Weald Basin 2018
Earthquake Cluster Analysis

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

Stuart Haszeldine & Andrew Cavanagh
University of Edinburgh

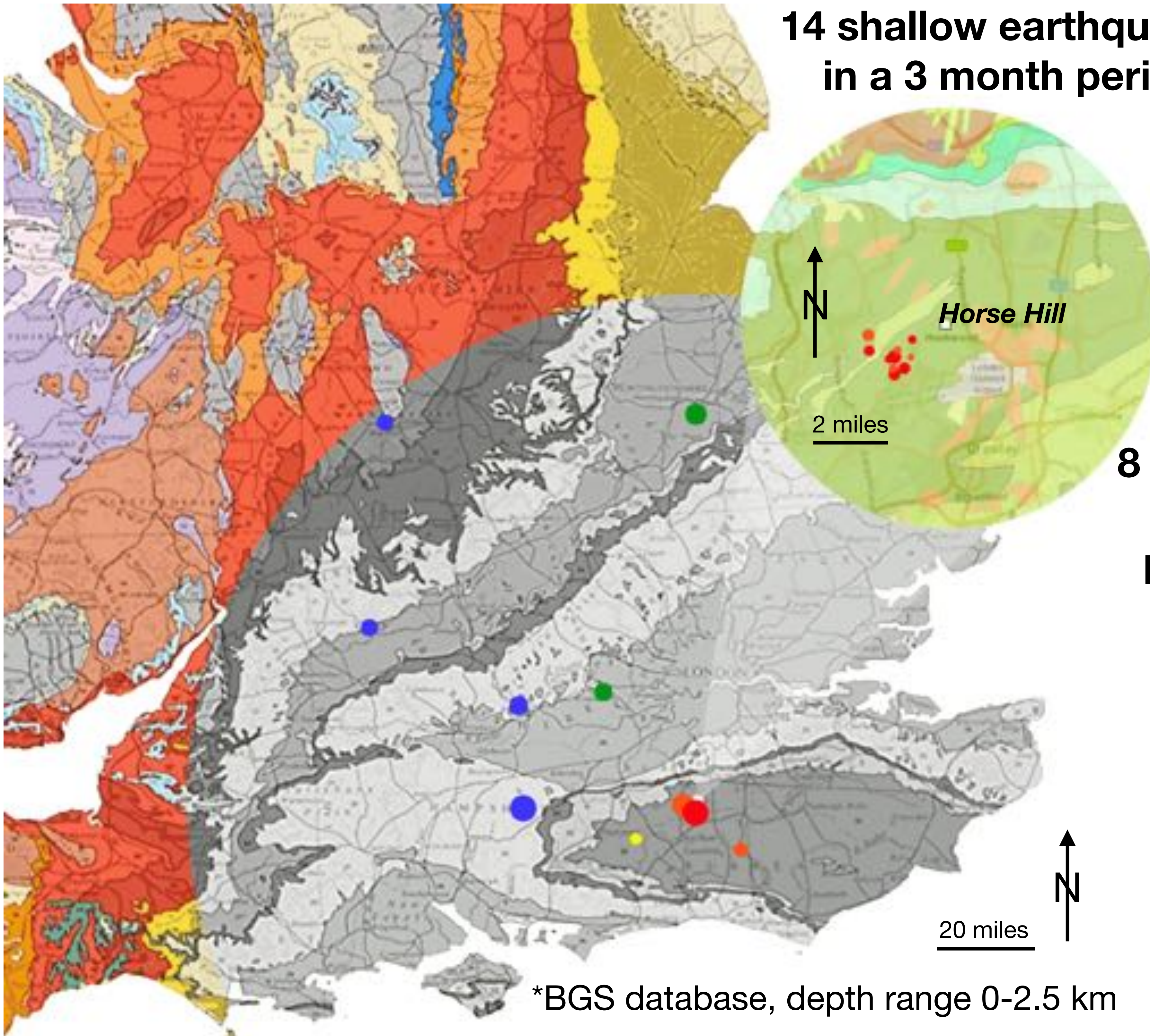
Davis & Frohlich (1993) Criteria:

1. Are these earthquakes exceptional in the region?
   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?
   Maybe… We propose the depressurisation of a critically-stressed fault zone.

1. Are these earthquakes exceptional in the region?

Yes… without precedent for the Weald Basin.

14 shallow earthquakes in a 3 month period



8 shallow earthquakes in regional area for preceding 40 years*

- 1980s
- 1990s
- 2000s
- April 2018
- July 2018

*BGS database, depth range 0-2.5 km

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2. Is there a correlation with HH-1 operations?

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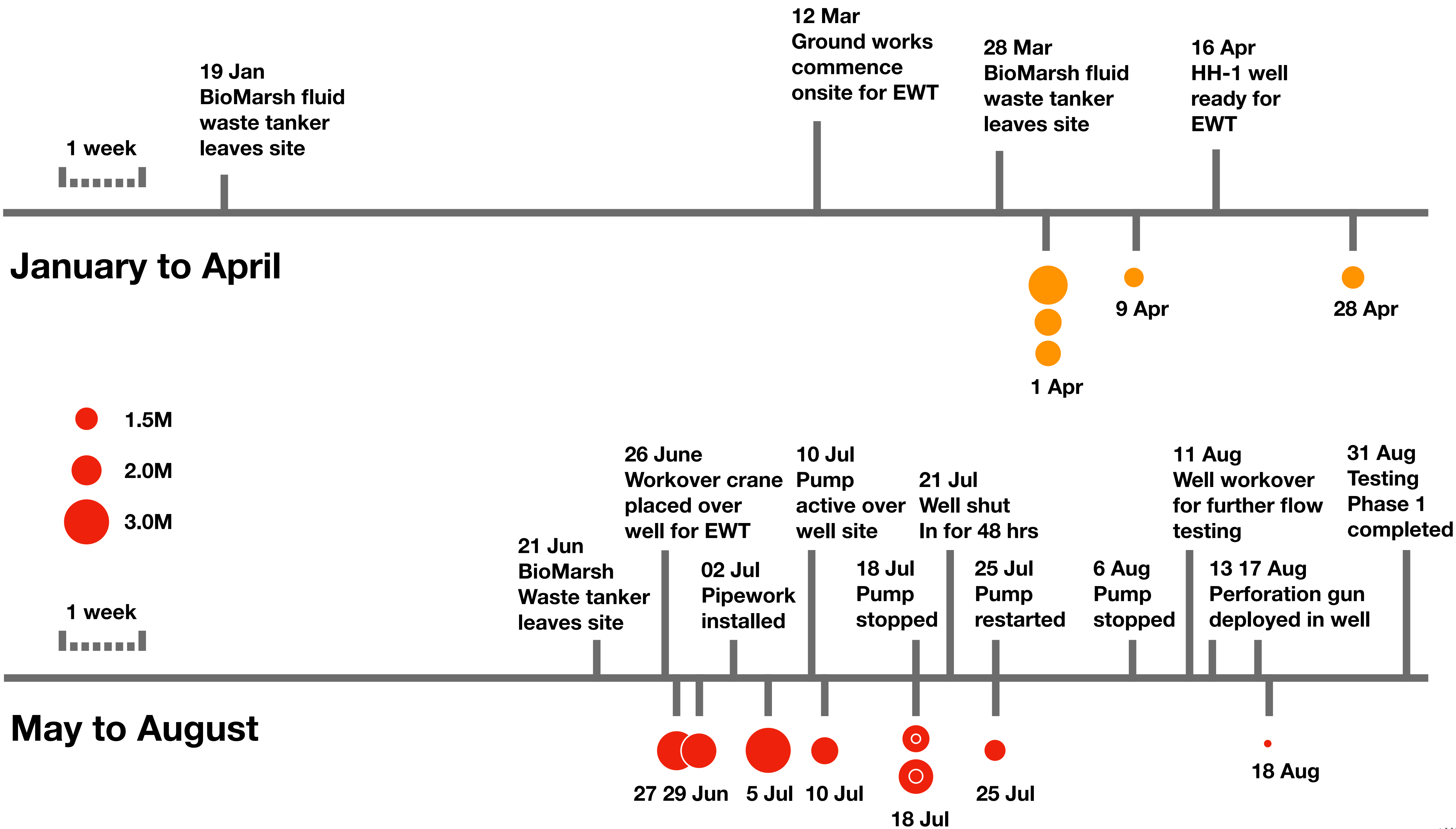

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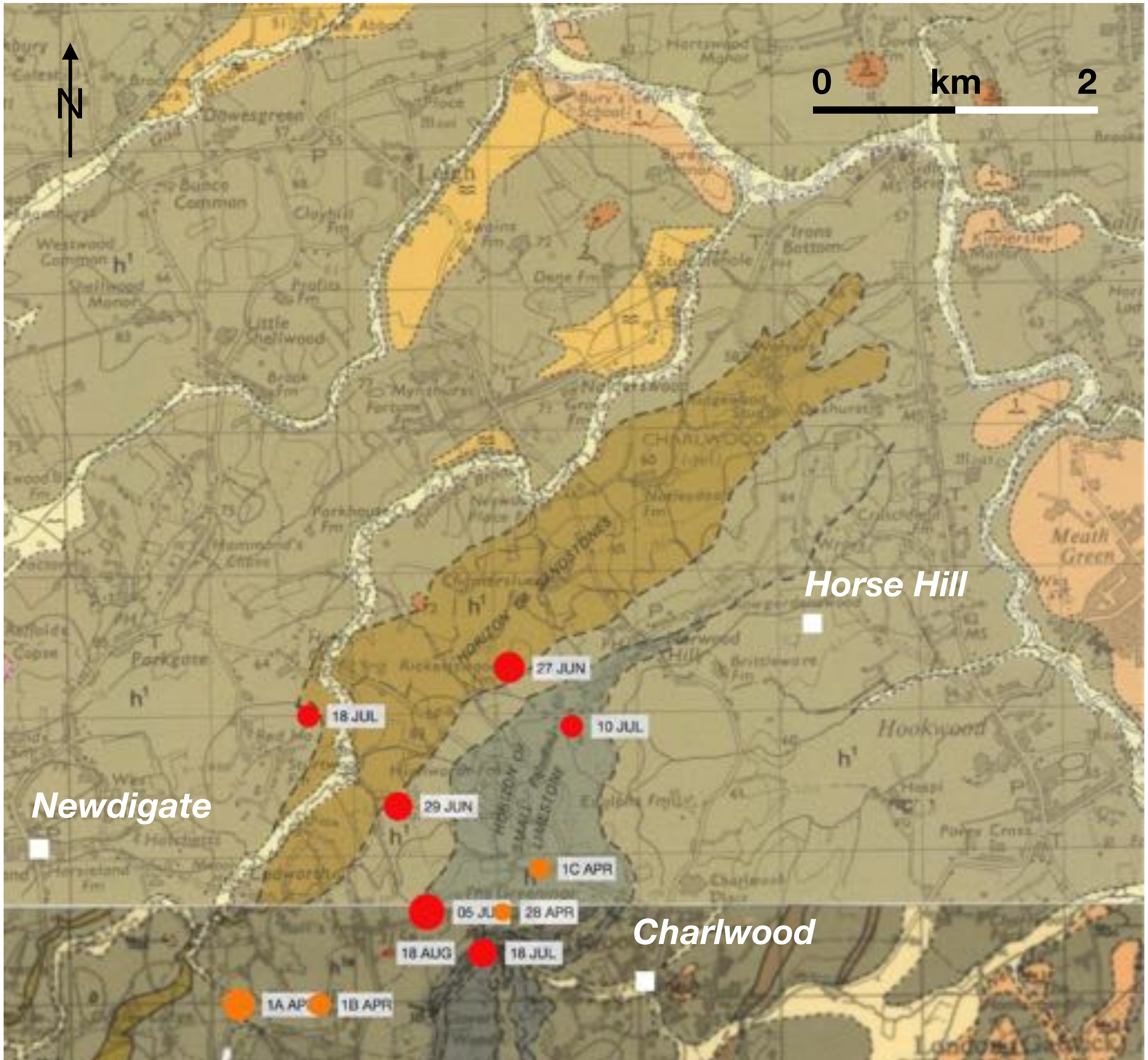

BGS Hypocentres

- April 2018
- July 2018

Earthquake magnitude

- 1.5 ML
- 2.0 ML
- 3.0 ML

Uncertainty ellipse +/- 0.005º

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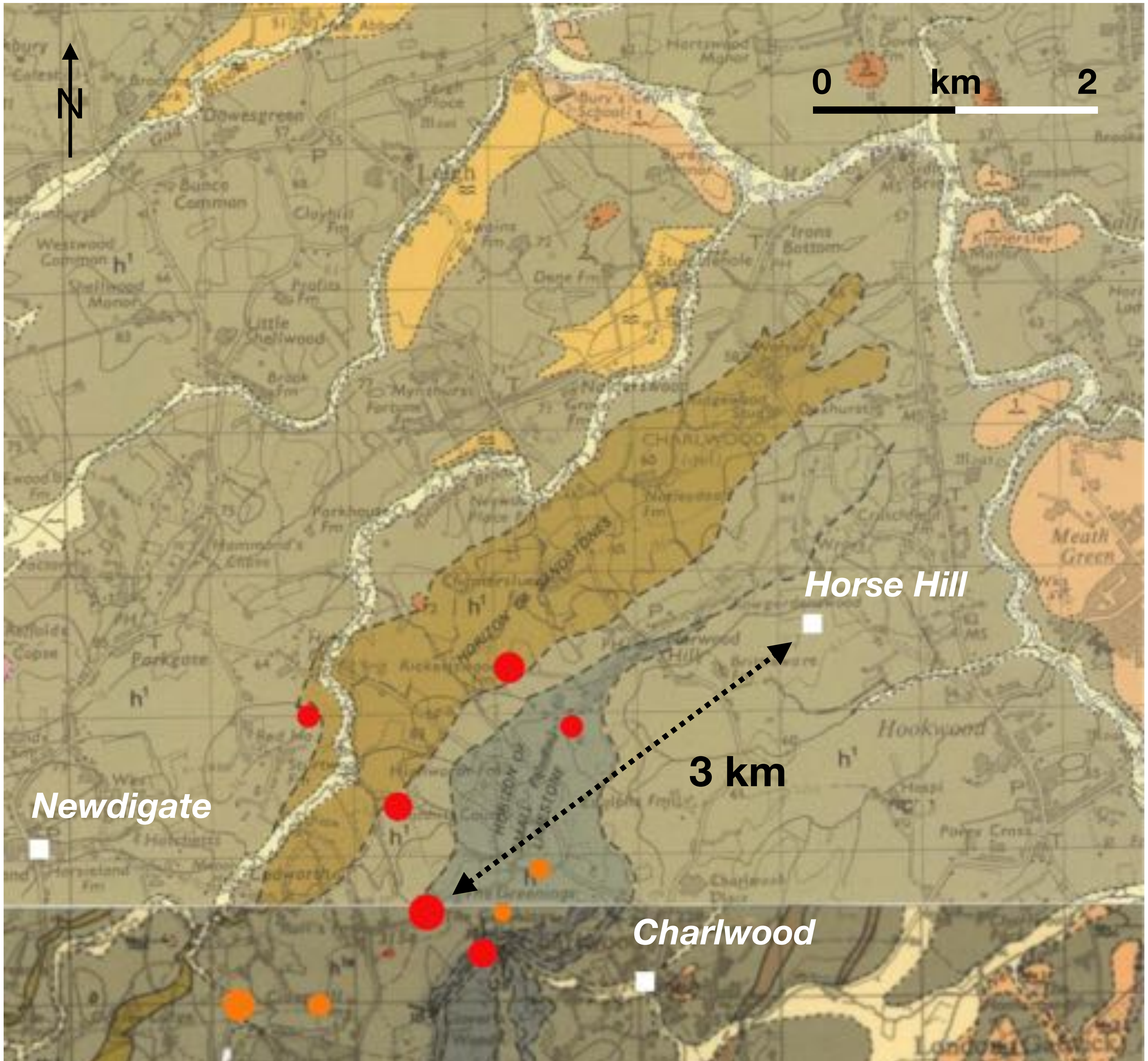

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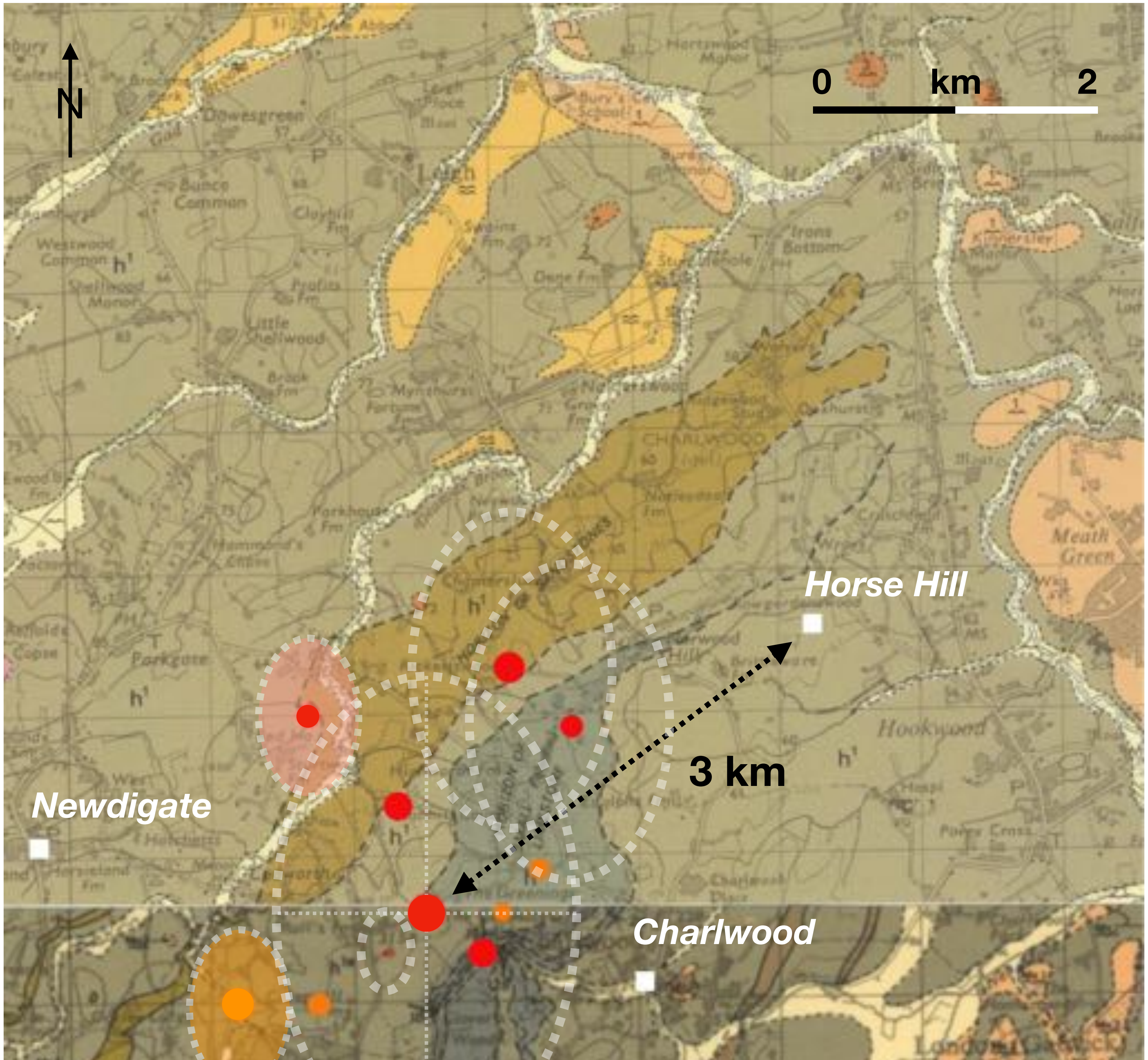

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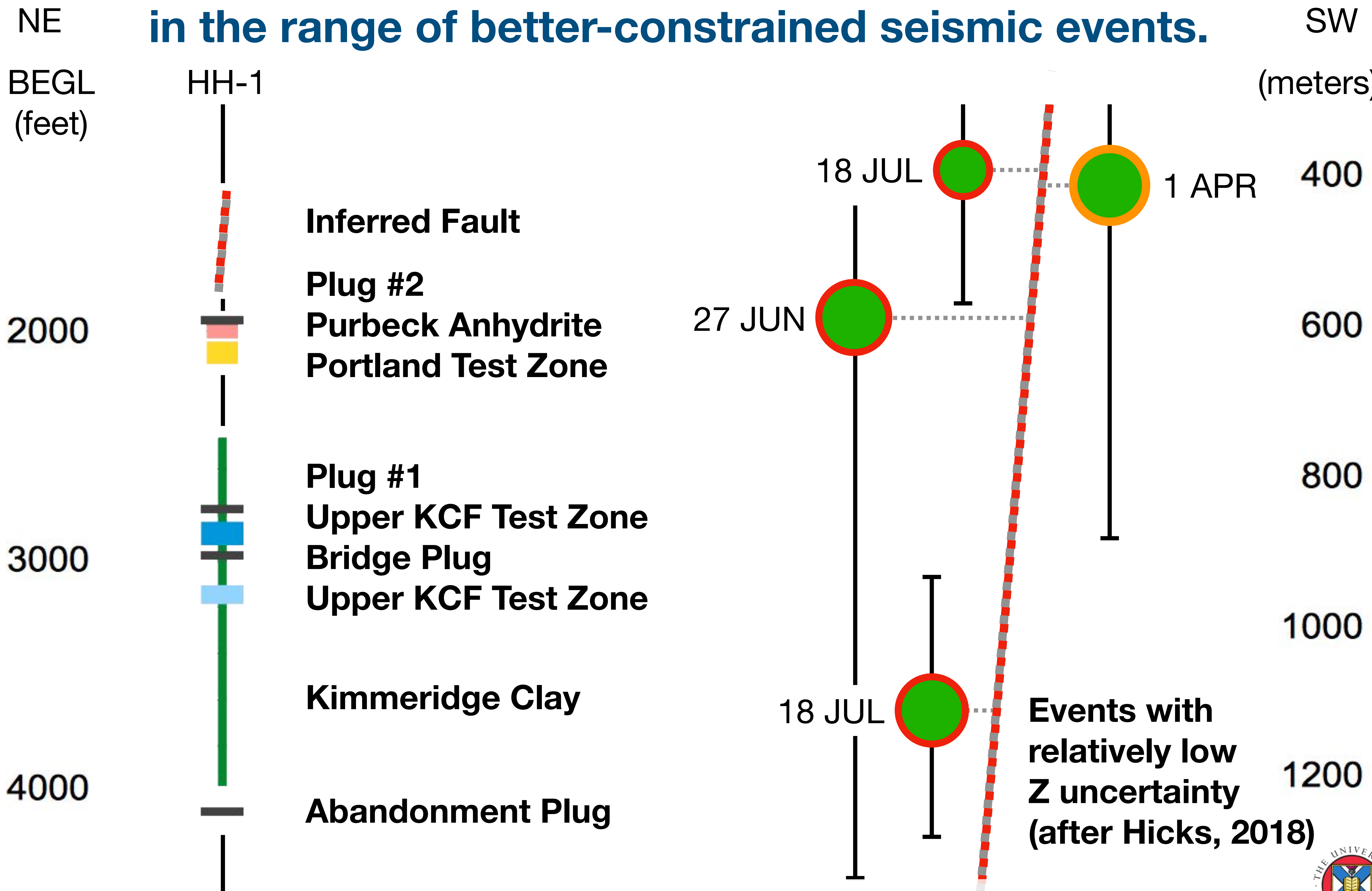
Yes… the Portland and Kimmeridge targets are all in the range of better-constrained seismic events.



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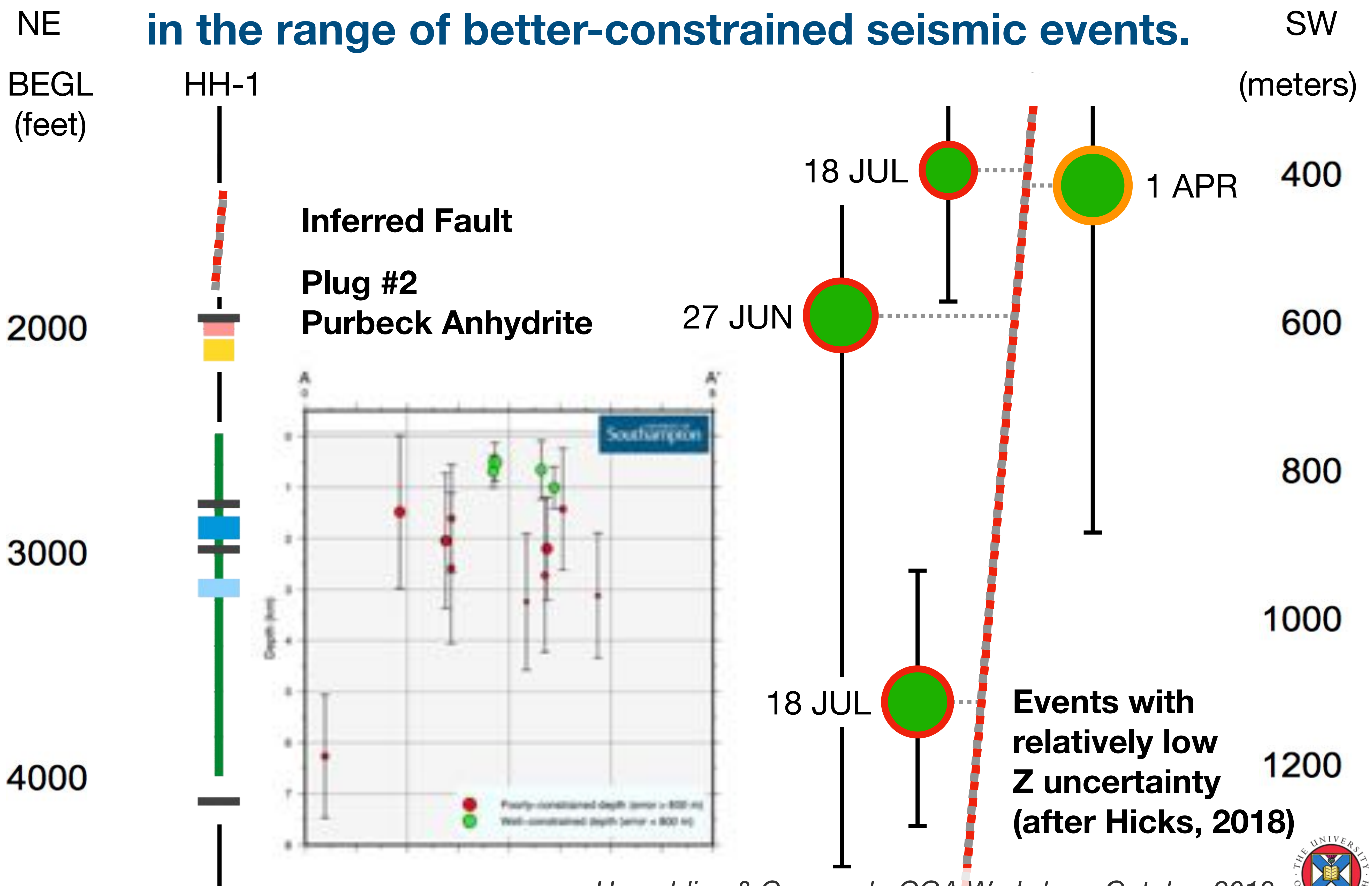

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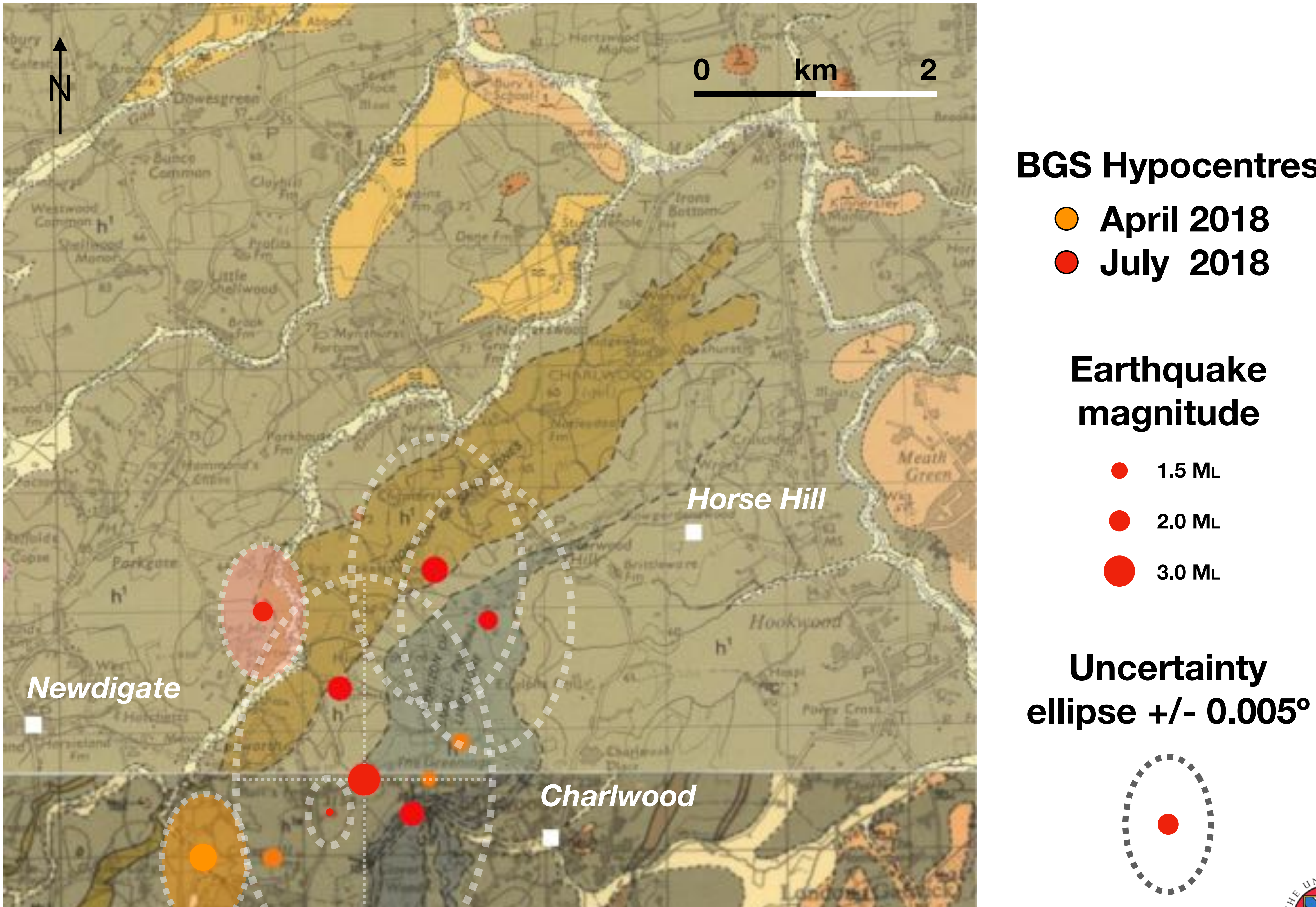

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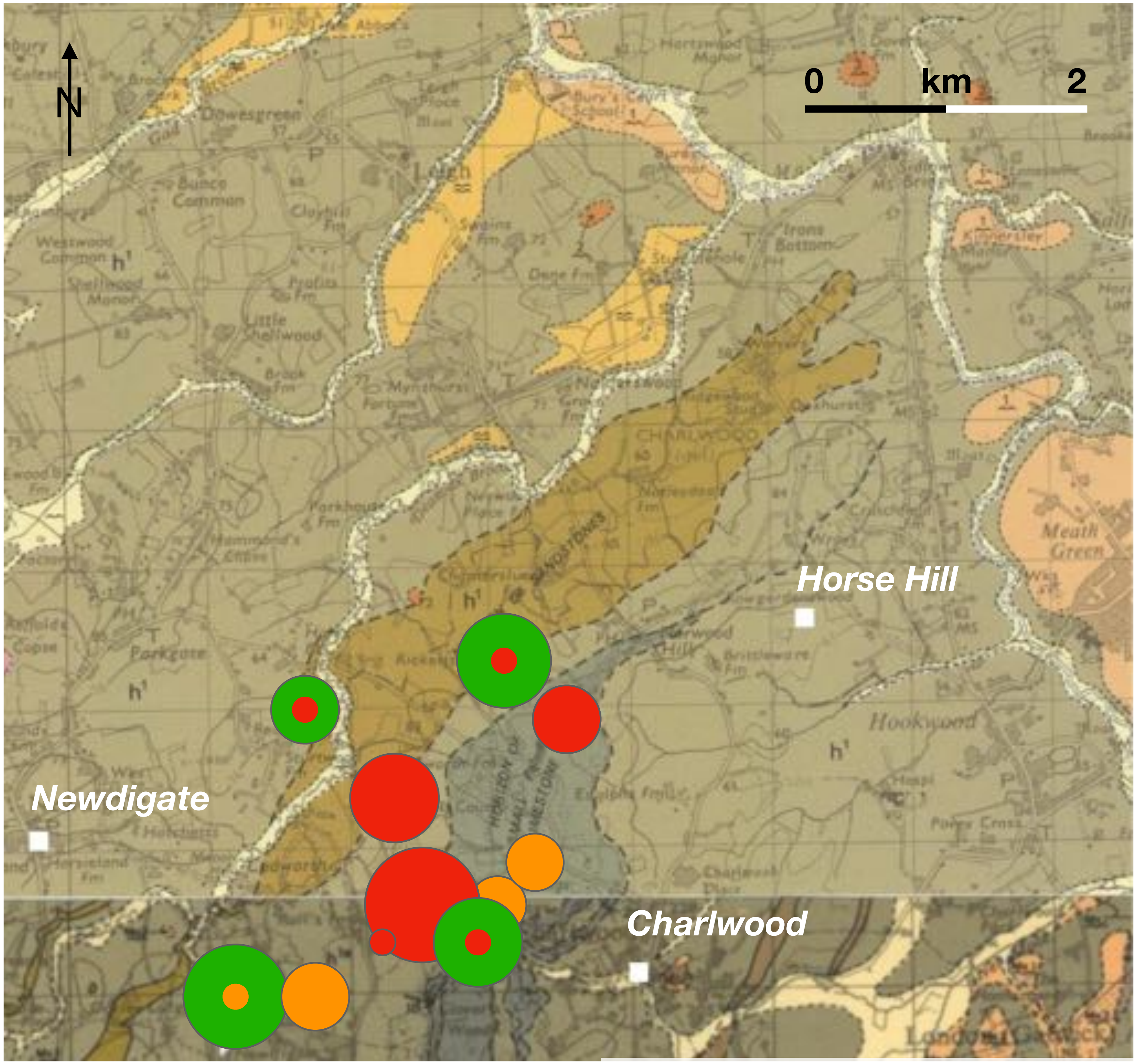

BGS Hypocentres

- April 2018
- July 2018
- Low Errors

Earthquake magnitude

- 1.5 ML
- 2.0 ML
- 3.0 ML

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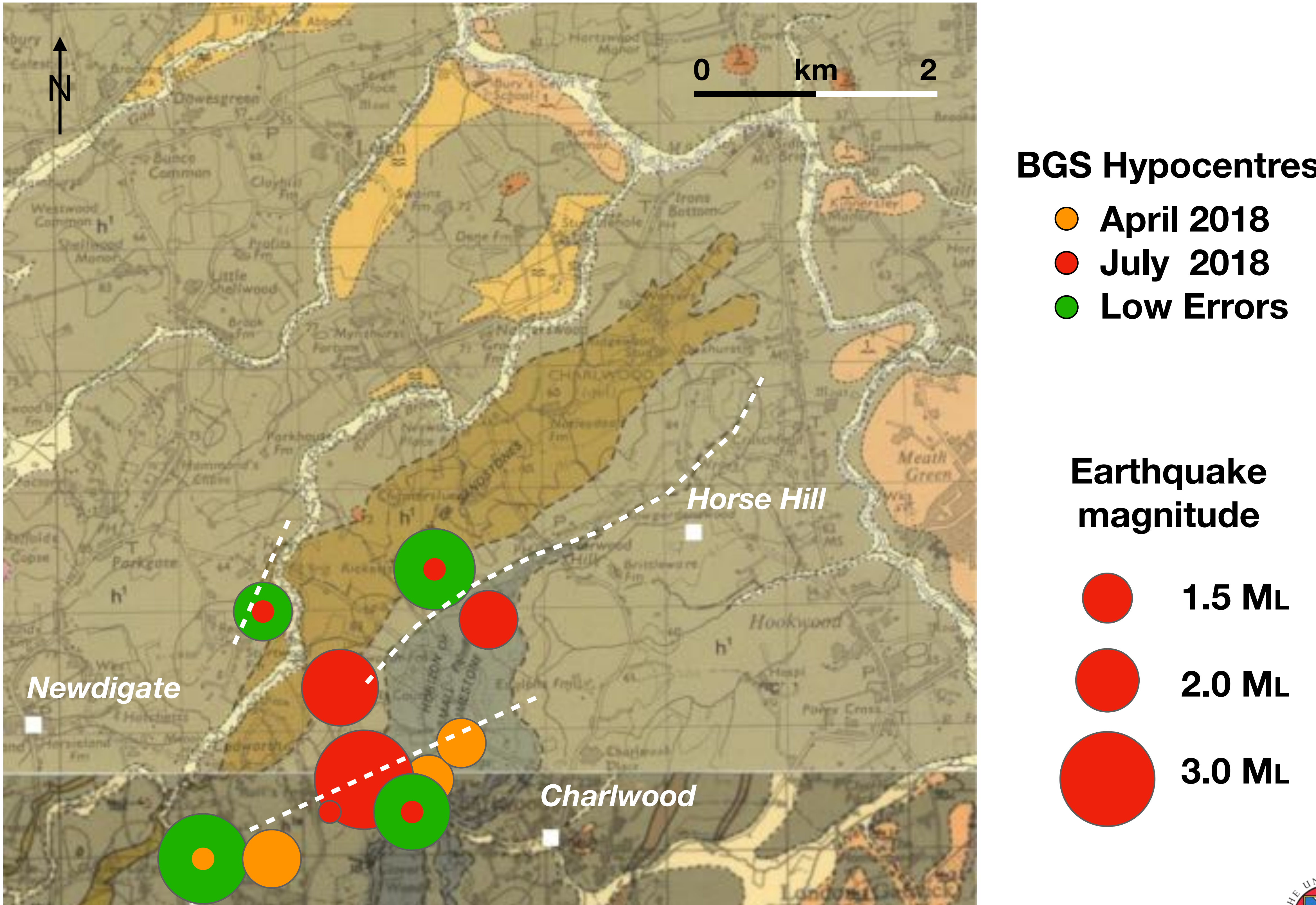

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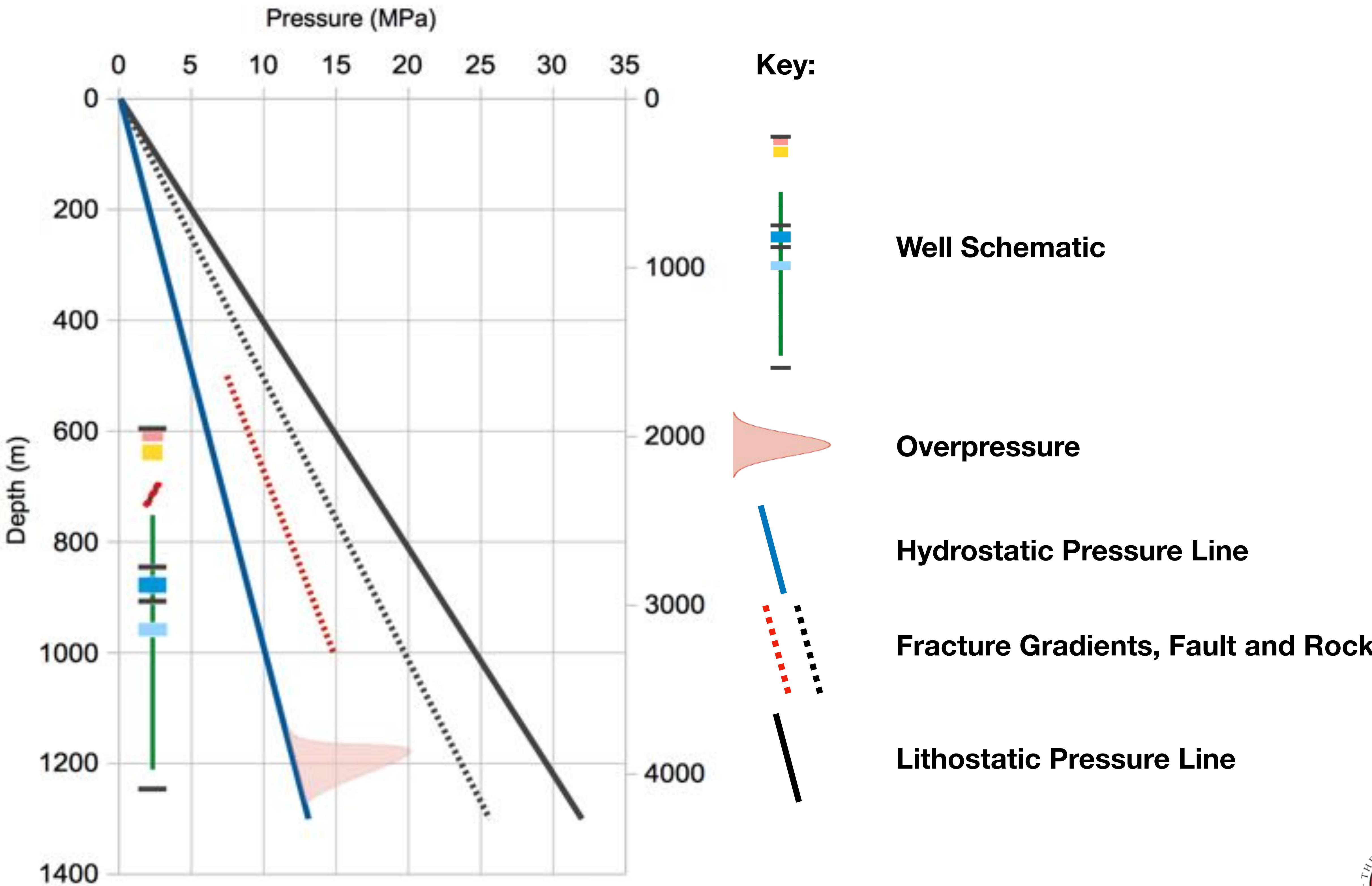

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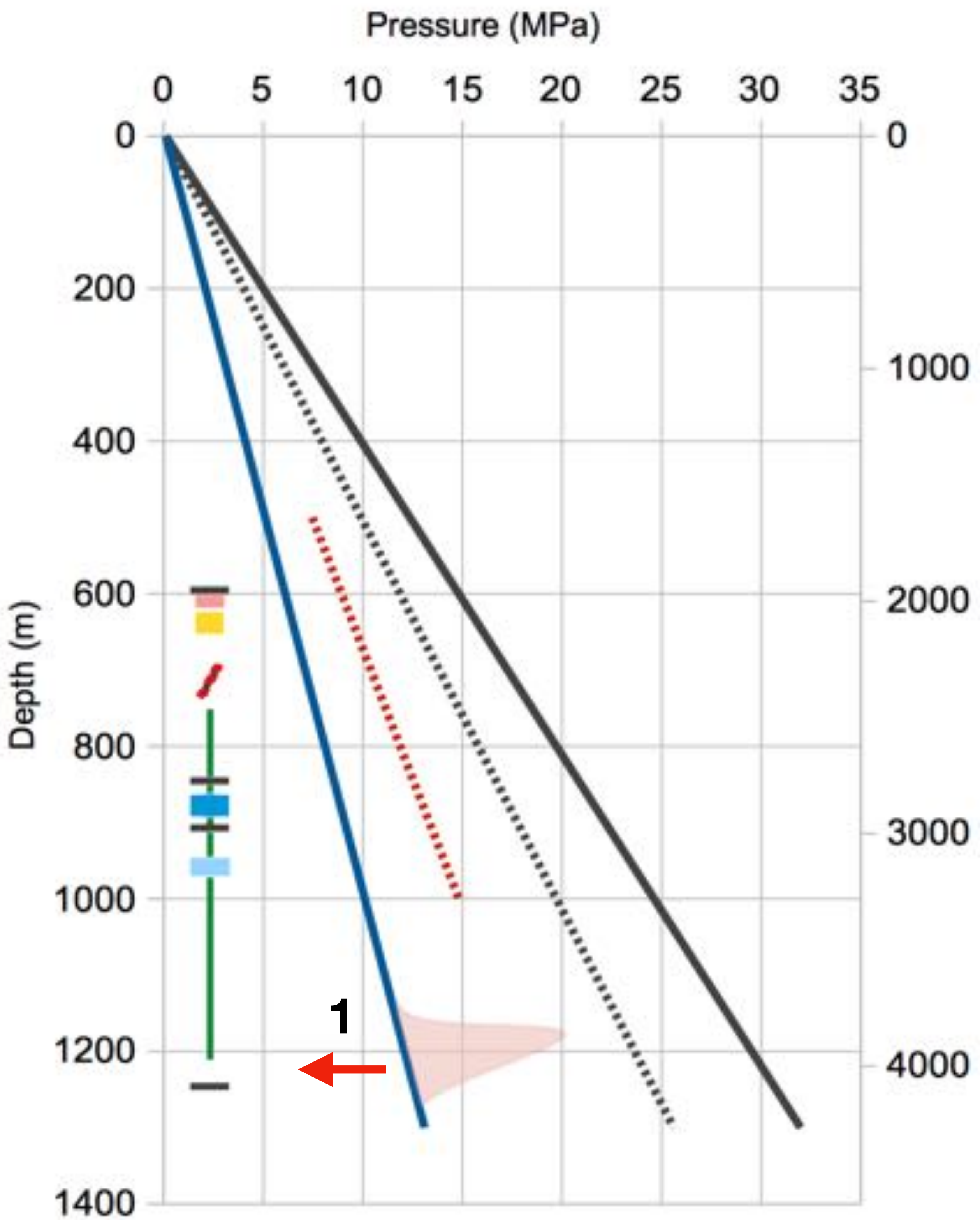

Gradual Pressurisation

1. The well intercepts a source of moderate overpressure (gas), deep in the KCF - the gas begins to seep into cement voids between the well casing and the rock.

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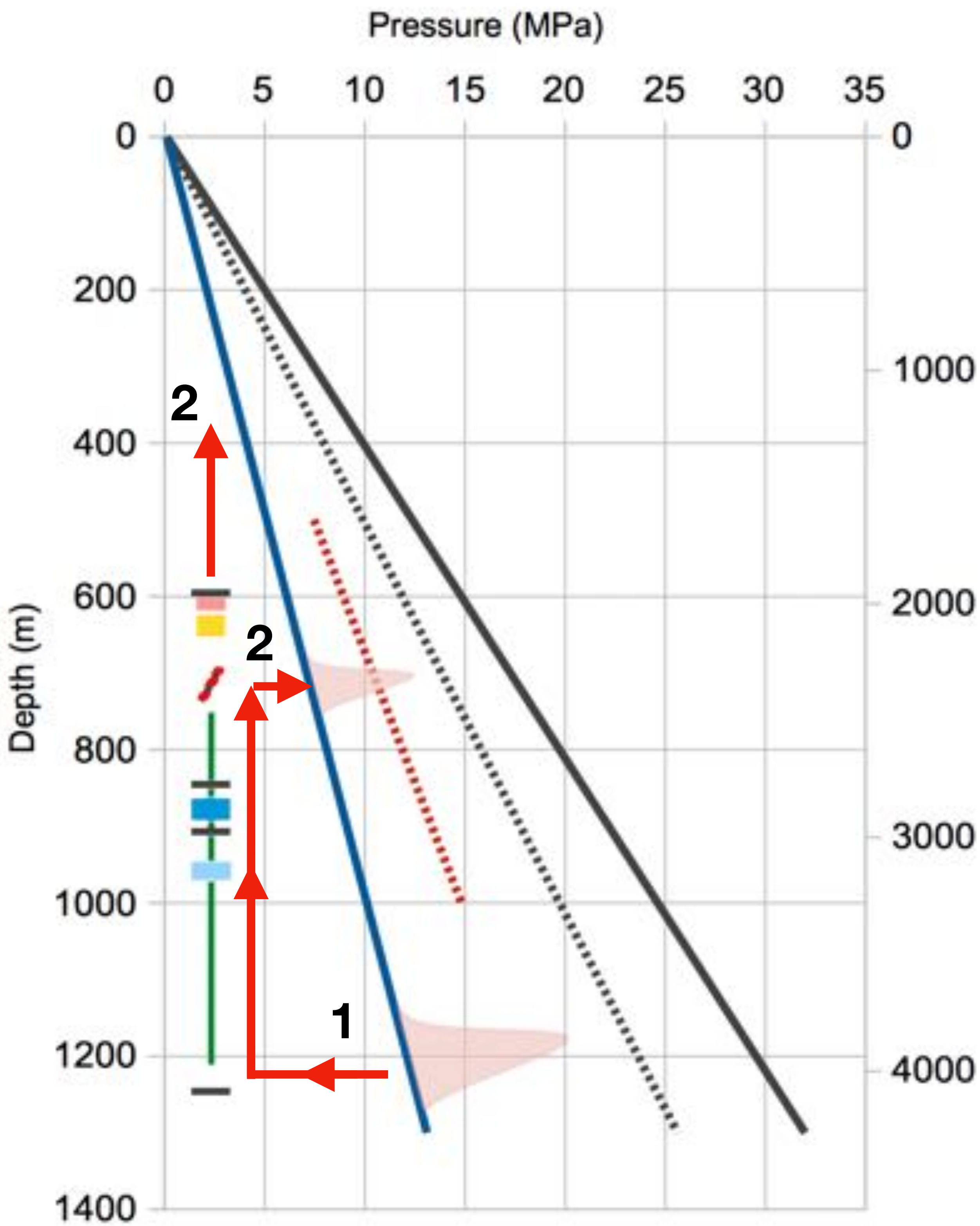

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1. The well intercepts a source of moderate overpressure (gas), deep in the KCF - the gas begins to seep into cement voids between the well casing and the rock.

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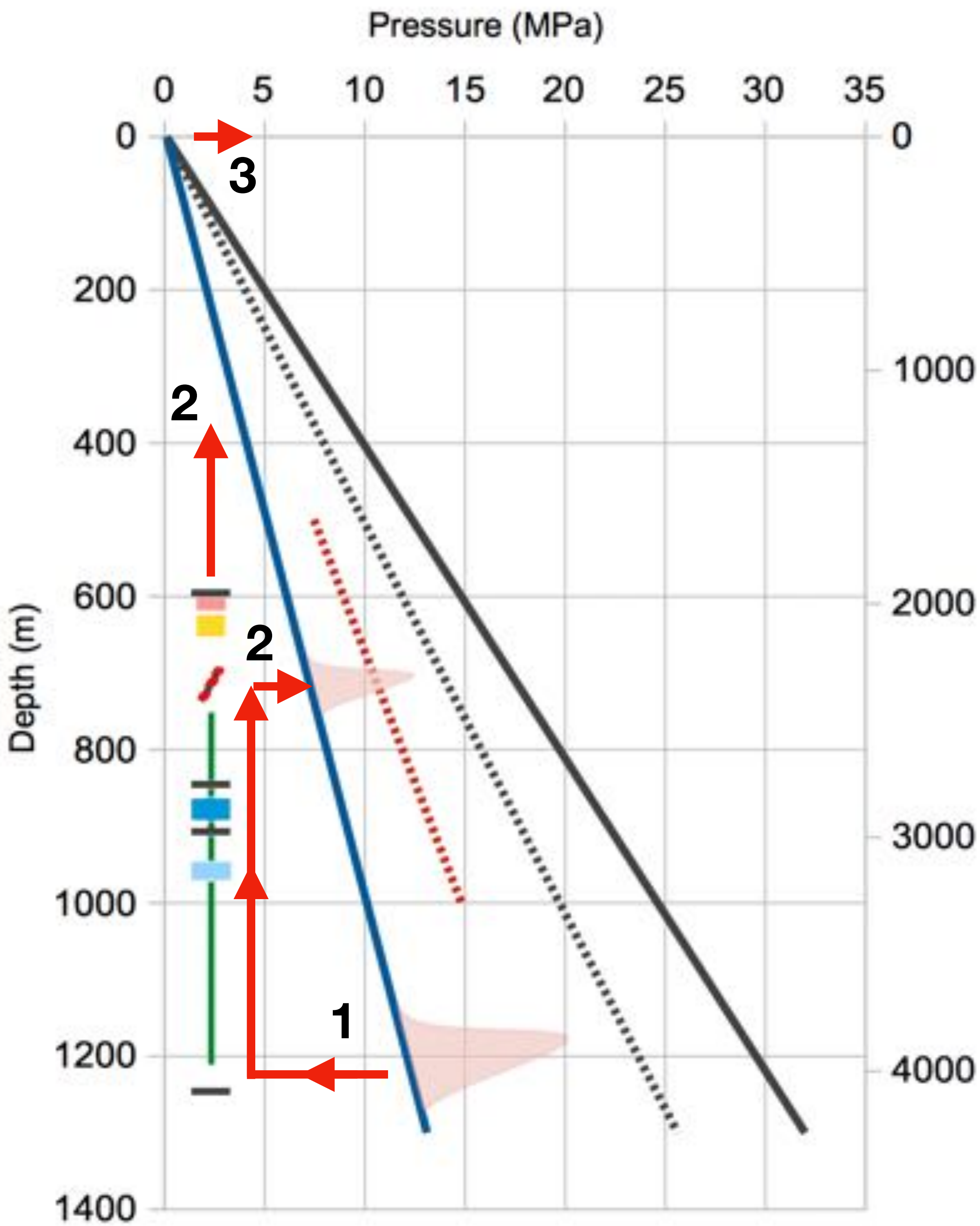

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3. The gauge at the well pad registers a moderate pressure increase (1 MPa) and the annulus is observed to be have bubbling fizzing porewater and creeping pressurisation.

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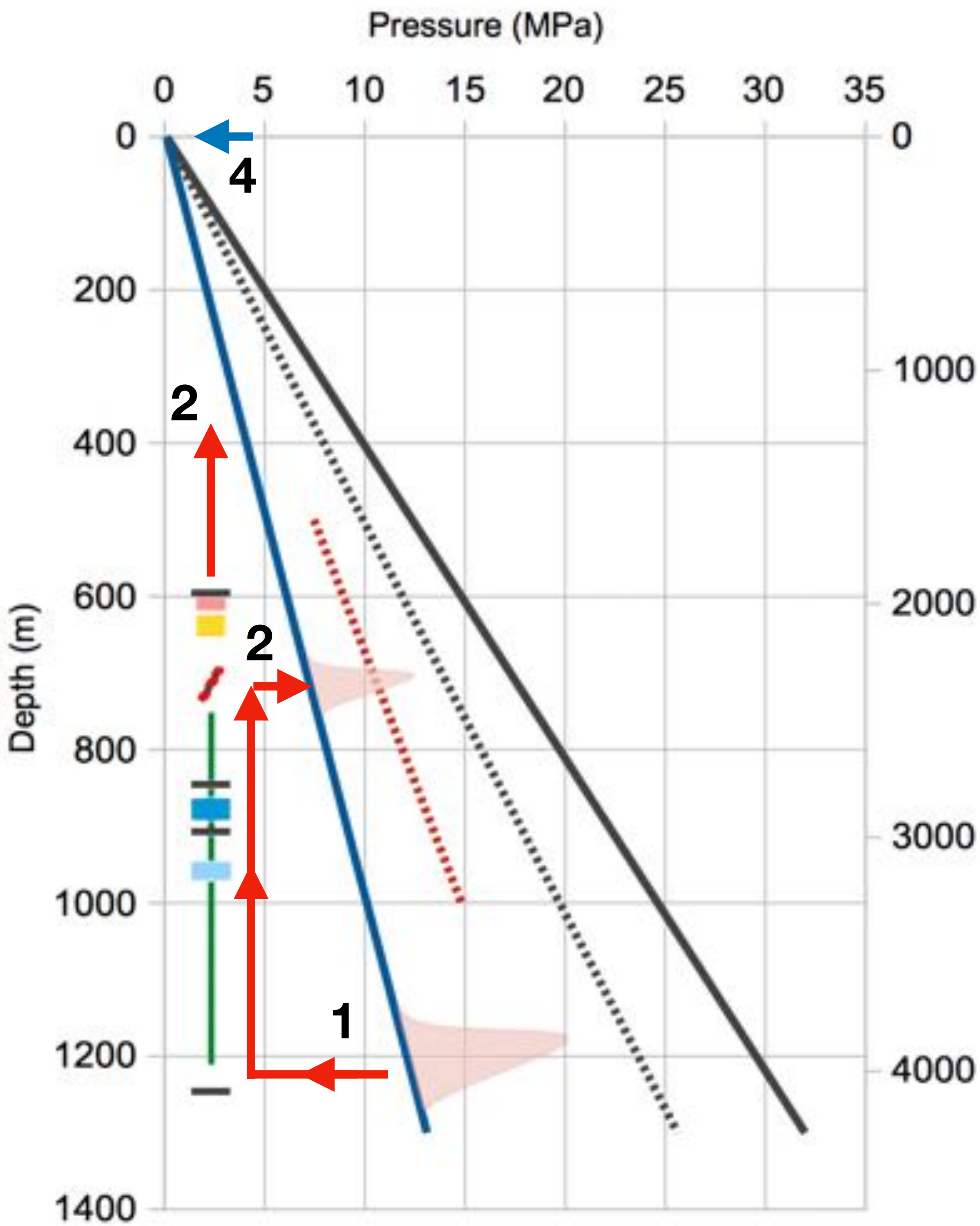

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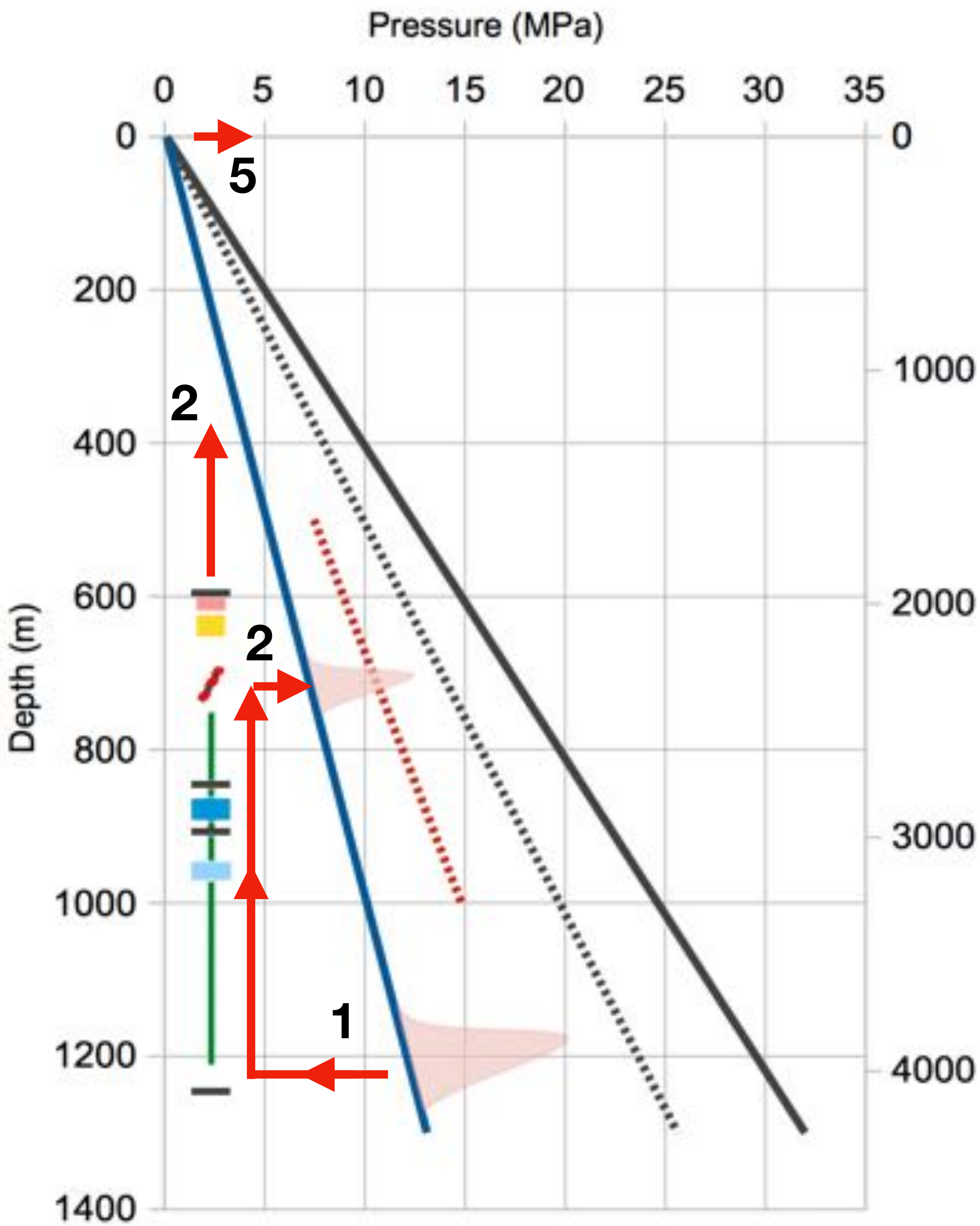

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5. The gas continues to charge the fault zone and annulus during shut-in period (2016-2018).

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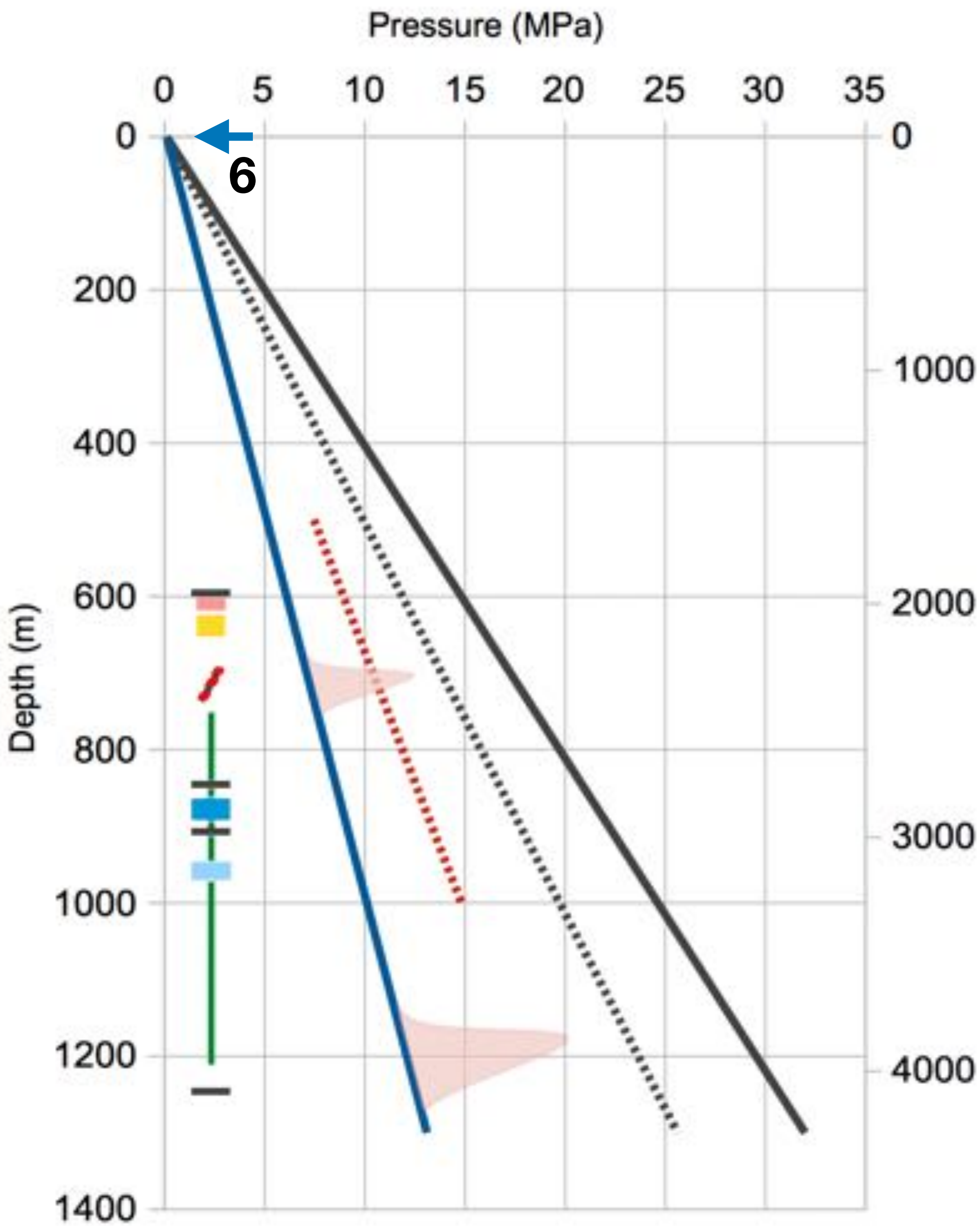

Rapid Depressurisation

6. The annular pressure is vented after a long period of shut-in. The void space has become almost entirely charged with gas, and a small volume of liquid is bled.

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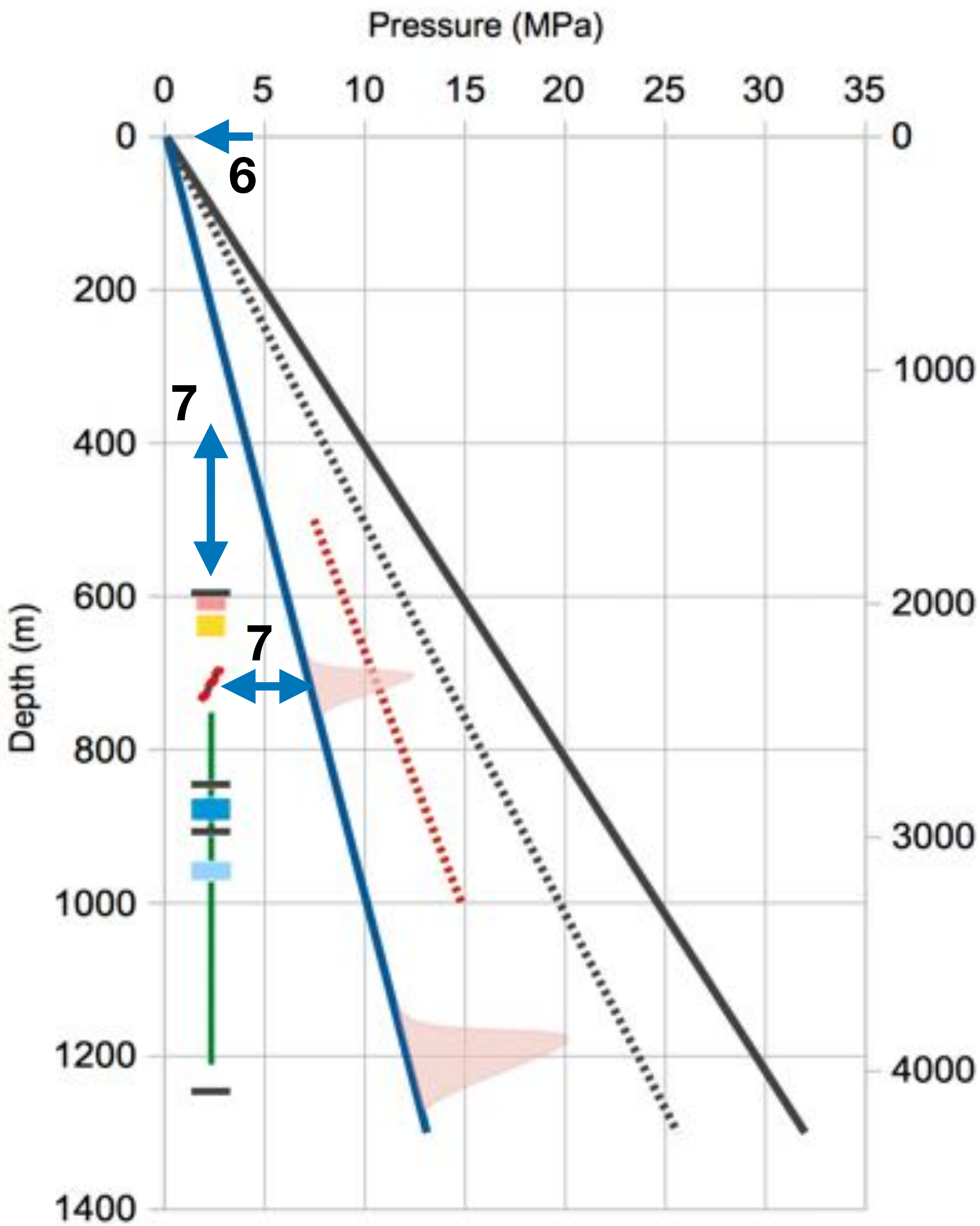

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7. The connected void space, including the annulus and gas-charged fault zone, are close to atmospheric pressure, dropping 8 MPa (a result of venting the entire gas column).

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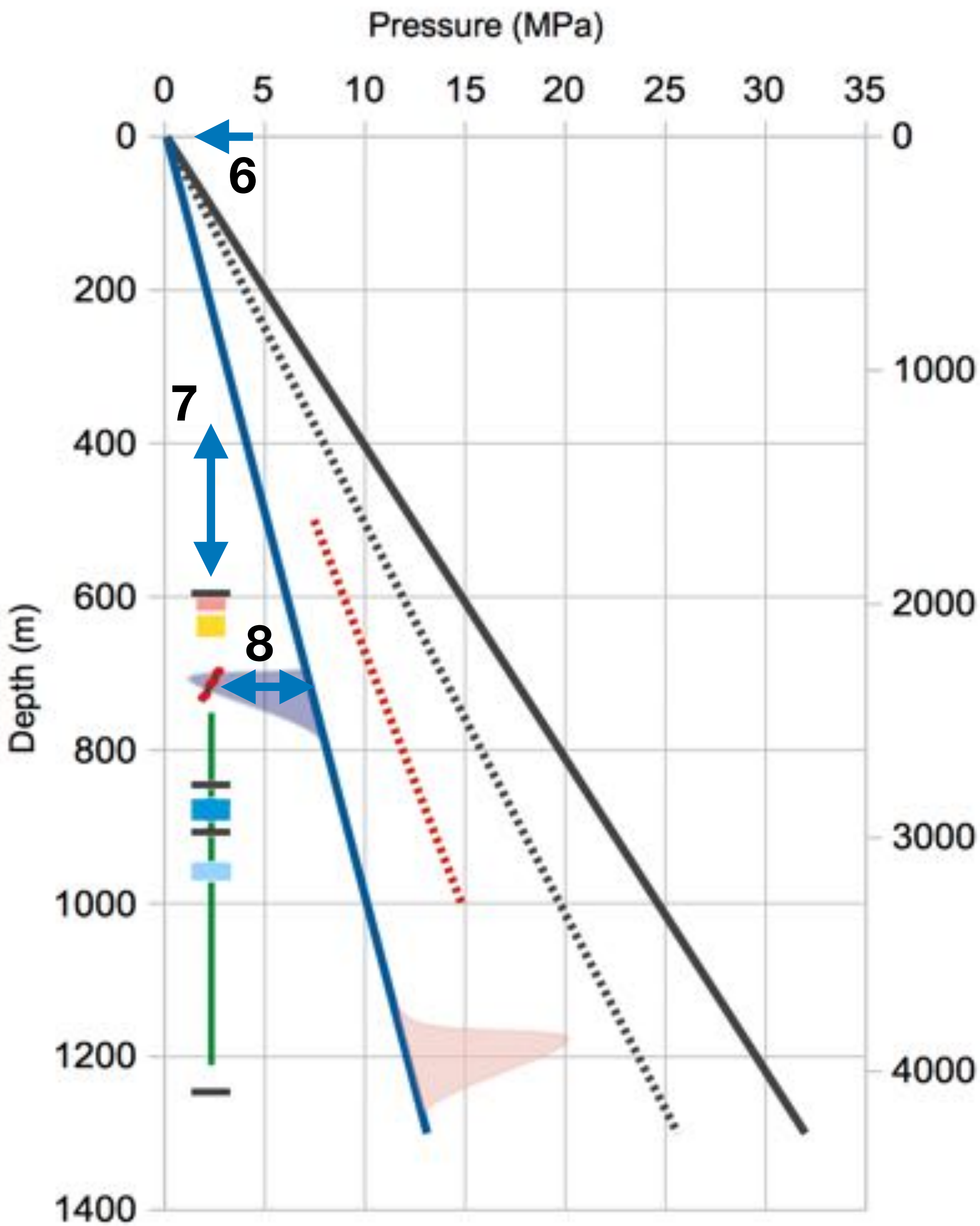

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8. The fault zone begins to equilibrate with the low pressure volume, draining a larger area of the fault and rapidly altering the distribution of pressure and fluid in the fault.

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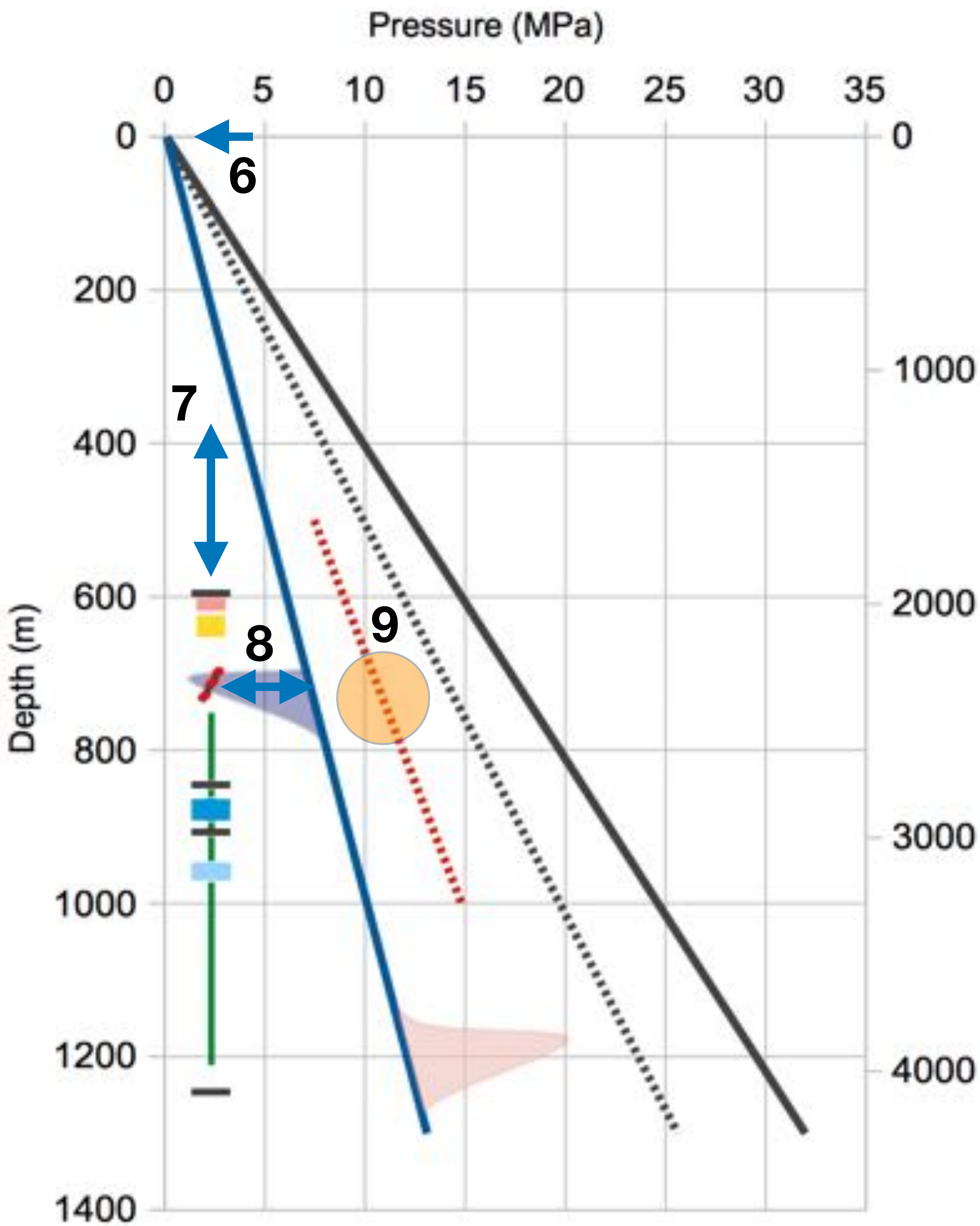

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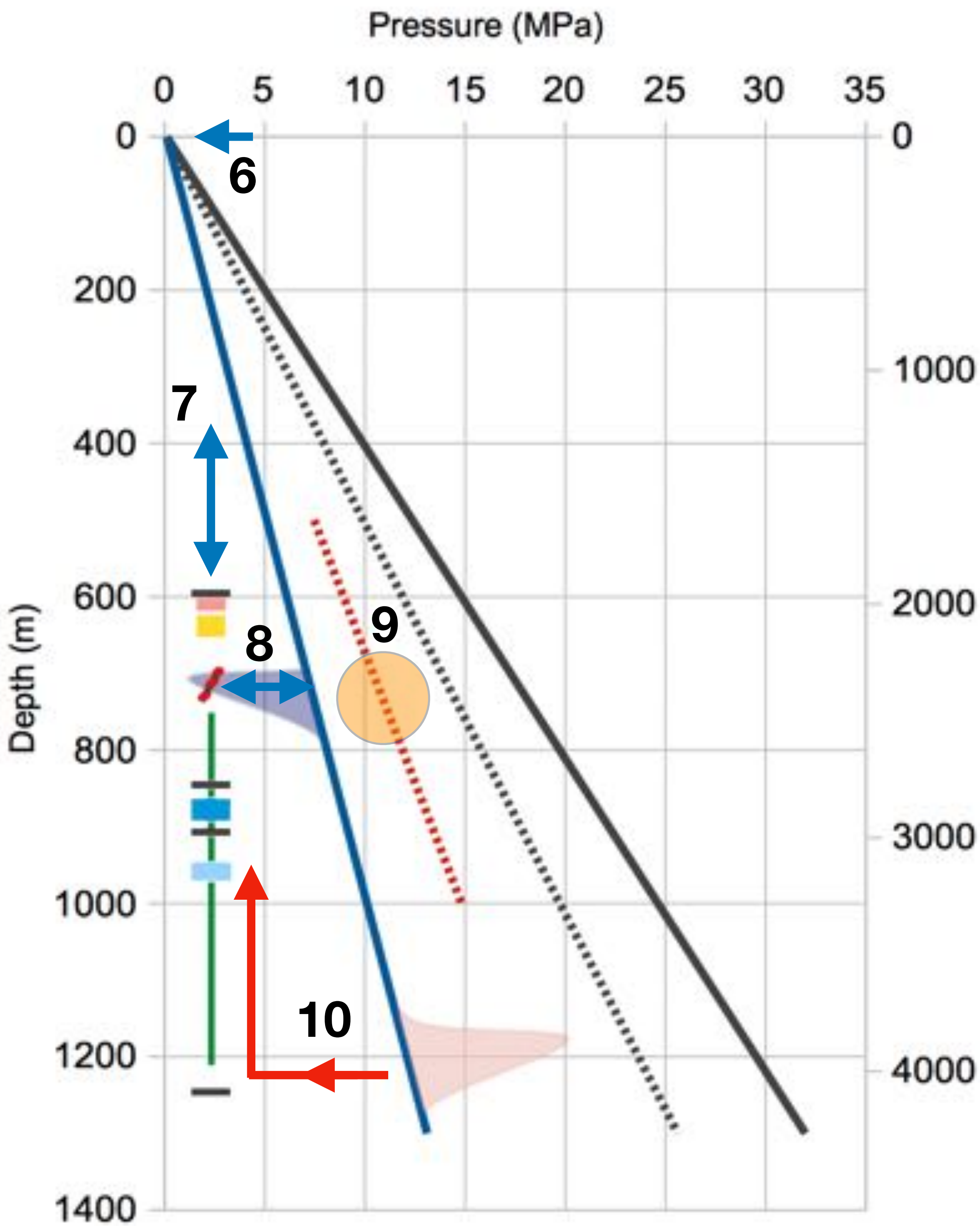

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10. The deep gas begins to recharge the annulus and fault zone to repeat the cycle.

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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Balcombe well head circa 2017

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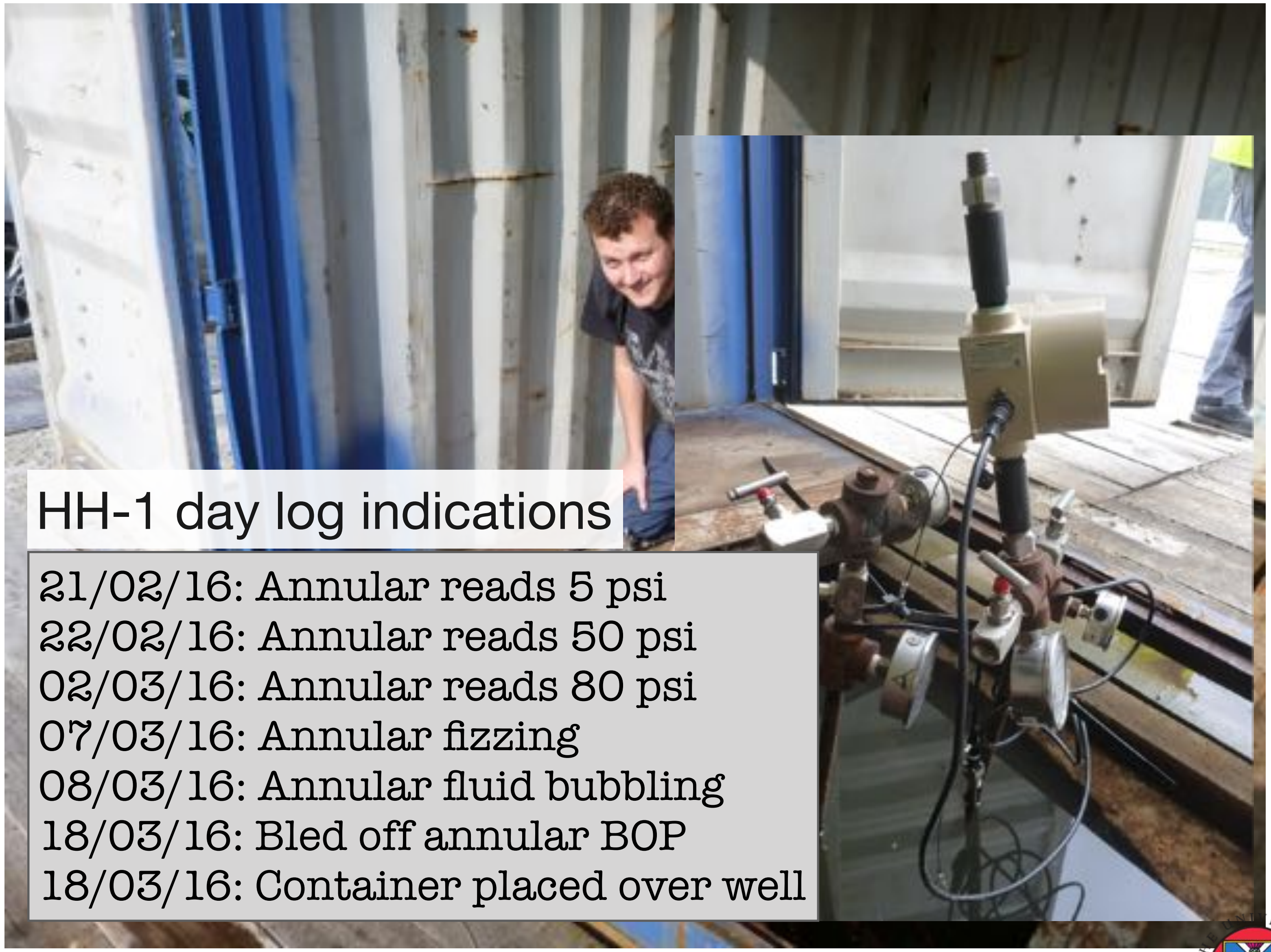

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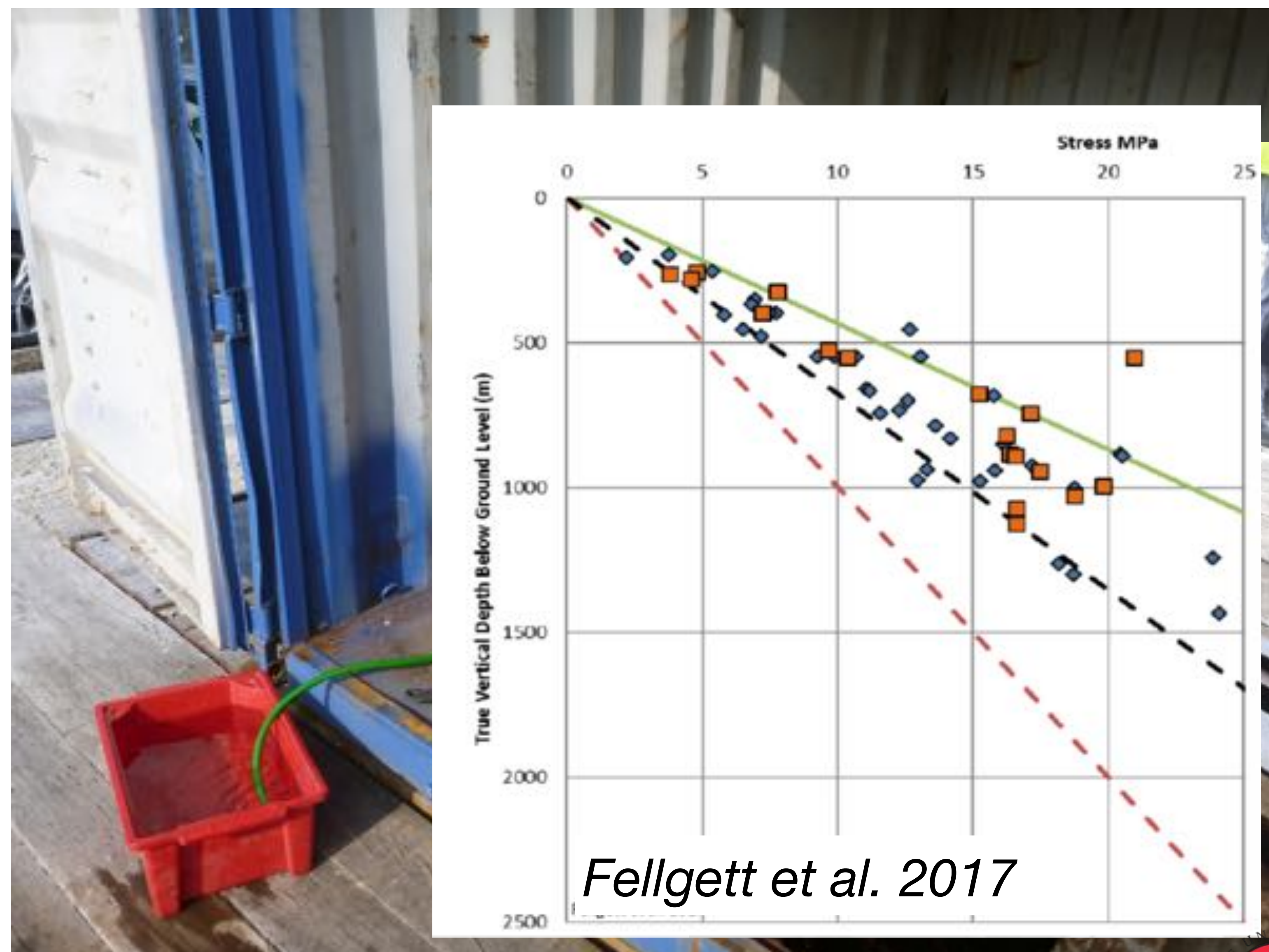

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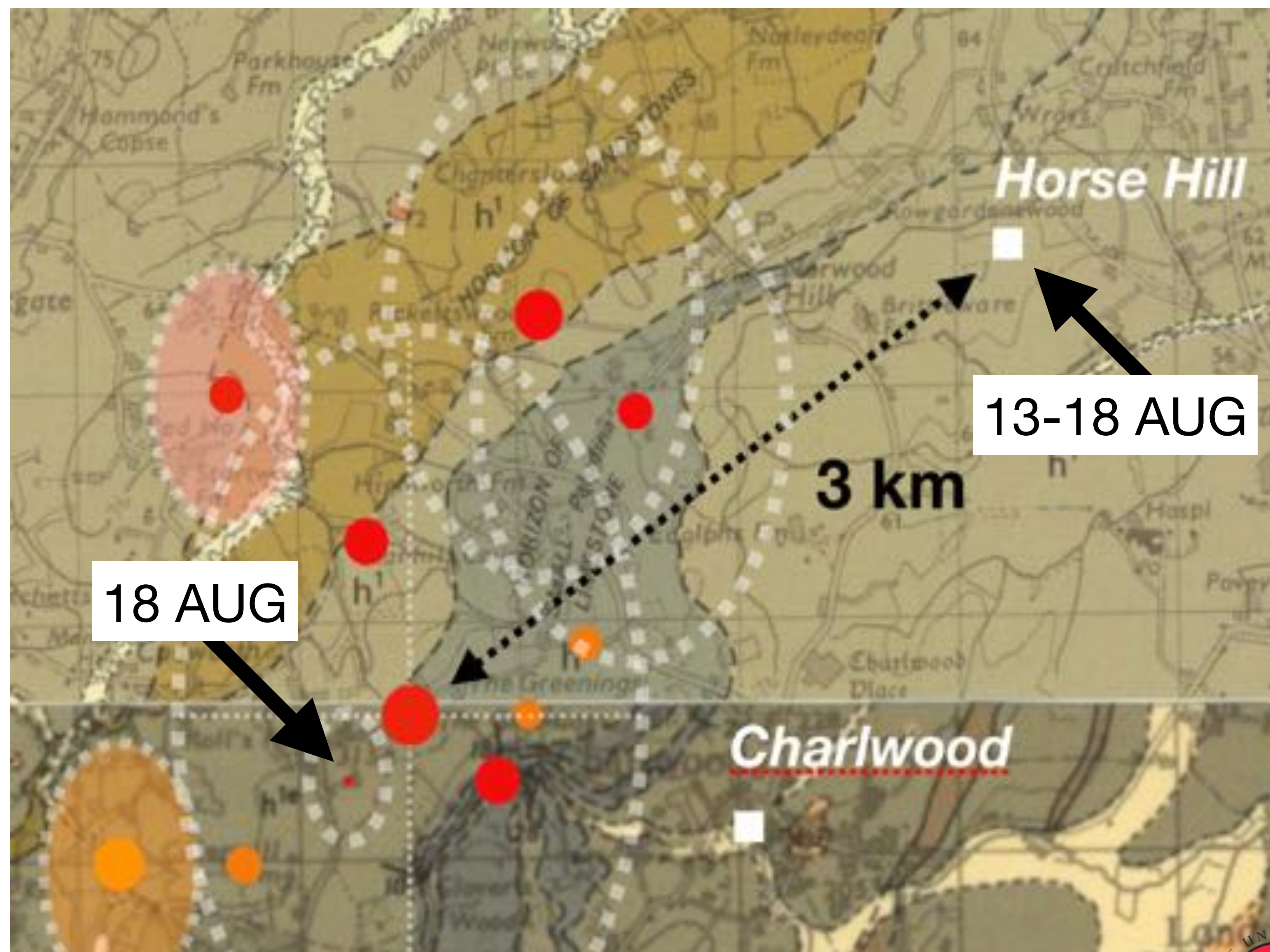

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Davis & Frohlich (1993) SRL: Did Fluid Injection Cause Earthquakes? Criteria For A Rational Assessment… Six Questions

- 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 af 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?