Unveiling the Global Heat Flow Database (GHFDB): A New Era for Geothermal Research and Subsurface Thermal Mapping

Sven Fuchs[1*], Florian Neumann[1,2], Elif Balkan-Pazvantoğlu[1,3], Samah Elbarbary[1], Alexey G. Petrunin[1], Ben Norden[1]

1. Section Geoenergy, GFZ Helmholtz Centre for Geosciences, Potsdam, 14471, Germany

2. MARUM Center for Marine Environmental Sciences, University of Bremen, Bremen, 28334, Germany

3. *Department of Geophysical Engineering, Dokuz Eylül University, İzmir,35390, Türkiye*

Abstract

After five years of coordinated international collaboration, the International Heat Flow Commission, together with Task Force VIII of the International Lithosphere Program, presents the first fully quality-controlled and authenticated Global Heat Flow Database (GHFDB). This milestone marks a transformative leap in the availability and reliability of global heat-flow data, critical inputs for geothermal exploration, resource assessment, and lithospheric modeling. The GHFDB integrates information from over 2,100 documents spanning the period from 1939 to 2025, employing standardized data formats, rigorous quality-assessment procedures, and consistent metadata structures. The result is a robust and traceable dataset that significantly enhances confidence in estimates of heat-flow density, thermal conductivity, and geothermal gradients, along with their associated metadata. For the first time, the scientific community and the geothermal industry have access to an open, globally harmonized, quality-scored database of surface heat flow density, comprising more than 130,000 data entries from approximately 79,000 locations across continental (56%) and marine (43%) settings. The GHFDB combines 85 years of scientific work, achieving high data densities in regions such as Europe, East Asia, Australia, and North America, while highlighting data gaps in polar regions, many African countries, and broad marine areas.This presentation outlines the framework and methodology underpinning the development of the IHFC Global Heat Flow Database, demonstrates key applications in geothermal resource characterization, and highlights opportunities for integration with other geoscientific data infrastructures. The GHFDB establishes a new benchmark for geothermal data quality and accessibility. We invite researchers, industry professionals, and data providers to explore this resource and contribute to shaping the next phase of global geothermal and geodynamic research.

1. Introduction

Terrestrial heat flow is one of the fundamental parameters for understanding Earth's thermal regime, lithospheric evolution, and the processes that govern energy transport from the Earth's interior to its surface. Quantifying the spatial and temporal variability of heat flow provides insights into crustal and mantle dynamics, the thermal structure of sedimentary basins, and the stability of permafrost and ice sheets under changing climatic conditions. It builds moreover the basement for modelling subsurface temperature-depth distributions in the geothermal exploration context. Since the first global compilation by Birch (1954), which contained 63 observations and limited metadata, successive efforts have expanded the spatial coverage and introduced more standardized approaches to data reporting.

Recent years have seen a rapid increase in the use of terrestrial heat-flow data across multiple disciplines, ranging from geothermal energy exploration (e.g., IEA, 2024, Franzmann et al., 2025) and sedimentary basin analysis to tectonic evolution (e.g., Krutenko et al., 2026), lithospheric modeling (e.g., Torne et al., 2023; Buitrago et al., 2024), and machine learning–based geothermal studies (e.g., Liu, et al. 2025, Zhang et al., 2025, Ji et al., 2025; Vega-Ramirez et al., 2025). The availability of the quality-scored, globally harmonized Global Heat Flow Database (GHFDB) has enabled these advances, providing a standardized foundation for research on Earth's thermal structure at regional to global scales.

Maintained by the International Heat Flow Commission (IHFC), the GHFDB now serves as the principal repository for continental and marine heat-flow data worldwide. Since 2019, major international efforts have focused on data harmonization, metadata completeness, and quality assessment, resulting in the implementation of uncertainty (U-scores), methodological rigor (M-scores), and site-specific perturbation flags (P-flags) as standard evaluation metrics (Fuchs et al., 2023). Together, these developments ensure that the GHFDB not only aggregates historical measurements but also delivers reproducible, quality-controlled datasets that meet the needs of both the scientific community and industrial stakeholders.

By 2026, the entire continental and marine dataset is fully assessed with standardized metadata and documentation, establishing the GHFDB as the primary global source for well-documented, quality-controlled heat-flow data. This comprehensive resource will provide a robust foundation for lithospheric modeling, geothermal resource assessment, and climate-related studies, supporting research from local investigations to global geodynamic analyses.

2. Background and previous work

Since its inception, the GHFDB has grown from 63 heat-flow observations with 7 metadata fields reported by Birch (1954) to about 91,000 observations and 62 metadata properties in the 2024 release. Over time, successive compilations expanded both data volume and descriptive detail, for example, ~2,000 observations with 12 metadata fields in Lee and Uyeda (1965), ~5,400 with 24

fields in Jessop et al. (1976), and ~60,000 with 43 fields in Hasterok and Chapman (2008). Early datasets provided only limited contextual information, which constrained data comparability and quality assessment. This gap, along with the increasing demands from data science and data interoperability for detailed metadata, led to the development of a comprehensive metadata scheme (Fuchs et al., 2021, 2023). This scheme was developed by the international heat-flow community under the IHFC and Task Force VIII of the International Lithosphere Program (ILP) lead, ensuring that modern heat-flow data are well-documented, interoperable, and suitable for diverse geoscientific applications.

3. Data compilation and methods

The GHFDB is the result of a collective scientific effort spanning over eighty years, from 1939 to the present. It brings together insights from over 4,100 publications, ranging from journal articles and books to reports, theses, and conference papers. These publications provide not only direct heat-flow measurements but also supporting temperature data, geothermal gradients, methods, and thermal conductivity information. By combining contributions from hundreds of researchers worldwide, the database reflects both the history and progress of geothermal research. Our geothermal library constitutes one of the most comprehensive collections of geothermal research, preserving legacy papers and reports alongside recent online publications. In total, the sources comprise approximately 2,706 journal articles, 581 books, 401 reports, 241 conference papers or proceedings, 166 theses, and around 45 datasets.

The compilation and assessment of the GHFDB faced several challenges that required a coordinated international effort. A major difficulty was the accessibility of the literature: many original heat-flow reports are not available in digital form and can only be found in libraries or institutional archives across different countries. To overcome this, we received support from the GFZ library, which facilitated the retrieval of numerous missing references through international interlibrary loan. Additionally, we directly contacted colleagues worldwide, who kindly assisted in locating and sharing legacy publications that would otherwise be difficult to obtain.

Another challenge was the linguistic diversity of the publications. Heat-flow studies have historically been published in many different languages, ranging from English, French, German, and Russian to Chinese, Japanese, Spanish, and others. To ensure accurate evaluation, we relied on the expertise of native-speaking scientists who reviewed and translated publications as part of ongoing scientific collaborations and through the IHFC Heat Flow Fellowship program.

The assessment process also revealed inconsistencies in site coordinates reported in older compilations. In several cases, locations derived from georeferenced maps or low-precision coordinates were inaccurate or duplicated across different sources. We systematically checked and verified the original coordinates and corrected misplacements where possible. These efforts were essential to enhance the integrity, spatial accuracy, and long-term usability of the GHFDB.

The global heat-flow dataset was compiled and evaluated in accordance with the new IHFC quality-assurance framework (Fuchs et al., 2023; Fuchs et al., 2025a). All records are organized in the parent–child structure. Parent entries represent the most reliable terrestrial heat-flow estimate for a unique location, while child entries capture/store the underlying determinations, including depth intervals, methods used to determine both thermal gradient and conductivity, corrections, and metadata. This hierarchical design preserves traceability, documents historical context, and enables reconstruction of the evolution of site-specific knowledge over time. Each heat-flow value was assessed using the three dimension quality scheme: (1) the U-score, quantifying numerical uncertainty; (2) the M-score, evaluating methodological quality of the temperature and conductivity data; and (3) the p-flags, identifying environmental perturbations (e.g., sedimentation, erosion, topography, paleoclimate, transient surface temperature, convection, or heat refraction) and whether they were corrected. Together, these components yield a transparent and reproducible quality score, with the representative parent entry reflecting the lowest quality ranking among the associated child records. This framework ensures that the global dataset is consistent, quality-controlled, and comparable across different regions and acquisition techniques, thereby maintaining the long-term integrity and usability of the GHFDB as an authenticated reference for scientific and applied studies.

4. Results and Discussion

4.1. Global Distribution and Metadata Coverage of the GHFDB (Release 2026)

The newly assessed GHFDB (Release 2026) comprises more than 130,000 individual heat-flow determinations from over 2,100 references and represents around 79,000 unique sites. Continental data represent nearly 56% of the total records, with the highest densities in Europe (~28,000 data at ~8,300 locations) and North America (~25,000 data at ~21,600 locations), followed by substantial contributions from Asia (~16,000 data at ~8,300 locations), (Fig. 1a). Africa and South America still remain less well covered. Marine data represent about 44% of the database, dominated by the North Pacific Ocean (~19,000 data at ~13,500 locations) and the North Atlantic Ocean (~9,500 data at ~6,200 locations), with further contributions from the Indian Ocean (~5,700 data at ~3,000 locations), the Arctic Ocean (~4,600 data at ~2,300 locations), and the Mediterranean Region (~4,900 data at ~2,500 locations), (Fig. 1b). In the South Pacific, South Atlantic, and Southern Ocean, data coverage is still limited. This distribution highlights both the strong concentration of high-quality data in well-surveyed regions and the persistent data gaps across polar areas, wide marine domains, and large parts of Africa and South America. The database is fully harmonized within the IHFC metadata scheme (Fuchs et al., 2023, 2025a), with each entry accompanied by standardized information on temperature measurement methods, thermal conductivity determinations, perturbation effects, quality scores, and references. This provides detailed information for every site, supporting transparent interpretation and further analysis (cf. Neumann et al., under review).

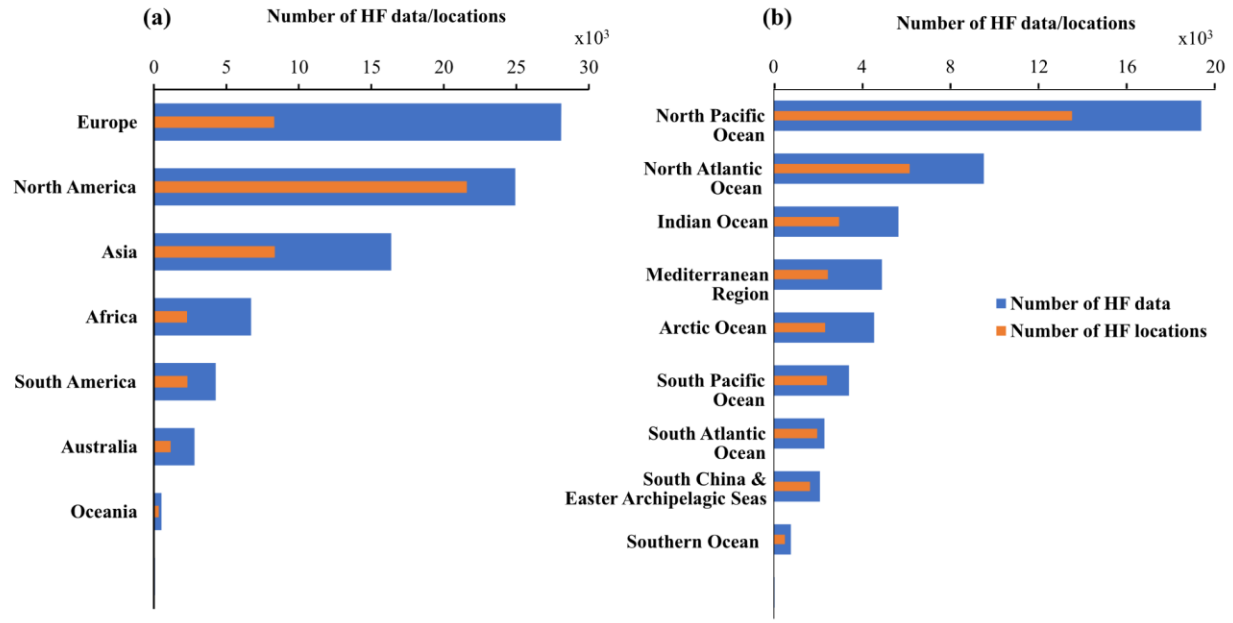


Figure 1. Number of heat-flow (HF) data entries (blue) and unique HF locations (orange) compiled in the Global Heat Flow Database (GHFDB) release 2026. (a) Continental distribution grouped by major continents. (b) Marine distribution grouped by major ocean basins and regions. Europe and North America dominate the continental dataset, while the North Pacific and North Atlantic dominate the marine dataset (as of November 2025).

The temporal distribution of heat-flow data in the GHFDB reflects more than eight decades of scientific effort (Fig. 2). Early records from the 1940s and 1950s are sparse, with a gradual increase beginning in the 1960s and accelerating during the 1970s and 1980s, coinciding with the rise of systematic geothermal exploration and lithospheric studies. The 1990s show sustained contributions from both continental and marine surveys. A sharp peak in 2004 corresponds to the inclusion of the large U.S. dataset compiled by Blackwell and Richards (2004), comprising nearly 20,000 site entries, many from industrial rather than academic sources. Since 2010, contributions have continued at a steady rate, with recent years reflecting both new field campaigns and the integration of legacy data. The cumulative curve (Fig. 2) highlights that over 80% of today's global heat-flow dataset was established after 1970.

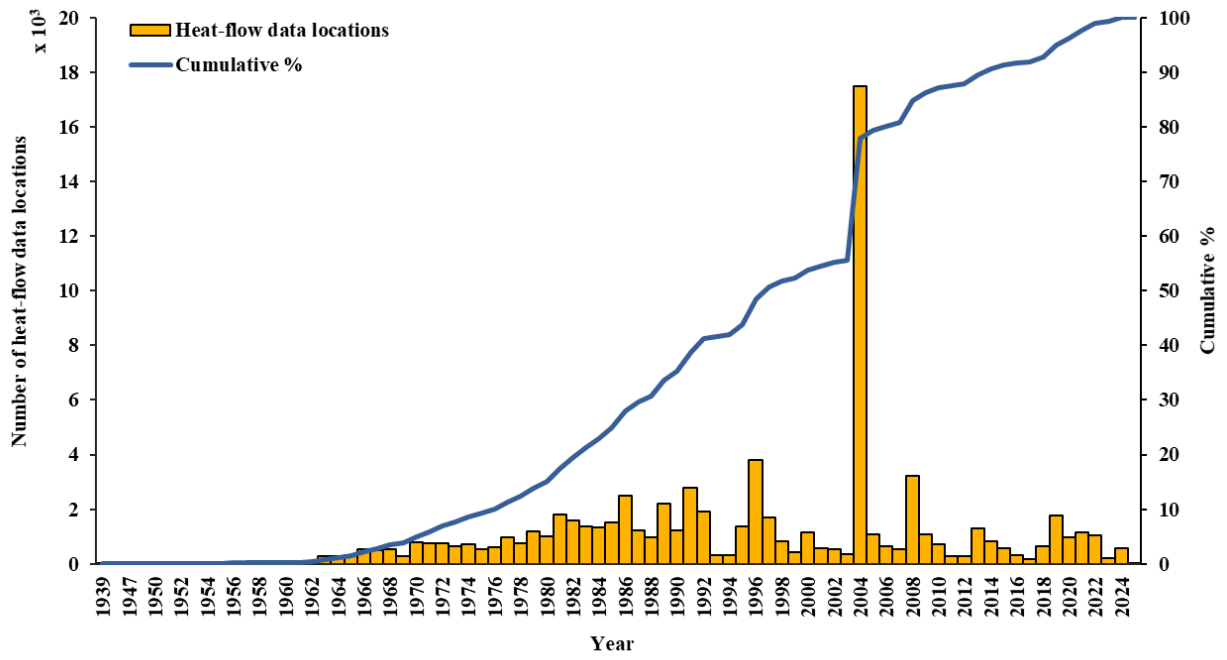


Figure 2. Annual additions and cumulative growth of the Heat Flow Database (1939-2025). The orange bars show the number of data locations added each year, while the blue line indicates their cumulative growth.

4.2. Quality Evaluation of Heat-Flow Determinations

The U-score quantifies numerical uncertainty in heat-flow determinations using the coefficient of variation (COV), defined as the ratio between the propagated uncertainty of the heat-flow calculation and the mean heat-flow value. Scores range from U1 (COV < 5%, highest quality) to U4 (COV > 25%, lowest quality), with Ux marking cases where essential metadata are missing (Fuchs et al., 2023). The marine compilation of the GHFDB 2026 release, includes data from roughly 51,000 assessed sites. Of these, approximately 3,000 entries belong to U1, 6,000 to U2, 1,600 to U3, and 1,200 to U4, while more than 40,000 sites fall into Ux. High-quality U1–U2 data are concentrated in the North Pacific and North Atlantic Oceans, whereas the South Atlantic, South Pacific, and Southern Ocean are dominated by Ux (Fig. 3), reflecting the prevalence of legacy data without sufficient documentation. In the continental dataset, about 44,000 sites were evaluated. Only around 1,000 entries are U1, while 2,200 are U2, 1,100 U3, and 700 U4, compared to nearly 39,000 in Ux (Fig. 3). North America contributes the largest share with more than 21,000 records, but the majority remain in the Ux category. In comparison, Europe, Asia, and Australia show a more even distribution, with a greater share of U1–U3 quality score data. This contrast highlights both the improved documentation in some well-studied continental regions and the prevalence of legacy data with missing metadata in others, underscoring the need for continued reassessment to enhance the reliability of global heat-flow information.

The M-score reveals a strong regional imbalance in data robustness across both continental and marine domains. Most heat-flow determinations fall into the Mx class, indicating insufficient or

missing methodological documentation. North America, Asia, and Europe contribute the largest portion of the continental data, predominantly within the M4-Mx classes (Fig. 4), reflecting poorly documented datasets or missing information. In contrast, Africa, South America, and Australia show moderate/intermediate representation, with most data distributed between the M3-M4 classes. In the marine domain, the North Pacific and North Atlantic Oceans clearly dominate, primarily within the M4-Mx classes (Fig. 4). Peripheral basins such as the Baltic Sea, Southern Ocean, and South China–East Archipelagic Seas are characterized by limited and incomplete methodological records. Overall, the results demonstrate that while the database contains a large number of heat-flow measurements, the quality and completeness vary widely, and many older records still require improved documentation.

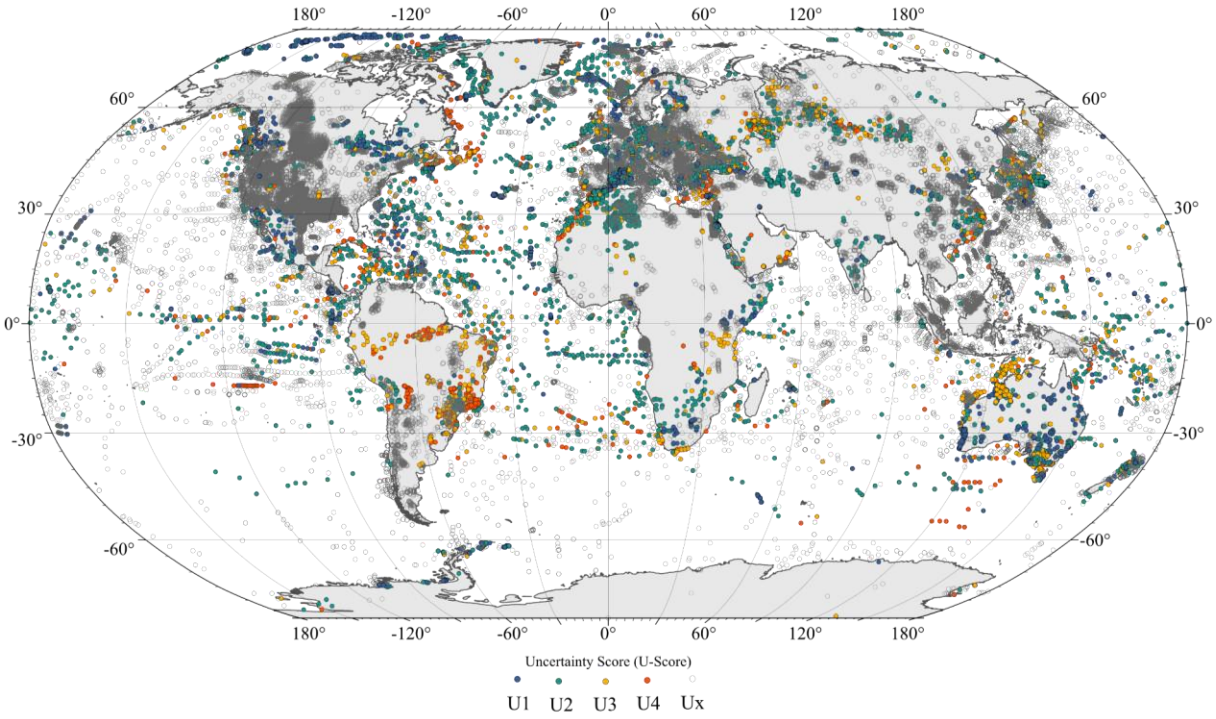


Figure 3. Global distribution of heat-flow data classified by uncertainty scores (U-scores). U1–U4 classes reflect increasing relative uncertainty from <5% to >25%, while Ux indicates records with insufficient metadata for quality evaluation (as of November 2025).

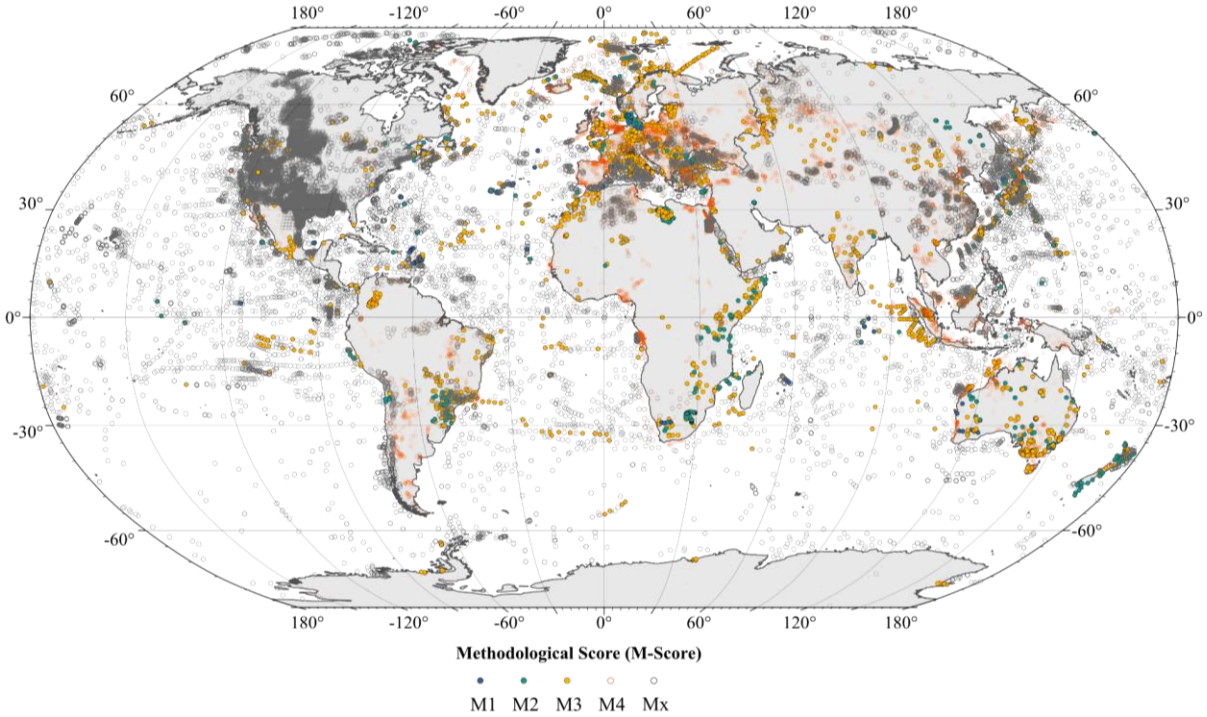


Figure 4. Global distribution of heat-flow data classified by methodological scores (M-scores) (as of November 2025).

4.3. Availability and utilization of data

The GHFDB (Release 2026 and all previous) is openly accessible through the dedicated IHFC data and community portal at https://www.heatflow.world/. It is operated by the GFZ Helmholtz Centre for Geosciences. The full dataset is available for download in multiple formats, with a persistent DOI for citation purposes (Global Heat Flow Data Assessment Group). The interactive portal features a global map for data exploration, advanced filtering by region, quality metrics, perturbation flags, and site type, as well as tools for generating custom visualizations, 2D heat-flow profiles, 1D geotherms, and digital boreholes. Users can create projects, collaborate with others, and integrate the data with external geoscientific datasets. The database supports diverse applications in geothermal exploration, resource characterization, and subsurface thermal modeling, as demonstrated in recent studies on machine learning-based heat-flow predictions (Liu et al., 2025; Zhang et al., 2025; Ji et al., 2025; Vega-Ramirez et al., 2025), lithospheric dynamics (Krutenko et al., 2026; Torne et al., 2023), and global energy assessments (IEA, 2024; Franzmann et al., 2025). Researchers, industry professionals, and data providers are invited to contribute new measurements or legacy data via the portal's upload system, which includes templates, metadata validation, and DOI assignment for contributions, ensuring ongoing harmonization and expansion of this critical resource.

5. Summary, conclusions and future outlook

The Global Heat Flow Database release in 2026 consolidates over six years of international effort into a repository of more than 130,000 terrestrial and marine heat-flow measurements from about 79,000 sites. Initiated in 2019, the implemented quality metrics (U-scores, M-scores, P-flags) approach addresses issues of data comparability, metadata completeness, and spatial accuracy.

The GHFDB provides a quality basis for both better pre-drilling subsurface temperature-depth predictions in the exploration phase and improved thermal models in the operational phase of geothermal projects. It also advanced interdisciplinary studies, including geothermal exploration, lithospheric modeling, and climate impact studies on permafrost and ice sheets. It also supports the application of machine learning methods to estimate heat flow in regions with limited data coverage, as well as integration with other geophysical datasets, such as seismic, gravity, and magnetic data. Future work should focus on addressing spatial data gaps and further collecting the metadata for the GHF measurement sites, as well as implementing automated quality assessment and GHF correction procedures that involve joint analysis of both GHFDB and geological/geophysical data.

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7. Data availability

The new heat flow data portal of the IHFC (https://www.ihfc-iugg.org) is accessible via www.heatflow.world and operated by GFZ Helmholtz Centre for Geosciences (www.gfz.de).

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