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Fault interactions, fault kinematics, and evolution of the structural framework in the Irish Lower Carboniferous

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European Union
European Regional Development Fund
Science Foundation Ireland
For what's next

In this display, we will show several examples of our ongoing research on the evolution of the Irish Lower Carboniferous basins, focusing on broader implications for fault interactions and fault kinematics in rift basins. This research is the result of a team effort over many years.

Resulting papers (all open access or freely accessible):
Kyne et al. (2019) *Economic Geology* **114(1)**, 93-116 https://doi.org/10.5382/econgeo.2019.4621
Torremans et al. (2018) *Economic Geology* **113(7)**, 1455-1477 https://doi.org/10.5382/econgeo.2018.4598
Walsh et al (2018) SEG Special Publications **21**, 237-269 https://doi.org/10.5382/SP.21.11

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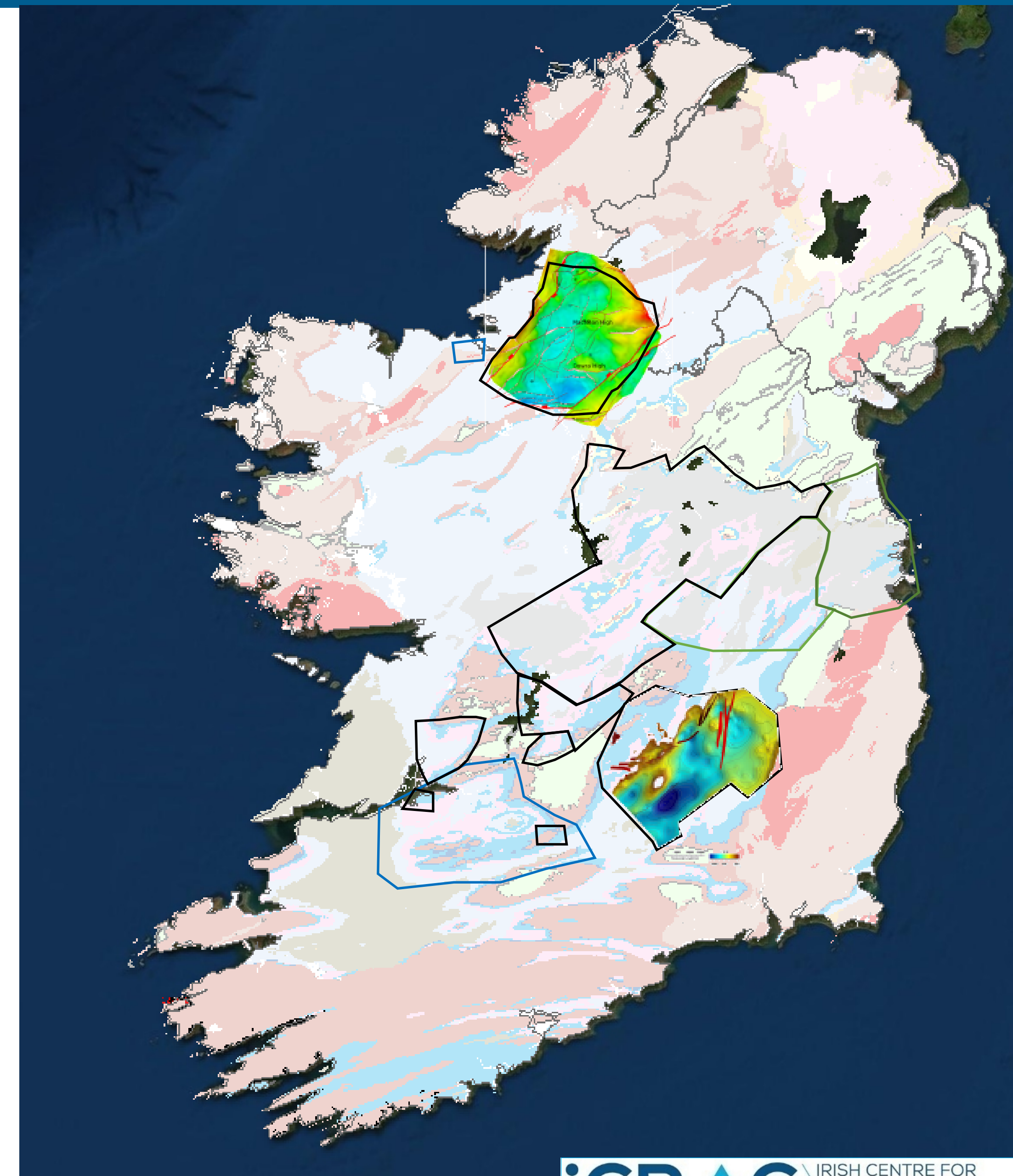
Our research is the result of several interrelated research projects supported by national and European funding agencies, and by our industry partners. Our collaboration with industry partners has been instrumental for this work. We are very grateful to our industry partners and project stakeholders for providing data, information and for collaborative research efforts on these topics, through continual two-way discussions, both in one-on-one technical exchanges and through regular technical sessions with larger groups of geologists. The research would not be possible without the above unique combination of several state-of-the-art geological spatial information analysis and modelling packages, which were kindly provided to use in various forms of academic licence agreements for the purpose of the projects.

- Facilitate the exploration for and management of our underground resources **for urban and rural development**
- Better understand and **more efficiently find and develop** world-class sedimentary-rock hosted **Zn -Pb-Ag deposits** in the Irish Orefield.
- Describe regional scale **structural and basin architecture** and establish target depths.
- Gain insights into **basin evolution** during the Mississippian in SE Ireland.



Map modified from Geological Survey Ireland, 2017

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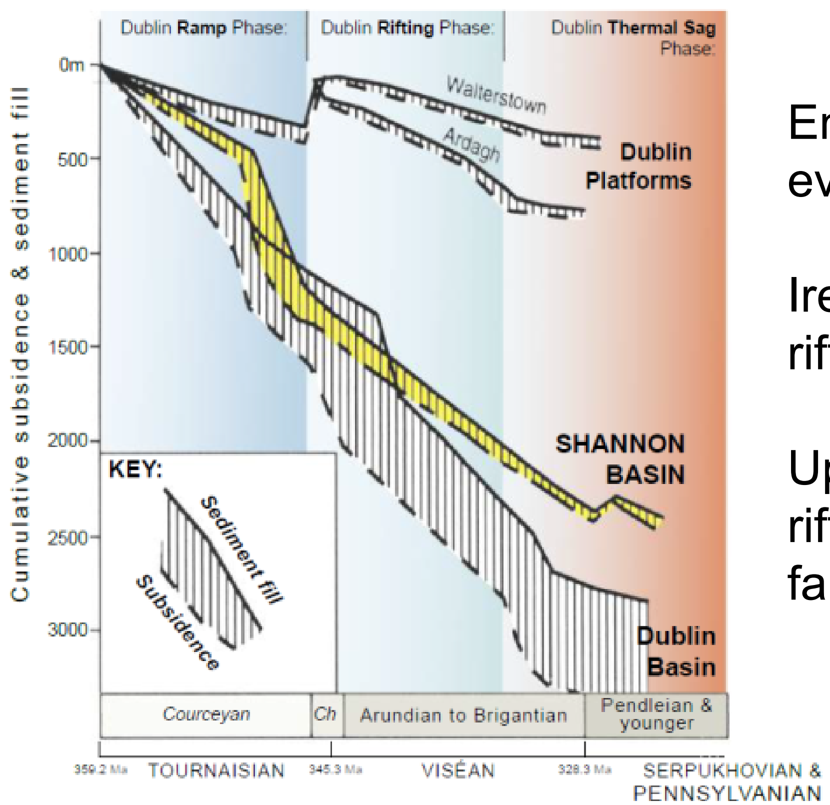
Fault systems in the Irish Lower Carboniferous are important in relation to subsurface resources, including groundwater, geothermal and mineral resources. For example, major base metal deposits in the world-class Irish Orefield occur in association with normal faults. Despite their economic importance, however, the fault networks and structural framework at depth are still poorly constrained.

Lower Carboniferous Basins

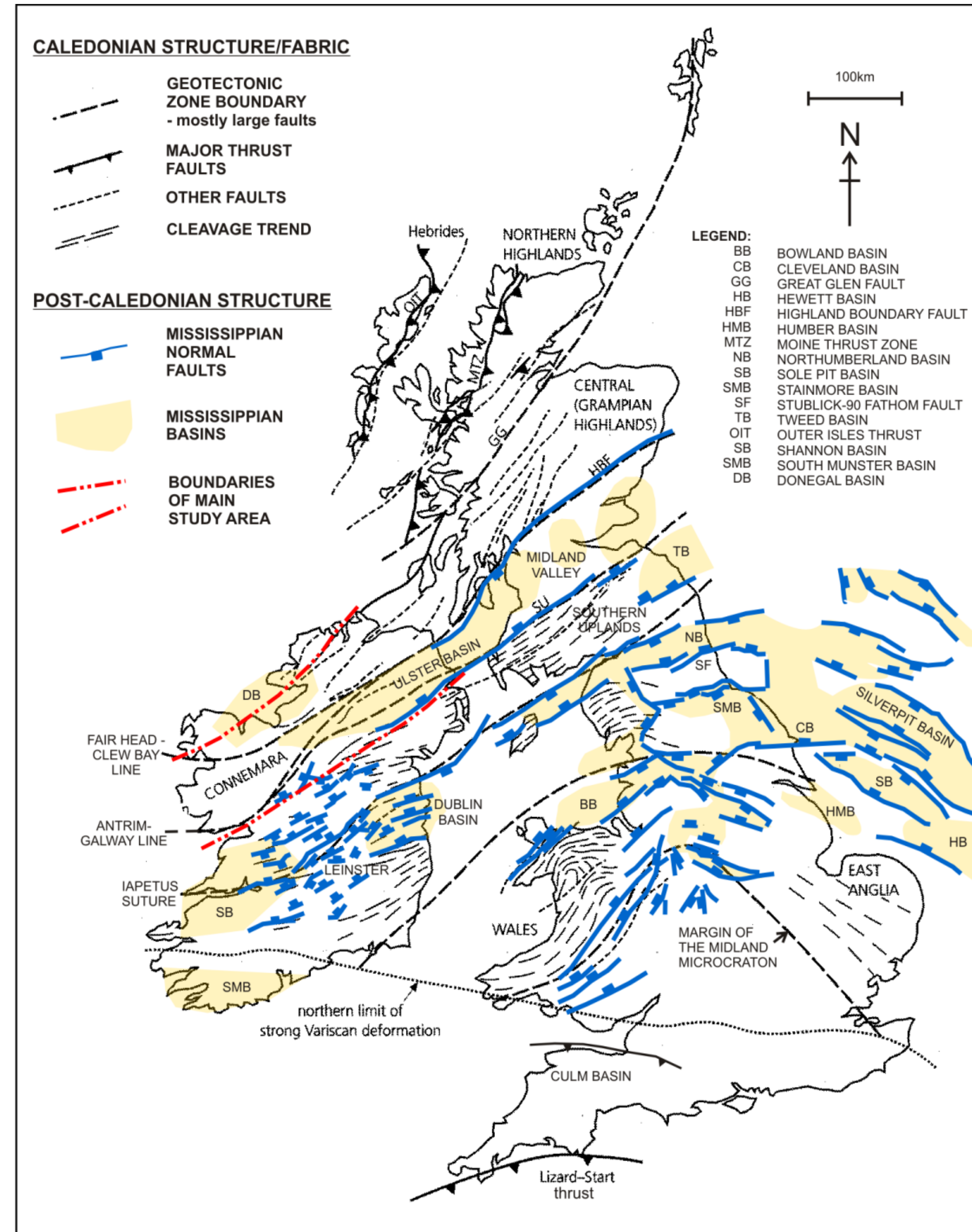
- Extend from North Sea through to Ireland.
- Discontinuous faults with associated basins and footwall highs.
- Horst and graben structures
- Inheritance from pre-existing Caledonian structures



England – 3 rifting events

Ireland – at least 2 rifting events

Upper Devonian rifting – often thin or fault wedges



John Murray (2010)

Worthington & Walsh (2011)

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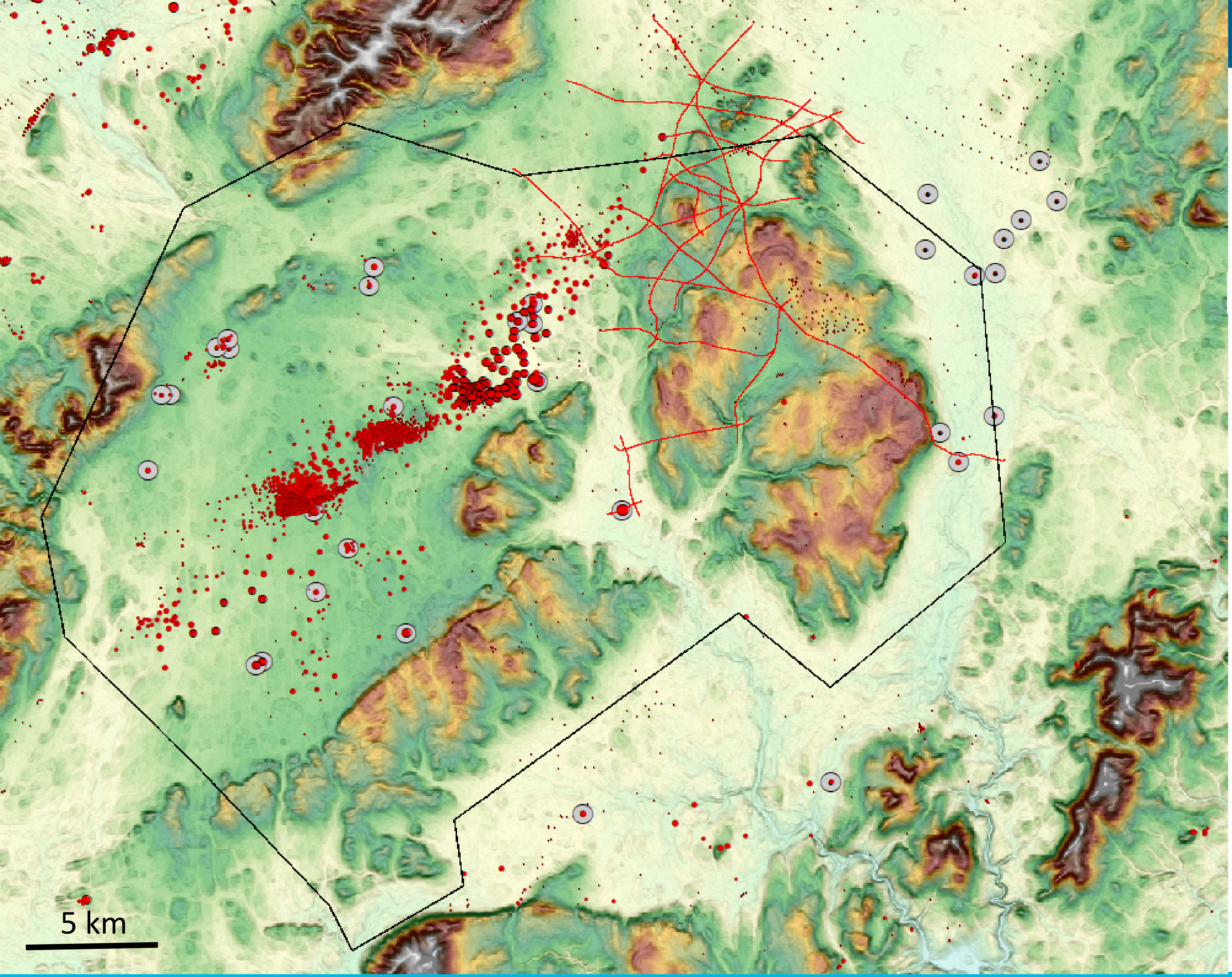
The Irish Carboniferous Basins are an excellent area to study the extensional fault systems and evolution of rift basins, given the relatively low amounts of later compressional deformation and metamorphism, and because high-quality subsurface datasets exist from several decades of mineral exploration.

Our work is aimed at developing a coherent structural framework for the Lower Carboniferous in Ireland, and at unraveling the geometries and kinematics of faulting in a carbonate-dominated rift basin that developed on top of a strong pre-existing structural template in the underlying basement rocks.

Data

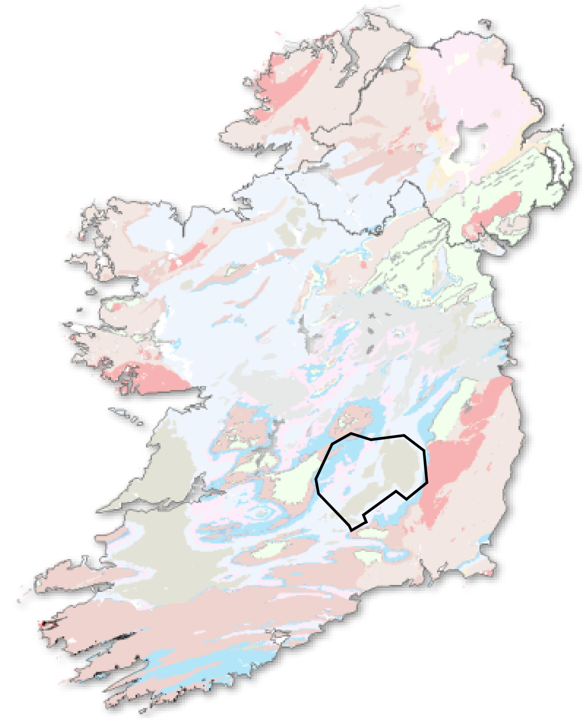


2D reflection seismic

10 m deep drill hole

1000 m deep drill hole

Detailed lithofacies study



Topography: JPL SRTM
Seismic from Petroleum Affairs Division, DCCAE
iCRAG UCD drillhole database, and Vedanta Ltd database
500k geology modified from Geological Survey Ireland, 2017

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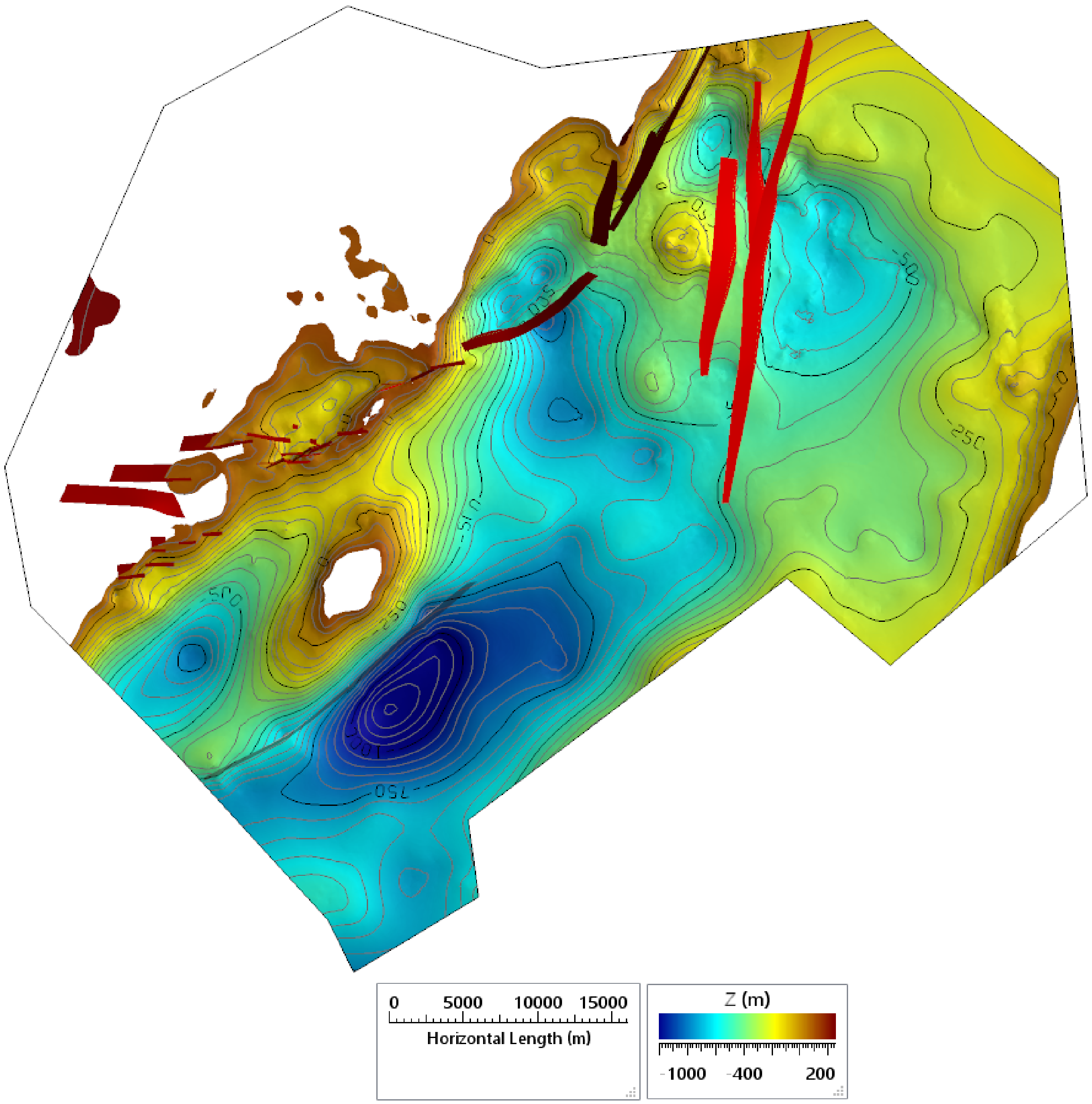
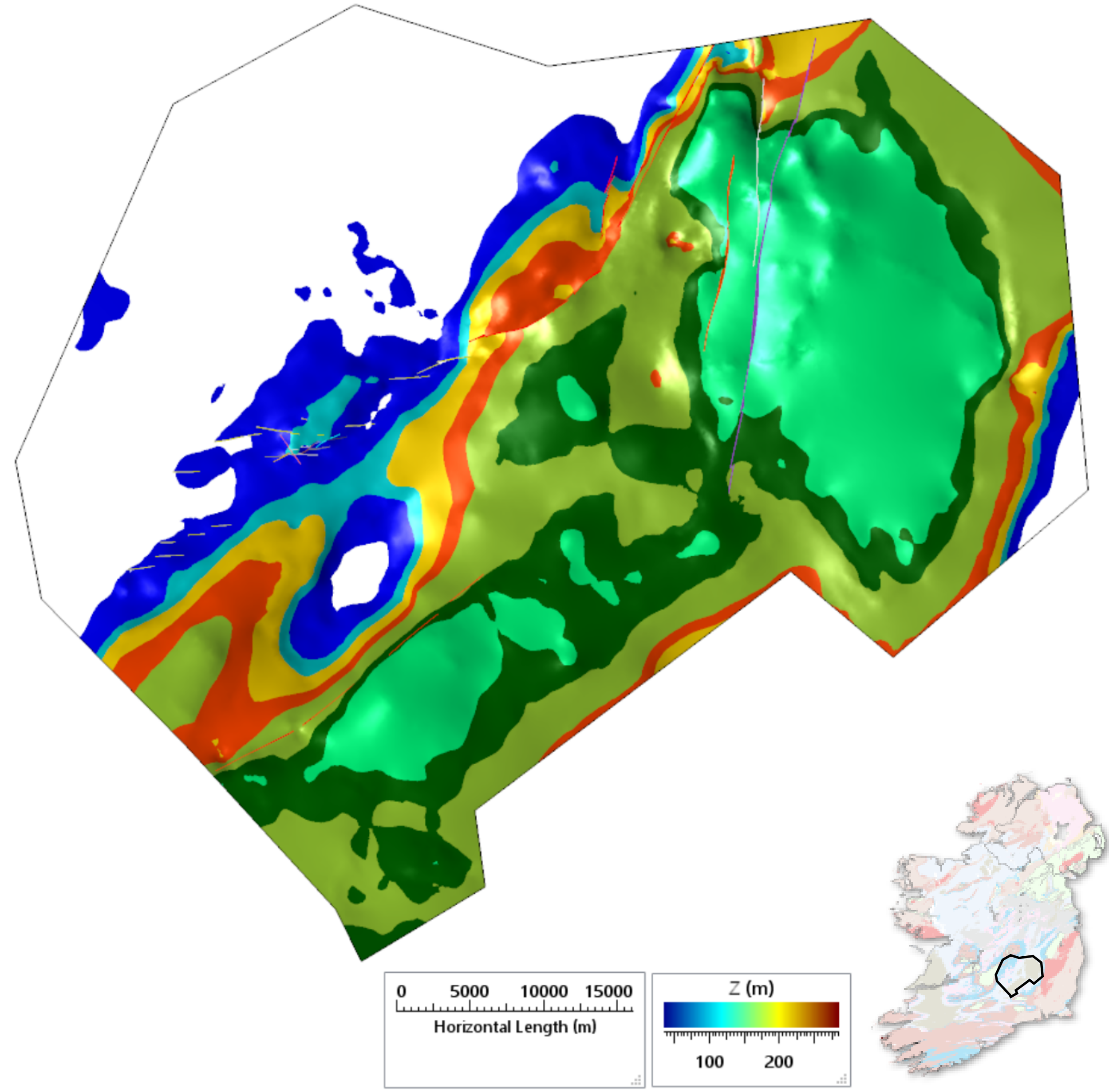
We have defined the geometry of key fault systems in the rift across a wide range of scales, using three-dimensional integrated analysis of large datasets. These datasets include public and proprietary onshore 2D reflection seismic, mapping, drillhole, micro-palaeontological, aeromagnetic, electromagnetic, and ground gravity data.

This image is an example of just one of the regional study areas within the Irish Lower Carboniferous. It depicts the typical data density of drilling and seismic that constrains our 3D geological modelling efforts and quantitative analyses.

Top Ballysteen Fm in SE Ireland





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Our ongoing regional 3D modelling efforts have resulted in large parts of the country now covered or in advanced stages of completion, including the entire Central and North Midlands area, the East Clare area, and SE Ireland. The figure on the right shows a snapshot of the different horizons within the regional 3D working model in the SE of Ireland, each of which are coloured differently. The left image shows the top of the Ballysteen Formation, of Courceyan age (the blue horizon in the right image). The red surfaces crosscutting this horizon are myriad complexly segmented normal faults that crosscut the stratigraphies. The unit right above this Ballysteen Formation, the Waulsortian Limestone Formation, hosts at its base many of Ireland's Zn-Pb deposits.

Some insight from our regional tectono-stratigraphic basin analysis

- The large-scale rift patterns are becoming increasingly clear. Several **large basin-bounding faults** are present in the central and eastern parts of the study area. Unit thicknesses also dramatically increase across these faults. As this is still a work in progress, many faults, of course, remain to be better constrained.

- There are many (buried) normal faults of Carboniferous age, which are not always easy to correlate along strike, attesting to the **complexly segmented** nature of the normal fault systems.

- A broad **spatial change in the polarity of faulting** in the Central-North Midlands is seen from mainly south-dipping in the east to predominantly north-dipping in the west, with a complex zone in the middle.

- Regional analysis shows a range in orientation of Carboniferous normal faults, resulting in variably trending, narrow, **fault-bounded horst and graben sub-basins** that are complexly interacting along strike.

- Distributed extension during the **Late Courceyan**:
  - Initially dense network of slow-growing segmented normal faults
  - concentration on fewer, but larger and faster-growing faults during **lower Visean time**.

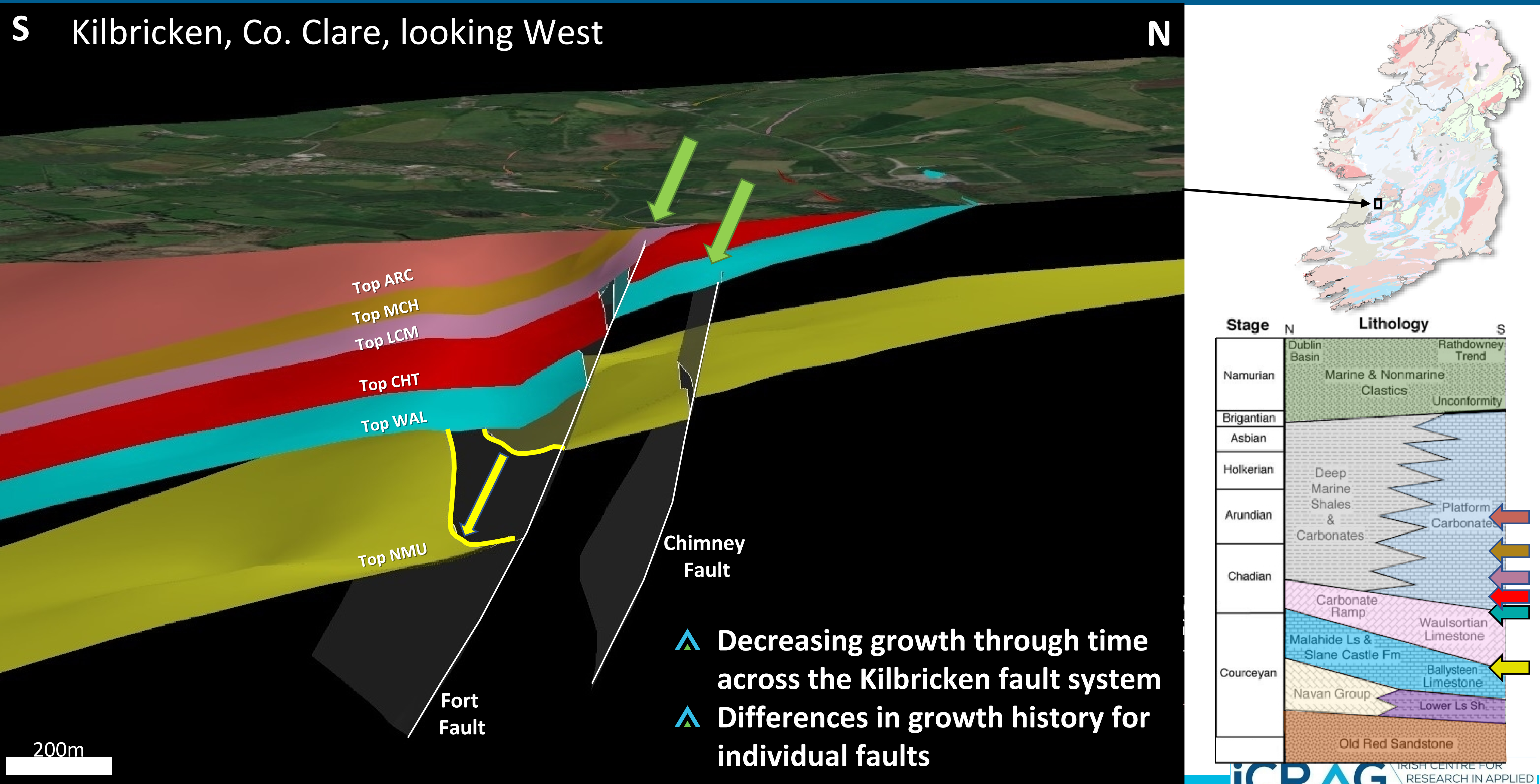


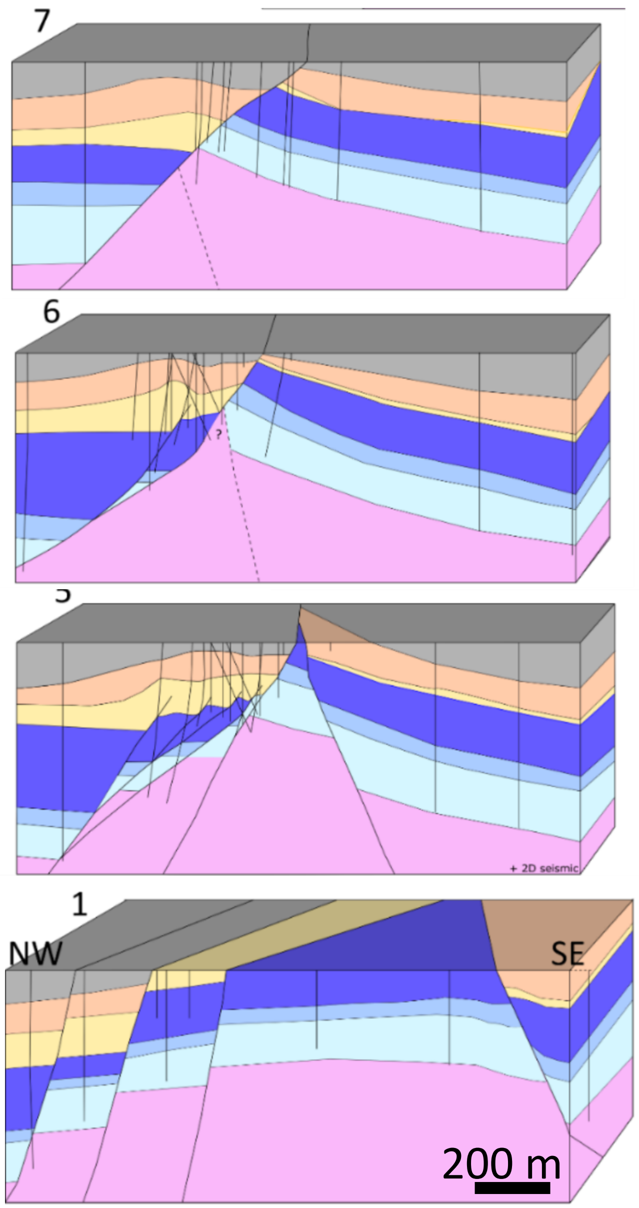
Image and model by Eoin Dunlevy; Geological map Geological Survey Ireland 2018; Stratigraphic column after Johnson et al. 2009

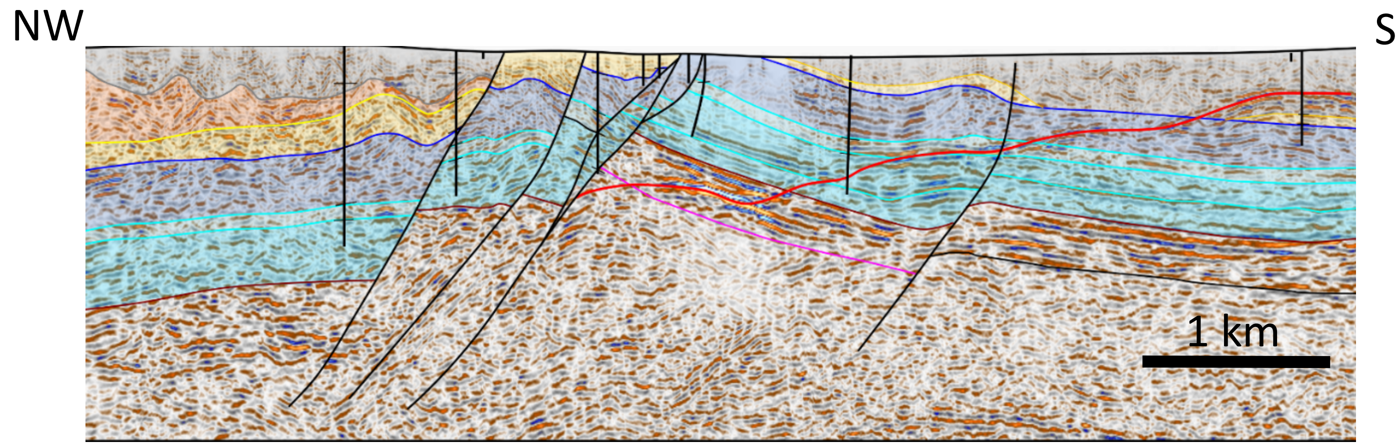
Quantification of fault parameters, kinematic analysis and kinematic restoration have allowed us to gain insights into the distribution of extension during rifting in time and space, using growth sequences and facies changes on faults.

These two faults near the Kilbricken Zn-Pb resource, exemplify the type of data we gather in our database. Both faults reveals strong growth that initiates during deposition of the Waulsortian Limestone Formation (between yellow and blue surface) halfway through the Courceyan. Growth is reflected in thickness changes across the faults, but also in subtle facies changes visible in drillhole correlations.

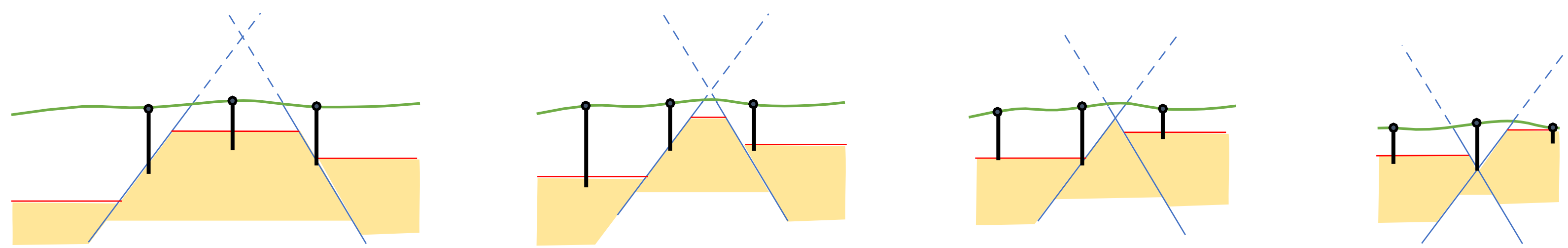
The Fort Fault continues growing well into the Chadian, possibly early Arundian, whereas the Chimney Fault has completely stopped growing before the Chadian.

Courceyan-Early Chadian fault geometries and influence on geology





- Along strike, faults can become multi-strand or join up into a single structure.
- Narrow horsts and grabens complexly interacting along strike.
  - 0° – 25° strike intersections
  - Interaction of N and S dipping faults



2D seismic courtesy Teck Ireland Limited; Torremans et al in prep

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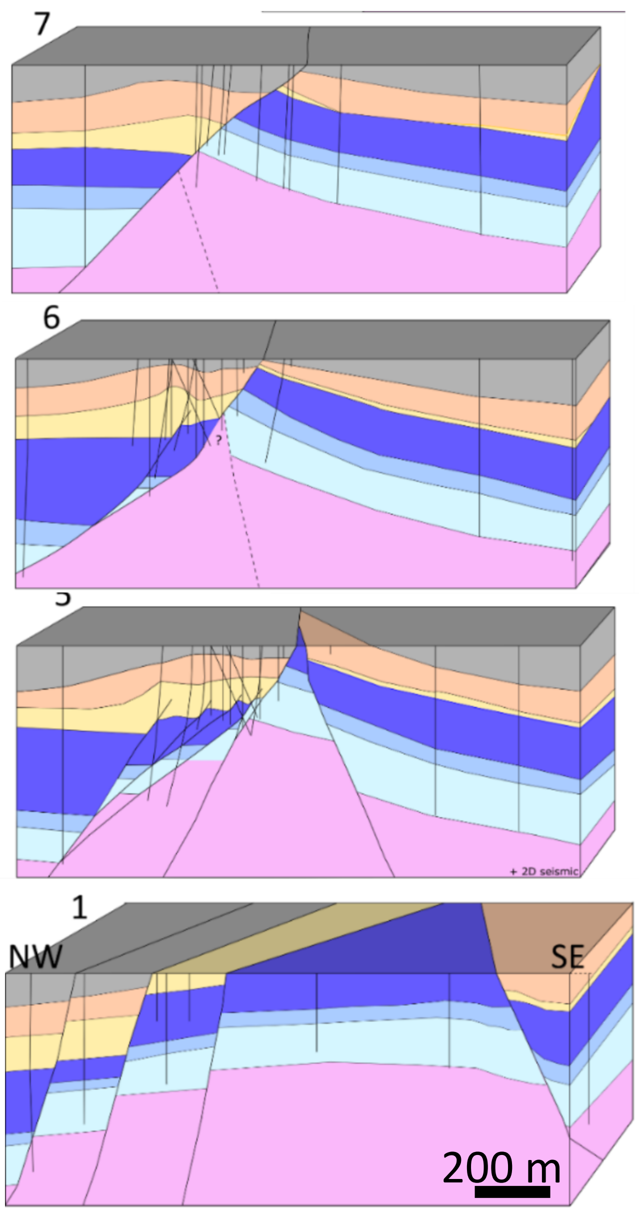
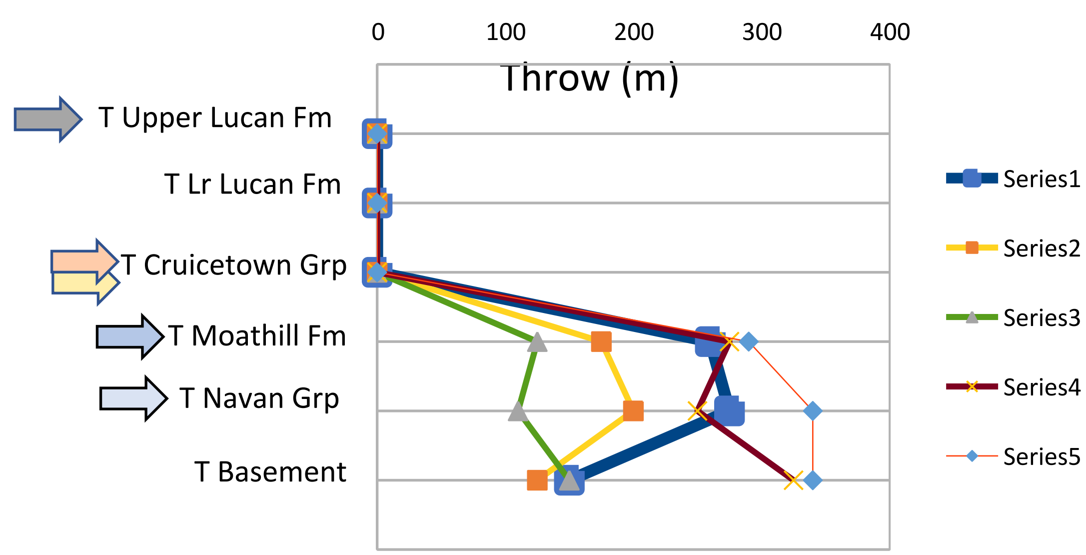
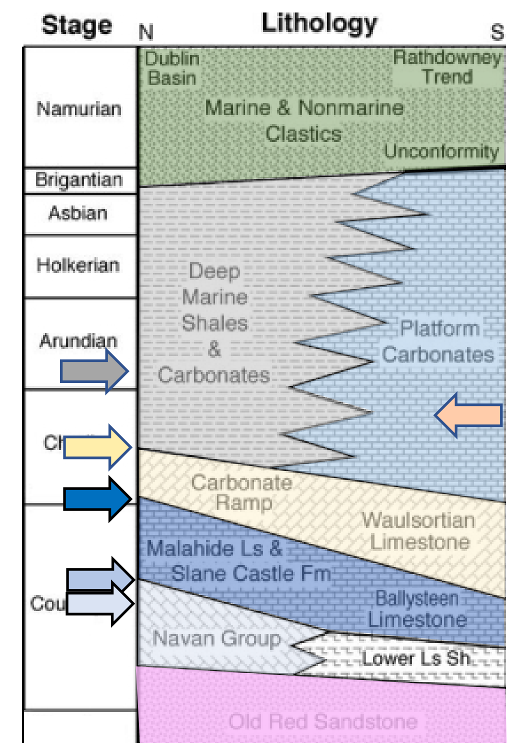
The four block diagrams on the left show an area along-strike the Ballinalack Fault system from SW (bottom image) to most NE (top image). Along-strike, this fault system changes from a multi-strand segmented fault, over a complexly faulted system with many fault lenses, into a throughgoing fault. The total throw across the system is 400m in all cases, but the way the displacement is distributed is quite different. Another SE-dipping fault of 200m displacement is intersecting this fault at an angle of 15 degrees, providing complex conjugate fault interactions along strike, and most importantly, the generation of fault rock, small fault lenses and fault breccias where the two faults intersect. The tie-line between the two faults is dipping ENE.
These geometries are ubiquitous and have significant implications on interpretation of (mineral) exploration drilling in these areas, as illustrated in the four simple diagrams at the bottom to bottom right of the page.

Courceyan-Early Chadian fault geometries and influence on geology



- **Courceyan faulting is ubiquitous and quite slow**
- Identification of **growth** on faults is sometimes quite subtle: minor up-fault throw decrease and **complex across-fault sequence facies changes** during early growth.
- Most faults also stop growing during Chadian-Arundian





2D seismic courtesy Teck Ireland Limited; Torremans et al in prep

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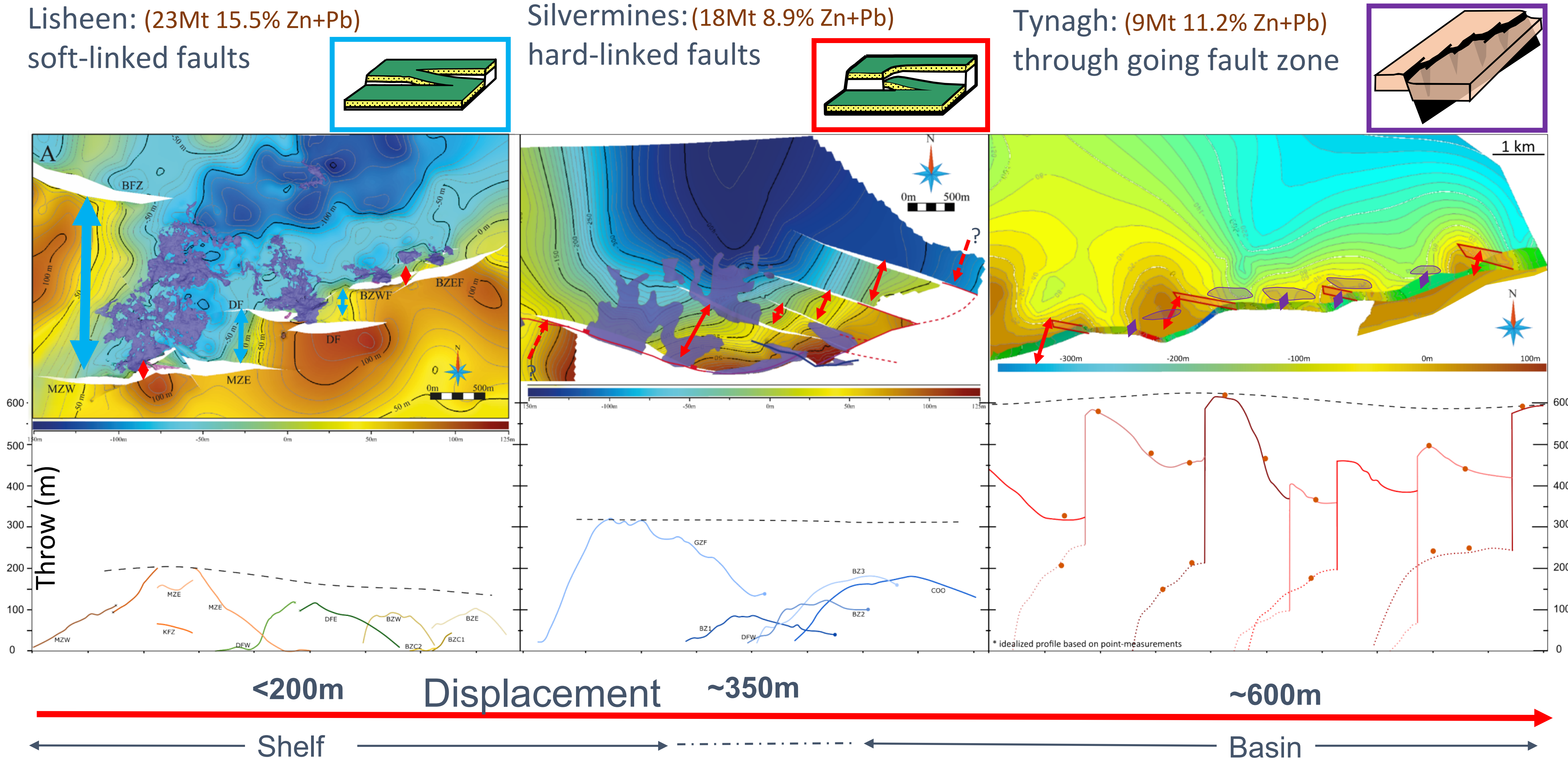
This Ballinalack Fault system reveals growth that initiated in the middle Courceyan (during deposition of) with facies variability (lithofacies but also gamma response) and thickness changes across the fault along its length. The fault is interpreted to have been active during deposition of the Moathill Formation and Cruicetown Group ( ), and then stopped growing some time before deposition of the Tober Coleen Formation and Lucan Formation ( ). The throw diagram quantitatively analyses this fault growth depicting the amount of throw present at a given location along various segments of the combined Ballinalack fault system (F1, F2, etc). Wherever the data allows, fault throws over time are currently being quantified for the Irish Carboniferous.

Evolution of segmented faults with increasing displacement



Kyne et al, 2019; Torremans et al, 2018; Torremans et al in prep

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The analysis of this structural framework in relation to several Zn-Pb mineral deposits, in combination with mapping lithofacies distribution and the development of bathymetry during basin formation, allows us to better understand current and past fluid flow pathways. The images show from left to right, 3D horizons models of the base Waulsortian Formation at Lisheen and Tynagh and base Muddy Reef unit of the Ballysteen Formation at Silvermines. Throw profiles along the main fault systems show displacements from 200m, to 350 to 600m, respectively, and bell-shaped and plateau-type throw profiles. As displacement gets larger, these fault systems evolve from soft-linked faults with intact relay ramps, over hard-linked fault systems with breached or doubly breached relay ramps, and ultimately into through-going fault zones with fault lenses and fault rock. The Zn-Pb mineralisation, in purple, is most strongly influenced by the early geometry of the, initial soft-linked segmented fault arrays.

Orthophoto source: IKONOS

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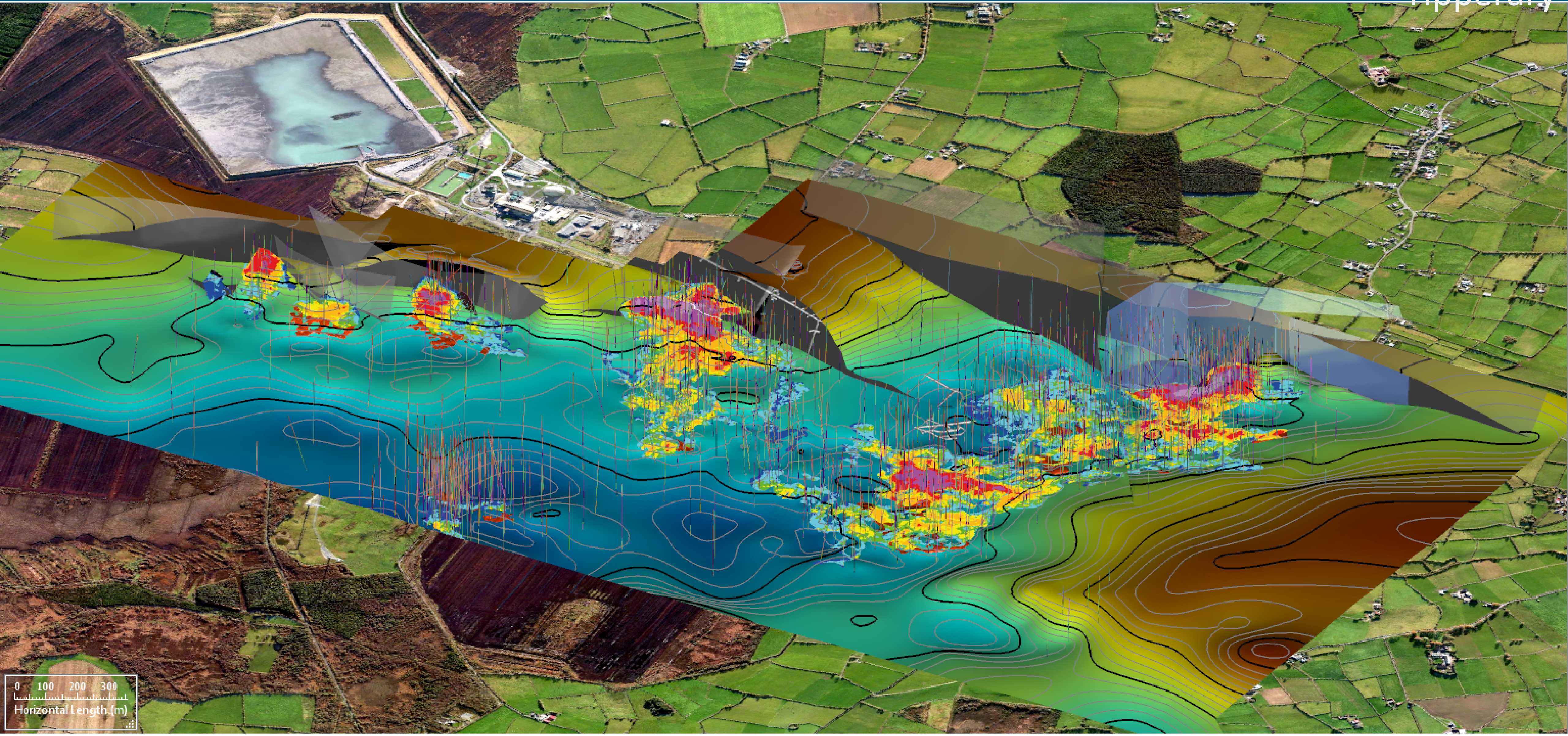
The Lower Carboniferous rocks in Ireland are host to world-class Zn-Pb base metal mineralization. These mineral deposits are strongly structurally controlled. This image shows an orthophoto of the Lisheen Zn-Pb mine site in Ireland in 2015 looking South.

Fault systematics and metal distributions at Lisheen, Co. Tipperary



Torremans et al. 2018; Walsh et al. 2018; Kyne et al. 2019

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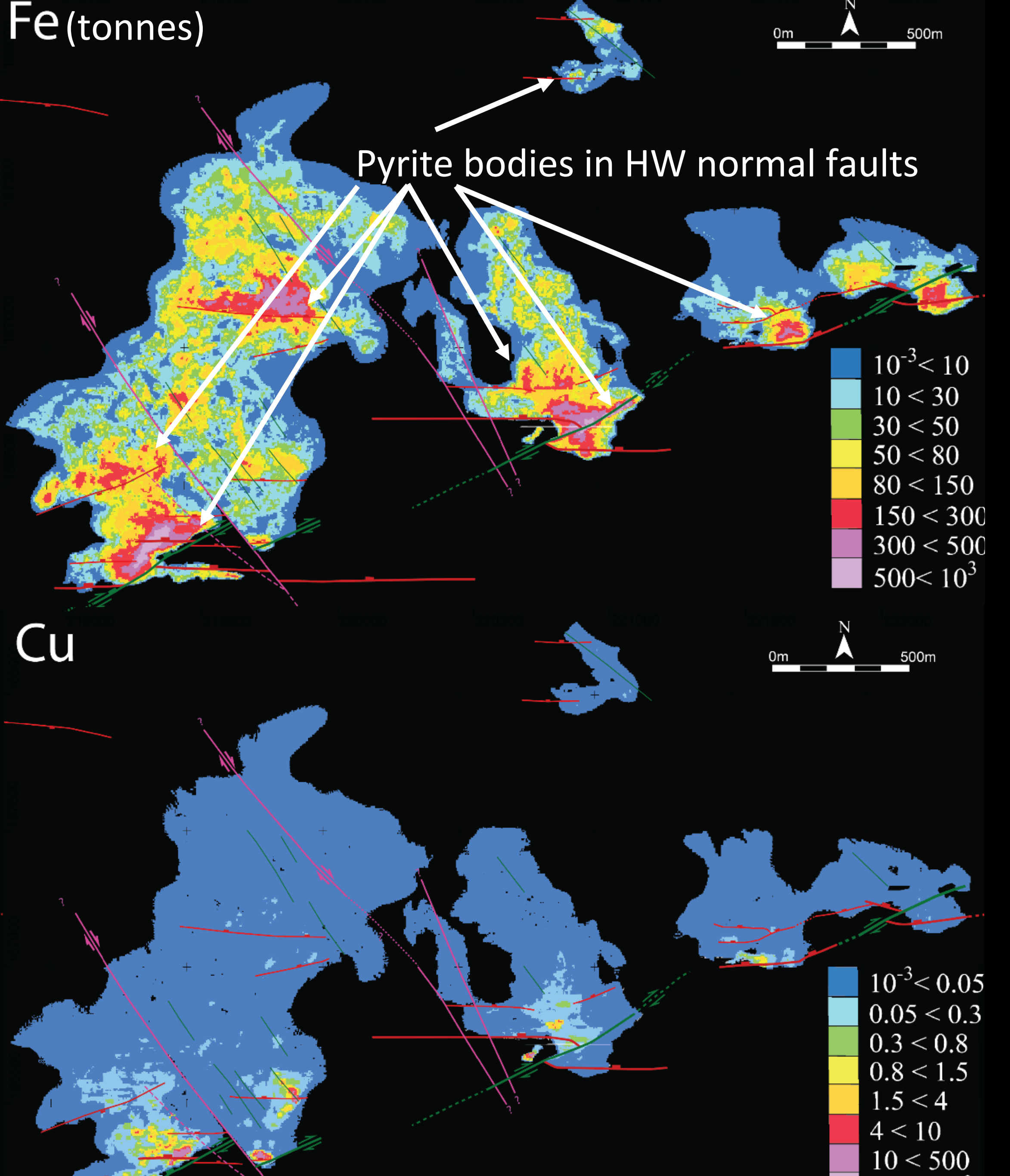
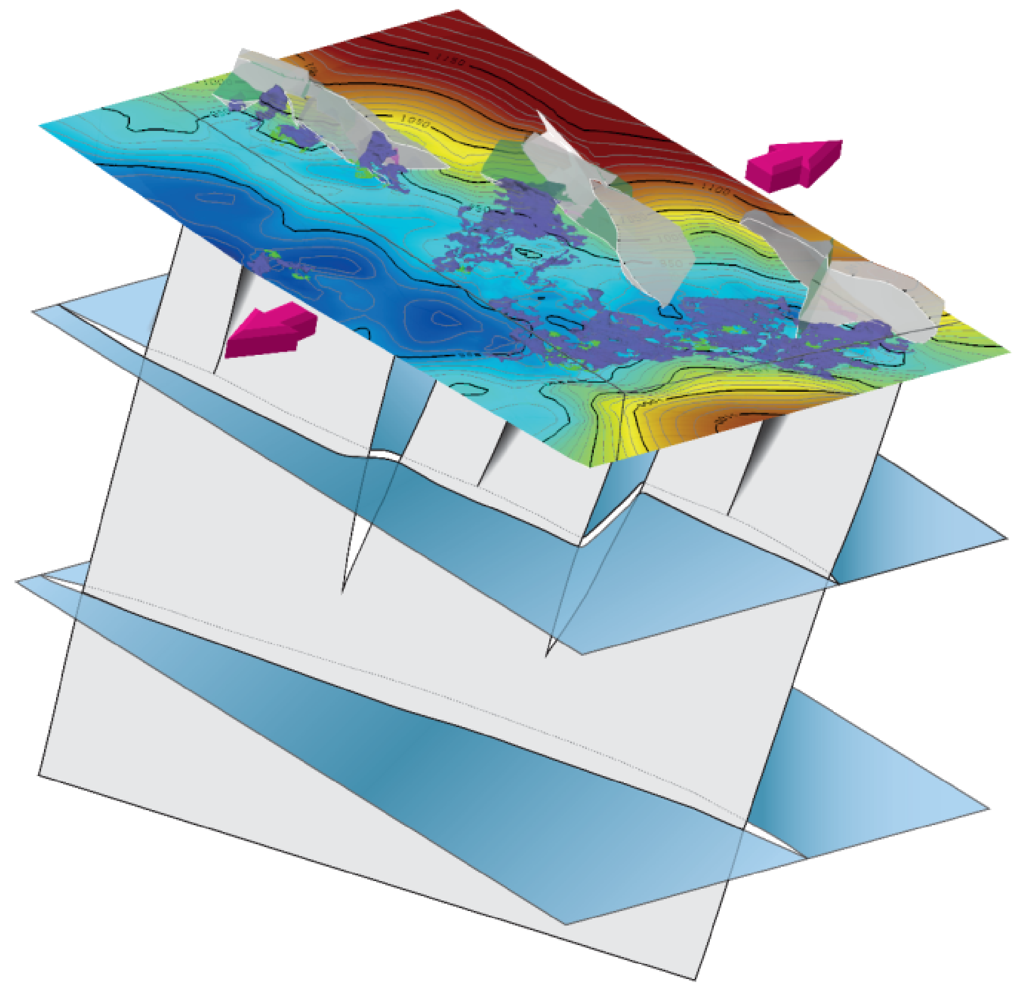
The cut-out image shows the horizon model for the base of the Waulsortian Limestone Formation at the Lisheen Zn-Pb mine. The orebody is located at or near the base of this unit. **The Waulsortian horizon surface is ripped by several normal fault segments that die out laterally and which structurally control the individual orebodies**. The contained distribution of total Fe tonnages in the orebody are also shown, draped on the economic orebody resource. These distributions are calculated from a geostatistically determined block model showing average Fe tonnages in 4x4m vertical columns through the orebody. Surface drillholes are shown, as well as the surface infrastructure and culture surrounding the Lisheen mine, where it is not cut out to show the subsurface geology.

Understanding ‘feeder’ zones





Torremans et al. 2018; Walsh et al. 2018; Kyne et al. 2019

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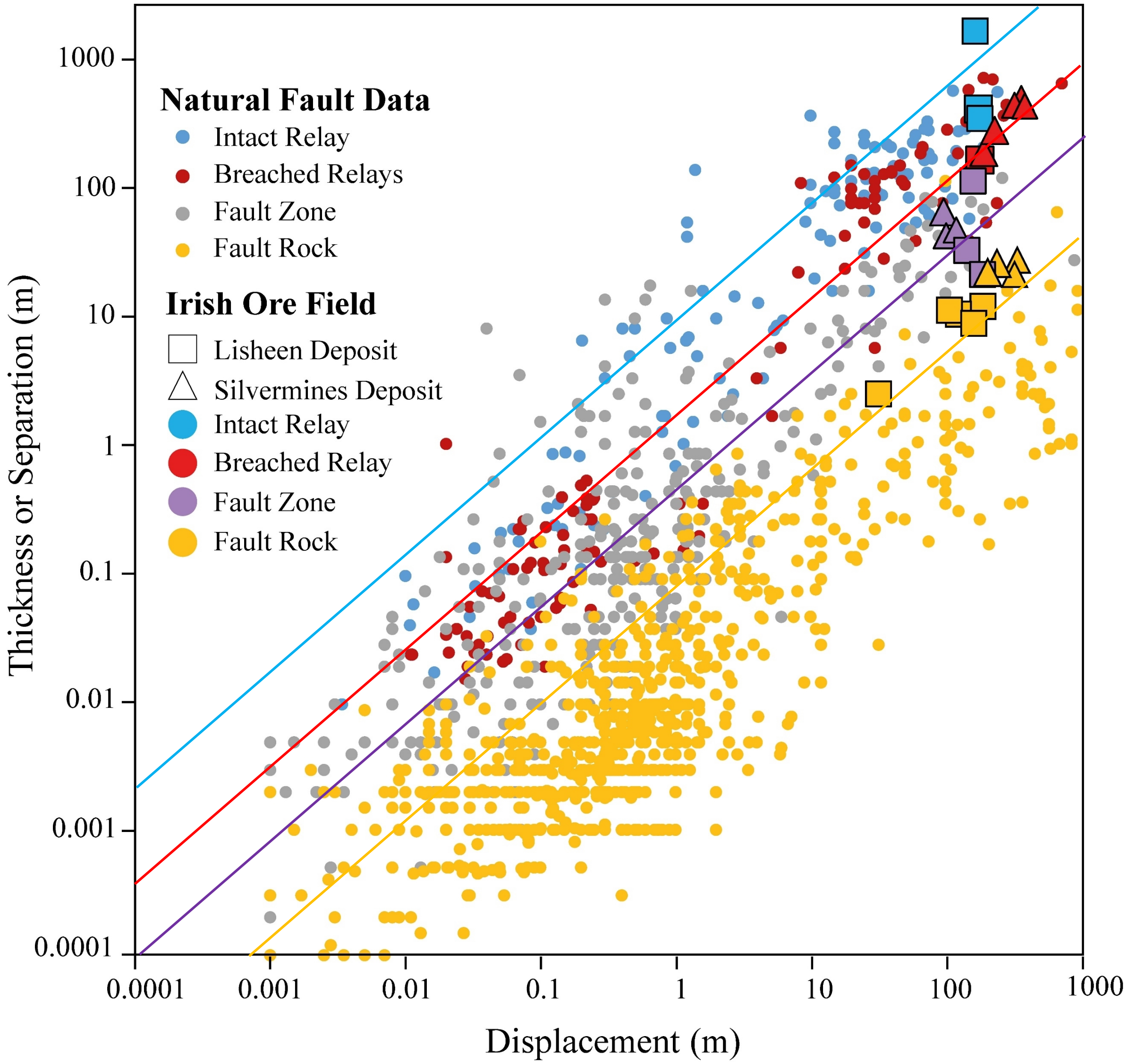
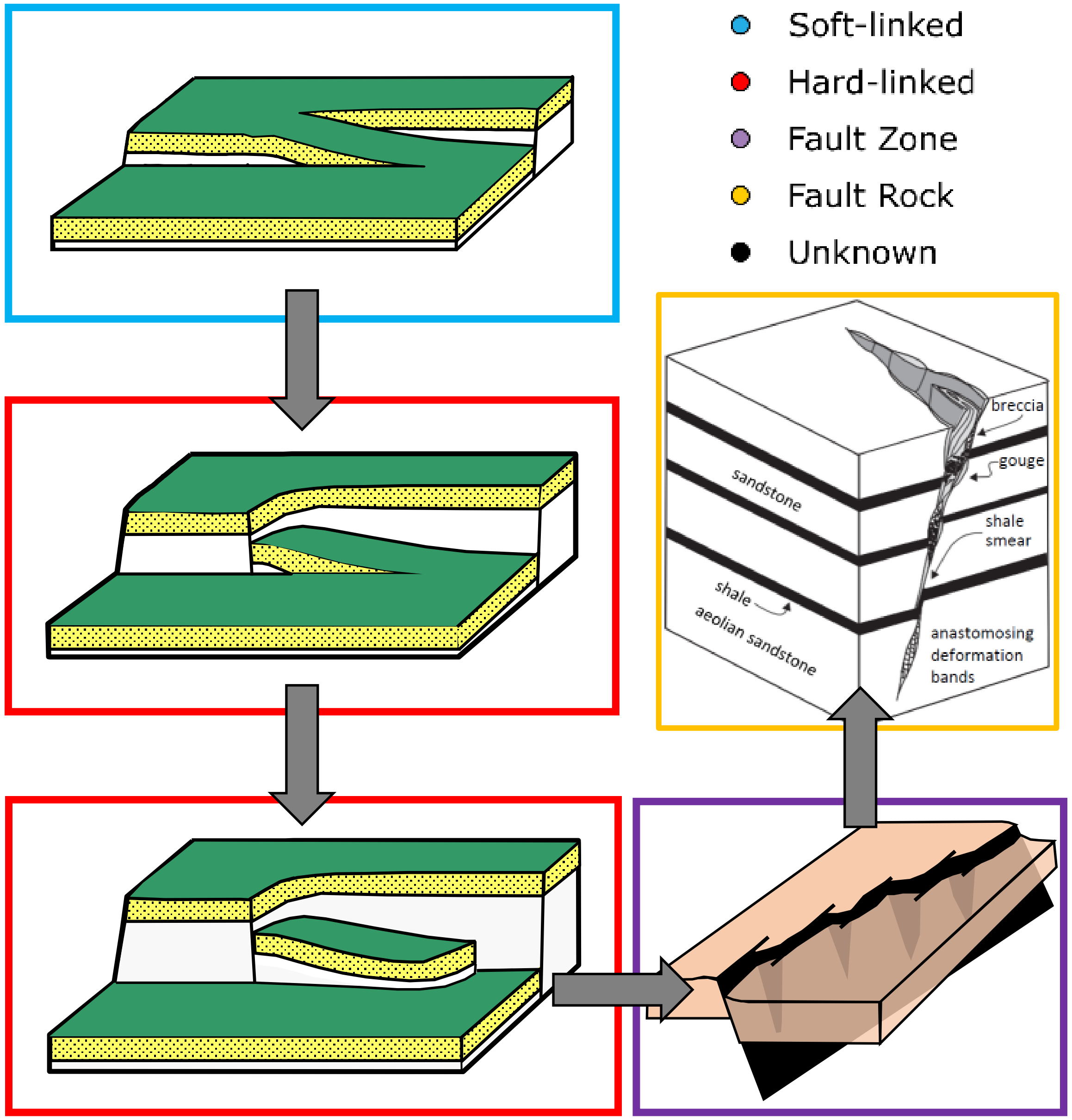
Segments occur on different scales and have a profound impact on structural evolution, with larger scale segments and intervening relay ramps defining distinct ore bodies within deposits and smaller scale segments and relays potentially providing paths for up-fault flow. The difference in behavior is attributed to the integrity of associated ramps, with **intact ramps** representing **ore body bounding structures**, and **smaller breached ramps** providing enhancing associated hydraulic properties and acting as **vertical conduits**, bringing up hot, metal-bearing hydrothermal fluids to mix with cold, dense, basinal brines subsequently precipitating ore. **Metal distribution patterns** identify these conduits as distinct points along the segmented normal fault array that acted as feeders to individual orebodies. The **position of feeders and fluid flow** changes as the structural framework evolves with increased extension.

Evolution of segmented faults with increasing displacement





IMPACT: Predictive model for relay integrity – ore bodies vs feeders.

Kyne et al 2019; World quantitative fault data compilation in background from Childs et al. (2009) and Fault Analysis Group, UCD

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Quantitative data for different fault zone components on a thickness or separation vs. displacement plot for a global database updated from Childs et al. (2009), and including Lisheen and Silvermines data (Kyne et al 2019). Separation represents the fault perpendicular distance between segments of intact relays, breached relays or lenses, and thickness refers to fault rock. Different fault zone components provide distinctive, albeit overlapping, distributions with an increased displacement to thickness (or separation) ratio, and therefore shear strain, from intact relays through breached relays and into fault zones and ultimately fault rock. The Irish ore field data in this figure appear to be consistent with global datasets, providing a quantitative basis for predicting fault zone structure and content.

Take home messages

- Regional analysis shows variably trending, narrow, **fault-bounded horst and graben sub-basins** that are complexly interacting along strike.
- Distributed extension during the **Late Courceyan**:
  - Initially dense network of slow-growing segmented normal faults
  - concentration on fewer, but larger and faster-growing faults during **lower Visean time**.
- The **degree of breaching of relay zones** is controlled by the scale of segmentation (separation and ramp length) relative to fault displacement.
    - Impact on fluid flow
    - Predictability
- Breached fault relay zones act as **vertical feeder conduits**, bringing up hot, metal-bearing hydrothermal fluids to mix with cold, dense, basinal brines subsequently precipitating ore.
- The **position of feeders and fluid flow** changes as the structural framework evolves with increased extension
- Lithology can influence fluid flow within fault network and determine site of fluid mixing

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(!) Torremans, K., Kyne, R., Doyle, R., Güven, J. F., & Walsh, J. J. (2018). Controls on Metal Distributions at the Lisheen and Silvermines Deposits: Insights into Fluid Flow Pathways in Irish-Type Zn-Pb Deposits. *Economic Geology*, *113*(7), 1455-1477. https://doi.org/10.5382/econgeo.2018.4598

(!) Walsh, J. J., Torremans, K., Güven, J., Kyne, R., Conneally, J., & Bonson, C. (2018). Fault-controlled fluid flow within extensional basins and its implications for sedimentary rock-hosted mineral deposits: Society of Economic Geologists Special Publications, v. 21. *Special Publication*, *21*, 237-269. https://doi.org/10.5382/SP.21.11

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