Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Introducing SEEBASE®, a bottom-up basement interpretation and geothermal model of the globe

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Keywords: basement geology, global, heat flow, radiogenic, transient

ABSTRACT

Geognostics' SEEBASE® is a global geospatial model of basement and basin evolution, developed over 30 years in the oil and gas sector. It provides a robust geological interpretation, and foundation datasets, to support ongoing exploration, data acquisition, and basin modelling across a range of resource sectors including conventional energy, geothermal, helium, natural hydrogen and deep groundwater exploration.

The SEEBASE® Geothermal model differs from conventional 'top-down' heat flow studies, which often rely on downward-extrapolated subsurface measurements and interpolation between data points. The workflow leverages the SEEBASE® model to build a conductive heat flow model from the lithosphere-asthenosphere boundary to the surface, including key geological elements such as the contribution of radiogenic heat production and transient heat flow (e.g., rifting, magmatic events).

INTRODUCTION

Most global and regional heat flow models rely heavily on geothermal data points, such as those available from the International Heat Flow Commission (IHFC; Fuchs et al 2023). In most heat flow studies, temperatures at depth are predicted by a downward extrapolation of shallow data, often without due consideration of how regional geology at depth controls the upward heat flow across the lithosphere. Moreover, density of geothermal data varies significantly, the quality is highly variable and heat flow values often show a large range over very short distances (Fuchs et al 2023). Still, most heat flow models mainly rely on an interpolation between these data points, without a significant role assigned to regional and local geology.

While a few relatively recent global heat flow models do consider geological and geophysical parameters (Goutorbe et al 2011, Lucazeau 2019, Kolawole and Evenick 2023) these are heavily reliant on constraining data and can be improved with better characterization and integration of detailed basement geology, radiogenic heat production, and transient heat flow.

SEEBASE® is a multilayer geospatial model of basement, developed using an iterative bottom-up interpretation, that provides the underlying elements for the SEEBASE geothermal modelling. We present key elements of this approach, using the open file Central Europe SEEBASE® study, developed in collaboration with OMV, as an example (Fig. 1), and show how these are integrated into a basement-focussed global geothermal model (Fig. 2).

1 THE SEEBASE® METHOD

SEEBASE® is developed through the iterative integration, interpretation and calibration of a range of geological and geophysical datasets and results in several key subsurface layers including depth to Moho, basement terranes, basement composition, major structures, and depth to basement (Fig. 1).

The workflow begins with an understanding of the tectonic evolution of the area and the identification of basement terranes, basement rheology and composition, tectonic events, and major crustal structures as the primary controls on the architecture of an evolving basin. Each layer in the SEEBASE® model is then interpreted in a customised geospatial environment, using integrated map and section views, to enable interpretation of potential field data (gravity and magnetic) alongside geological calibration and constraining data including surface geology/outcrop, wells, seismic data and cross sections from literature. Unlike algorithmic solutions, or interpolations between geological data points, this approach results in a geologically meaningful, internally consistent, interpretation away from geological data points.

The SEEBASE® Depth to Basement is a hand-contoured depth-to-basement surface and forms the base of all sedimentary systems.

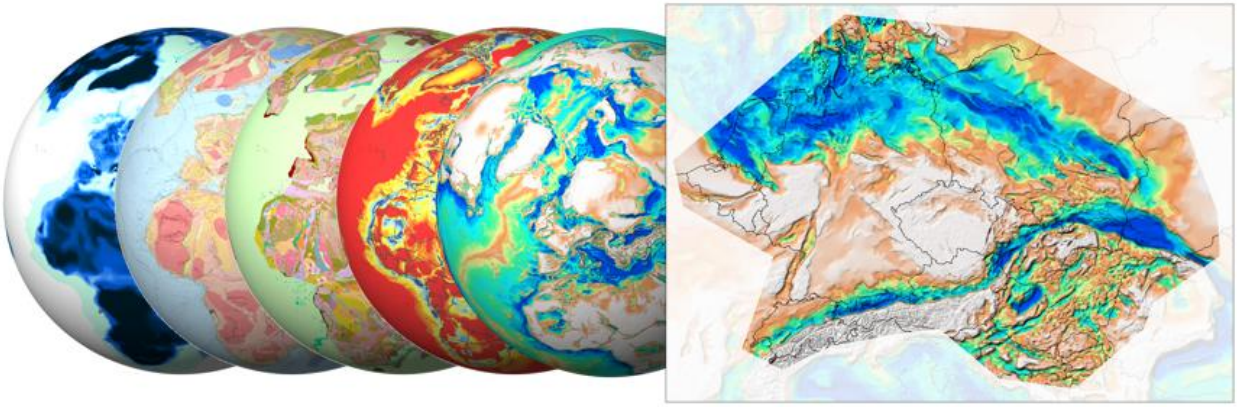


Figure 1. Layers contained in the Global SEEBASE model, from left to right: depth to Moho, basement terranes, basement composition, sediment thickness, and depth to basement. SEEBASE Depth to Basement from the open-file Central Europe SEEBASE Study is shown at far right.

2 HEAT FLOW MODELLING: SEEBASE® GEOTHERMAL MODEL

2.1 Introduction

A new regional-scale, full crustal heat flow modelling workflow has been developed, leveraging the upward series of elements provided by the SEEBASE® model. The SEEBASE® Geothermal model differs from conventional 'top-down' geothermal studies, which often rely on downward-extrapolated subsurface measurements, to instead build a conductive heat flow model from the lithosphere-asthenosphere boundary (LAB) to the surface, including key elements such as the contribution of upper crustal radiogenic heat production, basement and upper crustal thickness, and transient heat flow resulting from relatively young tectonothermal events.

The model predicts basement heat input at the base of sedimentary systems and helps to explain geothermal anomalies from a basement perspective. The combined geospatial and geological framework used in the SEEBASE® Geothermal model is comprised of custom databases, software, and geospatial geoprocessing tools, allowing for rapid integration of new data and modelling.

The SEEBASE® Geothermal model assumes heat transfer via conduction, which is expressed by the Fourier's law shown below in equation [1].

$$Q = -\lambda\left(\frac{\Delta T}{\Delta Z}\right) \qquad [1]$$

In this equation, Q is the heat flow (in W m^{-2}), λ is the thermal conductivity (in W K^{-1} m^{-1}), and ΔT/ΔZ is the geothermal gradient (in K m^{-1}).

The geothermal model starts at the LAB and progressively incorporates predicted heat flow through the lithosphere.

2.2 Lithosphere-Asthenosphere Boundary: LAB

The LAB is a key element in lithospheric heat flow modelling as it is the only zone at depth considered to have a known temperature (1603-1653 K; Afonso et al 2019, Rychert et al 2020).

Four publicly available global LAB models, those of Hamza and Vieira (2012), LithoRef18 (Afonso et al 2019), CAM2016 (Priestley et al 2018), and WINTERC-G (Fullea et al 2021), were evaluated. The models were evaluated based on how well these reflect lithospheric architecture and tectonic history, and compared against local LAB models where available, and this across both stable regions (e.g., cratons) and regions characterised by relatively young tectonothermal events. The models show significant variation, with frequent outliers and/or areas of unconstrained interpolation. Iterative testing of different LABs by incorporation in the geothermal modelling workflow also helped to identify suspect outliers. Based on this analysis the best results were obtained when using an average of the four aforementioned LAB models.

2.3 Radiogenic Heat Production and Upper Crustal Heat Flow

A radiogenic heat component is generated in the upper crust that contributes to the overall present-day heat flow (e.g., Hasterok et al 2018) and that is different for different lithologies (Mareschal and Jaupart 2013, Jaupart et al 2016). This radiogenic heat flow is controlled primarily by upper crustal thickness and basement composition (Jaupart et al 2016), both of which are provided by the SEEBASE® model.

The composition of basement determines the radiogenic heat production in the upper crust. The SEEBASE interpretation of undercover basement composition uses magnetic and gravity data and relies on a basinward extrapolation of basement outcrop and its geophysical signature and, where possible, is combined with information from wells and published studies. Radiogenic heat production values are based on an inhouse compilation of published radiogenic heat production and geochemistry databases.

The upper crustal thickness is estimated as a percentage of the total crustal thickness based on basement terrane type and age and literature (e.g., Hasterok and Chapman 2011, Mather et al 2018a, 2018b).

2.4 Transient Heat Flow

Tectonothermal events such as oceanic spreading and rifting and magmatic events, result in a heat flow component with decreasing effect over time. For relatively young tectonothermal events, this transient component will contribute to the present-day heat flow and therefore must be considered in heat flow modelling.

An important consideration is the time after which a past thermal event becomes negligible. Based on a literature review along continental margins (McKenzie 1978, Vitorello and Pollack 1980, Waples 2001, Pérez-Gussinyé et al 2024), a thermal effect is still noticeable up to ~100-120 my after break-up. Hence, the model incorporates transient heat flow of events younger than 120 Ma, occasionally also taking into account older events in order to validate the results.

Geognostics distinguishes several broad types of transient heat flow events, each with a slightly different approach to calculating the associated heat flow contribution.

- For heat flow in oceanic lithosphere, Hamza et al (2010) is used, assuming a conventional spreading rate of 20 km/Ma with additional adjustment possible for differing spreading rates and basal magma accretion.
- For transient heat flow caused by extensional basins in continental crust, such as rifting, pull-apart basin formation and back-arc basin formation, the aerial extent of the event, and an initial crustal thickness, are defined using the SEEBASE® model and a transient heat flow contribution is calculated based on equation 5 in Waples (2001), multiplied by an exponential negative function of time to allow for thermal decay. Values for the pre-rift asthenospheric heat flow Qao used are specific to the basin type, with the same values used across the globe.
- Transient heat flow associated with arc magmatism is calculated using a modified Hamza et al (2010) formula, applied to the transient event polygon of the magmatic arc.
- The approach for transient heat flow associated with hotspots is different for continental and oceanic lithosphere. For continental hotspots, transient heat flow is modelled by increasing the LAB temperature at the present-day location of the hotspot above the standard ~1603 K based on literature (Afonso et al 2019, Rychert et al 2020). For oceanic hotspots, transient heat flow is calculated using a modified Hamza et al (2010) formula with an elevated LAB temperature at the present-day location of the hotspot based on literature (e.g., Bao et al, 2022), after which the calculated heat flow is added to the oceanic heat flow. Where hot spot track data are available, an age-dependent thermal decay towards older positions along the track is also incorporated.

Over 700 transient event polygons have been defined including type, and termination age across the globe.

2.5 Model Validation and Results

Results were continually compared against data provided by the IHFC (Fuchs et al 2023) and global heat flow models (Goutorbe et al 2011, Lucazeau 2019), considering the geological setting and variability in geothermal data. Due to the variability in methodology of temperature measurements, and strong lateral variation in heat flow (Fuchs et al 2023), a semi-qualitative review was undertaken. As the model focusses on predicted heat flow at top basement, heat flow data points were selected based on available measured data at depths near top basement. Addition of sedimentary heat flow, using global constants for thermal conductivity and heat

production, results in total heat flow for comparison to existing models and heat flow data derived from shallow temperature measurements. Where model results showed significant discrepancies with the test data, and additional evidence was sufficient to support modification of the geological model, without introducing ad hoc localised adjustments, the geological model was updated and a new iteration of heat flow results was generated for further testing.

Overall, the SEEBASE® Geothermal model shows a good fit to the available heat flow data. Mismatches between the model and heat flow data were interpreted and are provided as an accompanying geospatial overlay, as these provide valuable insights into regional and local geothermal systems. For example, significant local mismatches in the current model can be attributed to areas of local convection along fault zones, evaporite occurrences at depth, lateral groundwater flow, or the blanketing effect of sediment deposition.

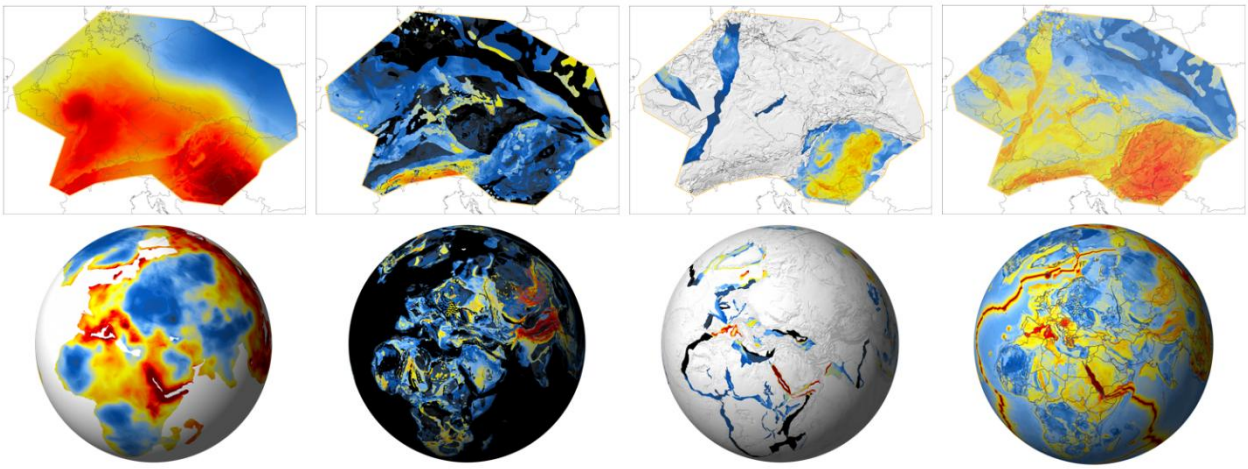


Figure 2. From left to right; predicted mantle heat flow, radiogenic upper crustal heat flow, transient heat flow associated with extensional basin formation, and heat flow at top basement from the open-file Central Europe SEEBASE Study (top) and Global SEEBASE (bottom).

3 CONCLUSIONS

SEEBASE® Geothermal is a regional model of heat flow that provides a geological framework for understanding geothermal systems and heat flow observations, prediction of heat flow away from existing temperature measurements, and improved inputs and boundary conditions for subsequent basin-scale modelling. The integrated geological and geothermal model enables improved modeling of radiogenic heat production in the upper crust, derived from interpreted basement composition, and transient heat flow based on tectonothermal history (Fig. 2).

The model can be maintained and further improved through integration of additional data, higher resolution potential data and/or focused study within specific countries or basins.

Acknowledgements

Geognostics gratefully acknowledges OMV Exploration & Production for funding and support of the Central Europe SEEBASE® Study.

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