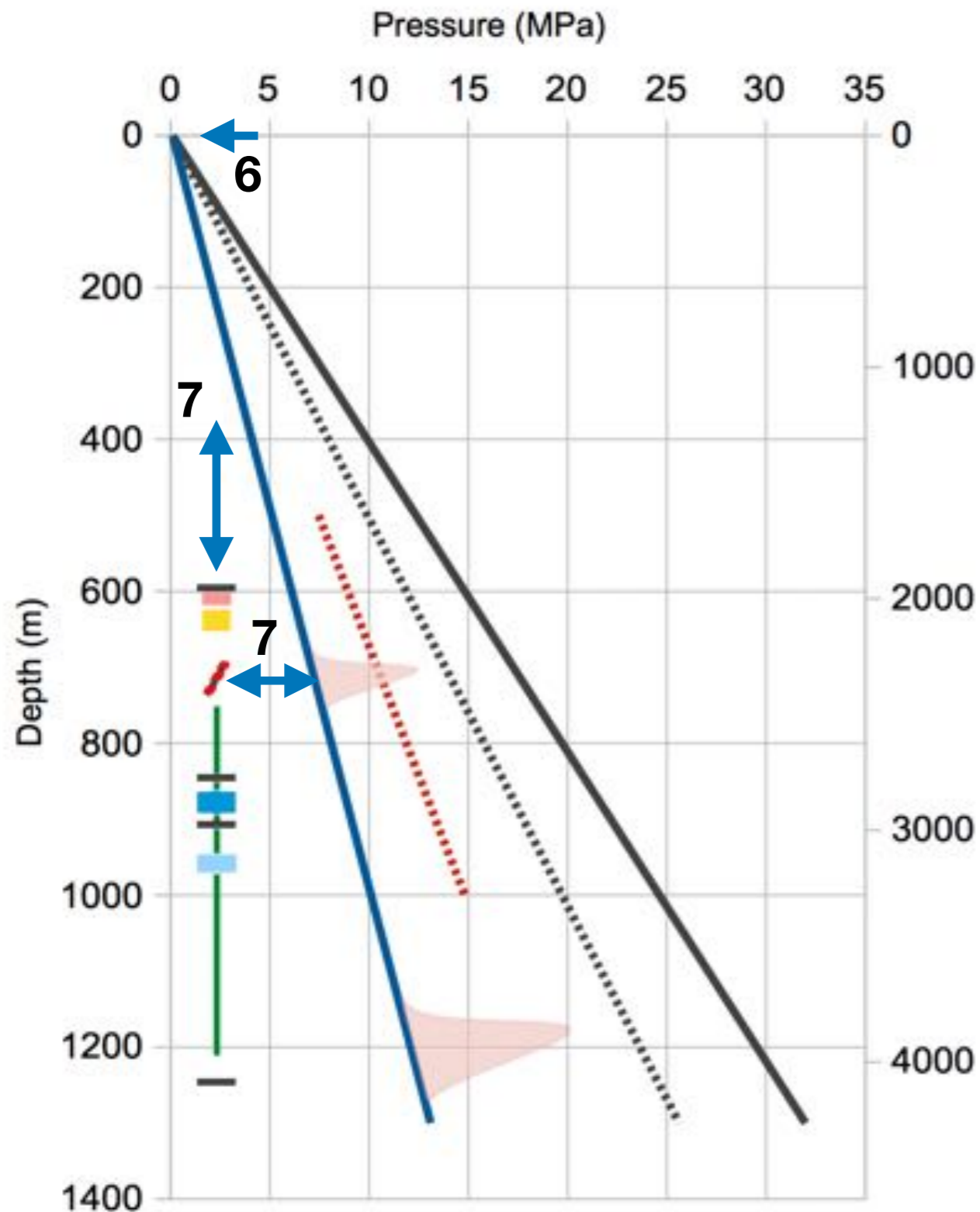
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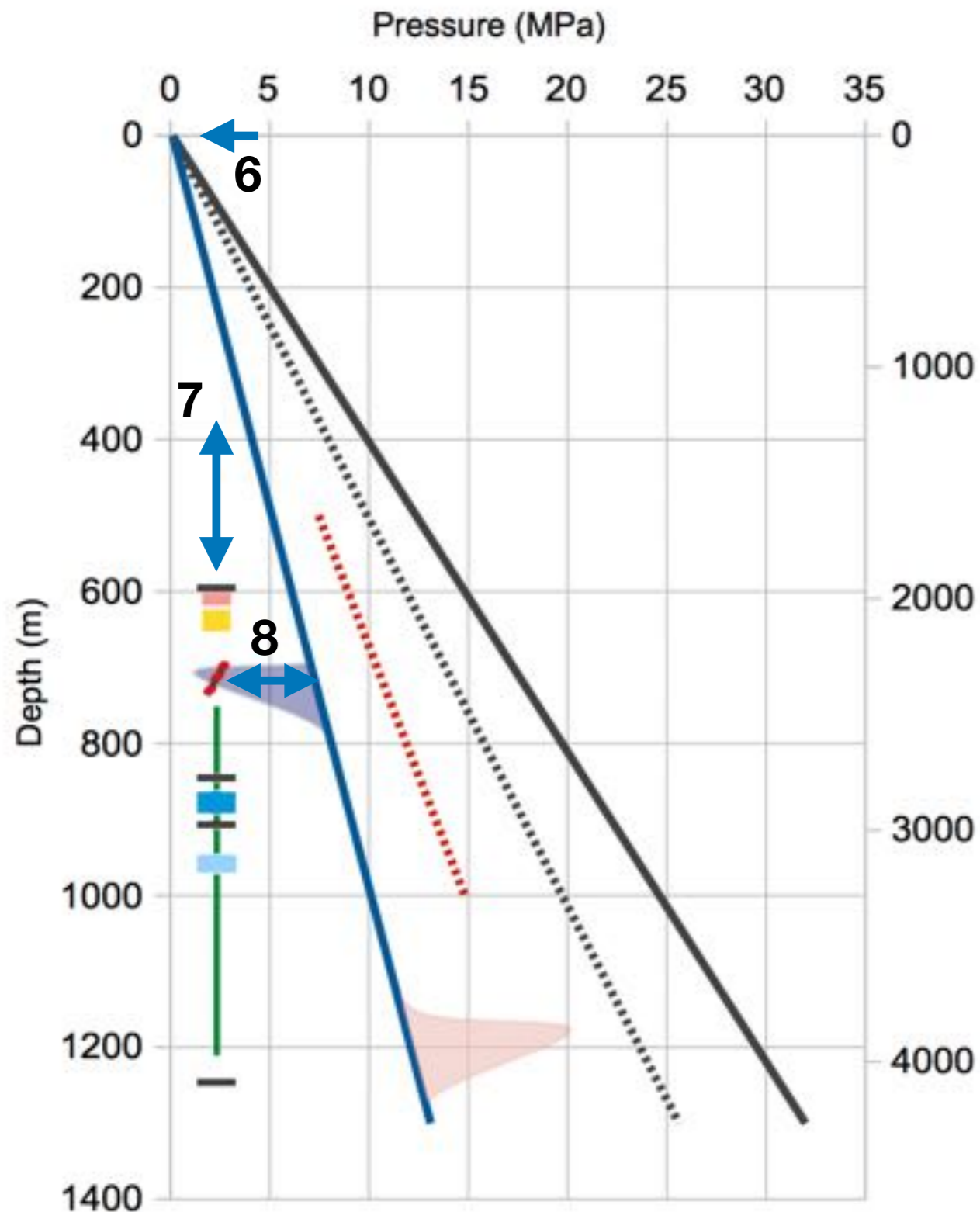


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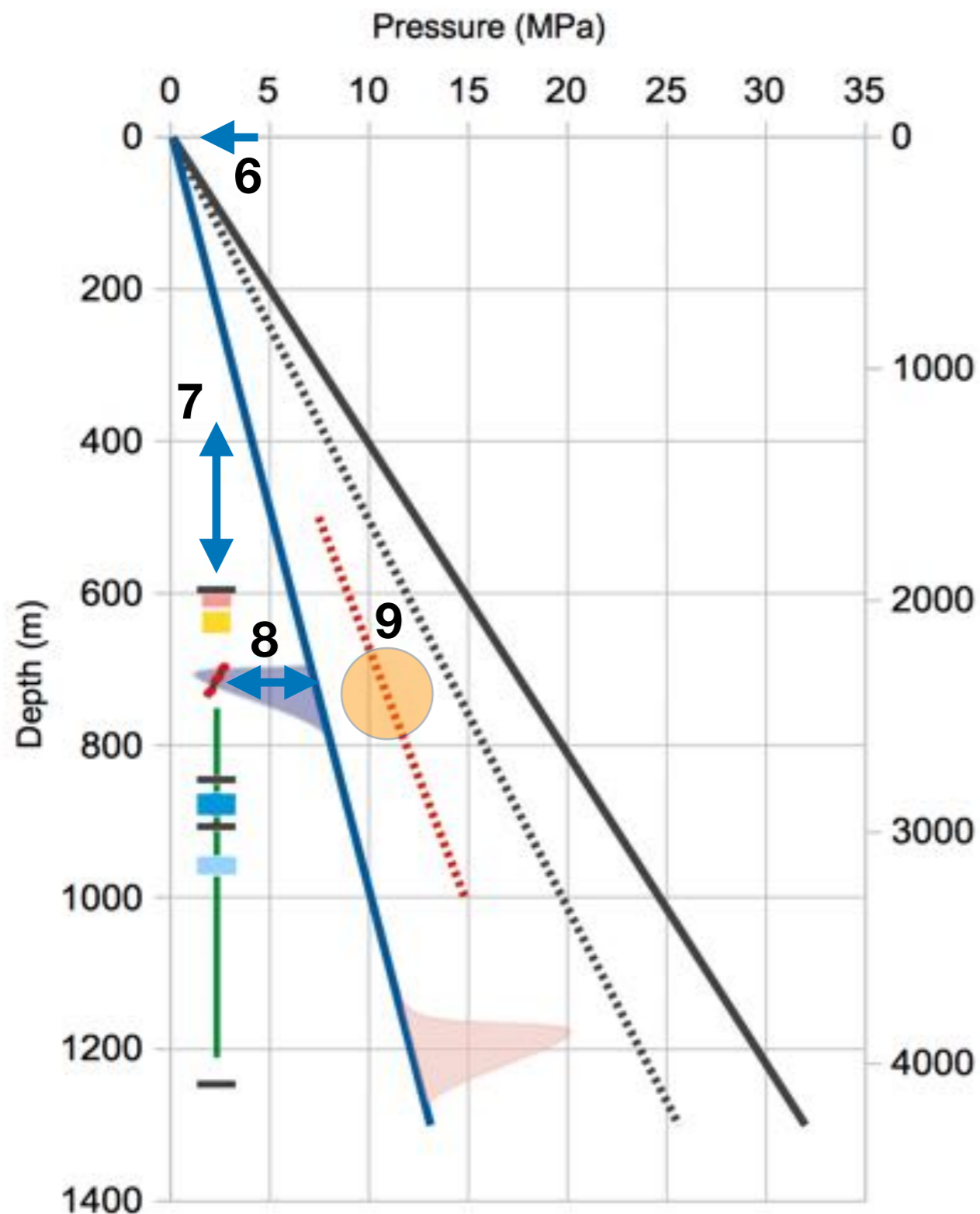
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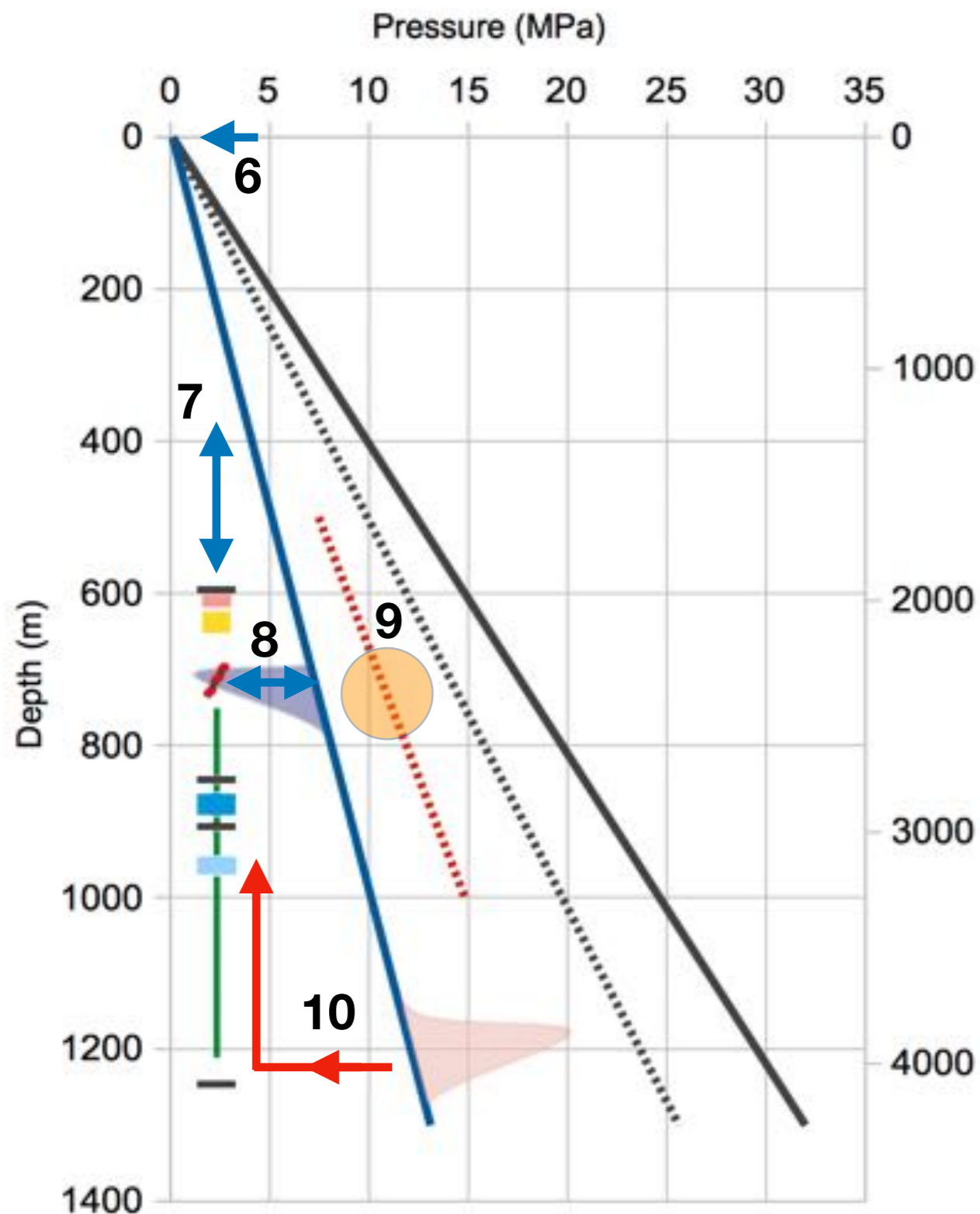
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10. The deep gas begins to recharge the annulus and fault zone to repeat the cycle.

D&F Criteria clearly support conclusion: HH-1 exploration induced Weald cluster.

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Tests for Hypothesis:

1: Pressure readings and sampling of annulus valve

2: Scrutiny of HH-1 well day logs and Horse Hill site logs

3: Local stress state analysis similar to BGS regional plot

4. Indications of km-scale pressure migration for small local events at HH-1 well such as perf' gun firing and M0 event at 2.5 km depth

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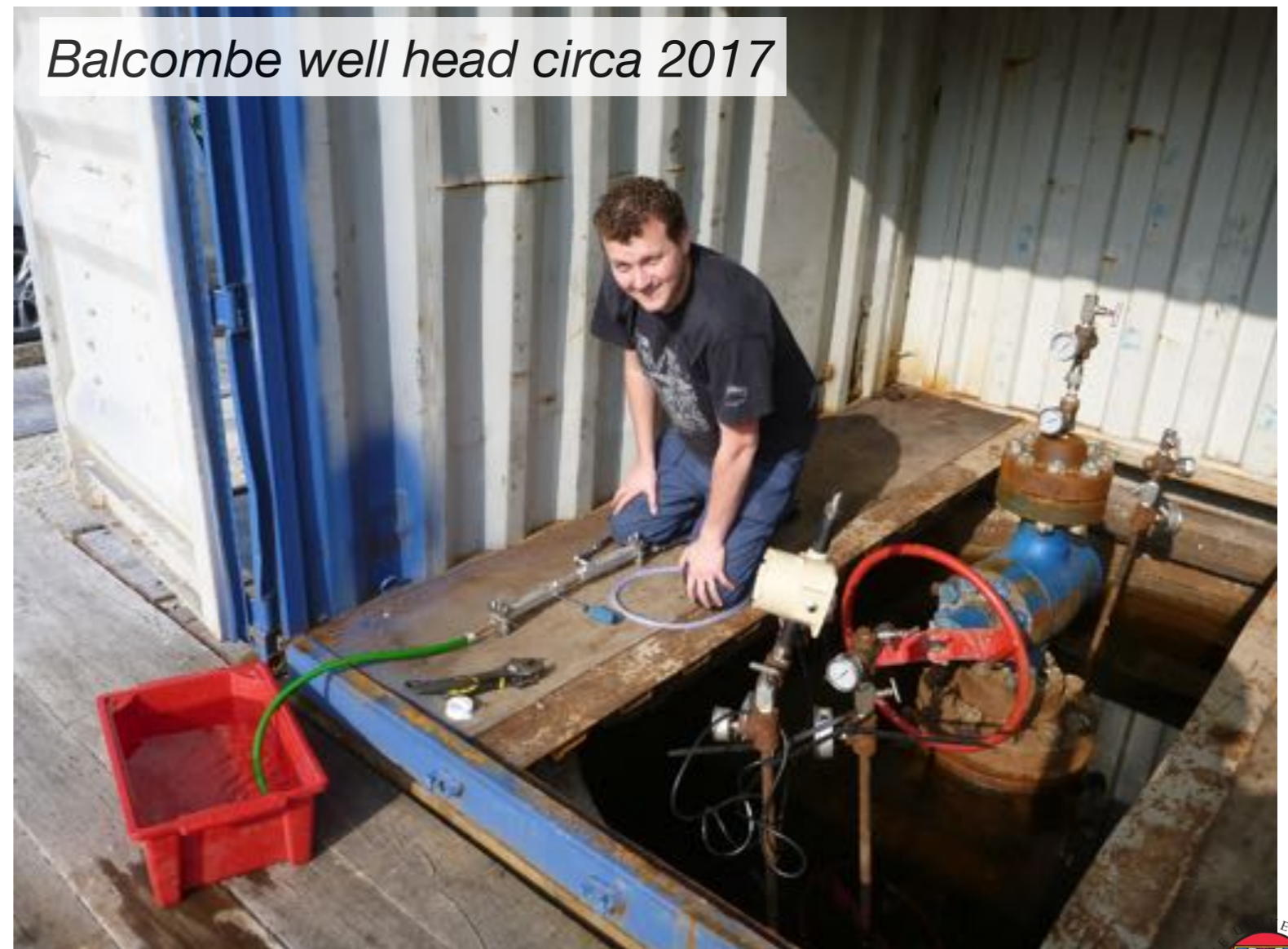
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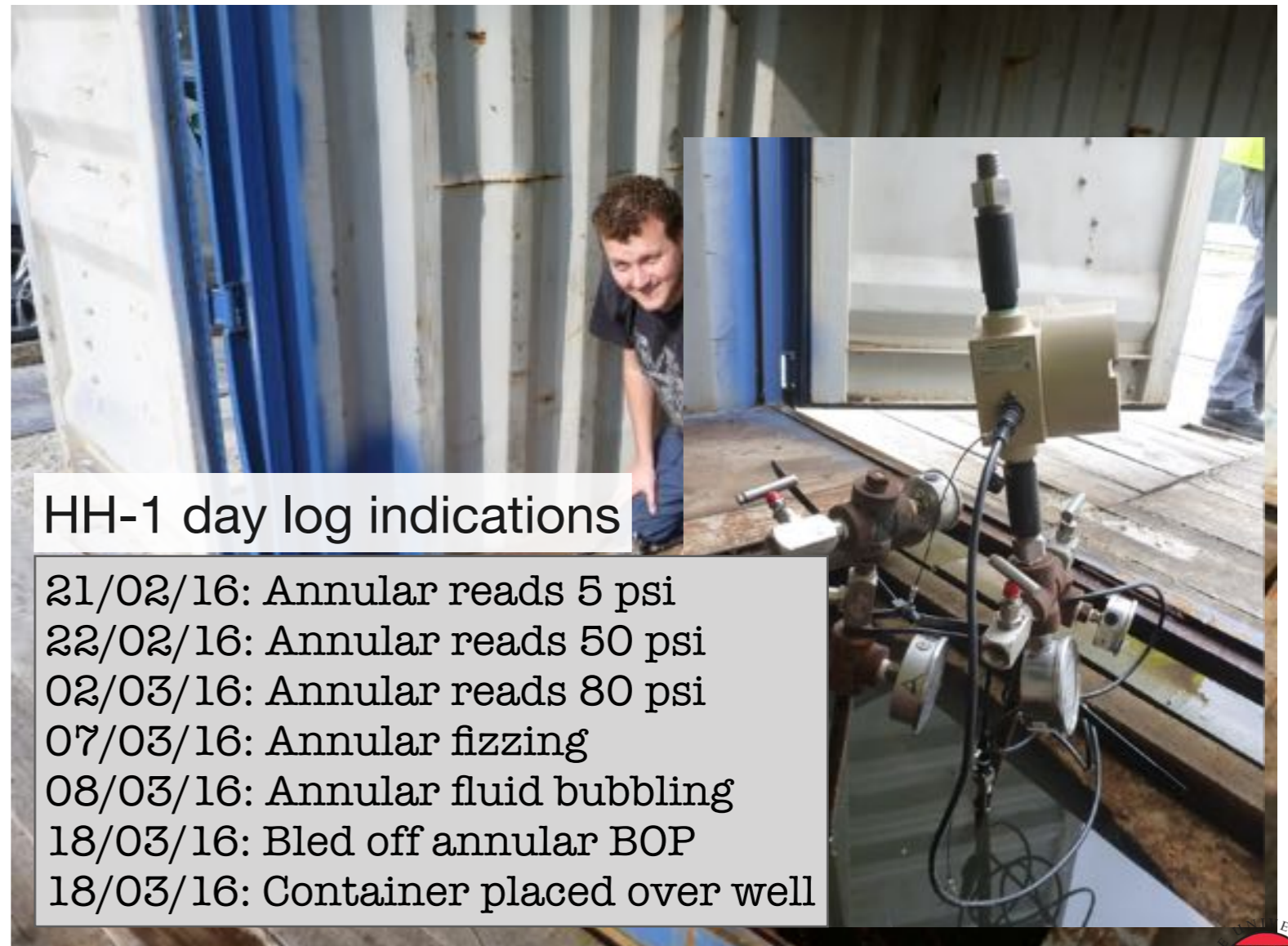
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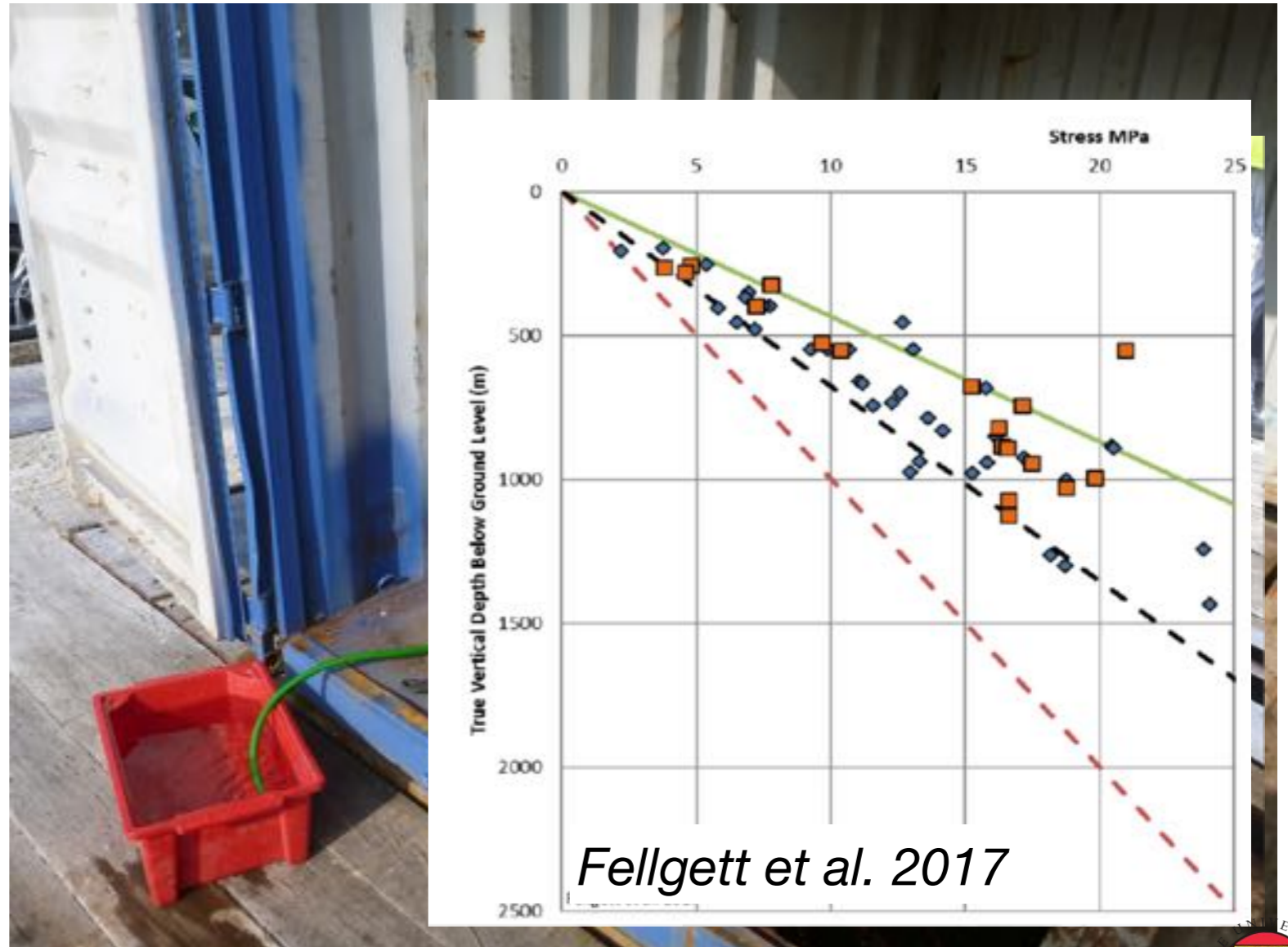
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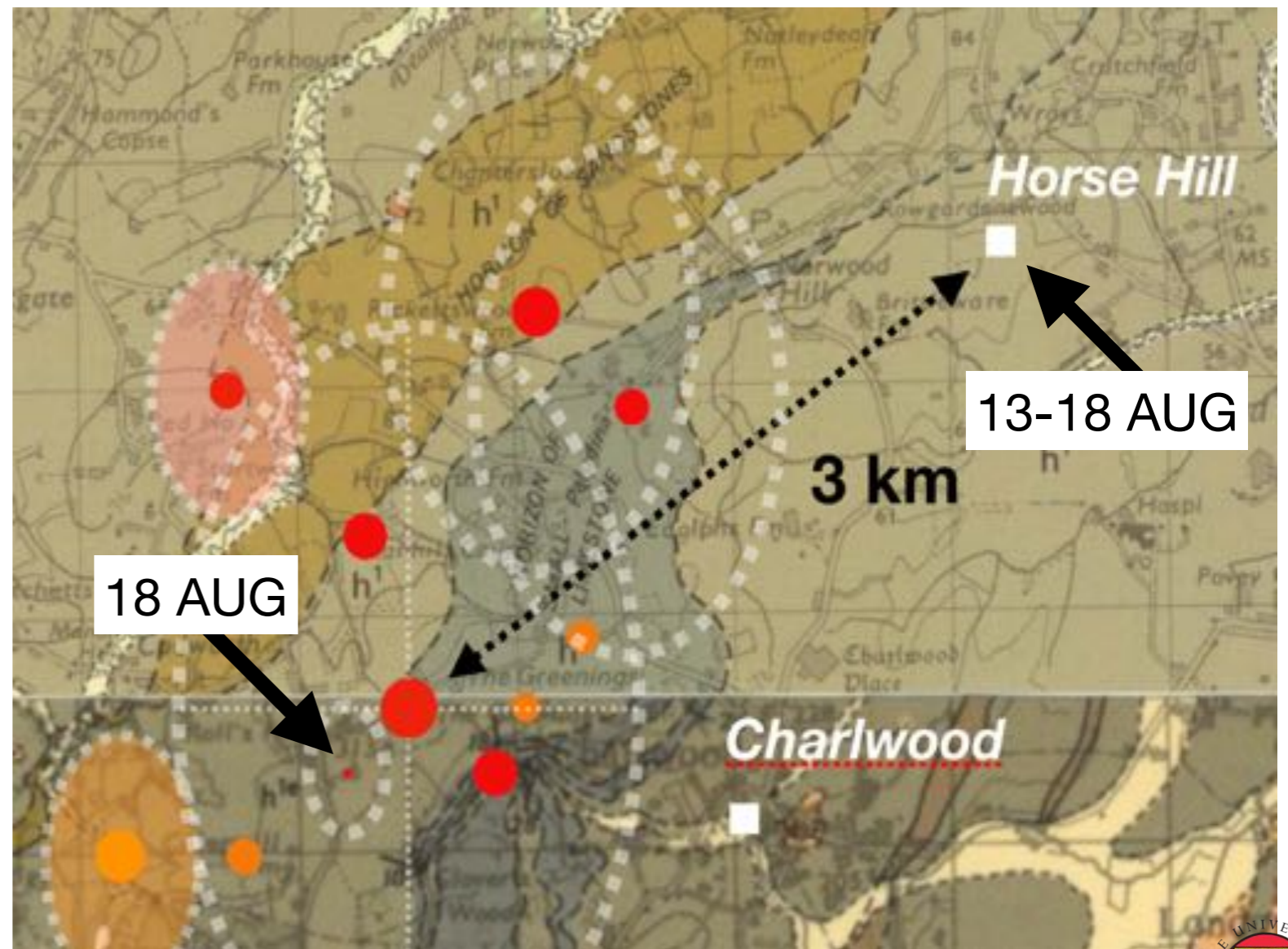
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Davis & Frohlich (1993) SRL: Did Fluid Injection Cause Earthquakes? Criteria For A Rational Assessment... Six Questions

- Background Seismicity: Are these events the first known earthquakes of this character in the region?
- Temporal Correlation: Is there a clear correlation between the time of injection and the times of seismic activity?
- Spatial Correlation: Are epicenters near the wells?
- Spatial Correlation: Do some earthquakes occur at depths comparable to the depth of injection?
- Injection Practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the bottom of the well?
- Injection Practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the hypocentral locations?

Frohlich *et al.* (2016) SRL: A Historical Review of Induced Earthquakes in Texas... Five Questions

- QT. Timing: In this location, are earthquakes of this character known to begin only after the commencement of nearby petroleum production or fluid injection operations that could induce seismic activity?
- QS. Spatial correlation: Are the epicenters spatially correlated with such production or injection operations (i.e., within 5 km for well-determined epicenters or within 15 km otherwise)?
- QD. Depth: Is information available concerning focal depths of earthquakes at this location, and does this suggest some depths are shallow, probably occurring at or near production or injection depths?
- QF. Faulting: Near production or injection operations, are there mapped faults or linear groups of epicenters that appear to lie along a fault? Here, “near” is within 5 km if the earthquake or earthquake sequence of interest has well-determined epicenters, or within 15 km otherwise.
- QP. Published analysis: Is there a credible published paper or papers linking the seismicity to production or injection operations?