Constraining heat production rates in Ireland's continental crust

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Heat production rate (HPR) ($\mu W/m^3$)

$$= 10^{-5}\rho\,(9.52C_U + 2.56C_{Th} + 3.48C_K)$$ (Rybach, 1988)

U and Th concentrations (C_U and C_{Th}) are in ppm; K concentration (C_K) is %; ρ is density (kg/m^3).

RESEARCH AIMS

"the identification of large-volume, high-heat production units, including radiogenic granite intrusions"

"analysis of an island-wide suite of multi-depth crustal samples to derive the first 3-D map of crustal heat production"

"new crustal heat production constraints" [to model thermal variations on lithospheric structure].

RESULTS

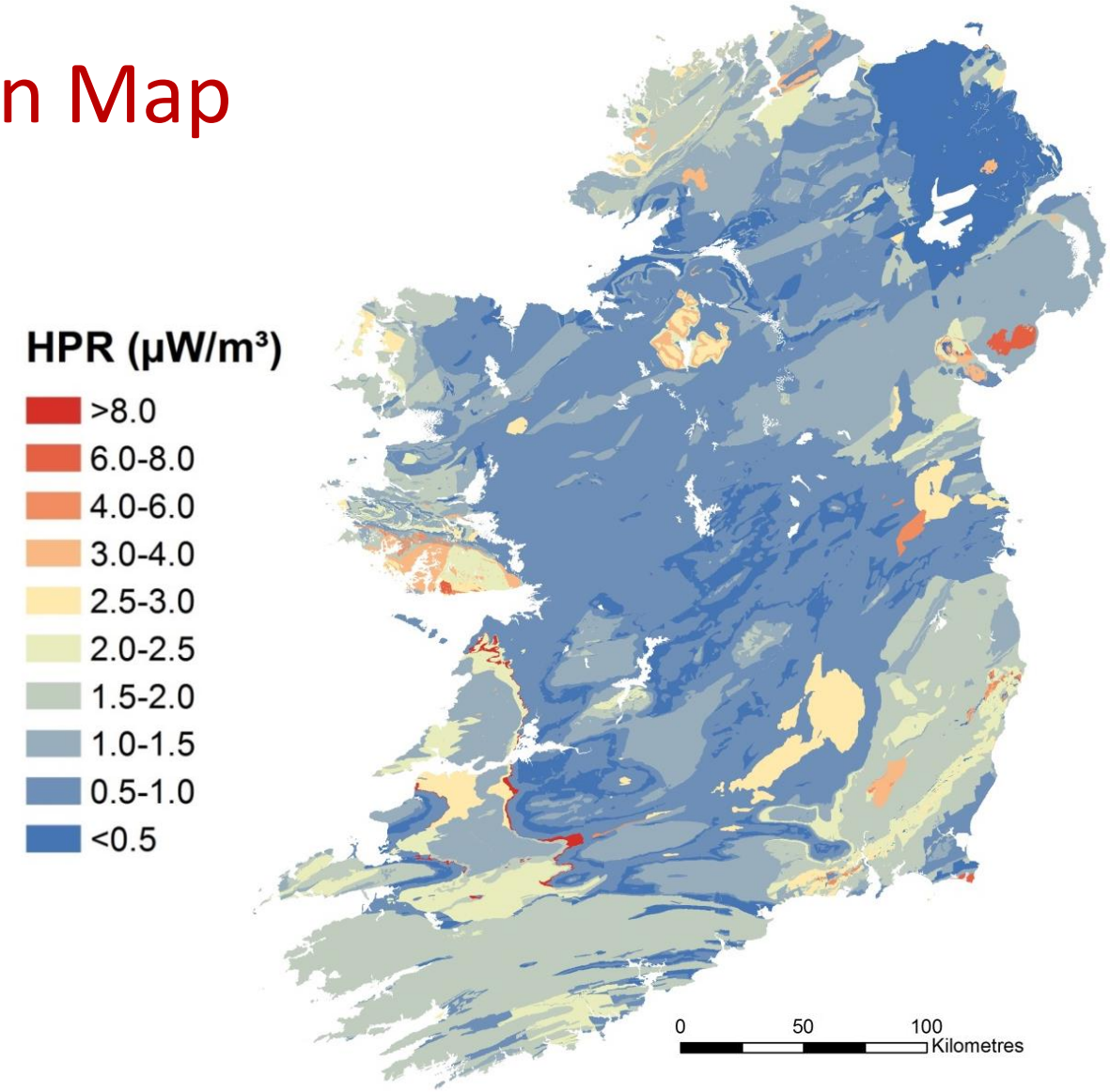
1. Map of heat production rate (HPR) that highlights high heat-producing granites and shale, and demonstrates a north south division in Irish Ordovician rocks.

2. HPR has been extrapolated to 3-D using basement exposure, lower crustal xenoliths and along-strike analogues, especially in Newfoundland.

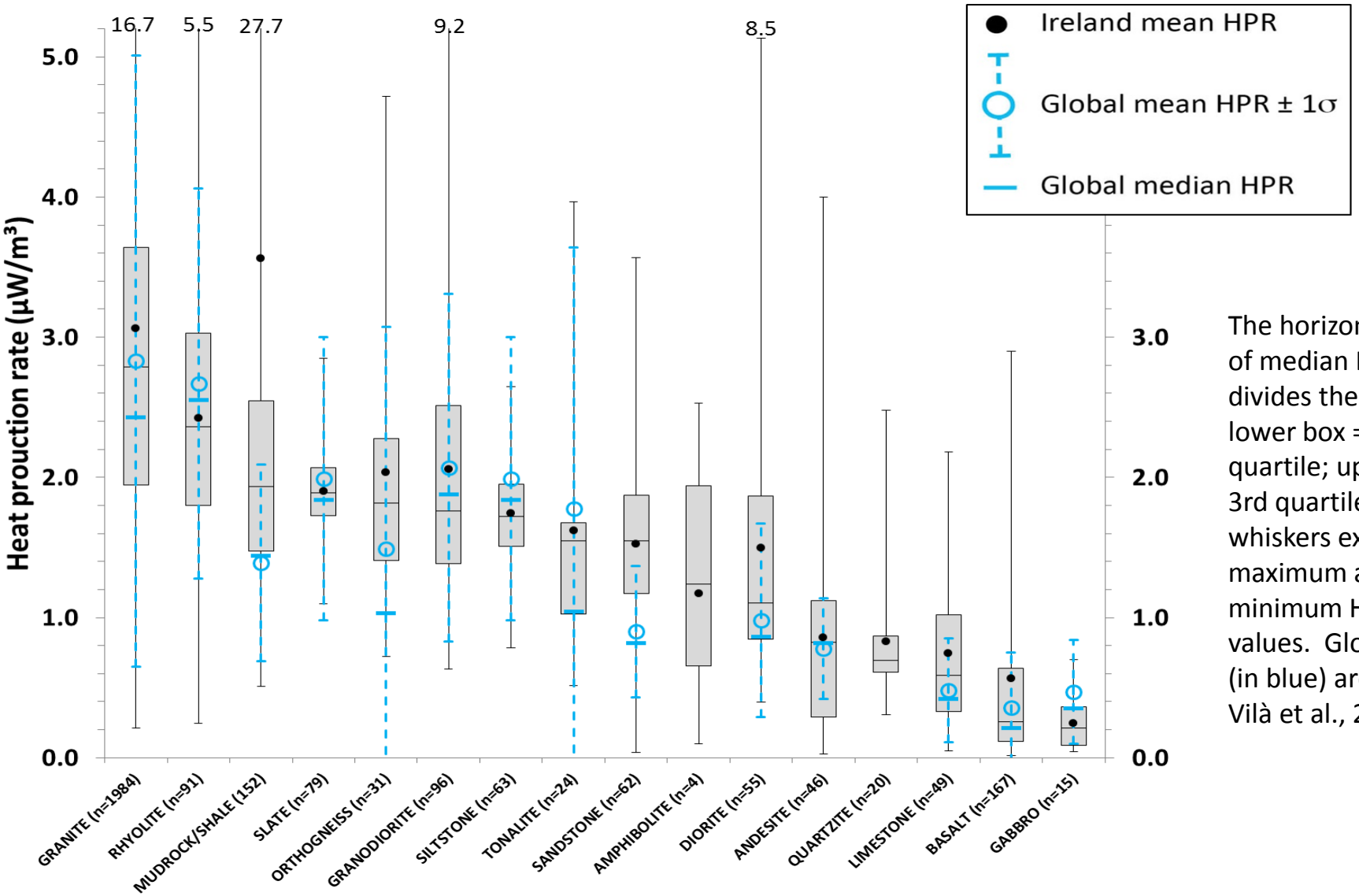
3. Constraining HPR at crustal scale enabled by accurate surface heat flow data and plausible mantle boundary values.

Heat Production Map

- Compilation of a database of over 3,500 geochemical analyses (over 700 new analyses); c1800 density measurements.
- Mean HPR calculated for each geological formation/rock unit.
- Using polygons from the GSI 1:100,000 bedrock geological map of Republic of Ireland and GSNI 1:250,000 bedrock geological map of Northern Ireland.
- Where no measured data for a formation, average HPR for stratigraphic unit or mean rock type equivalent used.
- HPR has strict boundaries as it is lithologically constrained.



HPR for some major rock types, Ireland

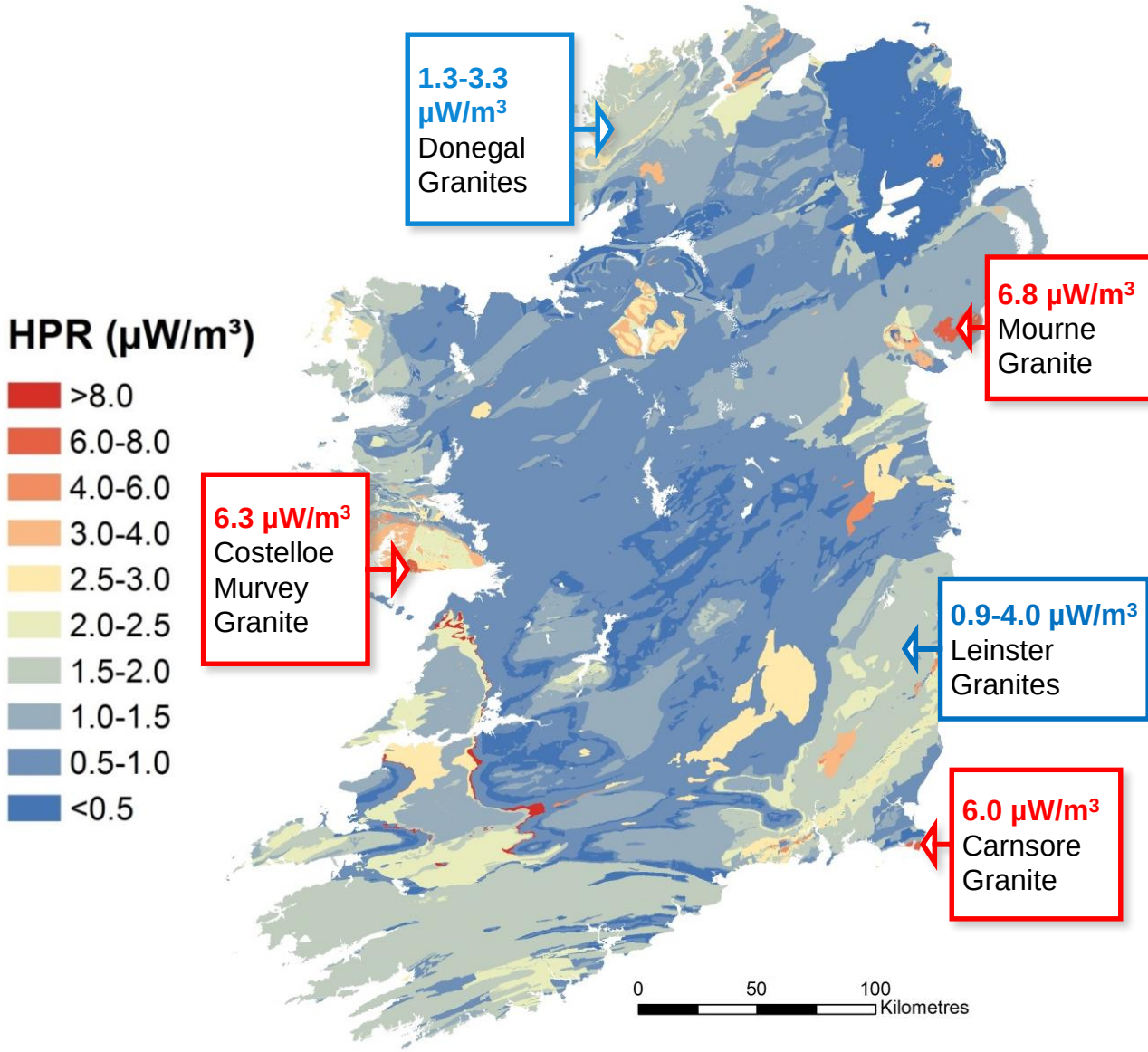


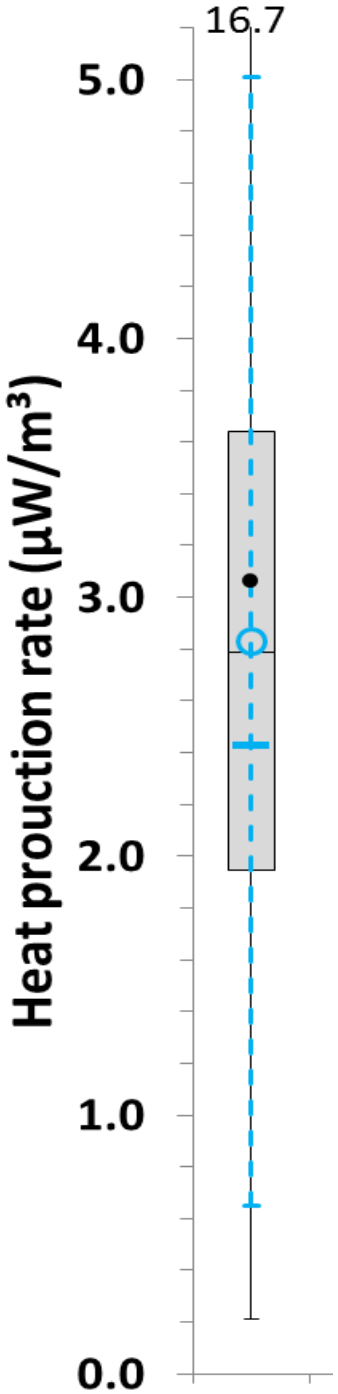
The horizontal line of median HPR divides the box; lower box = 2nd quartile; upper box = 3rd quartile; whiskers extend to maximum and minimum HPR values. Global data (in blue) are from Vilà et al., 2010).

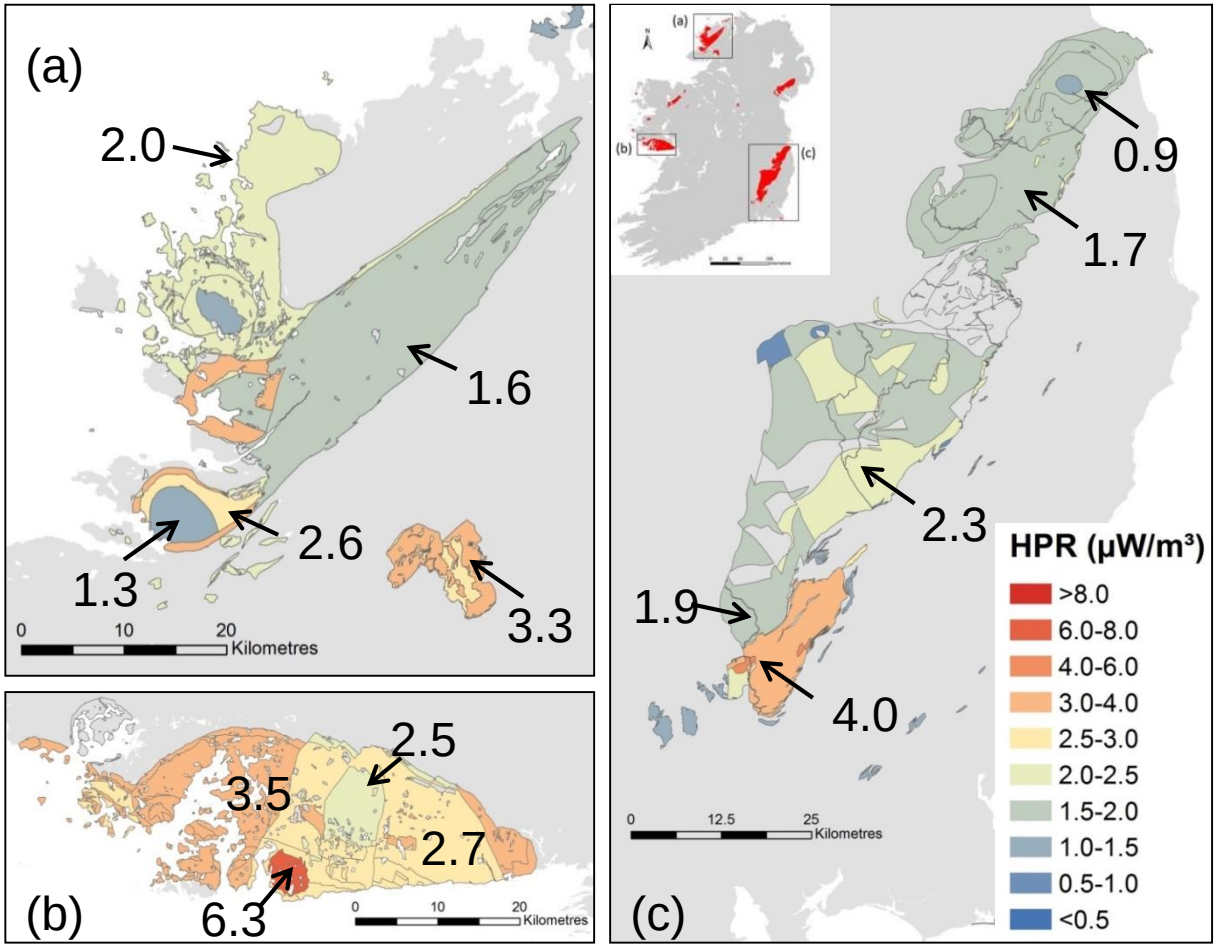
- Generally heat production varies with rock type.
- Variability within potential high-heat lithologies – acid igneous rocks and shales.

HPR: Granites

- Wide-ranging HPR values.
- No age correlation.
- No geographical correlation.

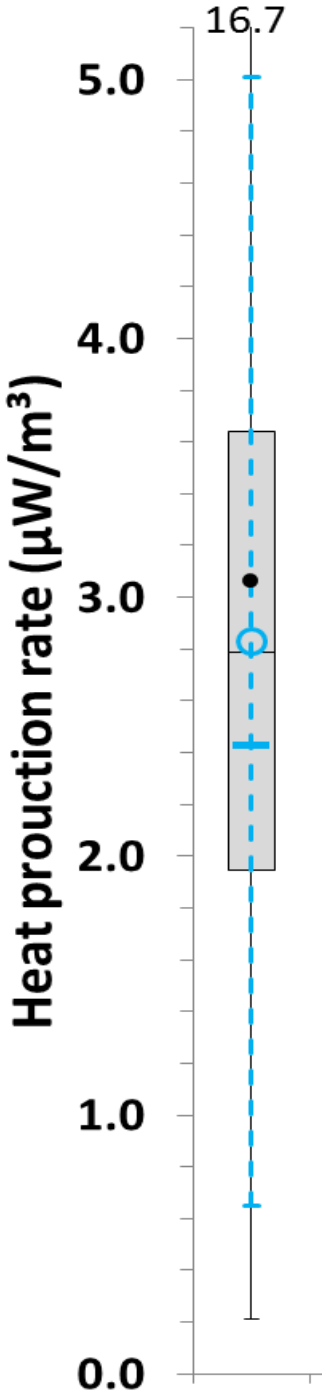


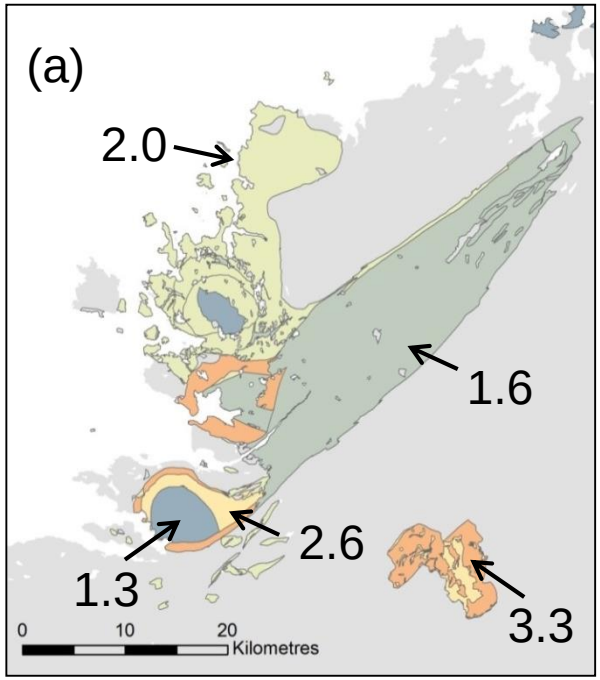


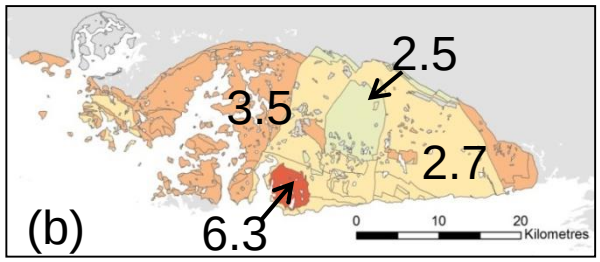


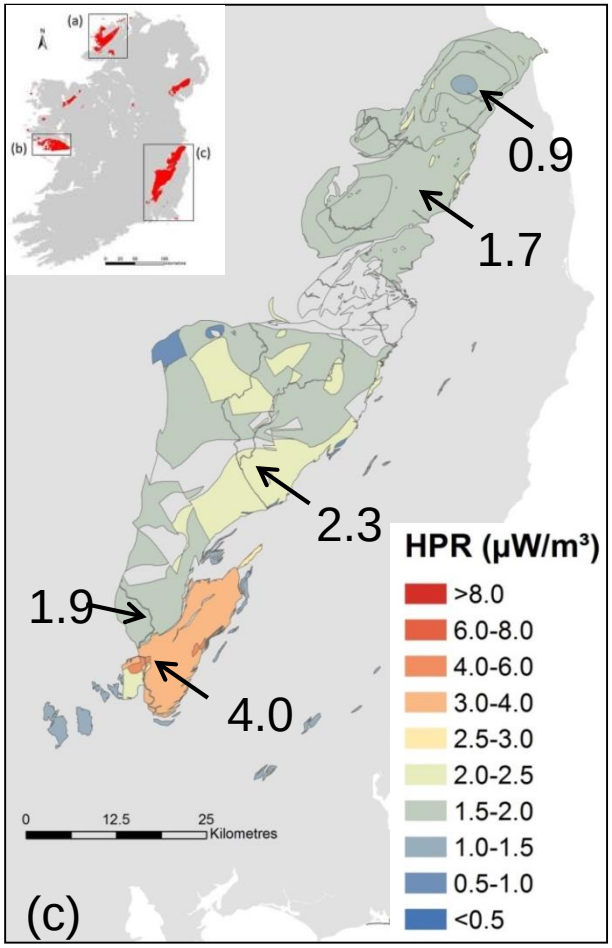
Irish Caledonian intrusive rocks have an area-weighted mean HPR of 2.1 µW/m³.

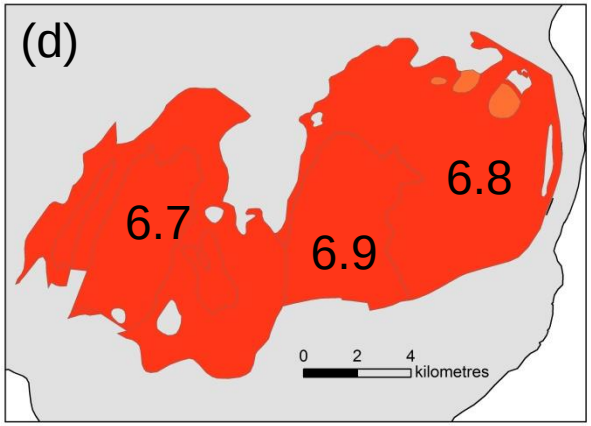
HPR variation within plutonic complexes can be considerable.







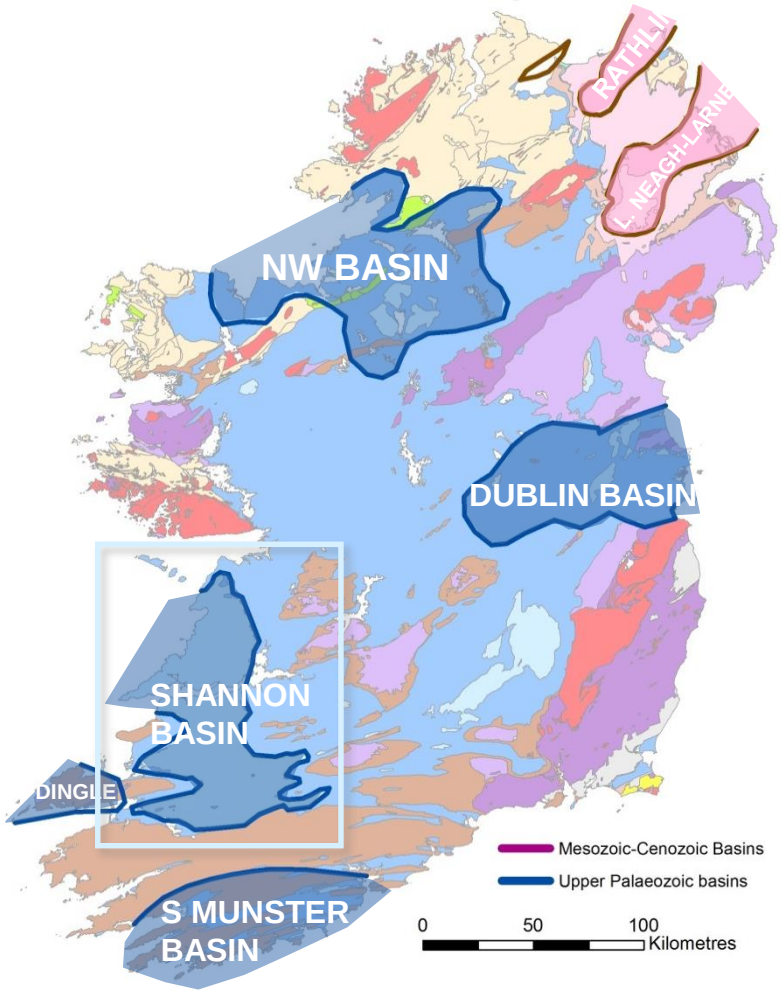


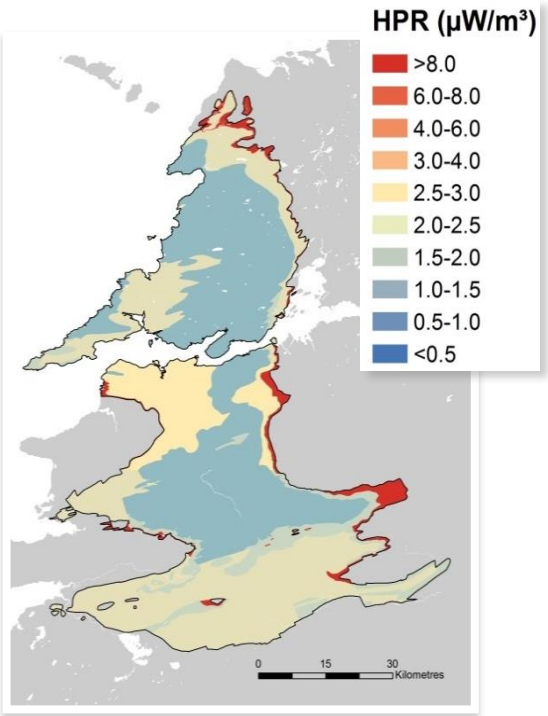


Mean HPR for Cenozoic Mourne granites G2-G5: **6.8 ± 1.9 µWm³.**

Not volumetrically extensive: 280 km³.

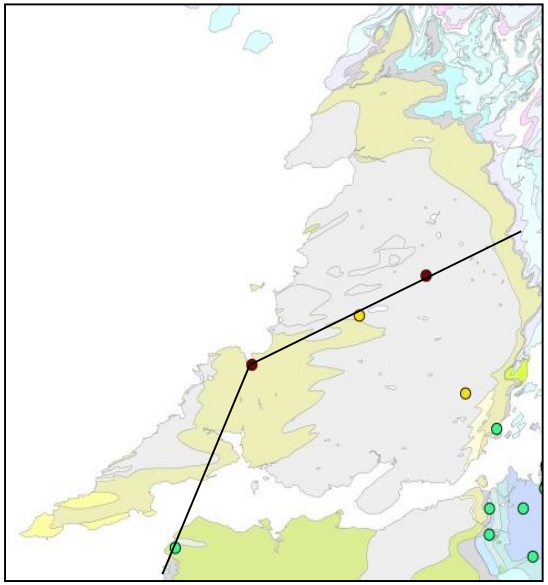
Sedimentary basins: Upper Palaeozoic and later





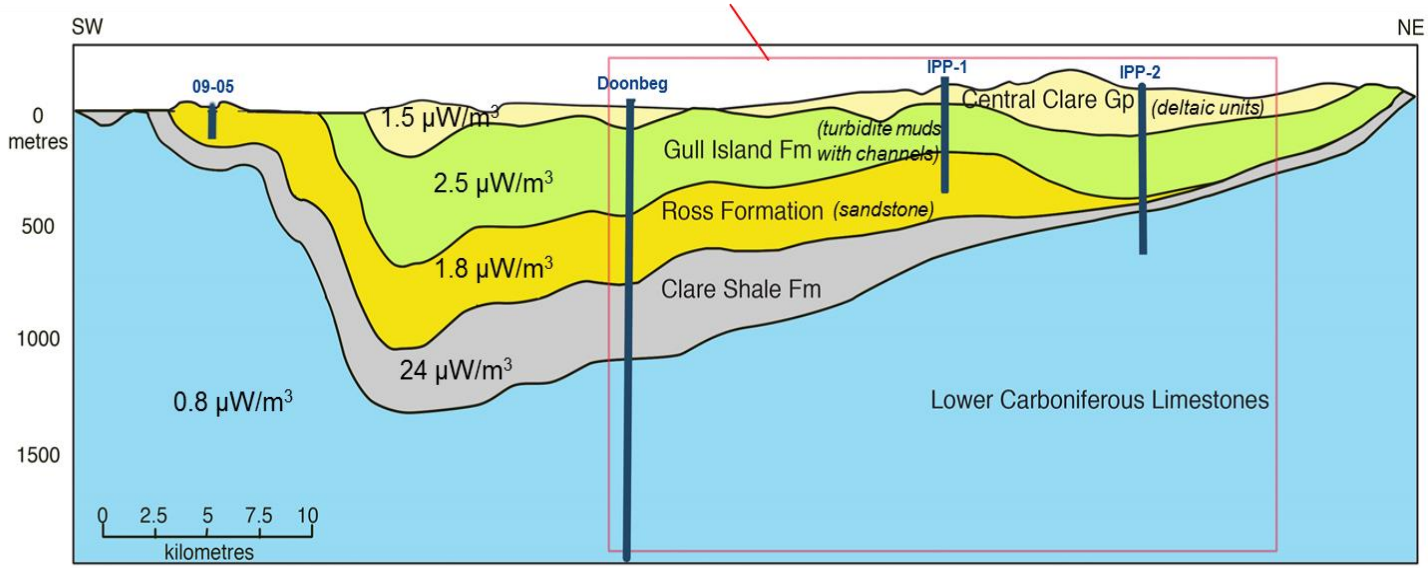
- Mean HPR for Clare Shale Fm (red): 24 µW/m$^{3.}$
- Small outcrop: may still represent stratigraphic units of significance for heat production calculations.

Shannon Basin



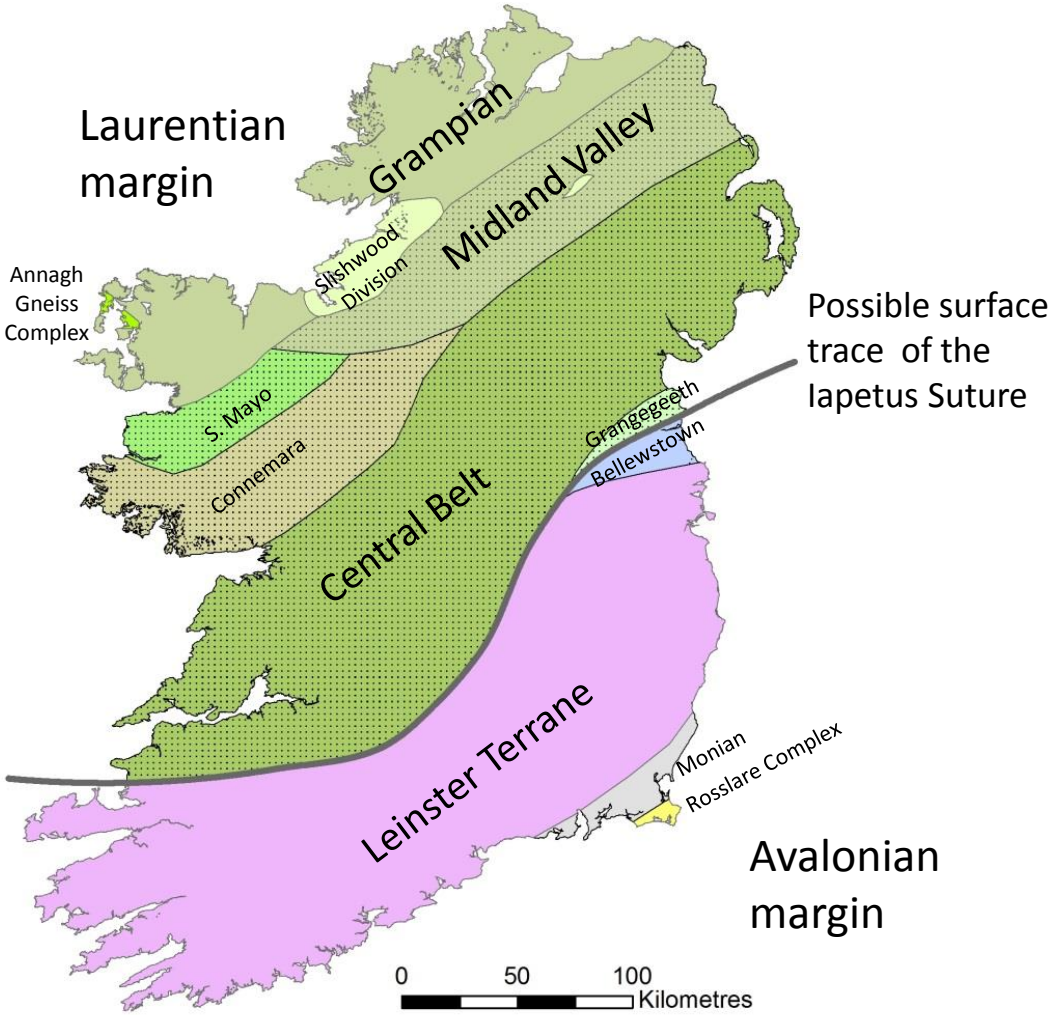
Location of cross section

- Doonbeg borehole: Clare Shale Fm = 270 m thick.
- As a percentage of the total basin, the volume of the Clare Shale Fm (~20%) is significantly greater than its surface area (<4%).
- Onshore volume of Clare Shale Fm: ~600 km^3; power contribution: ~14 MW.
- Uranium concentrations in phosphatic layers at base of section.
- Unfortunately, Ireland's other Upper Carboniferous shales do not share same level of U concentration.



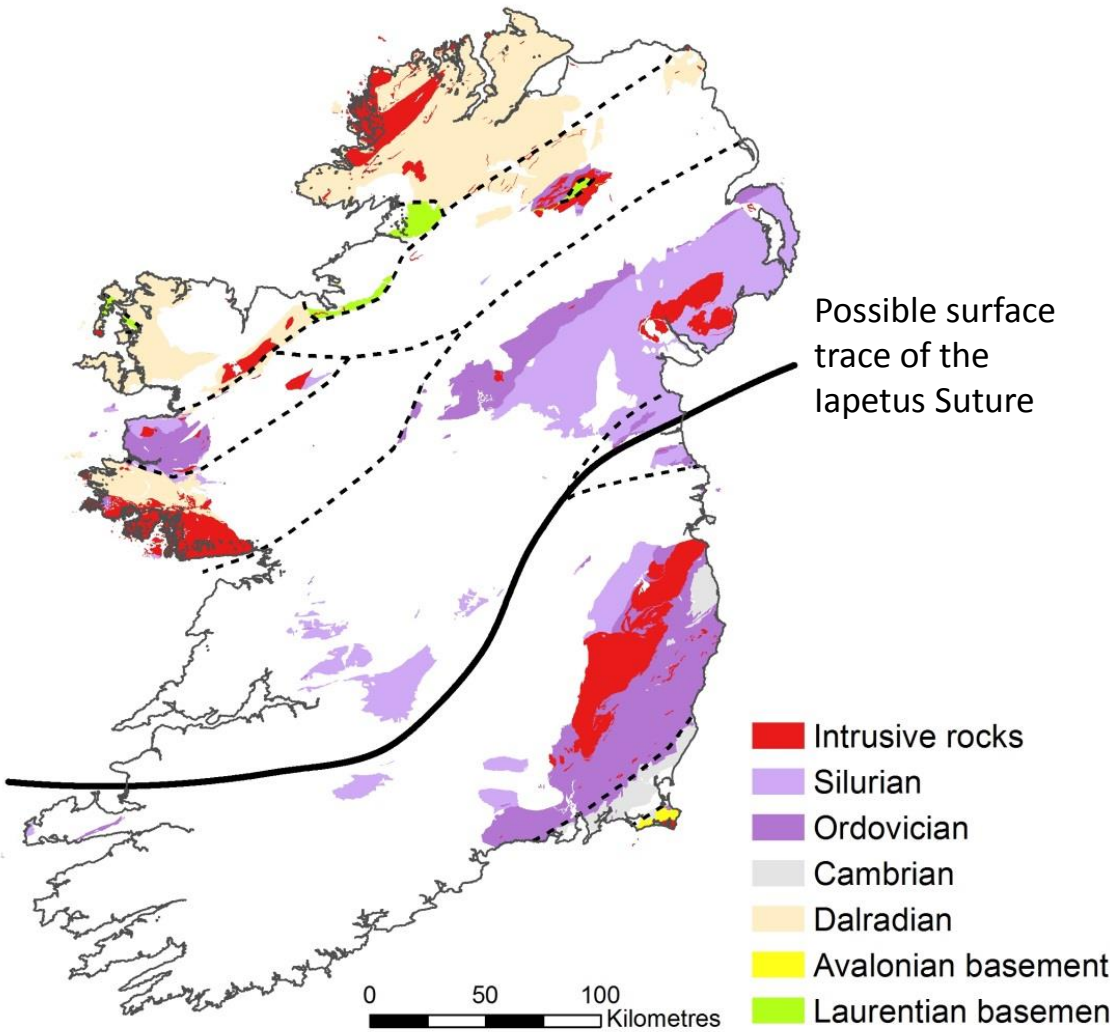
Ireland's basement terranes

- Laurentian margin to the north; Ganderian/Avalonian to the south.
- Several peri-Laurentian and peri-Gondwanan terranes accreted and imbricated during the Iapetus convergence, forming basement across the central region of Ireland.
- NE/SW orientation.
- Reactivated faulting juxtaposed different basement terranes.



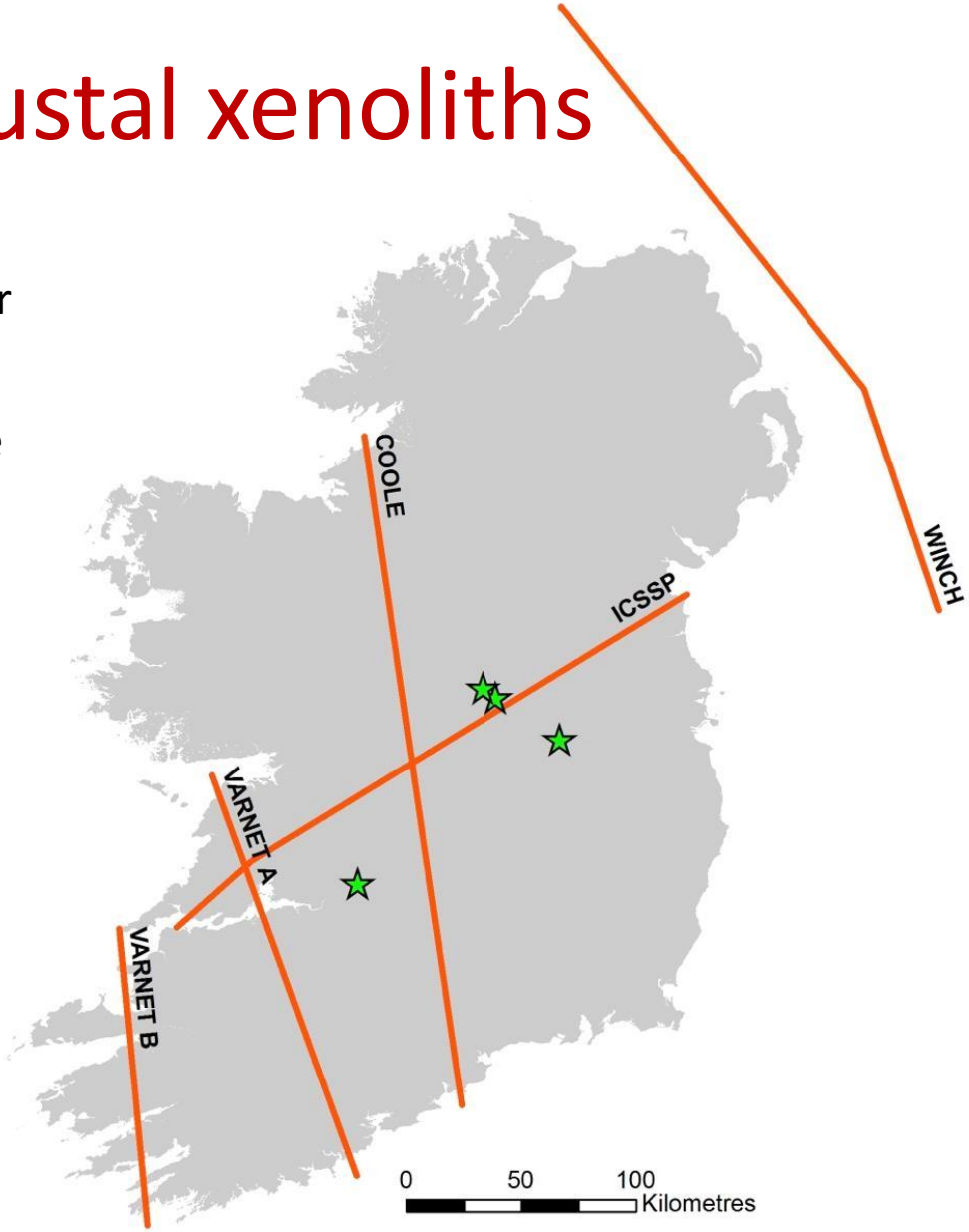
Exposed basement rocks

- Limited exposure of rocks that form Ireland's basement.
- HPR measurements made on these restricted outcrops proxy for voluminous equivalent rocks at depth, whose presence inferred by consideration of structural geology, seismics, gravity.

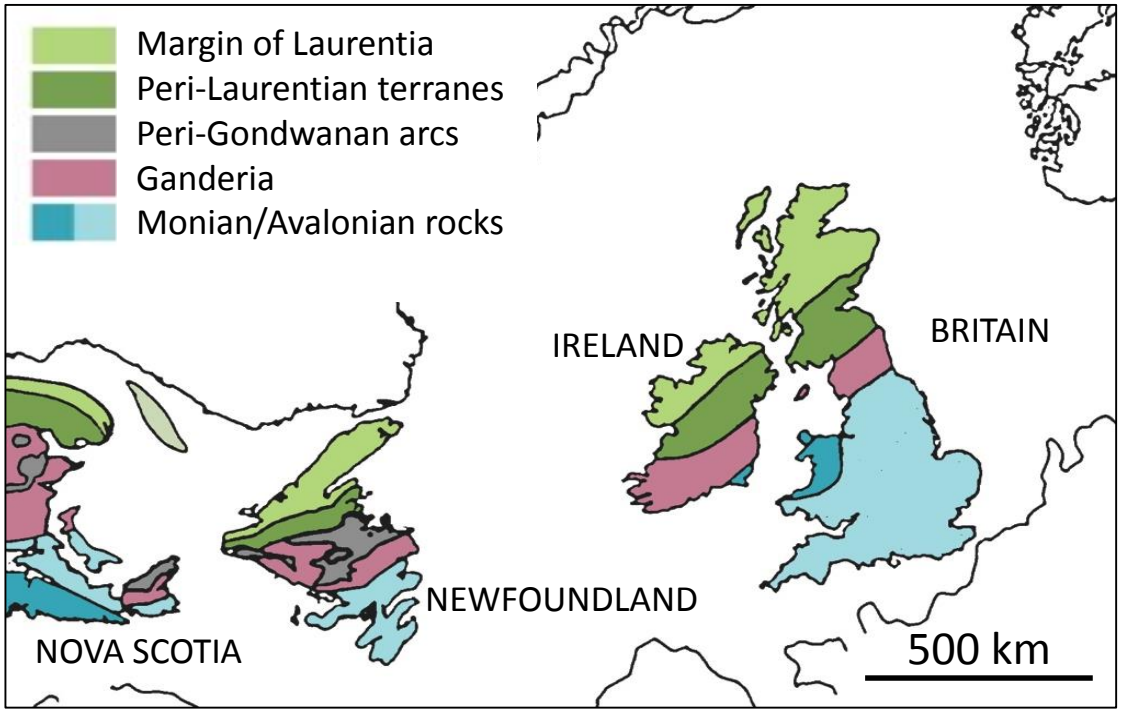


Ireland's deep crustal xenoliths

- Xenoliths emplaced in Lower Carboniferous volcanics are a proxy for the lower crust today.
- Seismic data: metapelitic xenoliths are representative of bulk crustal composition in central Ireland.
- Crust formed by tectonic accretion of volcaniclastic sediments of Lower Palaeozoic age, derived from Gondwanan margin (Daly & Van den Berg, 2004).
- Mean HPR (metapelites): 1.7 $\mu W/m^3$. Comparable to HPR of exposed equivalent Ordovician sedimentary rocks of S Ireland (1.9 $\mu W/m^3$).



Along-strike analogues: Newfoundland



Modified from Knott *et al.*, 1993

Map of the northern Appalachian and the British Caledonide orogens showing main domains in pre-Mesozoic configuration.

Advantages

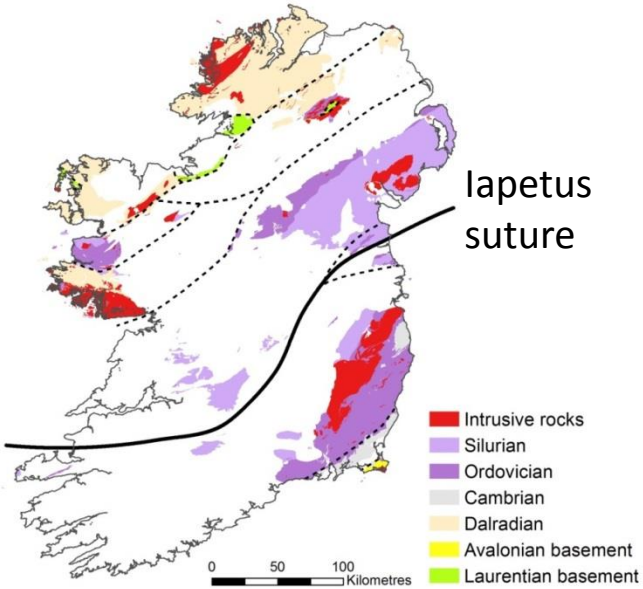
- Newfoundland surface geology not obscured by younger cover rocks.
- Iapetus Suture has surface expression.
- Large geochemical datasets available from Geological Surveys of Canada and of Newfoundland and Labrador.

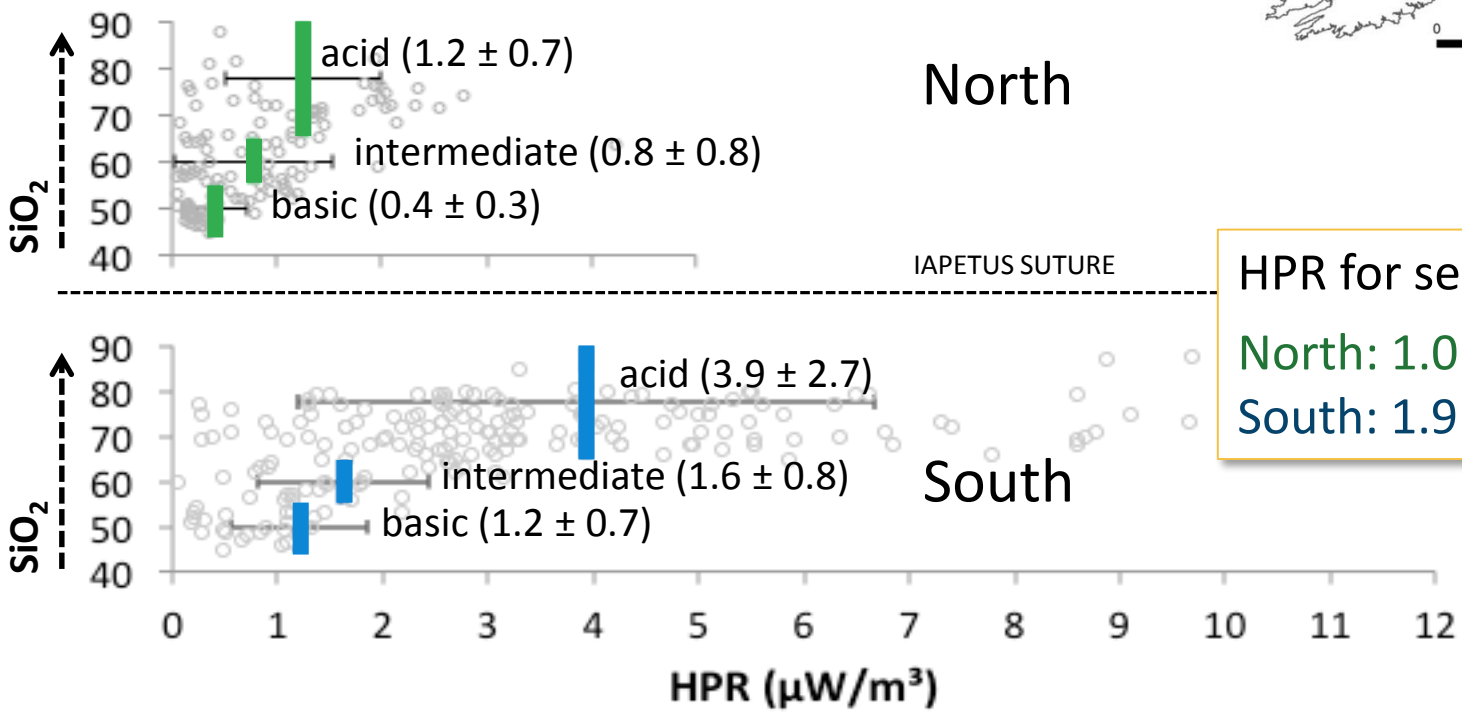
HPR is similar in Laurentian terranes for correlated regions:

- Buchans Gp / Tyrone Igneous Complex: 0.8 $\mu W/m^3$
- Annieopsquatch Ophiolite Belt / Tyrone Ophiolite: 0.4 $\mu W/m^3$
- Notre Dame Arc rocks, felsic and mafic: 0.9 ± 0.8 $\mu W/m^3$.
  Scottish Midland Valley xenoliths: 0.6 ± 0.6 $\mu W/m^3$.

Ordovician sedimentary and volcanic rocks are hotter in the south

- Sedimentary and volcanic rocks formed in belts roughly parallel to Iapetus margins.
- North: arc-derived rocks along Laurentian margin.
- South: volcano-sedimentary rocks attached to Gondwanan microcontinents or within the oceanic area.





HPR for sedimentary rocks:

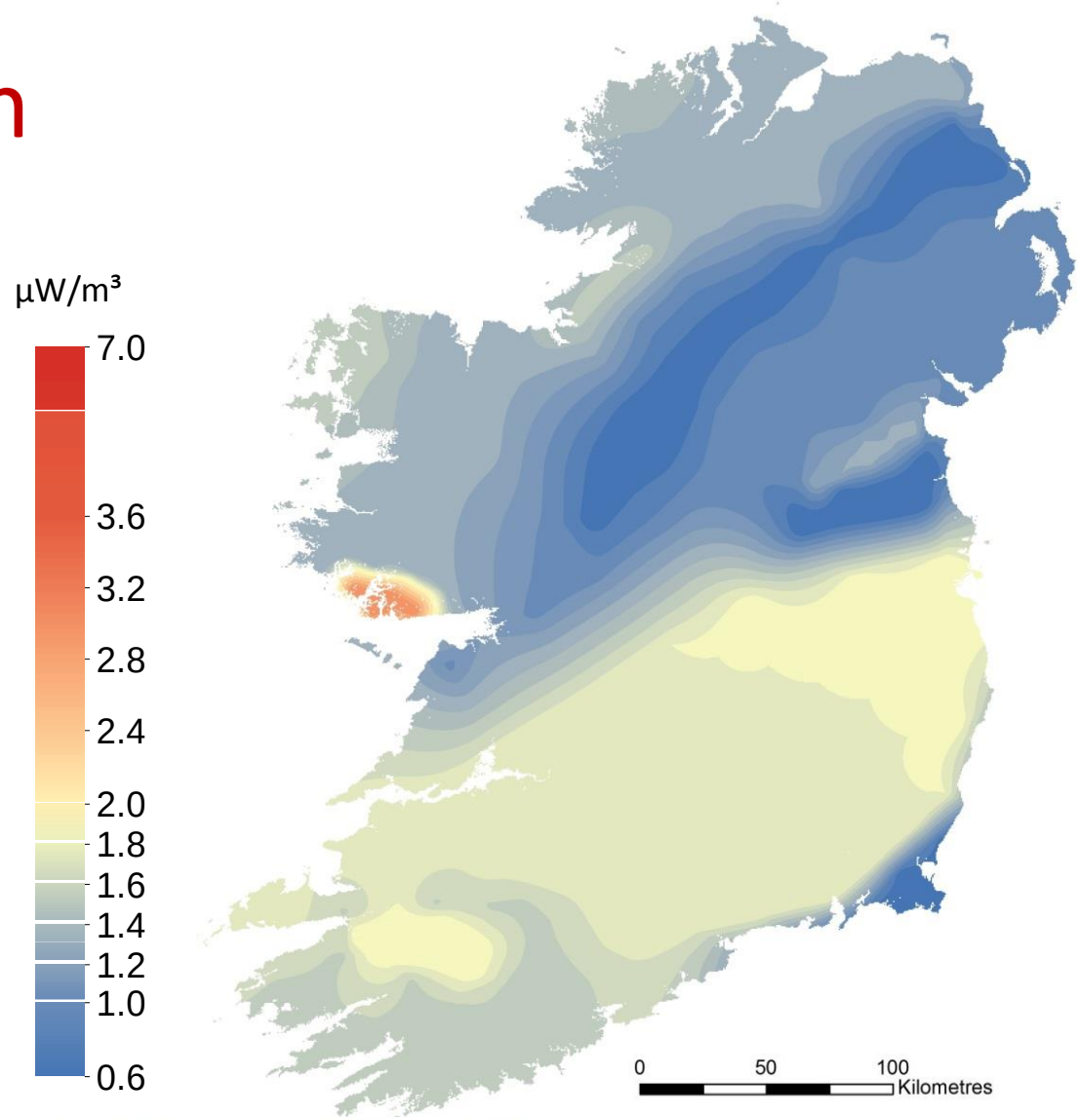
North: 1.0 ± 0.4

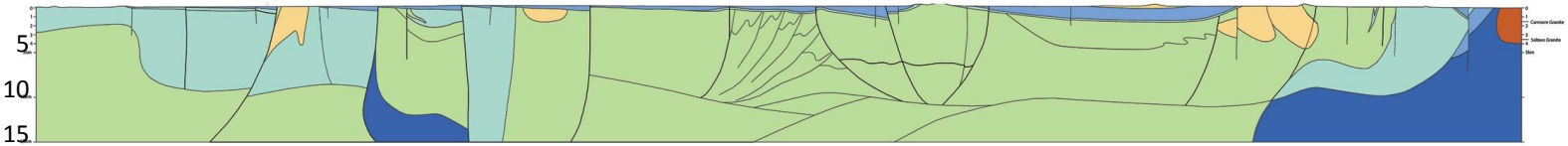
South: 1.9 ± 0.8

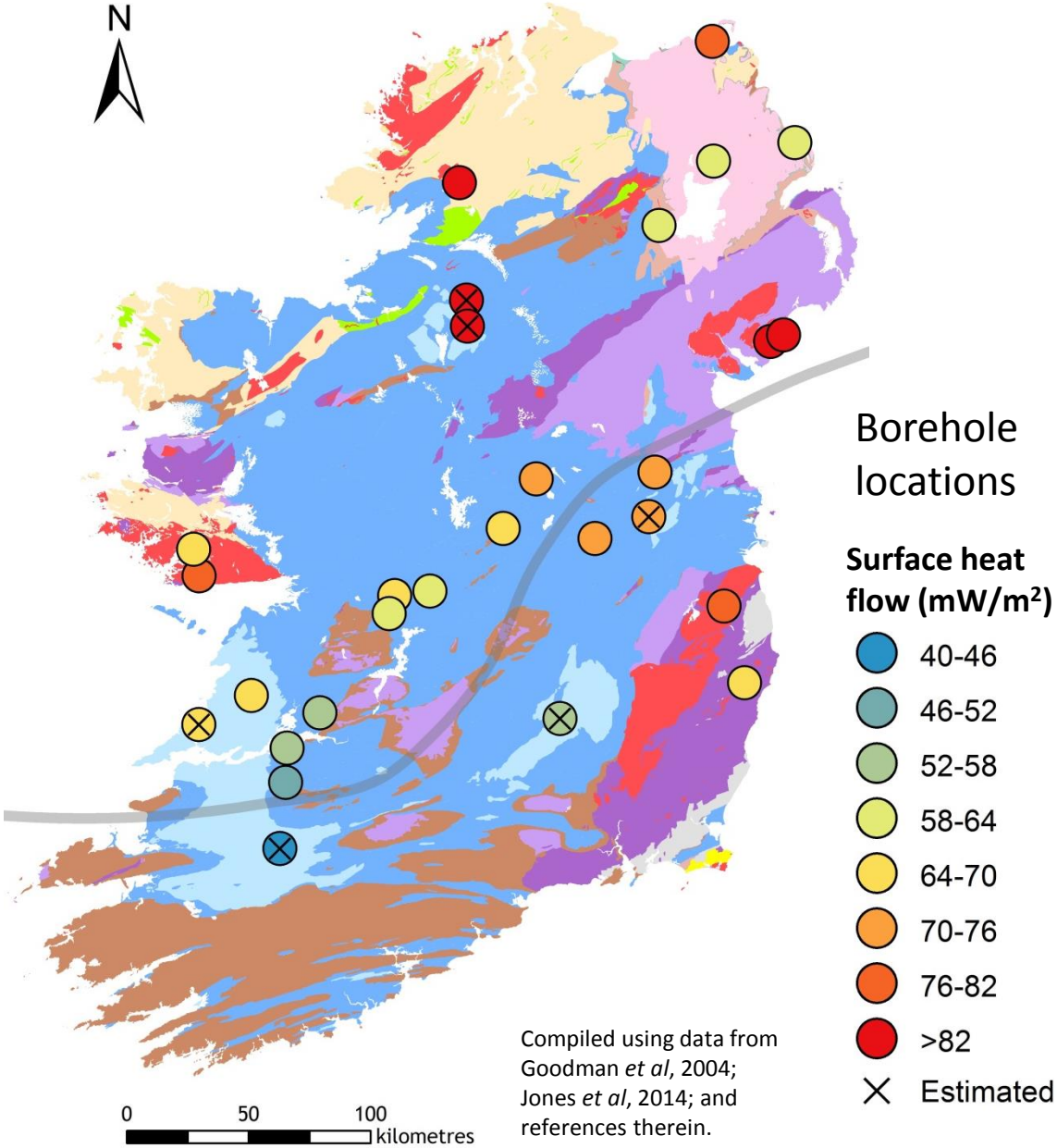
Horizontal error bars represent 1σ for the range of samples for each set.

HPR at 5 km depth

- Lower Palaeozoic volcanic and sedimentary rocks extend across most of the south of Ireland. Calculated mean HPR from Avoca region: **~1.9 µW/m³**.
- In NE, a series of Ordovician and Silurian accretionary terranes offshore of Laurentia, including Midland Valley, are low heat producing: **~1.1 µW/m³**.





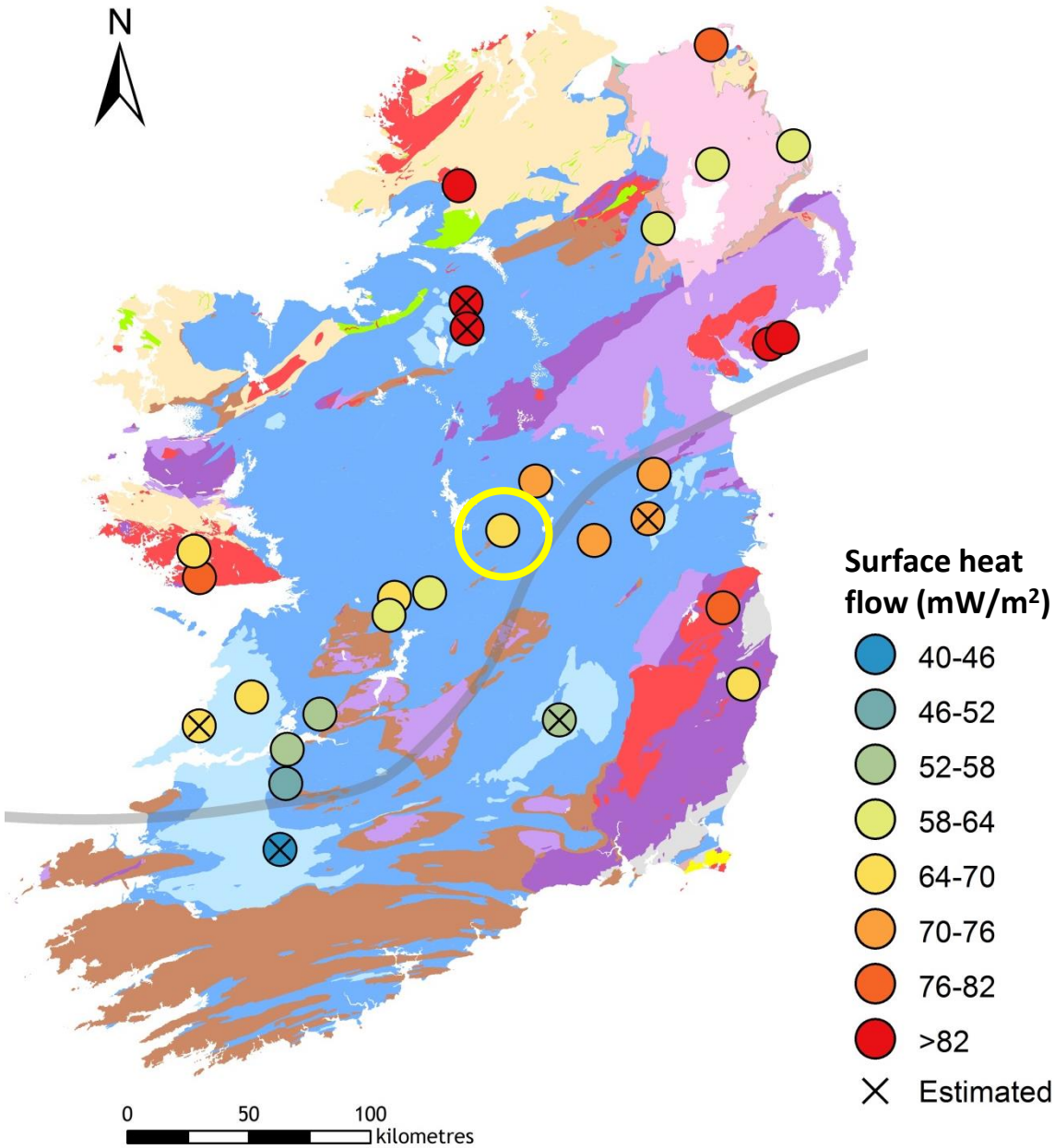


Compiled using data from Goodman *et al*, 2004; Jones *et al*, 2014; and references therein.

Heat flow

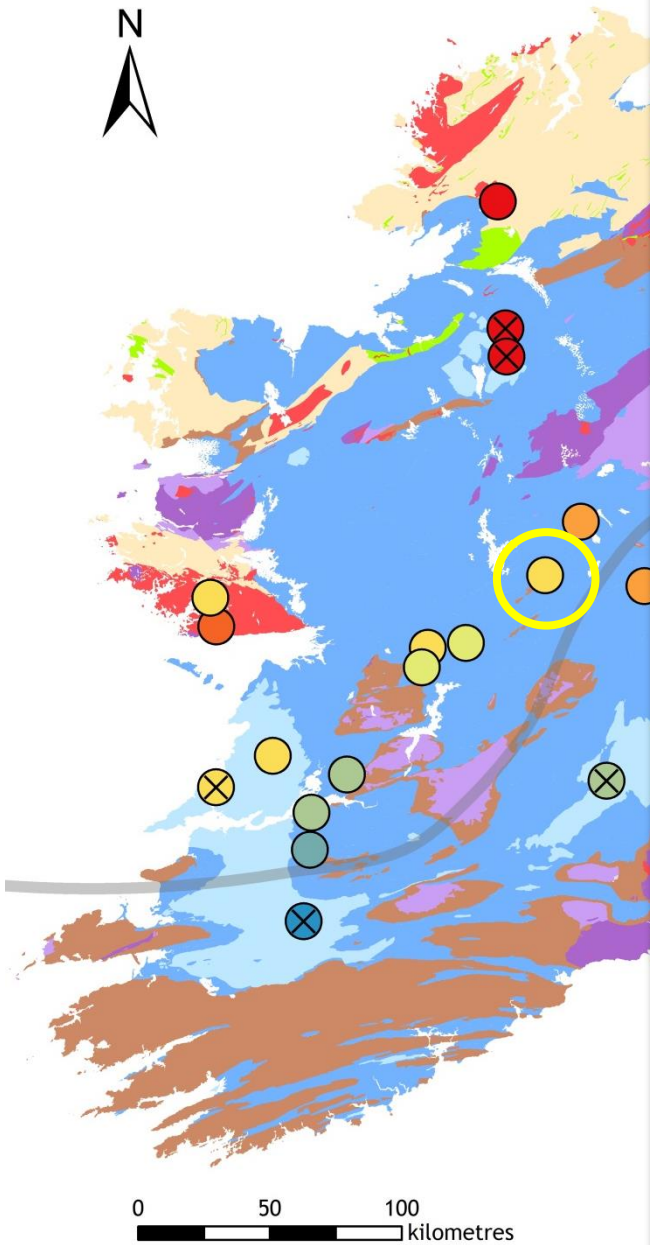
Surface heat flow density records the total heat produced in the crust plus the heat flow produced at the crust/mantle boundary.

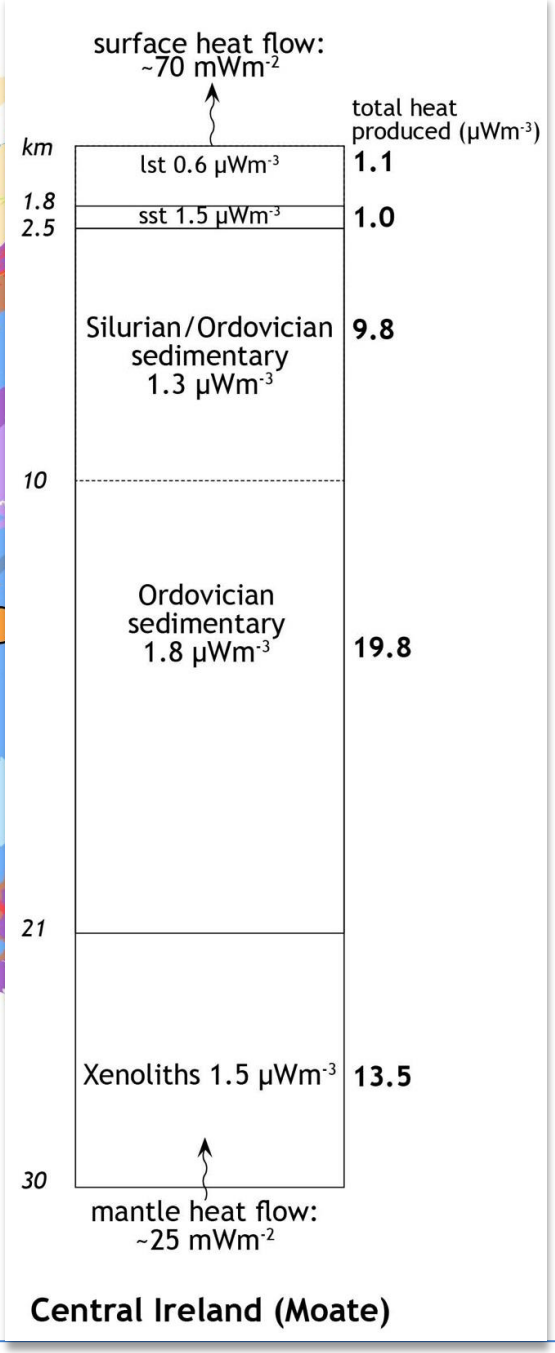
- Mantle heat flow density is regarded as about one-third surface heat flow: 11-18 mW/m^2 for Precambrian terranes; 15-21 mW/m^2 for Palaeozoic orogens (Jaupart and Mareschal, 2003).
- Possible mantle plume influence.



Central Ireland

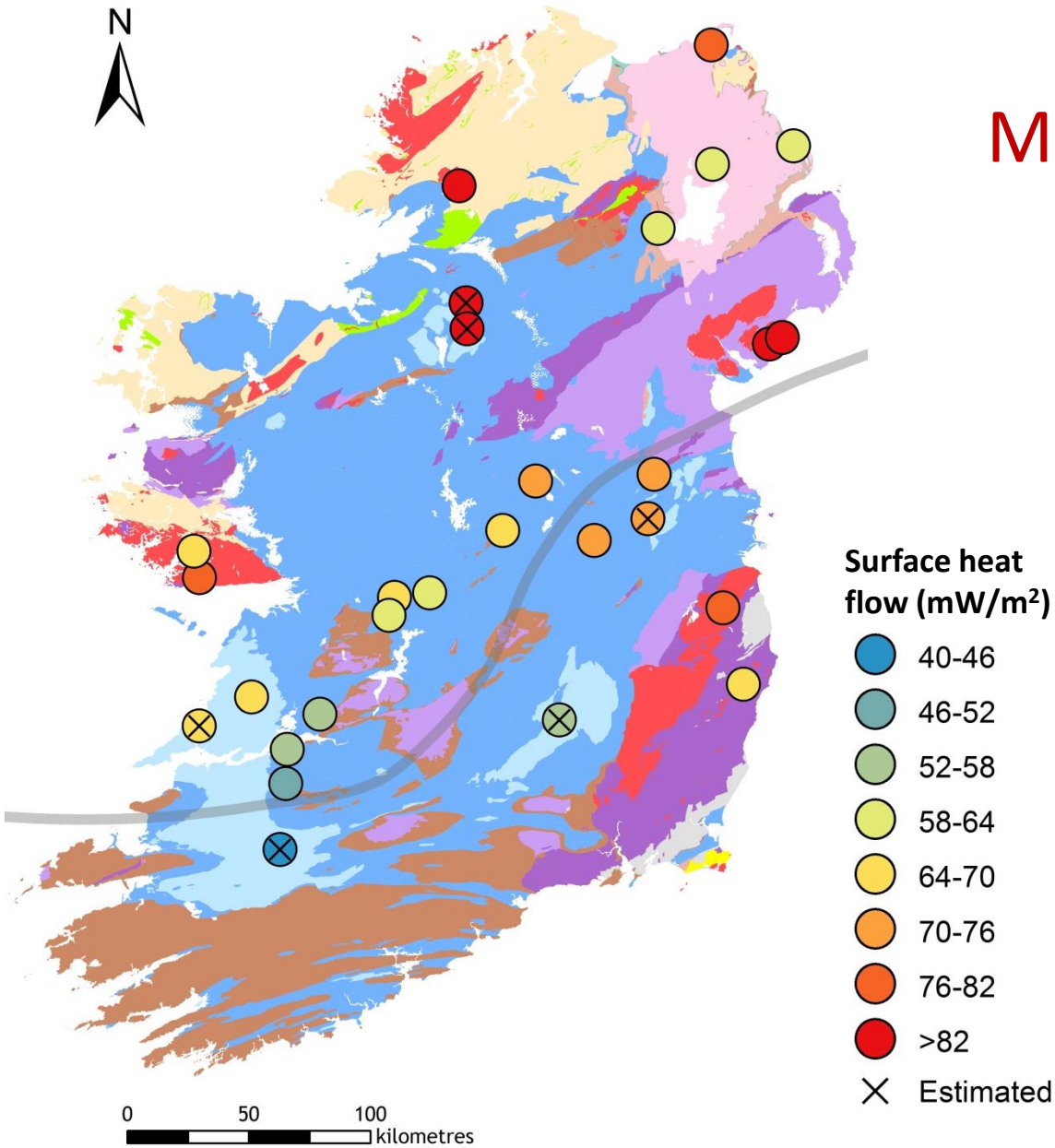
- Moate borehole: surface heat flow density: ~70 mW/m^2 (Brock and Barton, 1984).
- Close to xenolith location and cross-section of two seismic surveys.
- Test whether the HPR extrapolation to depth is realistic by examining whether the resulting mantle heat flow value is plausible.





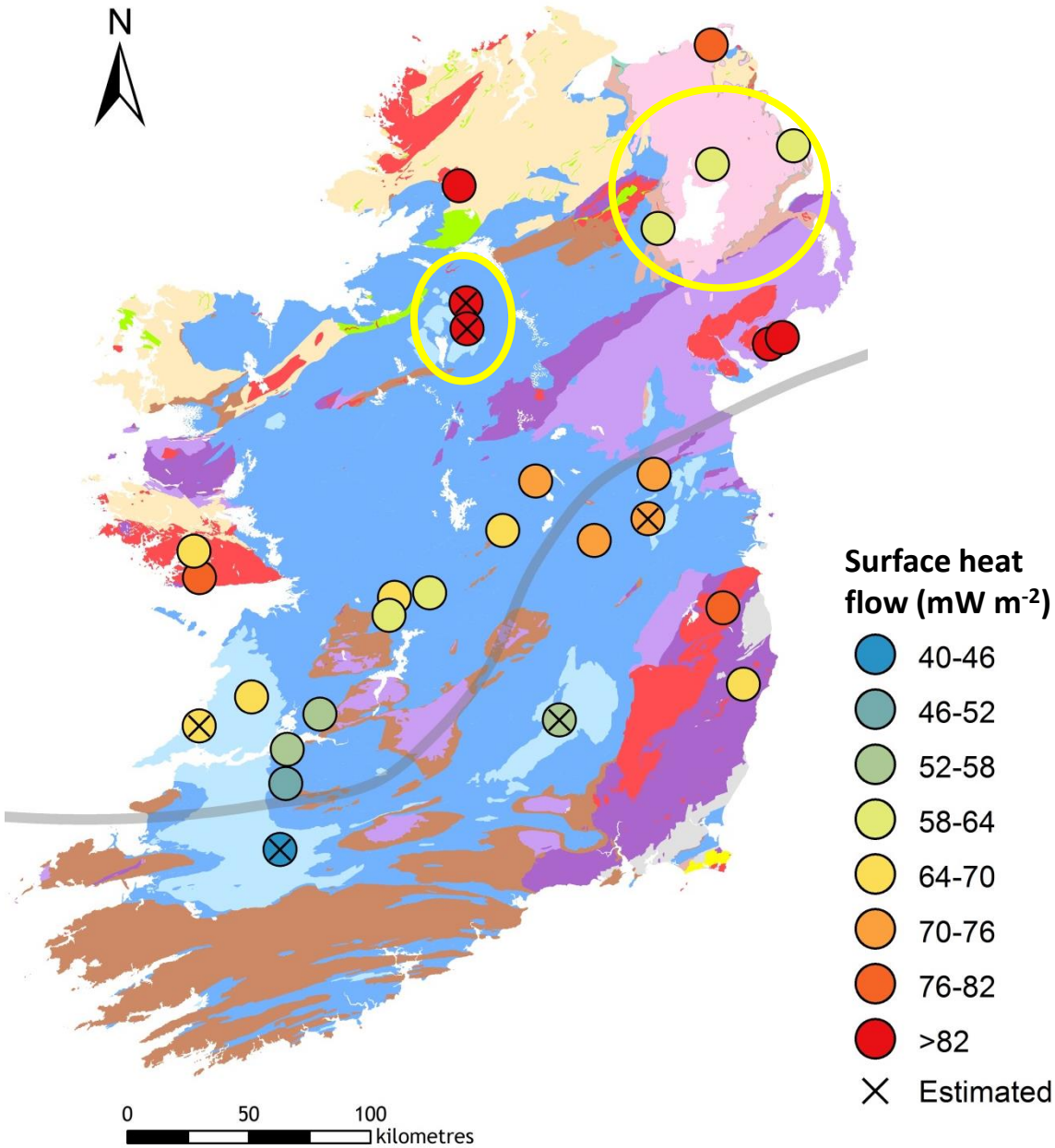
Central Ireland

- Heat flow contribution from crustal heat production: ~45 mW/m^2.
- The derived mantle heat flow of ~25 mW/m^2 is plausible if a little elevated.
- No evidence for changing HPR with depth.
- Gravity data may indicate presence of some granite bodies in vicinity.
- Continued refinement of middle crustal contribution.



Midland Valley Terrane

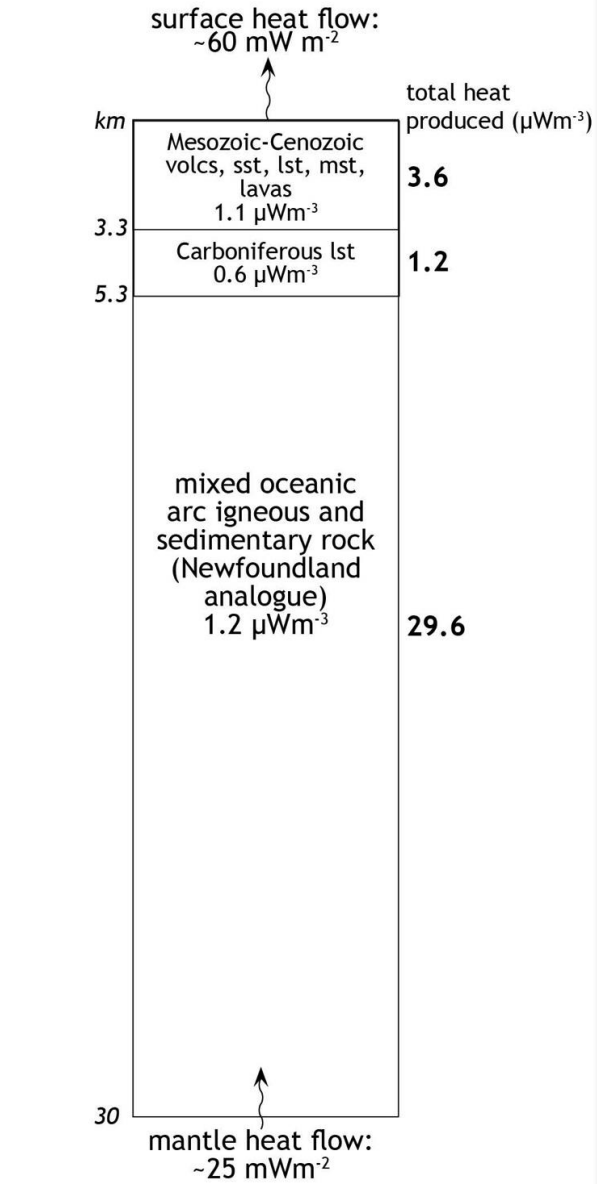
- Island arc remnant.
- No evidence for underlying basement rocks.
- Newfoundland analogue: Notre Dame subzone. HPR: 0.9 ± 8 μW/m^3 .
- Regional transtension in Ireland, opening up conduits for Early Devonian magmatism, elevating heat production.



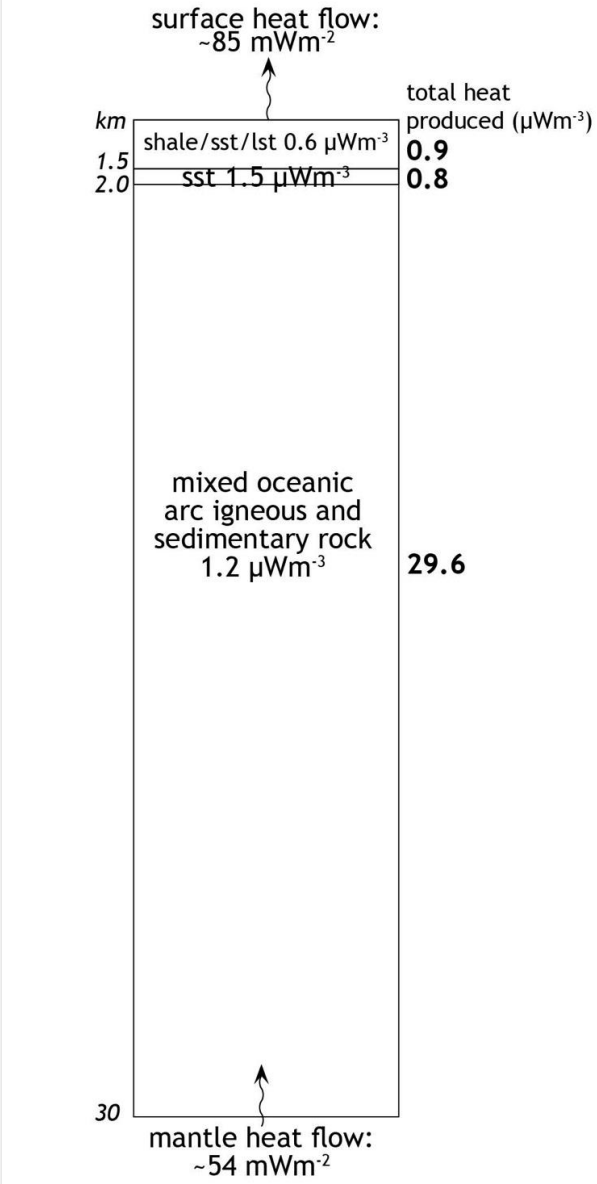
Midland Valley Terrane

- NE region: Larne and Lough Neagh boreholes. Heat flow: ~60 mW/m^2.
- Heat flow in Scottish Midland Valley (Busby *et al*, 2010): 50-70 mW/m^2.

W region: Dowra and McNean record 84 and 86 mW/m^2 from bht >1500 m.



Midland Valley terrane: NE region



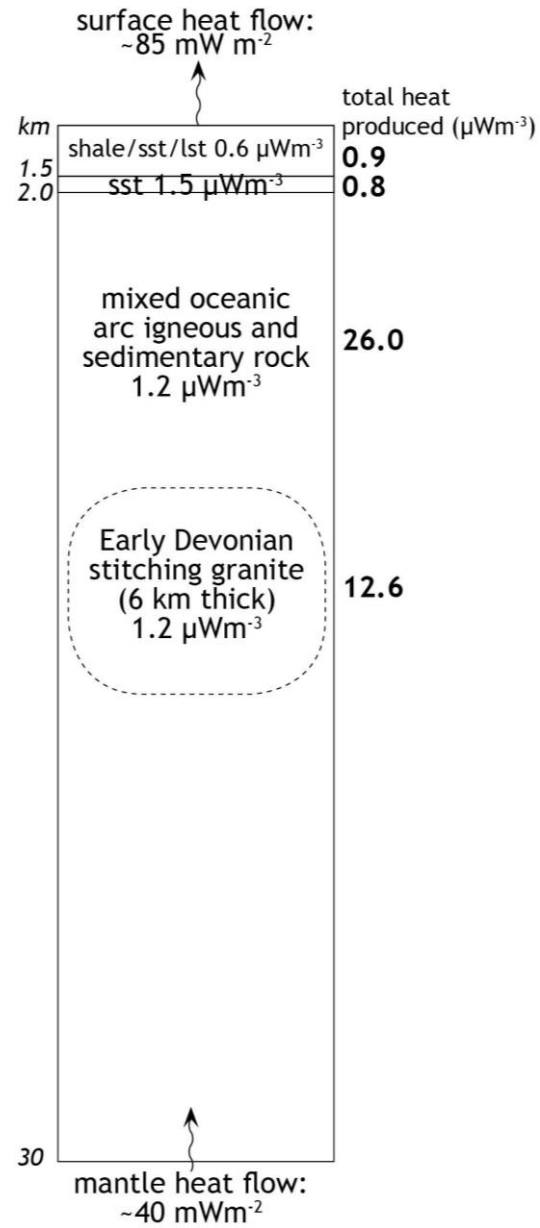
Midland Valley terrane: W region

Midland Valley Terrane

- NE region: Crustal heat production contributes ~35 mW/m^2 to heat flow budget.

  Mantle heat flow: ~25 mW/m^2

- W region: Same crustal HPR produces anomalously high mantle heat flow.



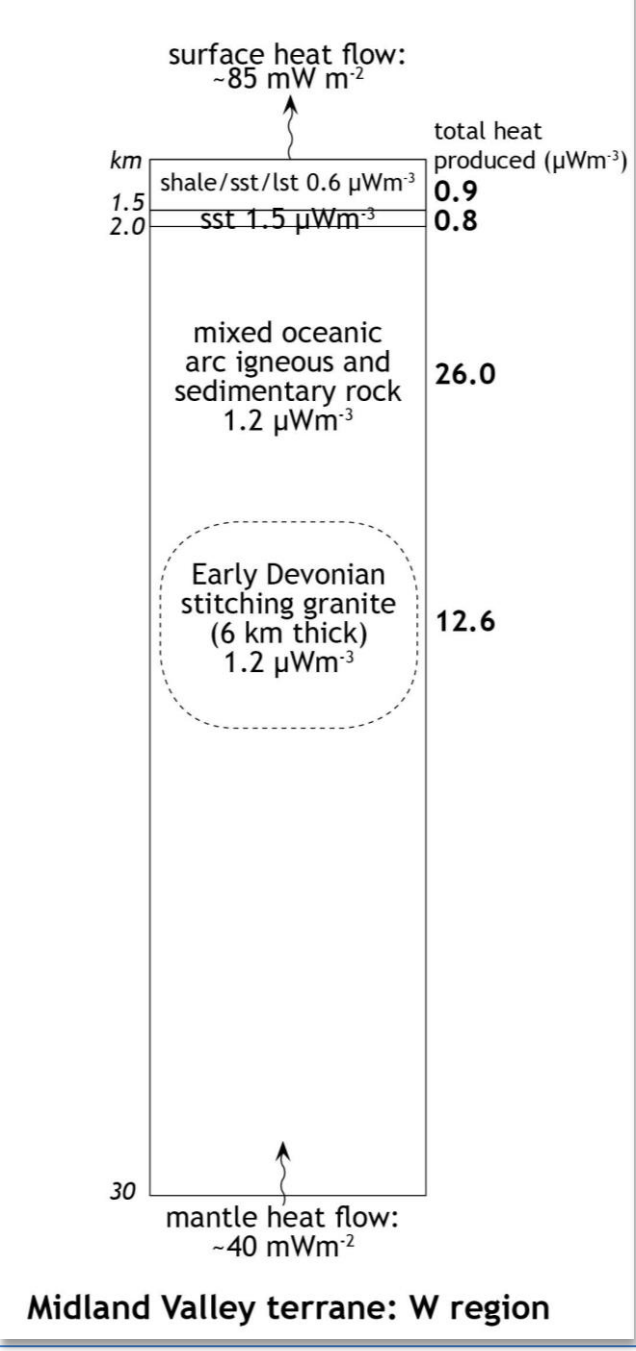
Midland Valley terrane: W region

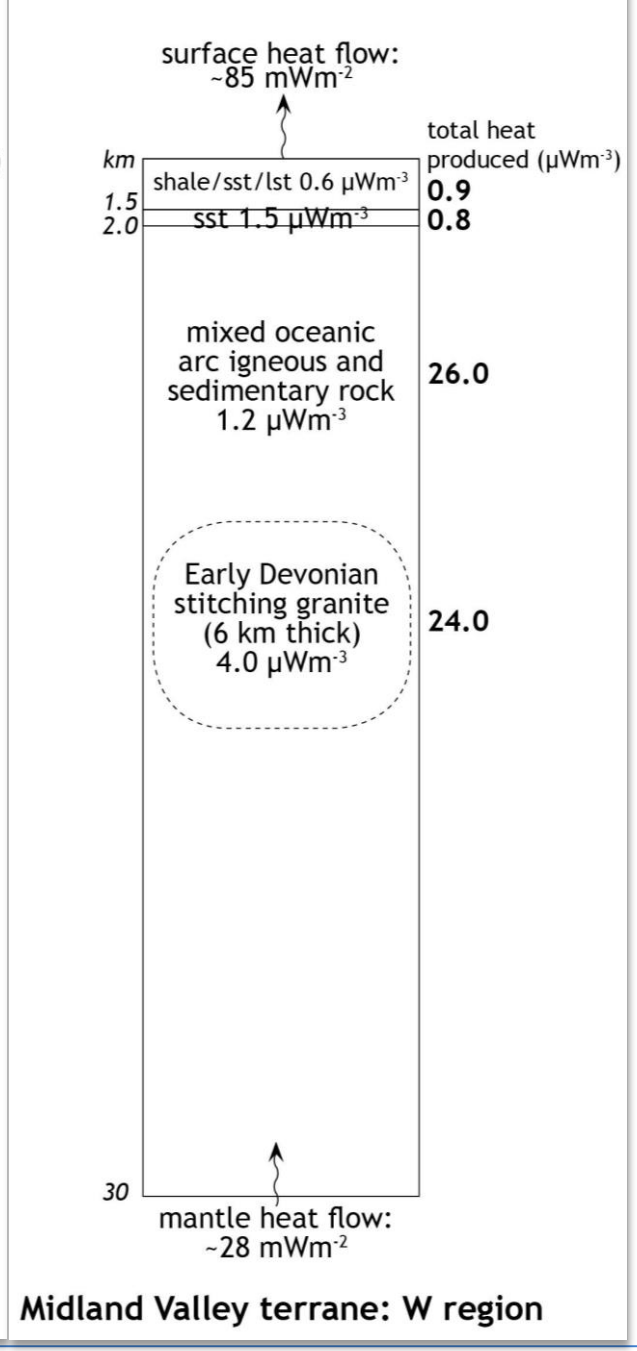
Midland Valley Terrane

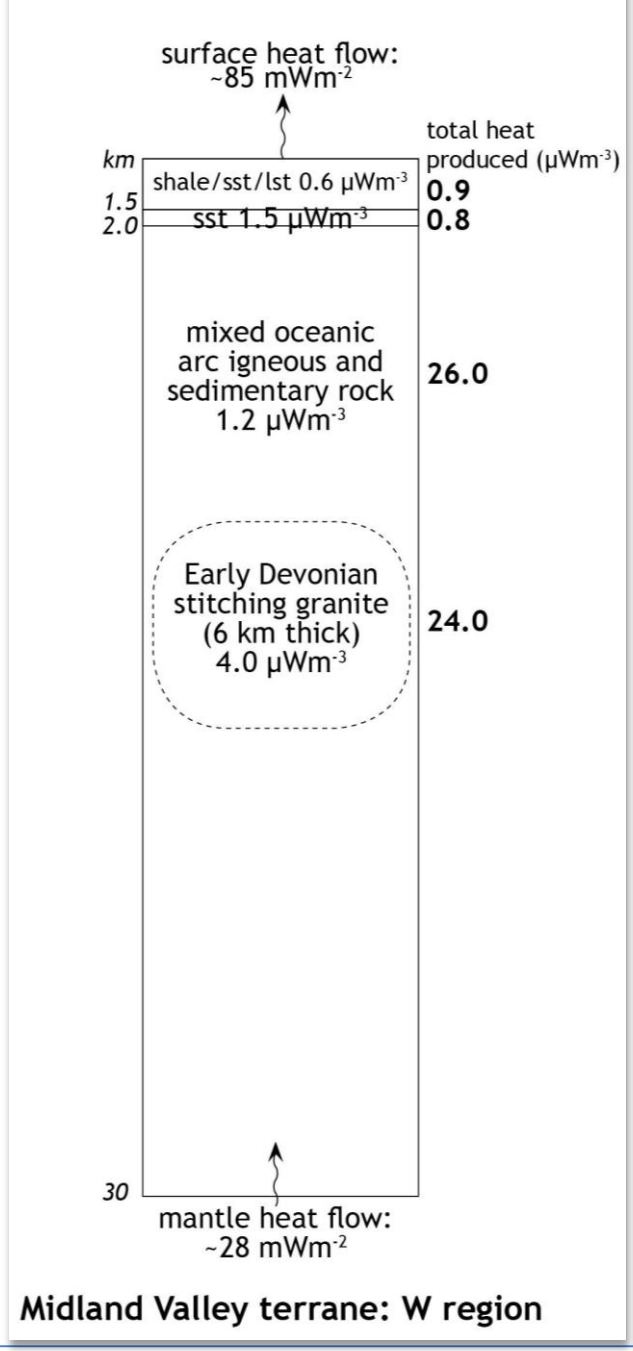
- The crustal contribution to heat flow must be greater.
- May indicate buried granite body(ies).
- Apply Caledonian mean HPR 2.1 μW/m^3 for a 6 km-thick intrusion still yields excessive mantle boundary heat flow.

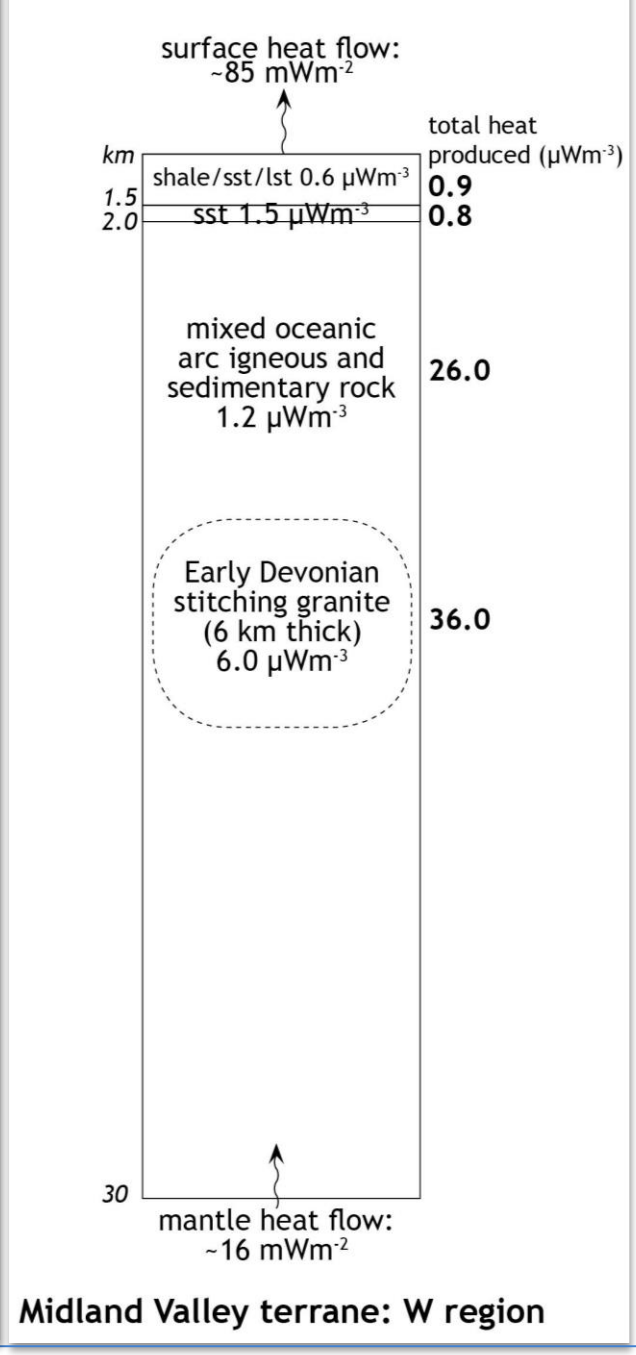
Midland Valley Terrane

- Apply HPR 4.0 μW/m^3 (Blackstairs Unit, Leinster Granite).



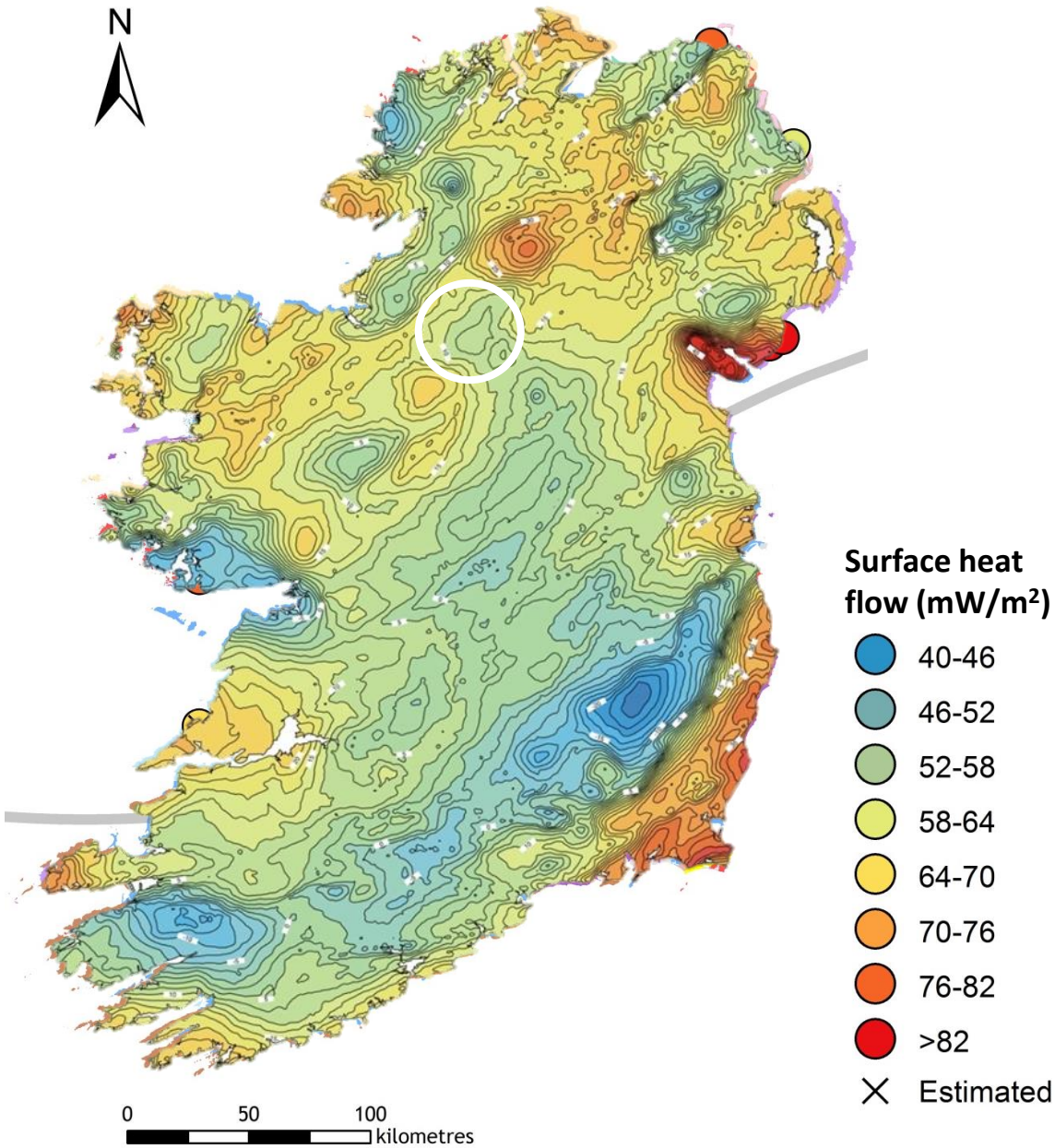






Midland Valley Terrane

- Apply HPR 6.0 μW/m^3 (Costelloe Murvey, Galway Granite).
- May be somewhere between the two.
- Variable options depending on thickness of unit(s).



Midland Valley Terrane

- Gravity low recorded in the region.
- A buried radiogenic, heat-producing granite at this location could form a target for further investigation.

Summary

- Well constrained map of HPR based on 3500 geochemical measurements (XRF and gamma-ray spectrometry) extrapolated based on GSI 1: 100,000 geological mapping units.
- HPR data suggest geothermal exploration targets: Mourne Granites (6.8 $\mu W/m^3$), Costelloe Murvey Granite (6.3 $\mu W/m^{3)}$, Clare Shales (24.0 $\mu W/m^3$).
- HPR extrapolated to -5 km, where Lower Palaeozoic volcanic arc and sedimentary rocks dominate, are higher (c. 1.9 $\mu W/m^3$) south of the Iapetus Suture Zone (ISZ) than in north (c. 1.1 $\mu W/m^3$).
- Good agreement between Ordovician HPR data for Newfoundland and Ireland north of the ISZ but not to south.
- In the Irish midlands HPR data yield plausible mantle heat flow values where crustal structure, 3-D HPR and heat flow (Moate borehole, 60 mW/m^2) are well constrained.
- High heat flow (85 mW/m^2) estimated in deep boreholes in Cavan (Midland Valley Terrane) require a high heat-producing body at depth, perhaps a granite, as suggested by gravity data.