Under pressure – the importance of pressure when thermally calibrating basin models

By David Gardiner

Calibration to measured data is an essential model validation process in any domain. The calibration of basin models, used to constrain the coupled thermal-burial history of sedimentary basins, has traditionally been a subjective and iterative process. Most basin modellers within the energy sector tend to spend a disproportionate amount of time and focus calibrating models to temperature (e.g., Horner corrected BHT, DST) and geothermometric/maturity data (e.g., vitrinite reflectance, AFTA), often reconciling both by parametrizing burial history (e.g., subsidence rates, erosion events), sediment lithology mixtures (e.g., thermal conductivity) and lithospheric structure/composition, among other inputs (e.g., surface temperature, water depth).

Pressure also plays a crucial role in the calibration of basin models, however, calibration to pressure data can often be a secondary consideration or overlooked altogether. Pressure intuitively affects numerous geological processes such as migration vectors and reservoir fluid phase behaviour, whilst accurate pressure prediction is critical to well design and drilling risks (e.g., mud weight design).

Crucially, but perhaps unintuitively, changes in the geopressure history, specifically overpressure, have a direct impact on the rates of dehydration and compaction during burial (Fig. 1a & c), significantly affecting the thermal conductivity of sediments (Fig. 1d), and thus are critical to the thermal calibration process.

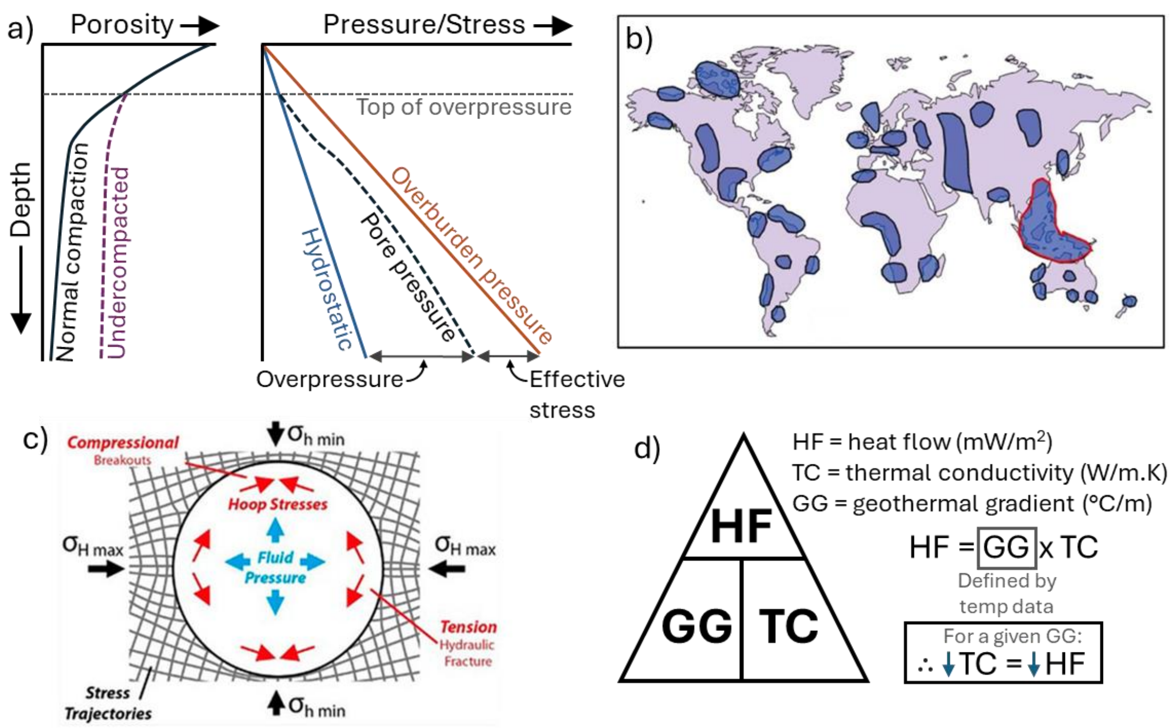

Figure 1: Summary concepts and context for overpressure, geomechanics and thermal calibration. a) Depth trend relationship of porosity and pressure/stress in normal and overpressured basins. Overpressure results in undercompaction; b) Global schematic showing areas of documented regional overpressure (after Ketaren *et al.* 2017); c)

Schematic of a fluid-bearing overpressured pore (from Flemings, 2021); d) Relationship between heat flow (HF), geothermal gradient (GG) and thermal conductivity (TC).

Overpressure is a common phenomenon in basins worldwide (Fig.1b), developing when fluid cannot escape fast enough in response to sedimentary loading (Fig.1c). The fluid will support part of the overburden and the effective stress will be reduced, resulting in excess porosity and over pressure (Fig.1a). Other causes of overpressure include fluid expansion (e.g., hydrocarbon generation), diagenesis (e.g., cement growth, clay dehydration reactions), tectonic compression, and pressure transfer (Zhao *et al.,* 2018).

Fluid saturated pores are poorer conductors of heat than grains, minerals, and cements, so the retention of fluid (water, petroleum) in overpressured regions typically reduces the bulk thermal conductivity of that unit, directly affecting thermal calibration by reducing heat flow and increasing the geothermal gradient (Fig.1d).

In Figure 2, an overpressured well from the Norwegian North Sea is used to demonstrate three 1-D modelling calibration scenarios. Calibration to temperature and vitrinite reflectance data is easily achieved when ignoring pressure data (Scenario 1), however the lithospheric structure does not match regional estimates (Maystrenko *et al.* 2017), requiring a much higher radiogenic heat production (RHP) from the crust.

But increasing the fluid pressure to match measured data (overpressure of *ca.*40MPa at 5,000mTVDKB) by introducing appropriate shale porosity/permeability properties and burial behaviour (Mondol *et al.*, 2007) also increases the geothermal gradient due to the reduction in thermal conductivity (Scenario 2), requiring a cooler basal model boundary condition to reconcile temperature and maturity with pressure data (Scenario 3).

This final scenario, which reconciles temperature, maturity, and pressure data is consistent with regional lithospheric models by Maystrenko *et al.* (2017) which indicate upper and lower crustal thicknesses of 10-12km each in the well location. We can only reconcile the well calibration data and published crustal structures by including overpressure.

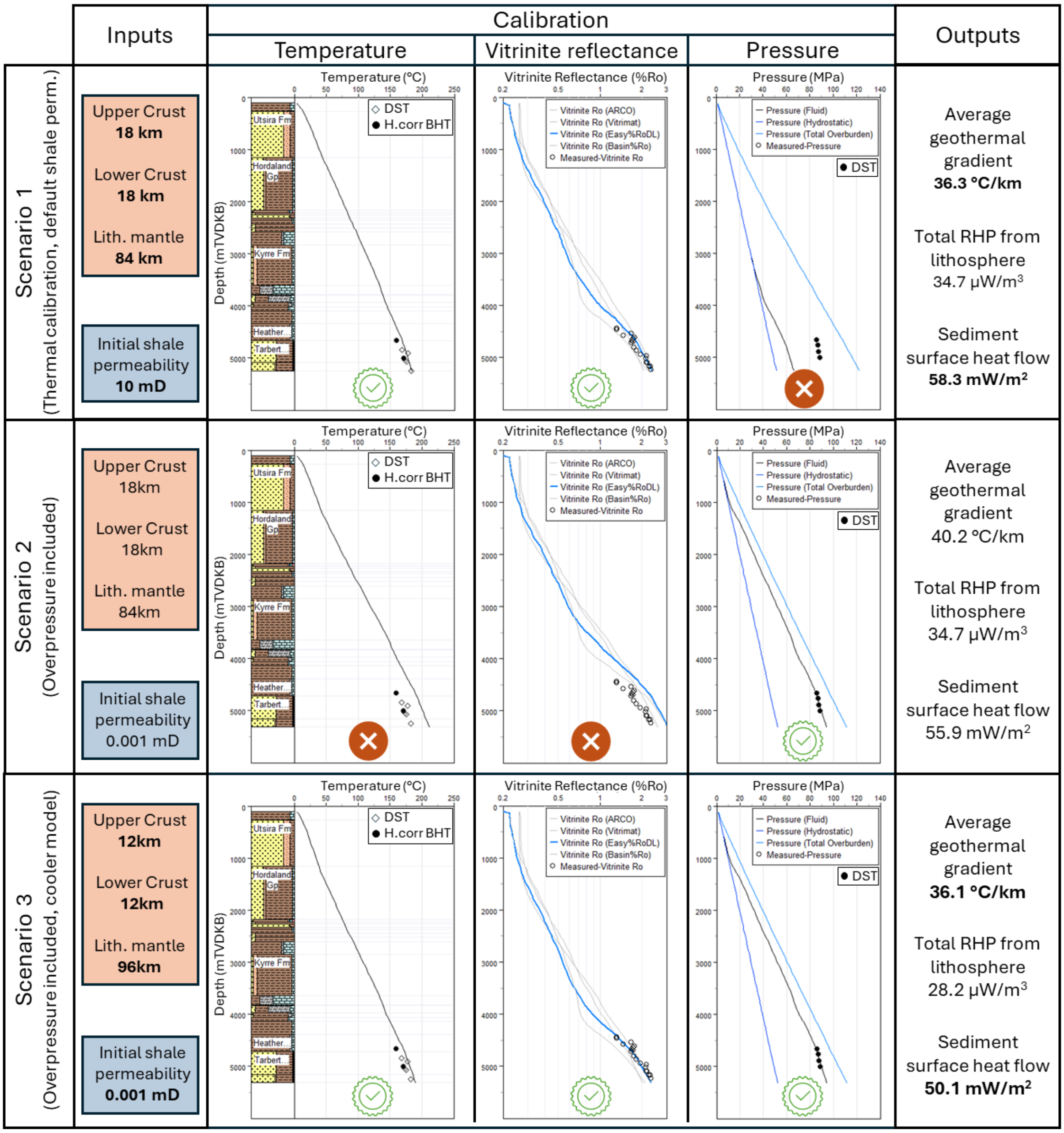

Figure 2: Thermal calibration scenarios for a Norwegian North Sea well (30/10-6) varying lithospheric structure (for thermal calibration) and initial shale permeability (for pressure calibration). Thermal calibration to temperature and vitrinite reflectance (VR) data can be achieved without and with considering overpressure (Scenarios 1 & 3, respectively), but requiring quite different lithospheric structures. Only Scenario 3 achieves calibration to temperature, maturity, and pressure data, with a crustal structure consistent with regional lithospheric models (e.g., Maystrenko *et al.*, 2017). Ticks and cross represent a subjective judgement on the quality of calibration. NOTE: the similar geothermal gradient but vastly different surface heat flow values due to the reduction of thermal conductivity caused by overpressure. VR calibration to Easy%RoDL kinetics. RHP = Radiogenic heat production; BHT = Bottom Hole Temperature; DST = Drill Stem Test.

There are numerous methods for achieving the cooling effect needed between scenario 2 and 3, typically by either increasing the distance to the base lithosphere (1,330°C isotherm), thinning the radiogenically-enriched upper crust, or by reducing the RHP of the crust and/or lithospheric mantle, but all of which have implications for the predicted lithospheric structure and composition.

Here we vary crustal thickness, reducing both the upper and lower crust thicknesses by 6km (12km in total) from Scenario 1 to 3 to reduce the RHP, and thus basal heat flow, to achieve thermal calibration in both scenarios. Calibration to temperature data dictates a similar average geothermal gradient of *ca.*36°C/km in both scenarios, but the reduction in thermal conductivity caused by the overpressured sediments reduces surface heat flow by *ca.*15% (Fig. 1d).

The key implication is the cooler basal heat flow conditions required for thermal calibration, which is more consistent with regional tectonic models in this area of the Norwegian North Sea (Maystrenko *et al.,* 2017), while also honoring the shale porosity/permeability characteristics and burial behavior introduced in Scenario 2.

In addition, if calibrating to surface heat flow (e.g., measurements or regional estimates) then the reduction in thermal conductivity caused by overpressure would invoke an increase in the geothermal gradient to calibrate to the same heat flow value. This could have significant implications on key petroleum system elements such as the depth to the oil/gas generation windows, prospect reservoir properties (e.g., temperature, quartz cementation) and PVT conditions.

Our experience shows that pressure calibration is *critical* and should be conducted *before* thermal calibration, or as part of the thermal calibration iterative process. Without accounting for overpressure in basin models, calibration to temperature, heat flow and maturity data is unreliable and, at worst, may impose adverse effects on your model, leading to discrepancies in the lithospheric structure, palaeo-heat flow, burial history, and/or present-day PVT regime from geological reality.

IGI Ltd. offer a 5-day course in Basin & Petroleum Systems Modelling which includes many workshops in ZetaWare Inc. software (Genesis, Trinity & Kinex).

References

FLEMINGS, P.B., 2021. Pore Pressure Prediction in Mudrocks, in *A Concise Guide to Geopressure: Origin, Prediction, and Applications*. Cambridge: Cambridge University Press, pp. 103–122.

KETAREN, L., AMBORO, B., AMBORO, ALAMSYAH, M. N., SYAFRIYA, A. & MUHTAR, L. 2017. Overpressure Mechanism Type – A Preliminary Prediction on Talang Akar and Gumai Formation of Betara Structure, Jambi Sub Basin. Conference: The 41st Indonesian Petroleum Association (IPA) Convention and Exhibition At: Jakarta, Indonesia.

MAYSTRENKO, Y., OLESEN, O., EBBING, J. & NASUTI, A. 2017. Deep structure of the northern North Sea and south-western Norway based on 3D density and magnetic modelling. *Norsk Geologisk Tiddsskrift*, 97, 169-210.

MONDOL, N. H., BJØRLYKKE, K., JAHREN, J. & HØEG, K. 2007. Experimental mechanical compaction of clay mineral aggregates: changes in physical properties of mudstones during burial. *Marine and Petroleum Geology*, 24, 289–311.

RADWAN, A. E., MENG, M. & ZHANG, J. 2022. Editorial: Overpressure in sedimentary basins and petroleum geomechanics. *Frontiers in Earth Science, 10*.

ZHAO, J., LI, J. & XU, Z. 2018. Advances in the origin of overpressures in sedimentary basins. *Petroleum Research,* 3**,** 1-24.