



Atlas of geochemical, petrophysical and mechanical rock properties of the crystalline basement in Germany – first release

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Abstract

A comprehensive and statistically robust understanding of rock characteristics is essential for reservoir characterization of the deep subsurface to accurately plan exploration campaigns, parameterize predictive 3D geological models, interpret geophysical data, and execute numerical thermo-hydraulic-mechanical-chemical simulations, thereby reducing economic risks and project
15 uncertainties. Despite growing interest in the crystalline basement in Germany for e.g., geothermal energy applications and the safe storage of high-radioactive nuclear waste, systematic datasets covering the major crystalline and metamorphic basement units and their physiomechanical characteristics remain scarce, fragmented, or lack the metadata required for robust evaluation. To address this data gap, the AMPEDEK project established a unified, multi-scale national reference database for geochemical, petrophysical, and mechanical rock properties of crystalline rocks in Germany. The framework integrated
20 extensive literature reviews, data from geological surveys, and newly conducted sampling and measurement campaigns, linking metadata, geochemistry, petrography, and physiomechanical rock properties through unique sample IDs. Existing data from more than 40 studies were compiled, evaluated, and integrated into the database. In addition, approximately 650 cylindrical plugs retrieved from drill cores and outcrop samples were systematically analyzed with respect to their mineralogical, geochemical, petrophysical, and rock mechanical properties to close remaining data gaps. Particular emphasis
25 was placed on sampling a broad spectrum of lithologies to ensure coverage of the major crystalline units in Germany. The resulting open-access repository (Weydt et al., 2026; <https://doi.org/10.48328/tudatalib-2167>) currently contains approximately 25,700 data points covering up to 34 parameters measured on 8,200 samples from more than 3,400 sampling locations across eight federal states in Germany. It represents the first standardized national-scale compilation of geochemical, petrophysical, and mechanical rock property data for the crystalline basement in Germany. The database provides a robust
30 empirical foundation for early-stage exploration, reservoir characterization, and the validation of analytical measurement methods. Future efforts will focus on expanding the database towards regions with low data density and on high-temperature and high-pressure experiments to improve the understanding of parameter variations under in situ conditions.



1 Introduction

35 Rock properties are required for a wide range of subsurface applications, including medium to deep geothermal projects, mining and resource extraction, the search for suitable repositories for radioactive waste, and geotechnical investigations. For all of these applications, a sound understanding of rock characteristics and their spatial variability is essential to accurately design and conduct exploration campaigns, reservoir assessments, and 3D subsurface simulations, thereby reducing overall project uncertainty. In particular, rock properties are indispensable for the interpretation of geophysical data, helping to reduce
40 the inherent ambiguity of geophysical methods. Furthermore, they provide valuable information on the expected risks and costs associated with deep drilling operations and underground construction projects.

Because drilling campaigns and especially the acquisition of continuous drill cores are expensive, outcrop analogue studies are frequently used as a cost-effective alternative to investigate target formations at the surface and assess their characteristics and spatial heterogeneity (Homuth and Sass, 2014; Aretz et al., 2015; Bertrand et al., 2021; Anees et al., 2024; Brémaud et al.,
45 2026). This approach enables the generation of large datasets that allow statistically robust estimates of reservoir properties and facilitate the assessment of spatial variability beyond the scale of individual boreholes. However, rock properties are often influenced by diagenetic, tectonic, metamorphic, and hydrothermal alteration processes (Howell et al., 2014; Busch et al., 2022) and therefore reflect a reservoir specific signature. Consequently, whenever possible, both outcrop analogue samples and drill core material should be investigated jointly (Homuth and Sass, 2014; Weydt et al., 2018, 2022; Sass et al., 2021;
50 Brémaud et al., 2026).

As comprehensive laboratory characterization campaigns are often too costly for smaller commercial projects or preliminary desktop studies, and because the required equipment and expertise may not always be available, literature data are frequently used during the early stages of exploration. However, such data are often insufficient for reliable reservoir assessments because they rarely capture reservoir specific characteristics and are commonly scattered across numerous publications, often
55 containing only a limited number of parameters and, in many cases, being inaccessible to the public.

To address these limitations, several comprehensive open access rock property databases have been developed in recent years for specific regions (Mexico: Weydt et al., 2021; Germany: Weinert et al., 2021; Iceland: Scott et al., 2023), while others are currently under development (Global Petrophysical Database, Sheldon et al., 2025; Finland, Crystal Clear database: Bischoff et al., 2025; Northern Canada, Miranda et al., 2026). The P³ Petrophysical Property Database (Bär et al., 2020) represents one
60 of the most comprehensive efforts with more than 75.000 data points, integrating publicly available datasets from studies worldwide and providing a systematic framework for sample classification and quality control. Building on this work, Weydt et al. (2021) proposed a standardized workflow for rock characterization under ambient conditions and highlighted the importance of determining all relevant rock properties on the same specimen whenever possible. Such comprehensive datasets enable the investigation of interdependencies among rock parameters and support the development of empirical and semi
65 empirical relationships as well as constitutive models.



In Germany, crystalline basement rocks are increasingly attracting attention for a variety of subsurface applications. Besides their traditional use as building stone, particularly in the major quarrying regions of the Bavarian Forest, the Fichtelgebirge, and the Black Forest, they are increasingly considered for deep geothermal energy utilization, thermal energy storage, and the disposal of high-level radioactive waste. Jung et al. (2002) estimated that approximately 95 % of Germany's deep geothermal electricity potential resides within crystalline basement rocks, assuming the application of advanced technologies such as Enhanced Geothermal Systems and deep closed loop concepts. Consequently, recent projects have focused on the utilization of crystalline rocks for deep geothermal energy production in the South German Molasse Basin (Falk et al., 2026), the characterization of fault controlled geothermal systems such as Soultz sous Forêts (Genter et al., 2010), and the combined extraction of geothermal energy and lithium from geothermal brines in the Upper Rhine Graben (e.g., Jungmann et al., 2025). Likewise, medium depth borehole thermal energy storage systems have recently been developed and tested within the framework of the SKEWS and Push IT projects (Seib et al., 2024; Sass et al., 2024).

Besides energy related applications, the crystalline basement has also been identified as one of the potential host rocks for the disposal of high-level radioactive waste in Germany (BGE, 2020). Due to its high mechanical strength, low solubility, low sensitivity to elevated temperatures, and low permeability under unfractured conditions, crystalline rock may provide favourable conditions for the long-term containment of radioactive waste (Bauer, 2021). Germany's repository site selection process follows a stepwise approach in which potential areas are progressively refined based on exclusion criteria, geoscientific weighting factors, and preliminary safety assessments. During Phase 1 of the site selection process, the Federal Company for Radioactive Waste Disposal identified several sub areas, seven of which are located within the crystalline basement (BGE, 2020).

Although the objectives of geotechnical projects, geothermal energy production, thermal energy storage, and radioactive waste disposal differ substantially, all of these applications require reliable information on the geochemical, petrophysical, thermal, hydraulic, and mechanical properties of crystalline rocks. Despite decades of geological mapping and local research activities, systematic datasets covering the major crystalline basement units of Germany remain scarce. This is largely because the crystalline basement has not been a primary exploration target for the oil and gas industry and only limited deep drilling campaigns have been conducted in many regions. Existing datasets are often restricted to individual lithologies, local study areas, or specific rock properties and have rarely been compiled into a unified and accessible framework.

To address this knowledge gap, the AMPEDEK project (Atlas of Mineralogical and Petrophysical Properties of German Crystalline Host Rocks) was initiated to establish a comprehensive reference database for crystalline basement rocks in Germany (Weydt et al., 2025). The project combines extensive literature reviews, data from geological surveys, and newly conducted sampling and measurement campaigns. Newly collected rock samples were systematically analysed for their petrophysical, hydraulic, thermal, magnetic, and mechanical properties and complemented by mineralogical, geochemical, and petrographic investigations. The resulting database includes detailed metadata and quality control procedures and aims to provide a robust basis for future geothermal, storage, repository, and geotechnical applications.



This paper presents the results of the first phase of the AMPEDEK project. The main objectives are to compile and harmonize existing datasets, generate new high-quality measurements from representative crystalline lithologies across Germany, and establish a comprehensive and publicly accessible reference database. Furthermore, the study aims to improve the understanding of the variability of reservoir relevant rock properties and their implications for the characterization and utilization of crystalline basement reservoirs.

2 Geological setting

The crystalline basement in Germany was mainly formed during the Variscan orogeny in the late Palaeozoic era, when the continents of Laurussia and Gondwana collided. According to Matte (1986) the pre-Mesozoic basement of southern Europe consisted of Proterozoic to Carboniferous terranes and younger granitoids, which were deformed and in part metamorphosed during the Variscan orogeny, and whose remnants are still present in various isolated massifs (Iberian System, American Massif, French Massif, Ardennes-Rhenohercynian, and Bohemian Massif). The resulting Variscan belt was about 3000 km long, 700-800 km wide and stretched from southern Iberia to northeastern Bohemia (Matte, 1986). In the case of Germany, the crystalline basement consists of the remnants of various smaller continents, such as Avalonia, a Silurian-Early Devonian magmatic arc (present-day northern Germany) and the American Terrane Assemblage, which were accreted in between Laurussia and Gondwana and whose collision caused the closure of the Rheic Ocean (Franke, 2000). The Rhenish Massif, Harz Mountains, Bohemian Massif and Black Forest and Vosges are part of the Variscan Belt in Germany. As a result of the Variscan orogeny, large areas of present-day Germany were uplifted and deeply eroded, resulting in the exposure of various units of the crystalline basement in the inner orogenic zone, which are now unconformably overlain by sedimentary covers (Reinhold, 2005). Thereby, the crystalline basement rocks are related to several structural zones (Fig. 1), which are (Behr et al., 1984; Kossmat, 1927): 1) Rhenohercynian Zone, 2) Northern Phyllite Zone, 3) Mid-German Crystalline High, 4) Southern Phyllite Zone, 5) Saxothuringian Zone, and 6) Moldanubian Zone.

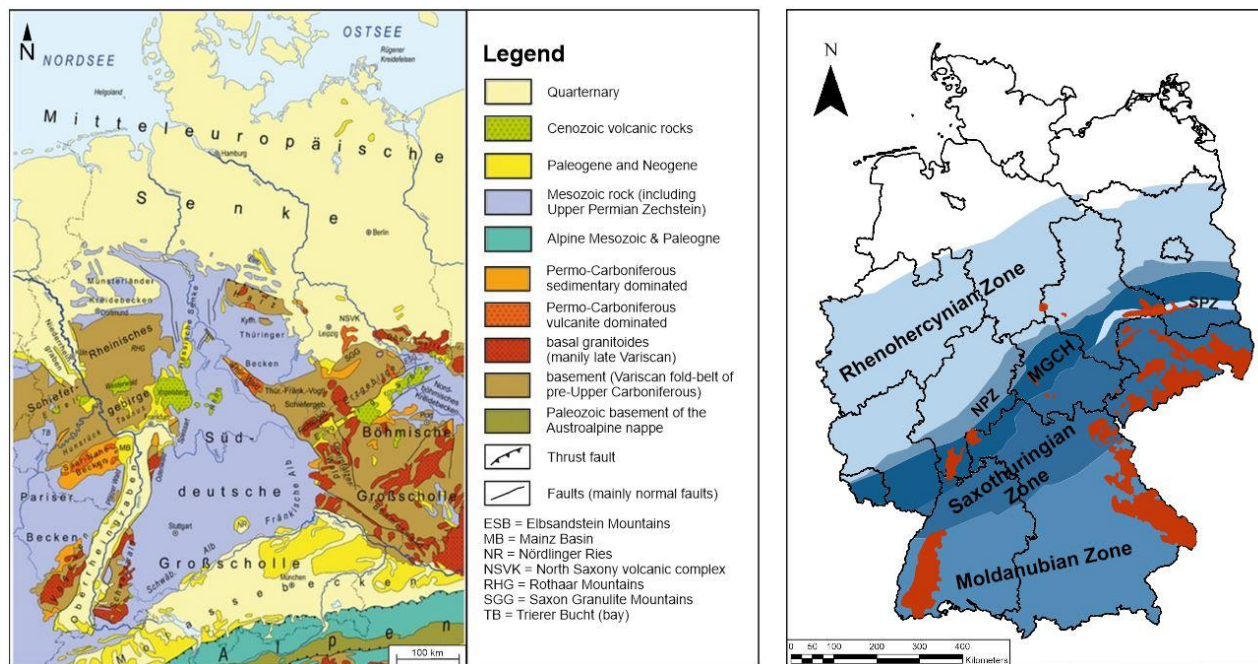


Figure 1: Simplified geological map of Germany (left) modified after Moeck et al. (2019) and references therein. Major structural zones of the Variscan basement in Germany, including a simplified outline of the outcropping crystalline basement rocks (red) are shown on the right (modified after Bauer (2021) and Reinhold (2005)). MGCH = Mid-German Crystalline High, NPZ = Northern Phyllite Zone, SPZ = Southern Phyllite Zone.

The Rhenohercynian Zone represents the northernmost exposed domain of the Variscan Belt and formed along the southern passive margin of Laurussia, including Avalonian crustal components, during Devonian rifting and subsequent evolution of the Rheic Ocean system (Reinhold, 2005). It is mainly exposed in the Harz Mountains and the Rhenish Massif (Walter, 1995), where it records the evolution of the northern Variscan foreland. The zone is dominated by weakly metamorphosed Paleozoic sedimentary rocks, particularly Devonian clastic shelf deposits, with subordinate pelagic and volcanic successions (Krawczyk and Franke, 1995; McCann et al., 2008b). While Devonian sequences reflect passive margin sedimentation, Carboniferous units are related to synorogenic basin development during Variscan convergence (Walter, 1995). In the Giessen–Werra–Harz nappe system, metabasalts and pelagic sediments are locally preserved (Franke, 2000). Crystalline basement rocks occur locally in tectonically uplifted anticlines, fault zones, and basement inliers such as the Lahn–Dill region and parts of the Rhenish Massif (Krawczyk and Franke, 1995). The Rhenohercynian Zone includes both parautochthonous and allochthonous tectonic units. Regionally, it can be traced from the Moravo-Silesian Belt to Cornwall and further into southern Ireland and Portugal, highlighting its continuity within the Variscan orogenic system (Franke, 2000; Kroner et al., 2008).

The Northern and Southern Phyllite Zones constitute narrow greenschist-facies tectonometamorphic belts within the German Variscides. Their lithological assemblages predominantly comprise phyllites, slates, and subordinate metavolcanic rocks and cherts derived from Neoproterozoic to Early Paleozoic successions (Linnemann et al., 2004). While both zones share a



predominantly low-grade metamorphic character, the Southern Phyllite Zone additionally contains allochthonous high-grade metamorphic units, indicating a more complex tectonic evolution. The Northern Phyllite Zone is situated between the Rhenohercynian Zone and the Mid-German Crystalline High (MGCH) and is widely regarded as part of the Avalonia–
 145 Armorica collision system related to the closure of the Rheic Ocean (Cocks and Fortey, 1982; Franke, 2000; McCann et al., 2008a,b). Its lithological spectrum includes metasedimentary rocks comparable to those of the Rhenohercynian domain, together with metapelitic and arc-related metavolcanic units (Anderle, 1987, 1995). Along-strike variations are interpreted to reflect the juxtaposition of crustal domains with Rhenohercynian affinities in the west and Armorican affinities in the east within a complex suture setting (Kroner et al., 2008). The Southern Phyllite Zone forms a less clearly defined Variscan
 150 boundary domain recording crustal amalgamation during closure of oceanic realms associated with the Rheic system and subsequent accretion to the Mid-German Crystalline High (Franke, 2000; Bankwitz et al., 2001). It locally contains tectonically emplaced high-grade metamorphic slices (Bankwitz et al., 2001). Together with the Mid-German Crystalline High, it is interpreted as part of a tectonic fragment belt assembled during Variscan collision, incorporating remnants of rift-related, arc-related, and Cadomian crustal components (Bankwitz et al., 2001).

155 The Mid-German Crystalline High (MGCH) is a NE–SW-trending Variscan complex, approximately 50–65 km wide and extending several hundred kilometres along strike (Weinert et al., 2021). It forms an internal zone between the Rhenohercynian and Saxothuringian domains and is bounded to the north by the Northern Phyllite Zone (Franke, 2000). The MGCH is composed predominantly of medium- to high-grade metamorphic rocks and extensive syn- to post-orogenic granitoid intrusions and is exposed in the Odenwald, Spessart, Ruhl Mountains, Palatinate Forest, and Kyffhäuser Crystalline Complex
 160 (Weinert et al., 2021). The MGCH is interpreted as a composite crustal domain within the internal Variscan orogen, recording convergence between Laurussia and Armorican-derived terranes during closure of the Rheic Ocean system, rather than representing a single coherent terrane or simple suture zone (McCann et al., 2008; Linnemann et al., 2008; Kroner et al., 2008). Although formerly considered part of the Saxothuringian Zone, the MGCH is distinguished by evidence of subduction-related and syn- to post-collisional magmatism (Anthes and Reischmann, 2001), which is not uniformly developed in adjacent units.

165 Accordingly, it is subdivided into (1) Variscan magmatic arc-related domains and (2) variably reworked metasedimentary and metabasitic successions of mixed pre-Variscan and Variscan affinity (Zeh, 1996; Oncken, 1997; Hansch and Zeh, 2000; Kroner et al., 2008), although this subdivision remains model-dependent. Mafic to felsic plutons are particularly abundant in the Bergsträsser Odenwald, where they comprise nearly 90% of the exposed lithologies (Stein, 2001), and are also common in the Spessart and Ruhl Mountains. In the Odenwald, Late Devonian gabbro dominates in the northern Frankenstein Complex (362
 170 ± 7 Ma; Kirsch et al., 1988), whereas the southern part consists of amphibolite-facies metasedimentary rocks and gneisses (342–332 Ma; Todt et al., 1995) intruded by Carboniferous plutons of variable composition (Timmerman, 2008). These contrasts reflect juxtaposed crustal blocks with distinct metamorphic and magmatic histories rather than simple lithological zonation. High-grade metamorphic basement rocks of Late Ordovician to Early Devonian age occur in the Böllsteiner Odenwald (~450 Ma; Reischmann et al., 2001), the Spessart Crystalline Complex (418–407 Ma; Lippolt, 1986; Dombrowski



et al., 1995), and the Ruhla Crystalline Complex (413–400 Ma; Brätz, 2000; Zeh and Wunderlich, 2003). They record a multi-stage pre-Variscan crustal evolution involving repeated magmatic and metamorphic events. Post-tectonic Carboniferous magmatism is most pronounced in the southeastern Spessart (~330 Ma; Anthes and Reischmann, 2001) and the Ruhla Mountains, where granites are widespread (Timmerman, 2008), and is interpreted as late- to post-collisional crustal melting linked to Variscan thermal relaxation.

The Saxothuringian Zone is a major internal unit of the Variscan Belt exposed in eastern and central Germany, including the Erzgebirge, Thuringian Forest, Saxony, Spessart, and Odenwald, as well as parts of the Bohemian Massif (Walter, 1995; Franke, 2000). It is situated between the Mid-German Crystalline High to the north and the Moldanubian Zone to the south. The Saxothuringian Zone comprises a heterogeneous assemblage of low- to high-grade metamorphic rocks derived from sedimentary and igneous protoliths, with locally preserved ultra-high-temperature and ultra-high-pressure metamorphic rocks in restricted crustal domains such as the Saxon Granulite Massif (Franke, 2000; Kroner et al., 2008). It is generally interpreted as a composite domain formed from multiple peri-Gondwanan crustal fragments. Its evolution includes locally preserved Cadomian basement units, overlain by Cambro–Ordovician rift-related successions and Upper Ordovician to Devonian marine deposits (Franke, 2000, cited in Reinhold, 2005). These stratigraphic elements vary significantly along strike, reflecting strong tectonic reworking during Variscan orogenesis. Cadomian remnants, Ordovician magmatism, and Paleozoic sedimentation are preserved in different crustal blocks (Kroner et al., 2008). Along the northern margin, locally preserved magmatic and metamorphic rocks are associated with subduction-related processes. Two major deformation phases are recognised (weinert et al., 2021): an early phase (ca. 370–340 Ma) linked to subduction and collision, and a later phase recording ductile deformation and exhumation of high-pressure metamorphic rocks, including locally UHP assemblages (Kroner et al., 2008). The timing of deformation is diachronous across different domains. Based on tectonometamorphic characteristics, the zone has been subdivided into a southern allochthonous domain, a central wrench-and-thrust zone, and a northern autochthonous domain (Kroner et al., 2007, 2008). The lithological architecture is highly variable and includes weakly to strongly metamorphosed clastic, carbonate, volcanic, plutonic, and volcano-sedimentary rocks ranging from Neoproterozoic to late Paleozoic age, together with widespread Carboniferous granitoids (Walter, 1995; Reinhold, 2005). Characteristic features include Variscan nappe systems and gneiss dome complexes such as the Saxon Granulite Massif, which records extreme P–T metamorphic conditions (Kroner et al., 2004; Reinhold, 2005).

The Moldanubian Zone represents the deep internal core of the Variscan orogen and forms the southeasternmost tectonic unit of the German Variscides (Franke, 2000). It is predominantly composed of high-grade metamorphic rocks, including amphibolite- and granulite-facies gneisses, together with widespread late- to post-orogenic granitic intrusions (van Hartmann et al., 2016). In Germany, Moldanubian rocks are mainly exposed in the Southern Black Forest, the Upper Palatinate Forest, and the Bavarian Forest, while large parts of the crystalline basement remain buried beneath the Molasse Basin. Borehole investigations indicate that the concealed basement is lithologically comparable to the exposed Moldanubian units of eastern Bavaria and the Black Forest (Rohrmüller, 2003; Reinhold, 2005). The Moldanubian basement is characterized by a complex



assemblage of metasedimentary and igneous rocks that experienced high-grade Variscan metamorphism. In the Southern Black Forest, the Moldanubian domain is dominated by metasedimentary rocks of presumed Neoproterozoic to Paleozoic age, locally accompanied by Cambrian orthogneisses and intruded by late Variscan granites emplaced at approximately 340–335 Ma (Hanel et al., 2001; Chen et al., 2000; Kroner et al., 2008; Zeh et al., 2025). Metamorphic conditions range from greenschist facies to eclogite- and granulite-facies conditions, reflecting the deep crustal evolution of the Variscan orogen (Zeh et al., 2025). In the Upper Palatinate Forest and Bavarian Forest, which form the western margin of the Bohemian Massif, two major lithological assemblages are distinguished (Reinhold, 2005). The “Monotone Group” consists predominantly of paragneisses derived from greywacke–pelitic protoliths and is interpreted as the sedimentary succession of a former passive continental margin (Zeithöfller, 2007). In contrast, the more heterogeneous “Bunte Group” comprises paragneisses, amphibolites, marbles, leucocratic gneisses, and graphite-bearing rocks, representing remnants of a volcano-sedimentary sequence of probable late Proterozoic to early Paleozoic age (Zeithöfller, 2007). Lower Paleozoic schists occur only locally within the Moldanubian basement (Stettner, 2001).

3 Workflow

To establish a comprehensive reference database of rock properties for the crystalline basement that reflects the current state of available data for future projects, the work within the AMPEDEK project was divided into two parts: (1) extensive literature review and data acquisition, followed by (2) new field and laboratory sampling and measurement campaigns.

3.1 Data acquisition and database set up

At the beginning of the project, data from literature sources and geological surveys were collected and systematically evaluated to determine their suitability for inclusion in the database (e.g., whether adequate sample descriptions and measurement information were provided). The structure of the initial reference database was modelled after the P³ Petrophysical Rock Property Database (Bär et al., 2020) and was continuously adapted to meet project-specific requirements (e.g., adding new rock parameters and data sheets, see section 4.2).

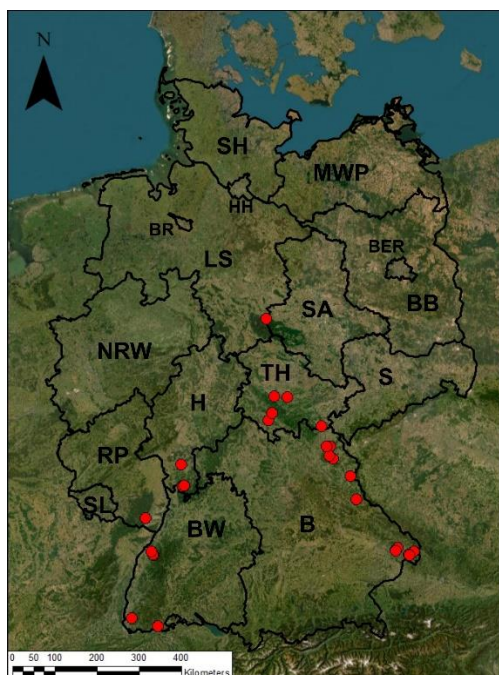
The P³ database is a relational, Excel-based system comprising multiple tables for storing metadata (e.g., references, sample locations, stratigraphy, petrography, sample dimensions, and measurement conditions) as well as a wide range of rock properties, including petrophysical, thermal, hydraulic, magnetic, electrical, and mechanical parameters. Each sample is assigned a unique sample ID to ensure traceability. In addition, the database incorporates quality indices to account for uncertainties related to metadata completeness and the documentation of measurement conditions. Data sets that met the minimum criteria were digitized and, where necessary, homogenized to conform to the format of the new AMPEDEK database. This process included, for example, converting units to SI units and transforming coordinates into the standard format used (see section 4.1). The data were plotted and visualized in 2D maps to allow statistical assessment of the quantity and spatial distribution of the data. The evaluation of the results was subsequently used to plan further sampling campaigns in order to



240 supplement the database in a meaningful way and to cover lithologies and regions for which no data had previously been available. The evaluation revealed that, for example, the crystalline basement in southern and eastern Germany was strongly underrepresented and that no measurement data from drill cores were available.

3.2 New sampling campaigns and rock property measurements at ambient conditions

245 New sampling campaigns and laboratory measurements were conducted to fill existing data gaps. Samples were collected from (1) eight drill cores from wells in Baden-Württemberg, Lower Saxony, and Thuringia, (2) outcrops in Baden-Württemberg and Hesse, and (3) numerous quarries in Hesse, Baden-Württemberg, Rhineland-Palatinate, and Bavaria. Figure 2 shows the spatial distribution of the sampling locations and coordinates of the drill cores.



250 **Figure 2: Spatial distribution of the locations of sampled outcrops, quarries, and boreholes that were investigated within the AMPEDK project. The black lines represent the border of Germany and its federal states. Federal states: B = Bavaria, BB = Brandenburg, BER = Berlin, BR = Bremen, BW = Baden-Wuerttemberg, H = Hesse, HH = Hamburg, LS = Lower Saxony, MV = Mecklenburg-Vorpommern, NRW = North Rhine Westphalia, RP = Rhineland-Palatinate, S = Saxony, SA = Saxony-Anhalt, SH = Schleswig-Holstein, SL = Saarland, TH = Thuringia.**

255 A total of 26 new lithologies of granitic and metamorphic rocks were sampled and subsequently analyzed at the TU Darmstadt laboratory according to the work flow described in Weydt et al. (2021). Approximately 650 cylindrical plugs were prepared, and the specimens were initially analyzed using non-destructive methods, followed by destructive testing wherever feasible. In addition, the geochemical and mineralogical composition was investigated using X-ray fluorescence (XRF), ICP-MS, X-ray diffraction (XRD), and thin section analyses. The measurement work flow included (Figure 3):



1. **Non-destructive measurements:** particle and bulk density, permeability, porosity, magnetic susceptibility, thermal conductivity and thermal diffusivity, specific and volumetric heat capacity, P-wave and S-wave velocities, dynamic E-Modulus, dynamic poisson ratio, dynamic shear modulus, dynamic bulk modulus,
2. **Destructive measurements:** uniaxial compressive strength, tensile strength, static E-Modulus, static poisson ratio, static shear modulus, static bulk modulus, cohesion and friction angle, shear strength,
3. **Geochemical and mineralogical analyses** (XRF, ICP-MS and XRD) and thin section analyses, calculation of radiogenic heat production.

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265 The laboratory methods for each parameter are described in detail in section 5.

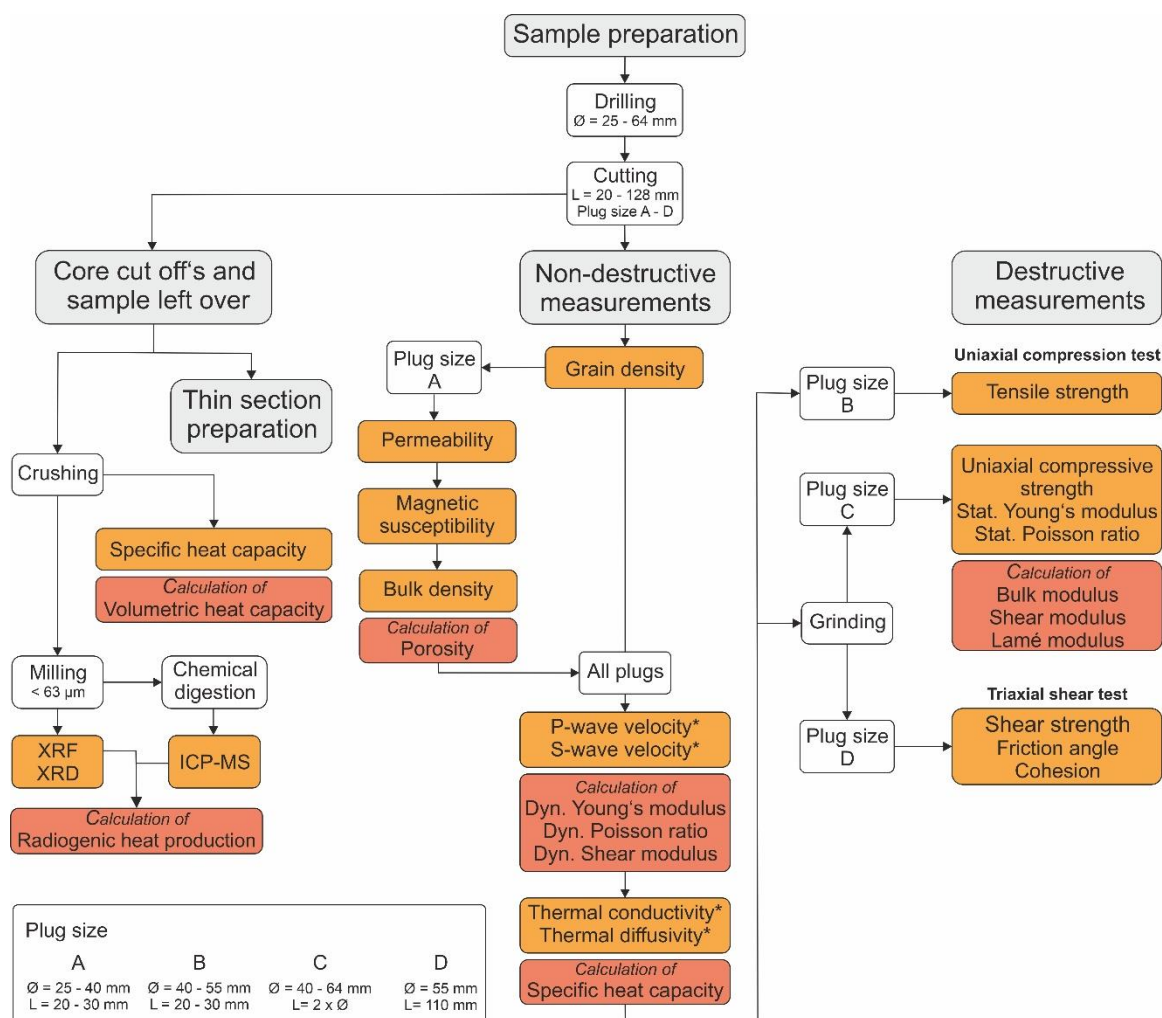


Figure 3: Schematic workflow of the experimental laboratory program at TU Darmstadt (modified from Weydt et al., 2021).



4 Structure of the database

The database is publicly available under <https://doi.org/10.48328/tudatalib-2167> (Weydt et al., 2026) and comprises petrophysical and rock-mechanical properties as well as geochemical and mineralogical data derived from laboratory experiments conducted within the framework of the AMPEDEK project, complemented by data compiled from the literature or provided by geological surveys. To ensure straightforward handling, the database is provided in a flat file Excel format. Its internal structure is based on the PetroPhysical Property Database – P3 (Bär et al., 2020) and Weydt et al. (2021) with some project-specific modifications (Fig. 4). The internal design comprises multiple tables covering petrography, stratigraphy, quality control, chemical analyses, and rock properties and follows the principles of relational database management (Codd, 1970). Each sample is assigned a unique sample ID, and all rock parameters measured under identical pressure–temperature conditions are stored within a single row. The original P3 database structure was extended by additional columns to accommodate thermal properties and dynamic mechanical properties measured under saturated conditions. In addition, new tables were introduced to integrate bulk-rock geochemical analyses (major, trace, and rare earth elements) and mineralogical data (XRD analyses). The main objective was to provide the data in a user-friendly and well-structured form, allowing easy filtering and a transfer of data into other database formats like SQL (structural query language) to easily visualize it or to implement it for modelling approaches.

The database includes data representative of laboratory-scale rock samples (centimetre to decimetre scale), in accordance with standardized measurement methods defined by national and international organizations such as Deutsches Institut für Normung (DIN), International Society for Rock Mechanics and Rock Engineering (ISRM), European Committee for Standardization (CEN), International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM International). Thereby, measurement and method descriptions were harmonized to improve comparability among reported values. As described in Bär et al. (2020), larger-scale data derived from geophysical logging, hydraulic testing, or field-based methods, which integrate over larger rock volumes or multiple lithologies, are not included to minimize bias from structural heterogeneities (e.g., fractures, bedding, or schistosity). Likewise, data from very small samples below the representative elementary volume (REV, Ringrose and Bentley, 2015) of crystalline rocks were omitted. All entries contain a minimum set of metadata to ensure meaningful interpretation, namely a literature reference and petrographic classification. Where available, additional metadata were incorporated, including sampling location and type, sample identifiers, stratigraphy, sample dimensions, measurement methods, instruments, and experimental conditions (pressure, temperature, stress, saturation). Where necessary, data from the literature sources were converted into SI units in order to create a uniform data set.

The Excel file contains seven data sheets titled 1) “Info”, 2) “MetaData_RockProperties”, 3) “Geochemistry”, 4) “Mineralogy”, 5) “Petrography”, 6) “Stratigraphy”, and 7) “QualityControl”. The first data sheet “Info” includes all relevant citations for the data sources, links to the laboratory infrastructure, and a list of contributors. The second and main data sheet comprises all analyzed petrophysical parameters and associated sample information (metadata) compiled during this project. Each analyzed sample was provided with a sample ID, which acts as the primary key for all records. The data are structured



into three main sections (super-entities), which consist of sets of related data tables and are described in more detail in the following sections. The first section, named “meta-information”, contains all descriptive information for each sample, including sampling location, sample type and dimensions, as well as petrographic and stratigraphic classifications. This section serves as the primary table for unique sample identification. The second section comprises the measured property values of the individual rock samples and is subdivided according to different property types (e.g., mechanical or thermal properties). The third section, referred to as “Quality Control”, contains all information required for assessing the reliability of each data record. In particular, it documents the measurement conditions, including the applied methodology, pressure and temperature conditions, and degree of saturation. This information forms the basis for a semi-automatic procedure used for data quality control and evaluation (Bär et al., 2020).

To keep the handling of the database as simple as possible, the geochemical and mineralogical measurement data, which require a different data structure than the rock property data, are presented separately in the data sheets 3 and 4. As described previously for the main data sheet, the sample ID links the measurement results to the other parameters and sample metadata. In addition, further experiment specific information related to the XRF and XRD analyses is included.

The data sheets “Stratigraphy” and “Petrography” include separate classification systems (Bär et al., 2020) and are described in detail below. The final worksheet, “Quality Control”, provides an overview of the applied quality indices, data ranking, and the results of the quality assessment for the data included in the reference database.



Sample ID			
Reference Primary reference Secondary reference Date of input Editor	Petrography Petrographic ID Petrographic parent ID Petrographic term (simplified) Petrography (in detail) Petrographic method	Petrophysical and hydraulic properties Grain density [kg m ⁻³] Bulk density [kg m ⁻³] Total porosity [%] Effective porosity [%] Apparent permeability [m ²] Intrinsic permeability [m ²]	Static mechanical properties Uniaxial compressive strength [MPa] Tensile strength [MPa] Static Young's modulus [GPa] Static shear modulus [GPa] Static bulk modulus [GPa] Static poisson ratio [-] Lamé modulus [-] Cohesion [MPa] Friction angle [°]
Sampling location Location type Location name Location county Location state/region Location country Location latitude Location longitude Location elevation (m a.s.l.) Radius of uncertainty TK25-Blatt Remarks	Sample rock type information Sample texture Sample homogeneity Sample layering Direction of measurement Sample consolidation Degree of alteration/weathering Remarks on sample	Thermophysical properties Bulk thermal conductivity [W m ⁻¹ K ⁻¹] Bulk thermal conductivity sat. [W m ⁻¹ K ⁻¹] Matrix thermal conductivity [W m ⁻¹ K ⁻¹] Specific heat capacity [J kg ⁻¹ K ⁻¹] Volumetric heat capacity [J m ³ K ⁻¹] Thermal diffusivity x10 ⁻⁶ [m ² s ⁻¹] Thermal diffusivity sat. x10 ⁻⁶ [m ² s ⁻¹] Radiogenic heat production [W m ⁻³]	Geochemistry Method of measurement Major elements [wt%] Trace elements [ppm] Isotopes [-] Age (mean ± min/max, time period) Computed values
Sample information Original sample ID Int. geo. sample no. (IGSN) Sample type Sample length (m) Sample height (m) Sample width (m) Sample diameter (m) Sample longitude Sample latitude Sample elevation (m a.s.l.) Sample depth (m b.g.l.)	Stratigraphy Stratigraphic ID Stratigraphic parent ID Chronostratigraphic unit Local stratigraphic unit	Electric properties Electric conductivity rock [S m ⁻¹] Electric conductivity fluid [S m ⁻¹]	Mineralogy Method of measurement Mineral content [wt%]
	Measurement conditions Temperature (K) Pressure (Pa) Saturating fluid Degree of saturation (%) σ ₁ (MPa) σ ₂ (MPa) σ ₃ (MPa) Pore pressure (MPa) Strain rate (kN s ⁻¹) Strain rate (MPa s ⁻¹) Strain rate (mm s ⁻¹) Remarks	Magnetic properties Magnetic susceptibility x10 ⁻³ [SI]	Quality control Geographic uncertainty indice Petrography indice Chronostratigraphy rank Stratigraphy indice Measurement conditions indice (e.g., device, temperature, pressure) Measurement parameter indice (single/mean value, min/max, SD) Bulk quality indice, class and frequency
		Dynamic mechanical properties P-wave velocity [m s ⁻¹] P-wave velocity sat. [m s ⁻¹] S-wave velocity [m s ⁻¹] S-wave velocity sat. [m s ⁻¹] Dyn. Young's modulus [GPa] Dyn. shear modulus [GPa] Dyn. poisson ratio [-] Dyn. poisson ratio sat. [-]	

Figure 4: Structure and content of the reference database, including sections for metadata, rock parameters, geochemistry, and quality control indices linked by sample ID.

4.1 Metadata

The metadata section includes all additional sample information from sample ID to sample dimensions and can be used for rapid filtering and the precise categorizing of parameters. The database starts with the most important entry, the sample ID, which acts as the primary key and connects all data entries of rock properties, geochemical and mineralogical data to the relevant meta data, and the data source (primary reference). Whenever available a secondary reference is provided as well as the date of input and editor. The sample ID is followed by the entities or sub-tables “sampling location”, “sample information”, “petrography”, and “stratigraphy”.

The sub-table “sampling location” includes 1) the location type such as outcrop, well or quarry, 2) the location name, 3) the county, state/region and country the sample was collected, 5) the coordinates of the location and elevation (provided in meter above sea level, m a.s.l.), and 6) the radius of uncertainty. The coordinates of the location are given in longitude and latitude of the sampling point at the surface in decimal degrees using the reference system WGS84 and/or the North and East values using UTM reference system. In the case of a core sample taken from a well, the latitude and longitude of the wellhead is given. In literature, the exact geographic information is often not provided and only location names or maps are available. For this reason, the column “radius of uncertainty in km” was introduced to allow for an estimation of the geodetic accuracy. For



example, the geodetic accuracy of samples collected from quarries or outcrops is commonly less than 100 m. Further information is provided in sub-section 4.7. If no information is given for the location, the longitude and latitude are noted as 999 to avoid wrong map displays when using the data in Geographic Information System (GIS) software ArcGIS or OpenGIS. The sub-table “sample information” contains additional information regarding the sample type (e.g. drill core, boulder, cuttings, powder material) and sample dimensions (length, width, height or in case of cylindrical plugs the diameter). In case of literature data, whenever available, the original sample ID and further information was added. When multiple samples are collected from the same site (e.g., a large outcrop or quarry), individual geographic coordinates (longitude, latitude, and elevation) may be specified for each sample. For samples obtained from cored boreholes, the sampling depth is additionally reported as measured depth (MD) and, where available, as true vertical depth (TVD) relative to ground level (i.e., metres below ground level, m b.g.l.).

Metadata related to the petrographic and stratigraphic classification of the sample material are contained in the main table “Metadata_RockProperties”, which is supplemented by the additional data sheets “Petrography” and “Stratigraphy” that provide independent classification schemes and explanatory information. More detailed explanations are given in sections 4.5 and 4.6. The sub-table “Petrography” contains detailed information on lithology and sample characteristics, such as sample texture, homogeneity, layering, and degree of consolidation. In addition to the specification of the direction of measurement, these descriptions are particularly important for the interpretation of anisotropic rock properties, such as thermal conductivity or permeability. The sub-table “Stratigraphy” provides the chronostratigraphic assignment and classification of the samples. Together with the petrographic information, this enables rapid filtering and statistical evaluation of the data.

4.2 Rock properties

The sub-table “Rock Properties” is divided into two sections: “Measurement Conditions” and the rock properties themselves. The “Measurement Conditions” section provides additional information on the experimental setup, including temperature and pressure (e.g., measurements under ambient laboratory conditions or during high-pressure/high-temperature experiments), saturation fluid and degree of saturation, as well as vertical and confining pressure, pore pressure, and strain rate in the case of rock-mechanical tests. The rock properties are grouped into the following categories: (1) classical petrophysical parameters; (2) thermophysical properties; (3) electrical properties; (4) magnetic properties; (5) dynamic mechanical properties; and (6) static mechanical properties. A complete list of the properties is provided in Figure 4.

The results are reported as single values or mean values, with standard deviation, minimum and maximum values, and the number of measurements provided for each plug or sample whenever available. In addition, the columns “measuring type” and “additional remarks” are included for each parameter to provide detailed information on the measurement device and experimental setup. This information is essential for statistical analyses and for ensuring the comparability of results obtained using different methods. In particular, the measurement method can have a significant impact on data quality and method-specific measurement uncertainty.



In total, 34 different parameters were determined in accordance with the recommendations of international standardization institutions and committees (e.g., ISRM, ASTM, and DIN).

4.3 Whole rock geochemical analyses (XRF and ICP-MS analyses)

370 The results of quantitative chemical analyses, such as XRF and ICP-MS analyses performed on composite sample material are presented in a second sheet titled “Geochemistry”. The structure of this sheet is based on the geochemical rock database presented in Gard et al. (2019) and is divided into five sections: 1) major elements and LOI, 2) trace elements including rare earth elements (provided in ppm), 3) isotope data, 4) information on sample age/dating, and 5) computed sample composition. The sample ID serves as the primary key, linking the whole-rock chemical data to the corresponding petrophysical data.

375 Additionally, complementary information regarding sample preparation (e.g., powder grain size, grinding duration, mill or grinding device), measurement procedures, and the hosting institute are included.

4.4 Mineralogical analyses (XRD analyses)

The results of the XRD analyses are stored in the third sheet, titled XRD. The structure is organized similarly to that of the whole-rock geochemical analyses described above. Metadata regarding sample preparation, measurement procedures, and the

380 hosting institution are provided. As before, the sample ID links the mineralogical data to the rock property data in the main sheet of the database. For semi-quantitative analyses, results are reported in percent along with the associated standard deviation.

4.5 Petrography

To relate the incorporated data and investigated samples to well-established and internationally recognized rock type

385 definitions, the petrographic classification scheme developed by Bär et al. (2019) was applied. This scheme is based, among other sources, on the well database of the Geological Survey of Hesse, Germany (Hessisches Landesamt für Umwelt, Naturschutz und Geologie, HLNUG), rock property compilations (Hantschel and Kauerauf, 2009; Schön, 2011; Clauser and Huenges, 1995a, b), and international conventions (e.g., Bates and Jackson, 1987; Gillespie and Styles, 1999; Robertson, 1999; Hallsworth and Knox, 1999; Le Bas and Streckeisen, 1991; Schmid, 1981; Fisher and Smith, 1991).

390 The structure of this classification scheme uses a hierarchical system to subdivide rock types, where the rock description generally becomes more detailed with increasing rank of petrographic classification (Fig. 5). It includes nine ranks encompassing 1494 petrographic terms. For example, rank 1 distinguishes between consolidated and unconsolidated rocks, and rank 2 distinguishes between migmatites, igneous, metamorphic and sedimentary rocks in the case of consolidated rocks. The petrographic assignment of each sample is based on the description provided in the original literature source or

395 measurement results in case of the newly collected sample material. Each petrographic term is linked to a unique petrographic ID and a corresponding parent ID, which establish hierarchical relationships among the classifications. Thereby, petrographic



classes of ranks 1 to 4 can generally be identified from macroscopic information derived from well logs, drill cores, and geological mapping. In contrast, petrographic classifications of ranks 5 to 9 require additional information on texture or grain size, modal mineral composition, or geochemical characteristics, which typically necessitate microscopic analyses or comparable specialized investigations. This classification structure enables higher-rank petrographic descriptions to be aggregated into more general lower-rank terms, facilitating statistical analyses of physical rock properties across different levels of petrographic detail. The petrographic classification system is stored in a separate sheet titled “Petrography”. In the main database sheet, “MetaData_RockProperties”, the petrographic ID, the corresponding petrographic parent ID, and a simplified petrographic term are recorded. Where available, the original petrographic descriptions from the primary literature were also included for each sample. Furthermore, several columns are included which provide information on texture, sample homogeneity, layering, the degree of consolidation, measurement orientation relative to internal structural features (e.g. bedding), and the degree of alteration or weathering along with any relevant remarks.

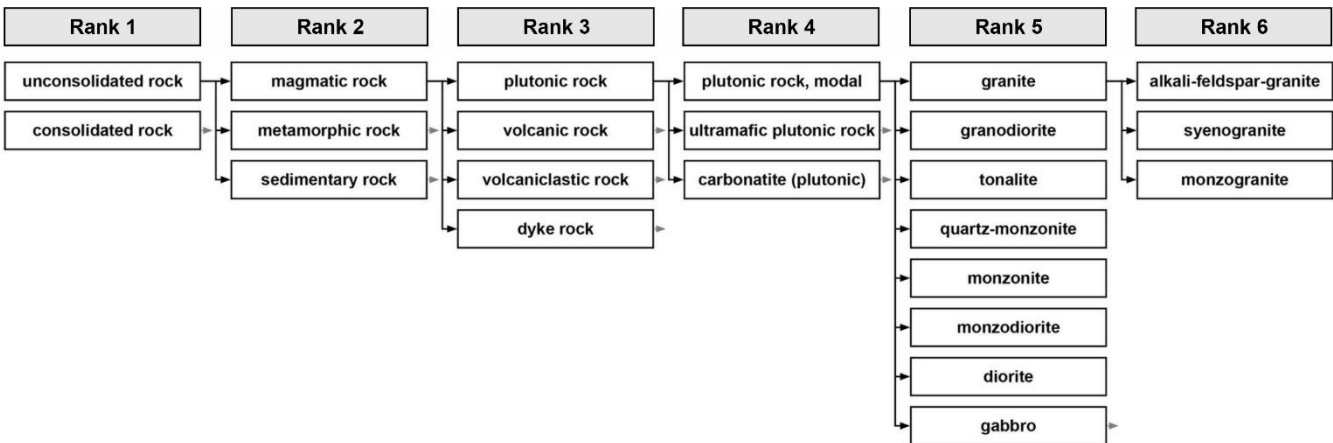


Figure 5: Standardized petrographic classification scheme on the example of granite following Bär et al. (2019) modified from Weinert et al. (2021). Black boxes indicate hierarchical ranks, white boxes show the granite classification example, and arrows represent relationships between terms.

4.6 Stratigraphy

The stratigraphic classification of the sample material is based on the international chronostratigraphic chart of the IUGS v2016/04 (Cohen et al., 2013, updated). The database allows the entry of the corresponding stratigraphic epoch, period, and erathem, as well as, where provided by the primary reference, a detailed description of the local stratigraphic unit. To enable statistical analysis of the data with respect to sample stratigraphy, the stratigraphic classification system introduced by Bär and Mielke (2019) was implemented (Fig. 6). This system assigns numerical identifiers, referred to as stratigraphic IDs and parent IDs, to each stratigraphic unit of the IUGS international chronostratigraphic chart (e.g., 175 stratigraphic IDs ranging from Precambrium = 1 to Holocene = 175). These stratigraphic IDs and parent IDs follow a hierarchical structure that allows original



stratigraphic and petrographic descriptions to be mapped onto a standardized catalogue, ensuring intercomparability among different datasets. Formations of a given age are thereby consistently linked to their corresponding stratigraphic epoch, period, or erathem. As a result, chronostratigraphic units are directly correlated via their stratigraphic IDs and parent IDs, enabling integrated analyses of the petrophysical properties of samples within the same stratigraphic unit. The stratigraphic classification system is provided in a separate sheet titled “Stratigraphy”.

Stratigraphic ID	Stratigraphic parent ID	Eonothem / Eon	Erathem / Era	Period	System	Series / Epoch	Stage / Age	Age Lower Boundary [Ma]	Chronostratigraphical Unit
73	23	Phanerozoic	Paleozoic	Carboniferous				358.9	Carboniferous
74	73	Phanerozoic	Paleozoic	Carboniferous	Mississippian			358.9	Mississippian
75	74	Phanerozoic	Paleozoic	Carboniferous	Mississippian	Lower		358.9	Lower Mississippian
76	75	Phanerozoic	Paleozoic	Carboniferous	Mississippian	Lower	Tournaisian	358.9	Tournaisian
77	74	Phanerozoic	Paleozoic	Carboniferous	Mississippian	Middle		346.7	Middle Mississippian
78	77	Phanerozoic	Paleozoic	Carboniferous	Mississippian	Middle	Visean	346.7	Visean
79	74	Phanerozoic	Paleozoic	Carboniferous	Mississippian	Upper		330.9	Upper Mississippian
80	79	Phanerozoic	Paleozoic	Carboniferous	Mississippian	Upper	Serpukhovian	330.9	Serpukhovian
81	73	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian			323.2	Pennsylvanian
82	81	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian	Lower		323.2	Lower Pennsylvanian
83	82	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian	Lower	Bashkirian	323.2	Bashkirian
84	81	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian	Middle		315.2	Middle Pennsylvanian
85	85	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian	Middle	Moscovian	315.2	Moscovian
86	81	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian	Upper		307	Upper Pennsylvanian
87	86	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian	Upper	Kasimovian	307	Kasimovian
88	86	Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian	Upper	Gzhelian	303.7	Gzhelian

Figure 6: Stratigraphic classification system after Bär and Mielke (2019), exemplified by the Carboniferous period.

4.7 Quality control

To assess the quality of the provided data, an automated quality assessment procedure developed by Bär et al. (2020) was implemented in the AMPEDEK database. During this process, several key criteria of the available metadata were automatically evaluated, including (1) the uncertainty of the geographic location, (2) the rank of petrographic classification, (3) the rank of stratigraphic classification, (4) the completeness of information on measurement conditions, and (5) the statistical type of the reported value (e.g. single value or mean value). For each criterion, a quality class ranging from 1 (excellent) to 4 (minimum requirement) was assigned (see Table 1). Subsequently, a bulk quality index was calculated as the arithmetic mean of the quality indices of the individual criteria. Values below 1.5 were classified as excellent, intermediate values were considered average, values equal to or greater than 2.5 were classified as poor, and values exceeding 3.5 were regarded as meeting only the minimum requirements.

According to Bär et al. (2020) the individual quality criteria are defined as follows:

- 1) Geographic uncertainty: Sample locations with a geodetic accuracy better than 100 m were classified as excellent, which is typically the case for outcrop samples and drill cores. Locations constrained to an area with a radius of <1 km



were rated as average, a radius of uncertainty between 1 and 100 km as poor, and larger uncertainties as meeting only minimum requirements.

- 2) Rank of petrographic classification: Petrographic descriptions allowing assignment of a petrographic rank ≥ 6 were classified as excellent, while rank 5 was considered average, as it enables differentiation at reservoir or site scale. Ranks ≤ 4 were classified as poor. Inclusion in the database required a minimum petrographic rank of 2, sufficient for continental-scale classification.
- 3) Rank of stratigraphic classification: Stratigraphic information at the stage or age level was rated as excellent, epoch or series level as average, and system or period level as poor. No minimum stratigraphic requirement was imposed, as stratigraphy does not directly control physical properties and can often be inferred retrospectively.
- 4) Measurement conditions: Recorded measurement conditions included temperature, pressure, saturating fluid, and degree of saturation, as well as stress state and pore pressure for mechanical properties. Additional parameters such as signal frequency (sonic velocities) and strain rate (mechanical tests) were also considered. Excellent quality required complete documentation of conditions and measurement device. Partial documentation resulted in average quality, while limited information was rated as poor.
- 5) Measurement parameter type: Single measurement values were classified as excellent. Mean values were rated as average if accompanied by the number of measurements, minimum, maximum, and standard deviation, and as poor if only the number of measurements was provided. Mean values without any information on sample size were included in the database but excluded from quality scoring.

Table 1: Quality index system for meta data, measurement conditions, and data stored in the database

Class	Geographic uncertainty	Petrography	Stratigraphy	Measurement conditions				Measurement
	Accuracy	Rank	Rank	Measurement device	Temperature	Pressure	Degree of saturation	Parameter value
1 - Excellent	≤ 100 m	≥ 6	≥ 5 stage/age or lower or numerical age	yes	yes	yes	yes	Single measurement
2 - Average	> 100 m ≤ 1 km	$= 5$	4 series/epoch	yes	optional	optional	optional	Mean value and n and standard deviation or minimum or maximum
3 - Poor	> 1 km ≤ 100 km	$= 4$	≤ 3 system/period or higher	optional	optional	optional	optional	Mean value and n
4 - Minimum requirement	> 100 km	≥ 2	NA	NA	NA	NA	NA	Value



5 Laboratory methods

The following sections describe the individual steps, as illustrated in Figure 3, that were required for the determination of mineralogical, geochemical, petrophysical, and rock-mechanical properties of the collected samples in the laboratories of TU Darmstadt. In addition, complementary analyses were conducted at GFZ Potsdam and FU Berlin.

5.1 Sample preparation

Sample preparation followed the international standards outlined in ASTM D4543-19 (2019). Cylindrical plugs with diameters ranging from 30 to 64 mm and lengths of approximately 25 to 128 mm were produced. The resulting plugs were first subjected to non-destructive analyses, followed, where feasible, by destructive testing. Due to the specific size requirements of the measurement devices, only plugs with lengths of approximately 25–30 mm and diameters of 30–40 mm were used for non-destructive petrophysical measurements of grain and bulk density, porosity, and permeability. For most destructive rock mechanical tests, a length-to-diameter ratio of 2:1 (uniaxial or triaxial test configurations) or 1:2 (Brazilian disc test configuration) is required. Accordingly, additional plugs with diameters of 30–64 mm and lengths of 60–128 mm were prepared. Furthermore, the flat end faces of the plugs intended for destructive rock mechanical testing were ground plane-parallel, with a maximum deviation of 0.05°.

Prior to measurement, all samples were cleaned in an ultrasonic bath and dried in a drying oven at 105 °C for 24 h, or, in the case of clay-rich samples, at 60 °C for 48 h. The samples were subsequently stored in a desiccator with sufficient silica gel at 20 °C and ambient pressure.

Within the AMPEDEK project, samples were numbered according to a fixed scheme resulting in a unique sample ID. The first abbreviation indicates the federal state where the sample was collected (e.g., B for Bavaria, BW for Baden-Württemberg, H for Hesse). This is followed by an abbreviation for the sampling location, then by a code for the rock type (GR = granite, GN = gneiss), and, if applicable, a code for the lithological unit or local name (e.g., TS = Thanstein Granite).

Subsequent abbreviations indicate the sample type and drill core numbering. B stands for a rock boulder collected from a quarry or outcrop (German: Block), and BK stands for a drill core sample (German: Bohrkern). These were numbered consecutively depending on the number of samples (e.g., B1 = Boulder 1, B2 = Boulder 2, etc.). The final number refers to the drilled core from that sample (1 = core 1, 2 = core 2, etc.), while lowercase letters (a, b, c, d and so on) indicate the plug extracted from the core, if applicable. The cylindrical cores were cut to meet the specific requirements of the laboratory devices and the resulting plugs were labelled so that numbering proceeds sequentially from the top to the base of the core (e.g., a = first plug/top; b = second plug/just below top; c = third plug, etc.). This classification allows for the unambiguous identification of the sample material and facilitates more efficient handling of the samples and data in the laboratory and during data evaluation.



5.2 Non-destructive measurements

5.2.1 Petrophysical and hydraulic properties

Rock density and porosity were determined using a combination of gas-displacement pycnometry and powder pycnometry.

495 First, the grain density of a plug was measured using a Micromeritics AccuPyc 1330 helium pycnometer, which operates based on the ideal gas law (Micromeritics, 1997). The AccuPyc system consists of a sample chamber and a reference chamber. To determine the grain density, the mass of the oven-dried sample was first measured using a precision balance. The sample was then placed into the sample chamber of the pycnometer and purged ten times with helium to remove residual gases that could affect the measurement. During the measurement, the sample chamber was pressurized with helium to a predefined pressure.

500 Subsequently, an expansion valve connecting the sample chamber to the reference chamber was opened, allowing the system pressure to equilibrate. The grain volume of the sample was calculated from the resulting pressure differences. Using the previously determined sample mass, the grain density was then calculated. According to the manufacturer, the measurement accuracy is $\pm 0.06\%$. The grain volume and grain density were measured five times per plug within a single measurement sequence.

505 The bulk volume of a plug was subsequently determined using a Micromeritics GeoPyc 1360 powder pycnometer, from which bulk density and porosity were calculated. The GeoPyc is equipped with a cylindrical measurement chamber filled with a fine-grained, graphitized glass bead powder (DryFlo) characterized by a narrow grain-size distribution and high flowability. First, an empty-cell measurement was performed, during which a piston compressed the DryFlo powder with a defined force. The piston displacement was recorded to determine the volume of DryFlo in the measurement chamber. The sample was then added

510 to the powder in the chamber, and the measurement was repeated, with the DryFlo completely surrounding the sample. The bulk volume of the sample was calculated from the volume difference between the two measurements and the sample mass. Bulk volume and bulk density were measured five times per sample within a single measurement sequence. Effective porosity was subsequently calculated from the difference between bulk and grain volumes. The accuracy of the method is reported as 1.1% (Micromeritics, 1998).

515 Intrinsic rock permeability was measured using a gas pressure-column permeameter (Filomena et al., 2014), operated with compressed air at TU Darmstadt. Samples were mounted in a cylindrical cell (Hoek cell) using a 1 mm thick latex membrane. Apparent permeability was initially measured under six pressure steps between 1 and 3 bar, at a constant confining pressure of 10 bar and a constant differential pressure of 800 mbar. The measurement principle is based on Darcy's law, extended to account for gas compressibility and viscosity to calculate gas permeability (Jaritz, 1999). Intrinsic permeability was

520 subsequently determined using the Klinkenberg correction (Klinkenberg, 1941). The measurement uncertainty of the permeameter at TU Darmstadt ranges from approximately 5% for highly permeable rocks ($K > 10^{-14} \text{ m}^2$) to up to 400% for very low-permeability rocks ($K < 10^{-16} \text{ m}^2$) (Bär, 2012).



5.2.2 Thermal properties

Thermal conductivity and thermal diffusivity were measured simultaneously on oven-dried samples using a Thermal Conductivity Scanner (TCS, Lippmann and Rauhen GbR). The measurement concept of the TCS is based on the optical scanning method described by Popov et al. (2016), which involves scanning a sample surface with a focused, mobile heat source and contactless temperature measurements using three infrared temperature sensors. In the TCS setup, the heat source and the three infrared sensors are mounted on a guiding rail and move at constant velocity and fixed spacing beneath the sample and reference standards of known thermal conductivity. The samples and standards are placed on a plate featuring a measurement slit. During scanning, temperatures of both the samples and the standards are recorded before and after heating by the moving heat source. Thermal conductivity and thermal diffusivity of the sample are then automatically calculated by comparing the resulting temperature differences between the sample and the standards. The plugs were measured up to three times on each flat end face ($n = 6$). For drill cores with larger diameters, measurements were additionally conducted on the lateral mantle surface ($n = 9$). According to the manufacturer, the measurement accuracy of the device is approximately 5%, when thermal conductivity and thermal diffusivity are measured simultaneously.

The specific heat capacity was calculated using the following equation (Buntebarth, 1980):

$$c_p = \frac{\lambda}{\rho \cdot \alpha} \quad (1)$$

λ	thermal conductivity	$[\text{W m}^{-1} \text{K}^{-1}]$
c_p	specific heat capacity	$[\text{J kg}^{-1} \text{K}^{-1}]$
ρ	density	$[\text{kg m}^{-3}]$
α	thermal diffusivity	$[\text{m}^2 \text{s}^{-1}]$

Volumetric heat capacity c_v (or VHC) was then calculated by multiplying the specific heat capacity by the sample density:

$$c_v = \rho \cdot c_p \quad (2)$$

c_v	volumetric heat capacity	$[\text{J m}^{-3} \text{K}^{-1}]$
ρ	density	$[\text{kg m}^{-3}]$
c_p	specific heat capacity	$[\text{J kg}^{-1} \text{K}^{-1}]$

For more accurate results, the specific heat capacity can also be determined experimentally in the laboratory. For this purpose, a dynamic heat-flow differential calorimeter (Calvet Calorimeter C80, Setaram Instrumentations) was used. The calorimeter consists of two cylindrical chambers, one serving as the sample chamber and the other as a reference chamber. Both chambers are surrounded by concentrically arranged sensor rings equipped with heat-flow sensors, which are in turn enclosed by heating elements and thermal insulation to ensure uniform heating and cooling of the chambers. To determine the heat capacity, an initial blank measurement was performed. Subsequently, crushed, oven-dried sample material was placed into the sample



chamber and the measurement was conducted. During the experiment, both the sample and reference chambers were heated uniformly to temperatures of up to 200 °C and subsequently cooled once the target temperature was reached. Throughout the entire measurement, both the heating rate (i.e. the temperature ramp) and the heat flows in the reference and sample chambers were continuously recorded. Based on the sample mass, the applied heating power, and the difference between the heat flows measured in the reference and sample chambers, the specific heat capacity of the sample was calculated (Clauser et al., 2006). According to Setaram (2009), the measurement uncertainty of the instrument is 1.1 %. As a single measurement requires approximately 24 hours, thus one representative sample was analysed per lithological unit.

5.2.3 Magnetic susceptibility

Magnetic susceptibility is a dimensionless, anisotropic property that describes the behavior of a material when subjected to an external magnetic field. In rocks, it is primarily controlled by small amounts of ferro-, antiferro-, and ferrimagnetic minerals (Schön, 2015). In magmatic rocks, magnetite (Fe_3O_4) is considered the most important carrier of magnetic susceptibility. Magnetic susceptibility was determined using a portable susceptibility meter (also referred to as a kappameter), the Magnetic Susceptibility Meter SM30 manufactured by ZH Instruments. The SM30 is equipped with an 8 kHz LC oscillator and a large coil acting as the sensor and is specifically designed for measurements on rocks. Inside the instrument, an electric current supplied by a battery flows through the coil, thereby inducing a magnetic field. The presence of a sample alters this external magnetic field. The oscillator detects the resulting change in the total magnetic field and responds by changing its oscillation frequency. This frequency shift is directly proportional to the magnetic susceptibility of the sample. In addition, the oscillation frequency of the oscillator depends on the distance between the sample and the susceptibility meter.

Cylindrical samples were measured four times on each flat end surface using the interpolation mode. Each measurement sequence consisted of an initial air measurement, followed by a measurement on the smooth sample surface, and a subsequent reference measurement in air. According to the manufacturer, the instrument has a measurement accuracy of up to 1×10^{-7} SI (ZH Instruments, 2008).

5.2.4 Dynamic mechanical properties

The compressional and shear wave velocities (P- and S-wave velocities) of the sample material were determined using the UKS-D ultrasonic measurement system from Geotron-Elektronik (2011), which consists of an ultrasonic generator (USG-40), a digital PicoScope oscilloscope, and two piezoelectric transducers (ultrasonic emitter and receiver). For the measurements, the cylindrical plugs were positioned between the transducers, and coupling gel was applied to the end faces. The transducers were then pressed against the parallel end faces with a contact pressure of 1 bar, and polarized high-voltage pulses with a frequency of approximately 80 kHz were generated using the USG-40 ultrasonic generator. The transmitted signals were automatically recorded by the PicoScope oscilloscope. The arrival times of the P- and S-waves were manually picked using



the accompanying LightHouse UMPC software, and the ultrasonic velocities were calculated taking into account the sample lengths.

Complementary P- and S-wave velocity measurements on selected core samples from the Harburg Gabbro were likewise performed at GFZ Potsdam using a Panametrics HV pulser–receiver (model 5058PR) in combination with an Agilent Technologies digital oscilloscope (model DSO6012A). High-voltage polarized pulses in a frequency range of 20 kHz to 1 MHz were applied, and the arrival times of the P- and S-waves were picked 32 to 64 times.

Following the determination of the P- and S-wave velocities, the dynamic Poisson’s ratio (ν_{dyn}), dynamic Young’s modulus (E_{dyn}), and dynamic shear modulus (G_{dyn}) were calculated using the following equations according to Zoback (2011):

$$\nu_{dyn} = \frac{V_P^2 - 2 \cdot V_S^2}{2 \cdot (V_P^2 - V_S^2)} \quad (3)$$

595	ν_{dyn}	dynamic Poisson ratio	[-]
	V_P	P-wave velocity	[m s ⁻¹]
	V_S	S-wave velocity	[m s ⁻¹]

600

$$E_{dyn} = \frac{V_P^2 \rho \cdot ((1 + \nu_{dyn}) \cdot (1 - 2\nu_{dyn}))}{(1 - \nu_{dyn})} \quad (4)$$

	E_{dyn}	dynamic Young’s Modulus	[GPa]
	V_P	P-wave velocity	[m s ⁻¹]
	ν_{dyn}	dynamic Poisson ratio	[-]
605	ρ	density	[kg m ⁻³]

$$G_{dyn} = \frac{V_S^2}{\rho} \quad (5)$$

	G_{dyn}	dynamic Shear Modulus	[GPa]
	V_S	S-wave velocity	[m s ⁻¹]
610	ρ	density	[kg m ⁻³]



5.3 Destructive measurements

5.3.1 Uniaxial tests

615 To determine the uniaxial compressive strength (UCS) as well as the static Poisson's ratio, static Young's modulus, static shear modulus, and static bulk modulus, non-cyclic and cyclic uniaxial tests were conducted using a hydraulic uniaxial press from FORM+TEST Prüfsysteme. For the determination of the UCS, cylindrical plugs with a length of 80 mm and a diameter of 40 mm were loaded in the hydraulic press at a constant loading rate of 0.5 kN s⁻¹ (up to 1000 kN vertical load) until sample failure. The maximum stress at failure was defined as the UCS and was calculated according to DIN 18141-1:2014-05. For 620 shorter samples not meeting the 2:1 length-to-diameter ratio, a correction factor was applied in accordance with the same standard.

To determine the static Young's modulus and Poisson's ratio, cyclic uniaxial tests were performed on three to five plugs (same dimensions as above) per sample unit following DIN 18141-1:2014-05 and Mutschler (2004). Three vertical and three lateral displacement transducers (LVDTs) were mounted around each plug at 120° intervals to record axial and lateral deformations. 625 Two loading cycles were applied: in the first cycle, 40 % of the previously determined UCS was reached, and in the second cycle, 60 % of UCS, both at a loading rate of 0.5 kN s⁻¹. At the maximum load of each cycle, a hold period of 5 minutes was applied (Mutschler, 2004). After the hold period of the second cycle, the LVDTs were removed, and the sample was loaded to failure to determine the UCS additionally.

Based on the results of the first unloading cycle, the static Young's modulus (secant modulus) of each specimen was calculated 630 as the ratio of the stress difference to the axial strain difference, following ASTM D3148-02 (2002).

$$E_{\text{stat}} = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (6)$$

E_{stat}	static Young's Modulus	[GPa]
$\Delta\sigma$	Spannungsdifferenz	[GPa]
$\Delta\varepsilon$	axiale Verformung/Dehnung	[GPa]

635 The static Poisson's ratio was calculated as the ratio of lateral deformation to the original plug diameter divided by the ratio of axial deformation to the original plug length.

$$\nu_{\text{stat}} = -\frac{\Delta d/d}{\Delta l/l} \quad (7)$$

ν_{stat}	static Poisson ratio	[-]
Δd	Durchmesseränderung	[m]
Δl	Längenänderung	[m]
d	plug diameter	[m]
l	plug length	[m]

640



Afterwards the static shear modulus G and bulk modulus K were calculated after ASTM D7012-14 (2014):

$$G_{\text{stat}} = \frac{E_{\text{stat}}}{2 \cdot (1 + \nu_{\text{stat}})} \quad (8)$$

645 G_{stat} static Shear Modulus [GPa]
 ν_{stat} static Poisson ratio [-]
 E_{stat} static Young's Modulus [GPa]

$$K_{\text{stat}} = \frac{E_{\text{stat}}}{3 \cdot (1 - 2\nu_{\text{stat}})} \quad (9)$$

650 K_{stat} static Bulk Modulus [GPa]
 ν_{stat} static Poisson ratio [-]
 E_{stat} static Young's Modulus [GPa]

Subsequently, the Lamé modulus was calculated after Yu et al. (2016):

$$\lambda_{\text{stat}} = K_{\text{stat}} - \frac{2}{3} G_{\text{stat}} \quad (10)$$

655 λ_{stat} static Lamé Modulus [GPa]
 K_{stat} static Bulk Modulus [GPa]
 G_{stat} static Shear Modulus [GPa]

Tensile strength (Brazilian disc test) was also determined using the uniaxial hydraulic press from FORM+TEST Prüfsysteme.

660 Cylindrical plugs with a diameter of 55 mm and a length of approximately 28 mm (corresponding to a 2:1 diameter-to-length ratio) were loaded in the press according to ASTM D3967-16 (2016) and Lepique (2008). The samples were loaded at a constant rate of 0.1 kN s^{-1} until failure. Taking into account the sample dimensions, the splitting tensile strength of each plug was subsequently calculated following Lepique (2008).

$$\sigma_t = \frac{2 \cdot F}{\pi \cdot d \cdot l} \quad (11)$$

665 σ_t tensile strength [MPa]
 F failure load [N]
 d plug diameter [m]
 l plug length [m]

670



5.3.2 Triaxial tests

To determine the internal friction angle (φ), cohesion (c), shear stress (τ), and normal stress (σ_n) of the sample material, triaxial compression tests were conducted at TU Darmstadt on oven-dried samples using a hydraulic triaxial press from Wille Geotechnik with a maximum load of 500 kN. Depending on sample availability, three plugs per sample (diameter 55 mm, length 110 mm) were tested at a displacement rate of 0.5 mm min^{-1} under different confining pressures (σ_3) of 10, 20, and 25 MPa until sample failure.

Following ASTM D2664-04 (2004), the confining pressures (σ_3) and the corresponding axial stresses (σ_1) were plotted in a normal stress–shear stress diagram (σ – τ diagram) to construct the Mohr–Coulomb failure envelopes and to determine cohesion and the internal friction angle. When necessary, the axial stresses obtained from UCS tests ($\sigma_3 = 0$) were included to define an additional Mohr circle in the σ – τ diagram, thereby improving the data evaluation.

The normal and shear stresses were calculated according to the following equations 11 and 12:

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3) \cdot \cos(2\theta) \quad (12)$$

$$\tau = \frac{1}{2}(\sigma_1 - \sigma_3) \cdot \sin(2\theta) \quad (13)$$

σ_n	normal stress	[MPa]
τ	shear stress	[MPa]
σ_1	axial stress	[MPa]
σ_3	confining pressure	[MPa]
θ	inclination angle of the fault plane	[°]

Subsequently, the Mohr–Coulomb failure criterion was determined, and the cohesion and friction angle were calculated:

$$\tau_{krit} = c + \sigma_n \cdot \tan(\varphi) \quad (14)$$

τ_{krit}	shear stress during sample failure	[MPa]
c	cohesion	[MPa]
σ_n	normal stress	[MPa]
φ	internal friction angle	[°]

Despite triaxial tests under ambient conditions performed at TU Darmstadt selected samples of the Harzburg Gabbro underwent triaxial compressive strength tests under elevated temperature and pressure conditions using the mechanical testing system “MTS” at GFZ Potsdam as described in Pei et al. (2018, <https://www.gfz.de/en/section/geoenergy/geoenergy-laboratories/rock-deformation-laboratory>). The MTS allows to test sample specimens under hydrostatic confining pressures of up to 140 MPa and temperatures of up to 150–200 °C. Pore fluid pressure was regulated via a Quizix C-6000-10 K hydraulic



system supporting pore pressures of up to 68.9 MPa with a volume resolution of 0.0000135 ml, while axial and lateral strains were continuously recorded using external and circumferential extensometers.

5.4 Geochemical and mineralogical analyses

Geochemical analyses were conducted at TU Darmstadt, GFZ Potsdam, FU Berlin, and a commercial laboratory to provide quantitative and qualitative information on the bulk geochemical and mineralogical composition of the sample material. Representative sample material was first selected for each unit (composite sample) and milled in the laboratory at TU Darmstadt using a disc vibratory mill (Siebtechnik) for 2.5 minutes at 1000 rpm in a tungsten carbide vessel to achieve a particle size of less than 63 μm . At GFZ Potsdam, about 30 g of the sample material was similarly ground in an agate vessel using a vibratory mill and sieved through a 63 μm stainless steel mesh. The following sections provide a brief description of the methods applied.

5.4.1 XRD analyses (mineralogy)

X-ray diffraction (XRD) measurements were conducted for the qualitative and semi-quantitative determination of the mineral composition of the sample material. The measurements were carried out at GFZ Potsdam and at FU Berlin laboratories. At GFZ Potsdam, mineralogical analyses were performed in the EIMiE-Lab (Elements and Minerals of the Earth Laboratory). Bulk-rock samples were crushed, powdered and sieved to a grain size of <62 μm . Analyses were performed using a PANalytical Empyrean X-ray diffractometer (Malvern Panalytical) with a Bragg-Brentano geometry at 40 mA and 40 kV, CuK α radiation, and a PIXel3D detector at a step size of 0.0131° 2 θ from 4.6° to 85° 2 θ and 60 s per step. The mineralogy was determined with the software EVA (version 11.0.0.3) by Bruker using an updated mineral library.

At FU Berlin, a Bruker D2 Phaser XRD (Bruker Corporation, Billerica, MA, USA) was used, operating with Cu K α radiation (1.54184 Å, 10 mA, 30 kV) and equipped with a LYNXEYE detector. Diffraction patterns were recorded from 6° to 80° 2 θ with 0.012° steps and an integration time of 0.1 s. Additionally, a detector slit of 8 mm and a standard divergence slit of 0.6 mm were used to control the illuminated area and improve the measurement resolution. Phase identification and semi-quantitative evaluation of the results were again performed using Bruker's DIFFRAC.EVA software.

5.4.2 XRF analyses (geochemistry)

To determine the quantitative composition of the major elements (as oxides) as well as selected trace elements (as elements) in the sample material, X-ray fluorescence (XRF) analyses were conducted. For this purpose, fused discs were created using Höchst Wax C. At TU Darmstadt, the fused discs were then analyzed for major and trace elements using a Bruker S8 Tiger 4 WD-XRF spectrometer with the Quant Express method. The measurement accuracy is <5 % for major elements and <10 % for trace elements. At GFZ, XRF analyses were performed using a PANalytical AXIOS Advanced spectrometer in combination with the SuperQ5.0i/Omnian software. Quantification level (QL) for wt.% range is 0.2 wt.% and approximately 20 ppm for



trace elements. The results of the XRF analyses are reported in the database as wt% for major element oxides and in ppm for
730 trace elements.

During the XRF measurements, the loss on ignition (LOI) of the samples was also determined. This involves heating 1 g of sample material to 1000 °C and subsequently cooling it to room temperature in a furnace. The LOI is reported as a percentage and is calculated from the difference in sample mass before and after heating.

Some samples were also analyzed at the commercial laboratory ALS/OMAC Laboratories in Ireland to determine the
735 composition of major element oxides and the loss on ignition (LOI), which was measured as described above. For the preparation of the fused discs, 0.66 g of sample material was fused with a 12:22 mixture of lithium tetraborate–lithium metaborate, containing lithium nitrate as an oxidizing agent, and cast into a platinum mold.

5.4.3 ICP-MS analyses (geochemistry)

ICP-MS analyses (Inductively Coupled Plasma–Mass Spectrometry) were conducted to quantify the amount of minor and
740 trace elements (e.g., rare earth elements, REE) in the sample material. At TU Darmstadt, powdered sample material was mixed with 0.2 g of lithium borate and fused at 1000 °C. Subsequently, a solution was prepared from the mixture of sample material and lithium borate using 80 mL of 5 % nitric acid (HNO₃). The solution was then transferred into a volumetric flask and diluted to 100 mL. For the actual ICP-MS measurement with a Analytik Jena Plasma Quant MS Elite® ICP-MS, the samples were further diluted by a factor of 20. The following high-purity chemicals were used for sample preparation: deionized water
745 (>18 MΩ, Milli-Q), nitric acid (ROTIPURAN® Supra), lithium metaborate/lithium bromide 99.5 % / 0.5 %, Fusion Flux Pure Grade (Katanax), and a multi-element standard REE mix 50 mg L⁻¹ (Sigma Aldrich).

Additional sample material was analyzed for minor elements and rare earth elements at a commercial laboratory (ALS/OMAC Laboratories in Ireland). For this, 0.25 g of sample material was digested using the “Four Acid” method, a multi-step decomposition procedure with HNO₃, HClO₄, and HF. As the final step prior to instrumental analysis, the solution was heated
750 and evaporated using hydrochloric acid (HCl). This method enables the determination of 48 minor and trace elements.

The results of the ICP-MS analyses are reported in the database in ppm.

5.4.4 Radiogenic heat production

Radiogenic heat production is caused by the radioactive decay of thorium, uranium, and potassium in rocks (⁴⁰K, ²³²Th, ²³⁵U, and ²³⁸U). It is a physical parameter of critical importance for accurately estimating temperatures within the lithosphere and
755 for understanding processes associated with the thermal evolution of the Earth (Hasterok and Webb, 2017). Based on the conducted geochemical analyses as described above, radiogenic heat production was calculated according to Rybach (1988) and Hasterok and Webb (2017):



$$A = \rho \cdot (9.76 C_U + 2.56 C_{Th} + 2.89 C_{K_2O}) \cdot 10^{-5} \quad (15)$$

760	A	radiogenic heat production	[W m ⁻³]
	ρ	density	[kg m ⁻³]
	C_U	uranium concentration	[ppm]
	C_{Th}	thorium concentration	[ppm]
	C_{K_2O}	potassium concentration	[wt%]

765

6 Status of the database

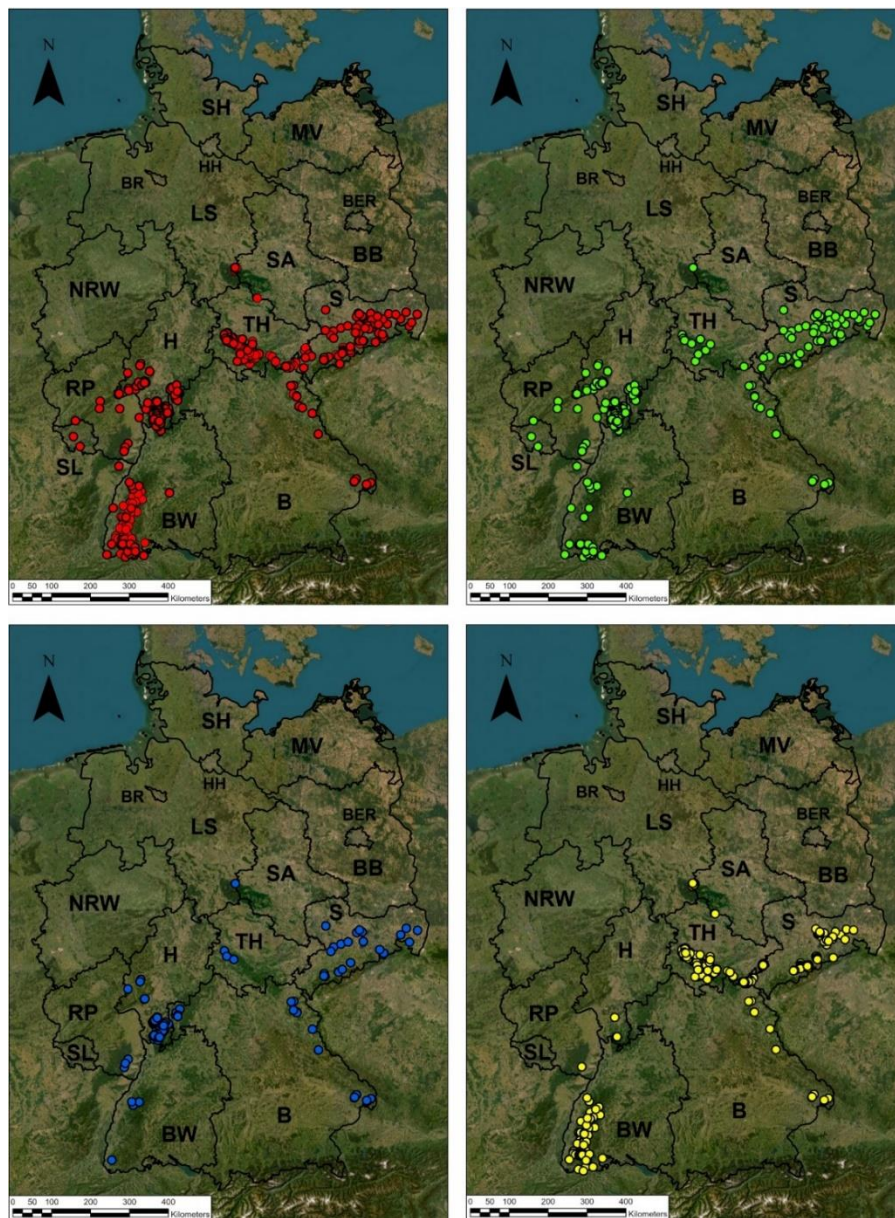
Tables 2 and 3 provide an overview of the number of measurements for each parameter included in the database, along with their respective data sources. During data acquisition, data from over 40 publications and datasets from geological surveys that met the defined quality control standards were identified and incorporated into the reference database, contributing >20,000 data points. An additional ~5,000 rock property data entries, along with complementary geochemical and mineralogical data, were generated through the newly conducted sampling and measurement campaigns within the framework of the AMPEDEK project. The database now includes more than 30 petrophysical and mechanical rock parameters, supplemented by geochemical and mineralogical analyses, derived from ~8,200 rock samples collected at over 3,400 sample locations across Germany, spanning eight federal states.

As shown in Figure 7, the amount of data and its spatial coverage differ considerably between the federal states. The figure also illustrates that most data originate from outcrop samples and quarries, resulting in a clustering of sample locations in areas where the crystalline basement is exposed at or near the surface. In addition, for most areas either petrophysical or geochemical measurement data are included, whereas rock mechanical data remain sparse. Complete datasets containing petrophysical, geochemical, and rock mechanical properties are currently limited to samples analyzed within the AMPEDEK project.

With respect to data quality, both the bulk quality index and the individual indices for geographic uncertainty, petrography, stratigraphy, and measurement conditions are shown in Figure 8. The data exhibit a broad distribution across all quality classes. The bulk quality index of most data entries falls within classes 2 and 3, indicating generally adequate supporting information and overall data quality. The indices for petrographic description, geographic uncertainty, and measurement parameters are predominantly assigned quality classes between 1 (excellent) and 3 (poor), whereas the indices for stratigraphic information and measurement conditions are largely concentrated in classes 3 and 4 (minimum requirement achieved). This distribution indicates that the documentation of stratigraphic context and experimental conditions is incomplete or insufficient for a substantial proportion of the compiled datasets. Consequently, uncertainties associated with these metadata categories represent the primary limitations to the overall quality of the database. These findings emphasize the importance of comprehensive reporting of geological metadata and laboratory measurement conditions, particularly during publication, and



790 highlight the need for standardized documentation protocols for experimentally derived rock-property data in the field of
 geosciences.



1.
 795 **Figure 7: Spatial distribution of the associated sampling locations in Germany of the measurement data in the reference database (red = all data, green = petrophysical measurements, blue = destructive rock mechanical tests, yellow = geochemical data). Federal states: B = Bavaria, BB = Brandenburg, BER = Berlin, BR = Bremen, BW =Baden-Wuerttemberg, H = Hesse, HH = Hamburg, LS = Lower Saxony, MV = Mecklenburg-Vorpommern, NRW = North Rhine Westphalia, RP = Rhineland-Palatinate, S = Saxony, SA = Saxony-Anhalt, SH = Schleswig-Holstein, SL = Saarland, TH = Thuringia.**



800 **Table 2: Number of measurements for each parameter displaying the current status of the AMPEDEK database**

No.	Parameter	Literature data	New measurement campaign
01	Grain density	1152	208
02	Bulk density	1085	164
03	Porosity (total)	21	0
04	Porosity (effective)	882	157
05	Apparent permeability	1008	2
06	Intrinsic permeability	54	26
07	Thermal conductivity (dry)	5219	397
08	Thermal conductivity (saturated)	29	8
09	Specific heat capacity	1136	157
10	Volumetric heat capacity	13	26
11	Thermal diffusivity (dry)	3152	387
12	Thermal diffusivity (saturated)	0	8
13	Radiogene heat production	17	35
14	P-wave velocity (dry)	1053	429
15	P-wave velocity (saturated)	0	4
16	S-wave velocity (dry)	1000	429
17	S-wave velocity (saturated)	0	4
18	Dynamic E-Modulus (dry)	920	429
19	Dynamic E-Modulus (saturated)	0	4
20	Dynamic poisson ratio (dry)	897	429
21	Dynamic poisson ratio (saturated)	0	4
22	Dynamic shear modulus	0	379
23	Magnetic susceptibility	0	440
24	Electric conductivity	4	0
25	Static E-Modulus	233	96
26	Static poisson ratio	133	96
27	Static shear modulus	23	96
28	Static bulk modulus	99	96
29	Lamé modulus	0	96
30	Cohesion	43	12
31	Friction angle	43	12
32	Shear strength (triaxial tests)	80	48
33	Uniaxial compressive strength	396	154
34	Tensile strength	192	123
35	Number of major and trace element analyses	1782	38
36	Number of XRD analyses	0	35
Sum		20.666	5.028
Total		25.694	



Table 3: List of studies and data sources included in the AMPEDEK database

No.	Reference	Petrophysical parameters (non-destructive tests)	Rock mechanical parameters (destructive tests)	Geochemistry
01	Aretz (2015)	x		
02	Bär (2008)	x		
03	Bär (2012)	x		
04	Bär (2019)	x		
05	Dillenardt (2010)	x		
06	Dutheillet de Lamothe (2016)	x	x	
07	Faridfar (2010)	x		
08	Förster (2018)	x		x
09	Gombojav (2003)			x
10	Hallas (2020)			x
11	Hepp (2003)			x
12	Hoffmann (2011)	x		
13	Hoffmann (2015)	x	x	
14	Hueckl (1966)	x		
15	Kappelmeyer (1974)			
16	Klaeske (2010)	x		
17	Klumbach (2010)	x	x	
18	Kohl (1996)	x		
19	Kraus (2009)	x		
20	Lambert (2016)	x	x	
21	Laštovičková (1993)	x		
22	LfULG (2019)	x	x	
23	LGRB (2019)	x		
24	Maire (2014)	x	x	
25	Orendt (2014)	x		
26	Pei (2009)	x	x	
27	Schaeffer (2012)	x		
28	Schäffer (2017)	x		
29	Schaeffer (2018)	x		
30	Schaerli (2002)	x		
31	Schintgen (2015)	x		
32	Stober (2007)	x		
33	Strohmeier (2003)	x	x	
34	Surma (2003)	x		
35	TLUBN (2022)			x
36	Vila (2010)	x		
37	Vogel (2016)	x	x	
38	Weber (2014)	x		
39	Welsch (2011)	x		
40	Welsch (2012)	x		
41	Welsch (2015)	x		
42	Wenk (1969)	x		
43	Wiesner (2014)	x	x	

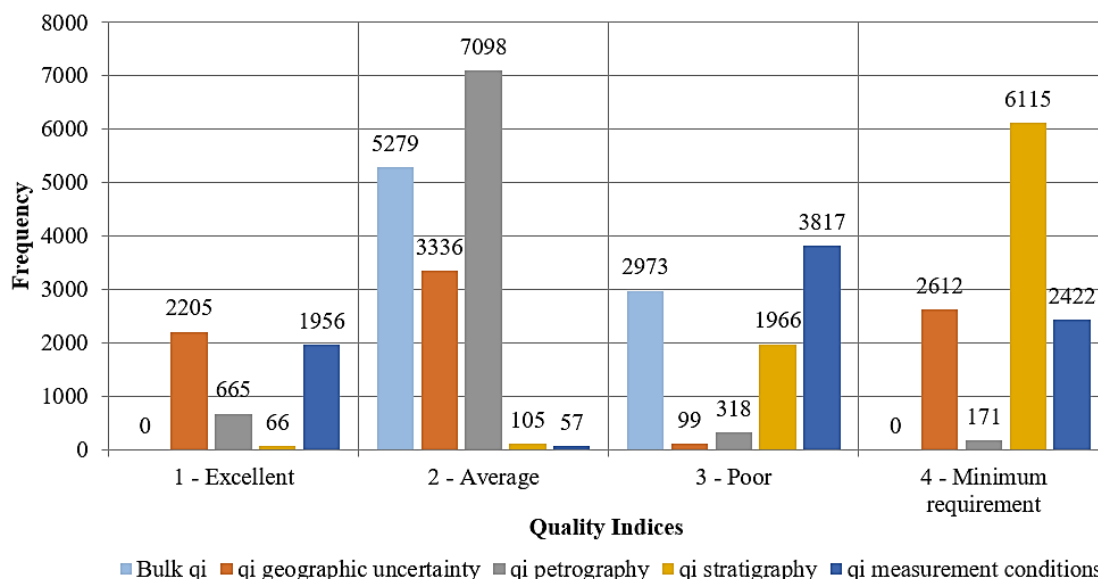


Figure 8: Frequency of data entries categorized by their total quality indices (light blue) and by the indices for geographic uncertainty (orange), petrography (grey), stratigraphy (yellow), and measurement conditions (dark blue).

810 7 Discussion

7.1 Data availability and application

Petrophysical and mechanical properties are among the most commonly used parameters for reservoir exploration, production modelling, stimulation scenarios, and geotechnical applications (Saller and Henderson, 1998; Rybacki et al., 2016; Gan and Elsworth, 2016; Ghassemi, 2017; Bohnsack et al., 2020). These properties have traditionally been measured routinely—and
 815 often mandatorily—in the oil and gas industry as well as in mining, and, depending on national regulations, have been compiled into extensive databases (e.g. the Canadian AccuMap (S&P Global, 2025) and geoSCOUT (geoScout, 2025) databases for well and core data). Thermal properties are primarily required to estimate geothermal gradients, subsurface temperatures, heat transport, and heat storage (Weides et al., 2013; Weides and Majorowicz, 2014; Ebigbo et al., 2016; Véléz et al., 2017; Miranda et al., 2020). Their standardized investigation has become increasingly important in recent years due to the growing interest in
 820 geothermal energy as a renewable resource. Magnetic and electrical properties are particularly useful for identifying lithological contrasts in geophysical exploration, especially at regional scale, and for detecting mineralized or hydrothermally altered zones (Hrouda, 2009; Nono et al., 2018; Lévy et al., 2019).

Studies on the characterization of crystalline rocks have primarily focused on geothermal reservoir characterization (Switzerland/Italy: Becattini et al., 2017; Europe/France: Surma, 2003; Bertrand et al., 2021; Poland: Labus et al., 2025; USA:
 825 Klee et al., 2021; UK: Schulz et al., 2022; Germany: Peacock et al., 2022), heat production and heat-flow estimations (Förster and Förster, 2000; Artemieva et al., 2017; Dalby, 2025; Kumar et al., 2025), mining and material science (Xiao et al., 2017;



Urueña et al., 2021; Bayram, 2025), and mechanical investigations for applications such as geotechnical engineering (Somodi et al., 2021; Santa et al., 2024). However, most of these studies address only a small number of parameters or are limited to specific regions. In Germany, publicly available petrophysical and mechanical rock property data have been largely restricted to areas such as the Upper Rhine Graben area (Surma, 2003; Klumbach, 2010; Kushnir et al., 2018), the Elbe Zone (Förster et al., 2018), Vogtland (Wagner et al., 2015) or the Erz Mountains (Förster and Förster, 2000). More comprehensive investigations were carried out within several student theses at TU Darmstadt, focusing on the Mid-German Crystalline High (e.g., Welsch, 2012; Weber, 2014; Hoffmann, 2015; Lambert, 2016; Vogel, 2016); these data are incorporated into the AMPEDEK database. In addition, extensive geochemical datasets for selected regions are included in e.g., Martin-Gombojav (2003, Harz Mountains), Hepp (2003, Black Forest), and Hallas (2020, Erz Mountains). Nevertheless, prior to the AMPEDEK project, Germany remained largely a blank map with respect to accessible rock property data for crystalline rocks, and no unified framework existed to compile and provide these data in a homogeneous and user-friendly form.

While numerous national and global databases have already been developed for geothermal well data (e.g., National Geothermal Data System NGDS, 2014; UK Geothermal platform, 2026; DOE Data Explorer, 2018), rock chemistry (e.g., Gard et al., 2019; National Geochemical Database USGS, 2014; North American Volcanic and Intrusive Rock Database NAVDAT, 2025), geochronology and petrology (New Zealand's Petlab, 2025), lithology (GLiM; Hartmann and Moosdorf, 2012), mineralogy (BRITROCKS Project, 2025), and petrography (RockViewer, 2025), a comprehensive and quality controlled compilation of laboratory measured rock properties has only recently been published by Bär et al. (2020), excluding fee based and non-open access industry databases (e.g., geoSCOUT, 2025). This effort was subsequently complemented by comprehensive, but region-specific datasets presented by Weydt et al. (2021), Weinert et al. (2021) and Scott et al. (2023), whereas Bär et al. (2020) provides a global compilation of rock property data. Building upon this, the Global Petrophysical Database, which is currently under development, already covers petrophysical data from more than 500 references (Sheldon et al., 2026). While the P³ rock property database presented by Bär et al. (2020), comprising more than 75,000 data points, substantially increased the availability of standardized rock property data, it has several limitations. First, the number of data points and parameters available for individual regions or stratigraphic units remains limited. Second, the database focuses exclusively on rock property measurements and does not include complementary geochemical or mineralogical data. Third, the internal data structure, in which each measurement is stored as a separate row, results in increasingly complex and inefficient data handling as the database size grows. Although the structure of the AMPEDEK database is based on the P³ database, these limitations were addressed by modifying the database structure following the approach proposed by Weydt et al. (2021), such that all parameters measured on a given sample under identical temperature and pressure conditions are stored within a single row. This modification results in a more concise database design and enables more efficient data handling. Furthermore, the database was expanded by additional data sheets containing bulk rock geochemical data derived from XRF and ICP-MS analyses, following the approach of Gard et al. (2019), as well as mineralogical data obtained from XRD measurements. This, for example, provides the opportunity to derive petrophysical rock properties from their mineralogical or



860 geochemical composition using phenomenological constitutive models (Sun et al., 2017; Chopra et al., 2018; Gard et al., 2019).
 In addition, the measurement workflow presented and applied here (section 3.2), in which each parameter was analyzed on
 each plug whenever possible, allows for the identification of formal or causal relationships between the parameters. In
 combination with the provided metadata and quality indices, the database enables rapid filtering as well as detailed statistical
 and geospatial analyses, which are crucial for upscaling or downscaling rock property data for subsequent applications (e.g.,
 865 3D modelling; Linsel et al., 2020). The ability to correlate datasets also facilitates and expedites the identification of key
 reference values for rock parameters within specific regions, rock types, or stratigraphic units. In combination with other large
 datasets, the measurement workflow and level of detail of the newly analyzed samples presented here also allow for the
 application of machine learning approaches (Okoroafor et al., 2022; Bu et al., 2026). Furthermore, the database enables
 systematic analyses of how property values depend on measurement conditions, as well as the benchmarking of different
 870 measurement methods.

7.2 Data limitations

Despite the advantages outlined above, databases are inherently subject to limitations and uncertainties. The data included in
 the reference database are based on literature sources, student theses conducted at TU Darmstadt, data provided by geological
 875 surveys, and newly acquired sample measurements performed within the framework of the AMPEDEK project. Although it
 has been possible to compile and structure a substantial amount of relevant rock property data for crystalline rocks in Germany
 to date, no database can ever be complete. Data availability strongly depends on prior research focus, existing literature,
 accessibility of suitable sampling locations, and laboratory analytical capabilities. For example, each federal state in Germany
 manages subsurface data differently, and only a few operate scientific programs that include the systematic analysis and storage
 880 of subsurface rock properties. Furthermore, not all state geological surveys had the capacity to contribute to the AMPEDEK
 database at the current stage of the project, and not all collected data sets were suitable for inclusion. Similar to the observations
 reported by Bär et al. (2020), published data often lack sufficient metadata related to sampling context, stratigraphic unit, or
 measurement conditions, which limits their reuse and interpretability. Although the introduced quality control indices can
 identify such deficiencies, they cannot compensate for missing or ambiguous information in the original sources. This
 885 emphasizes the need for more centralized approaches to outcrop, borehole, and laboratory analyses in research projects, as
 well as more standardized procedures for data handling, storage, and reporting in scientific publications and industry projects.
 In addition to the often challenging identification and accessibility of suitable outcrops, only a limited number of wells in
 Germany have penetrated the crystalline basement (Rohrmüller, 2003). For bureaucratic reasons, access to all of these wells
 was not possible during the initial phase of the project, preventing comprehensive analyses of the available rock material.
 890 Consequently, the spatial representativeness of the data must be carefully evaluated. The majority of the data are derived from
 measurements on outcrop samples, whose properties may differ from those of deep reservoir rocks due to hydrothermal
 alteration, metamorphic overprinting, and differing stress conditions. Furthermore, the database exclusively comprises



laboratory measurements conducted on centimeter to decimeter scale samples (also defined as mesoscale), which primarily represent matrix properties measured under ambient laboratory conditions (atmospheric pressure of 0.1 MPa and room temperature of ~21 °C) and do not directly capture reservoir scale behaviour (Weydt et al., 2021). Properties such as porosity, permeability, thermal conductivity, electrical resistivity, and elastic moduli are known to vary significantly with pressure, temperature, stress state, fluid saturation, and alteration history (Zimmermann et al., 1986; Clauser and Huenges, 1995a; Heap et al., 2014; Hatakeda et al., 2017; Weydt et al., 2022). Transferring laboratory values to in situ conditions therefore is not trivial and requires the application of empirical or analytical correction functions and upscaling approaches (e.g., hydraulic properties: Zimmermann et al., 1986; Heap and Kennedy, 2016; thermal properties: Zoth and Hänel, 1988; Vosteen and Schellschmidt, 2003; Rühaak et al., 2015; Clauser, 2020; electric properties: Kummerow et al., 2020; Nono et al., 2020; mechanical properties: Vinciguerra et al., 2005; Vagnon et al., 2021; magnetic properties: Ohnaka, 1969; Ali and Potter, 2012; Zhang et al., 2020), which remain associated with considerable uncertainty (Ding et al., 1992; Qi and Hesketh, 2005).

For this reason, measurements of thermal, hydraulic, and mechanical properties of crystalline rocks under elevated temperature and pressure conditions are currently being conducted to better estimate the physiomechanical behavior of the target reservoir rocks under in situ conditions (Weydt et al., 2025). These high temperature and high pressure experiments include, for example, measurements of thermal conductivity, thermal diffusivity, and specific heat capacity at temperatures ranging from 20 °C to >250 °C, long term cyclic flow through experiments under varying temperature and pressure conditions using the thermo triaxial device at TU Darmstadt, as well as triaxial shear tests under elevated temperature and pressure conditions conducted with the mechanical testing system MTS and, in the near future, a newly built true triaxial apparatus at GFZ Potsdam. The results of these high-temperature and high-pressure experiments will be included in future releases of the AMPEDEK database. At the current stage of the project, laboratory or field measurements aimed at determining reservoir rock properties at larger or smaller scales were not yet included in the AMPEDEK database. These include, for example, microstructural analyses such as thin section and electron microscope investigations, microCT measurements, as well as hydraulic well testing and geophysical well logs. This deliberate restriction was implemented to ensure data comparability, to avoid scale dependent biases within the database, and to keep data handling and application as straightforward as possible (Bär et al., 2020).

In the second stage of the AMPEDEK project, complementary petrographic and microstructural analyses of the collected sample material are planned in order to better understand how microscale rock characteristics influence bulk rock properties measured at the mesoscale, particularly under high-temperature and high-pressure experimental conditions. As crystalline basement rocks have historically not been the primary targets of drilling campaigns in Germany, for example in the oil and gas industry, geophysical logs and well data are scarce or not yet available. Ongoing geophysical exploration campaigns and drilling activities in the Tromm pluton within the framework of the GeoLab project (Kohl et al., 2025) will provide the first comprehensive reservoir scale dataset for a plutonic body in Germany. During the second stage of the AMPEDEK project, it is planned to integrate results from both projects in order to improve the understanding of the scale dependency of reservoir properties in crystalline rocks.



Another limitation arises from the heterogeneity of measurement methods and experimental conditions. Although the majority of rock property data in the AMPEDEK database is based on laboratory measurement campaigns conducted at TU Darmstadt, which ensures a high degree of data comparability, data retrieved from other sources were obtained using different analytical techniques and instruments, each associated with specific uncertainties and potential biases. Consequently, direct comparability of values is not always guaranteed, and statistical analyses are only meaningful if methodological differences are explicitly taken into account. While the documentation of the original sources enables verification of the applied methods and experimental setups, the responsibility for appropriate data selection and interpretation ultimately lies with the user.

8 Data availability

The dataset is available in the TUDatalib repository at <https://doi.org/10.48328/tudatalib-2167> (Weydt et al., 2026).

9 Conclusion and outlook

Within the framework of the AMPEDEK project a comprehensive rock property data base for crystalline basement rocks in Germany was created based on literature data, student theses, data from geological surveys, and new sampling and measurement campaigns. The resulting database comprises roughly 25,700 data points covering up to 34 rock properties and geochemical data, derived from over 8,200 samples collected at more than 3,400 locations across eight federal states in Germany. The data is provided in a flat file Excel format, which comprises multiple tables for meta data, rock properties, geochemical analyses, petrography, stratigraphy, and quality controls and follows the concept of relational database management. Each sample is assigned a unique sample ID that serves as a relational key across the database tables, with all rock parameters measured under identical pressure–temperature conditions stored in a single row.

The compiled dataset provides a robust basis for a wide range of applications (e.g. geotechnical engineering and tunnel construction, deep and/or enhanced geothermal systems, closed-loop systems, or nuclear waste storage) for future projects targeting crystalline basement rocks in Germany or elsewhere. It enables the prediction of rock properties for target formations at early stages of exploration or in regions with limited data availability, and, thus, supports the assessment of reservoir potential and facilitates the estimation of economic risks and associated uncertainties. The data can be used to populate 3D geological models, including numerical thermo-hydraulic–mechanical–chemical (THMC) simulations, and allows for statistical analyses to identify property relationships and trends required for upscaling approaches. In addition, the dataset serves as a valuable reference for the validation and comparison of different analytical and measurement methods.

The literature review and data acquisition revealed that, for a large proportion of crystalline basement units in Germany, available information is largely limited to either petrophysical or geochemical data, while rock-mechanical properties remain underrepresented. In addition, many published data sets lack the comprehensive metadata required for detailed evaluation, reuse in future projects, or robust comparison with other databases. The data compilation and workflow presented here address



these limitations and provide a structured framework that will improve the planning and execution of future research efforts. The study shows that the systematic characterization of geochemical, petrophysical and mechanical properties from outcrop and reservoir core samples is essential for reliable reservoir characterization and should be more widely integrated into future geoscientific studies to enable more accurate predictions of subsurface reservoir properties.

960 The AMPEDEK database will be continuously updated and expanded through new sampling and measurement campaigns, particularly targeting regions with low data density. In addition to characterizing previously underrepresented lithologies, future efforts will emphasize high-temperature and high-pressure experiments to improve the understanding of variations in hydraulic, mechanical, and thermal parameters under in situ conditions and to apply or develop new upscaling approaches. Furthermore, the effects of anisotropy and weathering on rock properties, as well as the homogeneity of plutonic bodies with
 965 respect to their rock characteristics, will be investigated.

Author contributions

This study was conducted by LMW, who wrote the original manuscript, conceptualized and managed the study, and was responsible for sample and data acquisition, laboratory analyses, data curation, and the final rock property database. AARG assisted with sample acquisition and preparation as well as selected petrophysical and mechanical rock measurements at TU
 970 Darmstadt. LM contributed to sample and data acquisition and performed complementary laboratory analyses at GFZ. AMS and FD contributed to the study by conducting geochemical and mineralogical analyses. IS was responsible for funding acquisition and project development. All authors read and reviewed the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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