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Overview of the thermal properties of rocks and sediments in Slovenia

Pregled toplotnih lastnosti kamnin in sedimentov v Sloveniji

Dušan RAJVER & Simona ADRINEK

Geological Survey of Slovenia, Dimičeva ul. 14, SI-1000 Ljubljana, Slovenia; e-mail: dusan.rajver@geo-zs.si

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Abstract

The use of geothermal energy, which comes from both deep geothermal systems and the shallow underground, has been developing rapidly in the last few decades. The purpose of the paper is to present the results of measurements of the thermal properties of all rock samples and sediments that were available from boreholes, two tunnels and numerous surface locations in Slovenia in the period from 1982 to the end of 2022. In relation to the shallow geothermal potential, a special effort is needed to characterize the thermal properties of the rocks and sediments and to implement thermal energy transfer technology. In this sense, knowledge of the thermal conductivity of rocks and sediments is required to assess the possibility of low-enthalpy heat exchange in a given local area. The largest number of measurements was taken to determine thermal conductivity. Determinations of thermal diffusivity were carried out on a much smaller number of rock and sediment samples, as well as determinations of radiogenic heat production in rocks. The results of thermal conductivity measurements on 430 samples from 119 wells, 20 samples from two tunnels and 156 samples from surface locations are shown. The highest thermal conductivities are shown by samples of dolomite, quartz conglomerate and conglomerate, phyllonite, quartz phyllite and gneiss, while the lowest are measured in sediments such as clay, lignite with clay, peat and dry sand. The determined radioactive heat generation is the lowest for milonitized dolomite and highest for dark grey sandstone with shale clasts. Our results are comparable to those already published worldwide, and they could be the basis for the possible future Slovenian standard for the thermal properties of measured rocks and sediments.

Izvleček

Raba geotermalne energije, ki izhaja iz globokih geotermalnih sistemov kot tudi iz plitvega podzemlja, se v zadnjih nekaj desetletjih hitro razvija. Namen prispevka je prikazati rezultate meritev toplotnih lastnosti vseh vzorcev kamnin in sedimentov, ki so bili na voljo iz vrtin, dveh predorov in številnih površinskih lokacij v Sloveniji v obdobju od 1982 do konca 2022. V zvezi s plitvim geotermalnim potencialom je potrebno posebno prizadevanje za karakterizacijo toplotnih lastnosti tal in plitvega podtalja ter za izvedbo tehnologije prenosa toplotne energije. V tem smislu je potrebno poznavanje toplotne prevodnosti kamnin in tal za oceno možnosti izmenjave toplote z nizko entalpijo na določenem lokalnem območju. Številčno največ meritev je bilo za določitev toplotne prevodnosti. Določitve toplotne difuzivnosti so bile izvedene na precej manjšem številu vzorcev kamnin in sedimentov, prav tako določitve produkcije radiogene toplote v kamninah. Prikazani so rezultati meritev toplotne prevodnosti na 430 vzorcih iz 119 vrtin, na 20 vzorcih iz predorov in na 156 vzorcih iz površinskih lokacij. Najvišje toplotne prevodnosti kažejo vzorci dolomita, kremenovega konglomerata in konglomerata, filonita, kremenovega filita in gnajsa, najniže pa so izmerjene v sedimentih, kot so glina, lignit z glino, šota in suh pesek. Ugotovljena radiogena tvorba toplote je najmanjša pri milonitiziranem dolomitu in največja pri temno sivem peščenjaku s klasti skrilavega glinavca. Naši rezultati so primerljivi z že objavljenimi v svetu in lahko predstavljajo osnovo za morebitni bodoči slovenski standard toplotnih lastnosti merjenih kamnin in sedimentov.

Introduction

The energy potential that exists due to the large temperature difference between the inner parts of our planet and its surface, in theory, far exceeds all existing conventional sources (Ravnik, 1991). The total thermal energy in the Earth, calculated above the default average surface temperature of 15 °C, is of the order of $12.6 \cdot 10^{12}$ EJ, and only that thermal energy in the Earth's crust up to a depth of 50 km amounts to $5.4 \cdot 10^{9}$ EJ (Dickson & Fanelli, 2004; Clauser, 2006; Rajver et al., 2012). The exploitation of geothermal energy, in addition to some technical problems, has certainly natural limitations due to the low thermal conductivity and diffusivity of rocks, but the available energy is still huge.

The depths that are of importance for geothermal energy utilization today are a maximum of 10 km, while geodynamics and theoretical geothermics investigate thermal conditions up to a few thousand kilometers depth (Ravnik & Uran, 1984; Uyeda, 1988; Pollack & Sass, 1988). The accumulation of heat, which is today or will be technologically and economically usable in the near future, is located only at depths of less than 10 km, and in most cases less than 4 km. The exploitation of heat and geothermal fluid in low (<90 °C)-, medium (90-150 °C)- and high (>150 °C)- temperature fields (e.g. after Muffler & Cataldi, 1978) for district heating, thermal tourism, greenhouse heating, electricity and thermal energy production requires the knowledge of geological, hydrogeological and thermal characteristics of the area (Di Sipio et al., 2014). In such a context, low enthalpy geothermal energy with its ubiquitous potential is one of the most useful renewable energy sources for heating and cooling of buildings. The successful implementation of low enthalpy geothermal systems, such as ground source heat pump (GSHP) systems (open or groundwater HP and closed-loop or ground-coupled HP systems), operating in the heating-cooling mode entails a better characterization of the thermal and petrophysical properties of subsoil (Di Sipio et al., 2014). Since all this research refers to different depths, we must also know these properties at different temperatures and pressures.

This paper deals predominantly with the results of measurements of thermal conductivity on rocks and loose sediments from numerous boreholes, two tunnels and numerous surface locations in Slovenia, all performed at the Geological Survey of Slovenia (GeoZS) since 1982. The results of thermal diffusivity measurements carried out on rock samples from eight Slovenian boreholes and many surface locations since 2017 are also mentioned. In addition, the results of radiogenic heat production determination in the sampled rocks are presented. It does not go into the study of thermal properties at extremely high pressure and temperature (pT) conditions. The purpose of the paper is to show the values of the thermal conductivity of the sampled rocks in Slovenia, which should be used on a regional scale to provide the necessary information for the dimensioning of closed-loop systems with heat pumps (BHEs, pipes, horizontal collectors), and to better predict the geothermal conditions for the planning of deep boreholes. Our purpose was also to test how well the thermal conductivities measured on rocks from Slovenia match the ranges of values measured on rocks from the other parts of the world, which are mentioned in standards and literature.

Three aspects are required to be taken into consideration when a new closed-loop GSHP system is designed (Dalla Santa et al., 2020): (1) climate and location of the building, (2) building characteristics, such as its use, size and insulation level, and (3) ground (subsoil) conditions. The first two aspects determine the heating and cooling demand of the building while the thermal exchange potential depends on the geological and hydrogeological conditions (Sarbu & Sebarchievici, 2014). Therefore, the determination of ground thermal parameters is crucial in designing the total borehole length to be installed, the borehole heat exchangers (BHEs) spacing and layout, the number of BHEs and mutual position, all of which affect the short-term installation costs and the long-term maintenance of adequate energy efficiency of the GSHP system (Di Sipio et al., 2014; Dalla Santa et al., 2020). The most essential thermal properties of the local underground to be considered when designing a new closed-loop geothermal system are (Dalla Santa et al., 2020):

1. *thermal conductivity* (λ), defined as the ability to transfer heat, usually expressed in W/(m·K). In addition to the temperature gradient, thermal conductivity is the most important parameter in calculating the regional heat-flow density (the basic parameter for evaluating the geothermal potential of a territory), the heat transfer between underground and engineering solutions and the potential of geothermal reservoirs. Thermal conductivity is usually used for geothermal modelling and for validating data obtained by indirect control methods (geoelectrical sounding, magnetotelluric methods, etc.) applied in situ (Banks, 2008; Galson et al., 1987; Di Sipio et al., 2014).

2. *heat capacity* (C), defined as the ability to store heat. It is the ratio between the amount of heat to be transferred to a certain mass or volume to achieve 1 K change in temperature, thus it is expressed in J/K. It depends on the material but also on the mass/volume and, hence, the "specific" heat capacity (c) is usually used, in J/(kg·K) or J/(m^3·K).

3. *thermal diffusivity* (a), that is the ratio of the thermal conductivity and specific heat capacity, defined as the physical property governing the heat diffusion in transient conditions measuring the penetration of temperature changes into a material.

4. *undisturbed ground temperature profile*, which varies in the shallower layers due to annual variation of the ground surface temperature, while from about 10 m, is stable throughout the year and increases with depth based on the local geothermal

heat flux. Regarding determination of the annual mean ground temperature, if this cannot be measured it can be assessed using an alternative approach presented by Rajver et al. (2019) in four ways according to the available data at a given location.

Additionally, the local groundwater flow in the aquifers can significantly affect the heat exchange capability by adding a significant contribution of heat transported by convection, which is not accounted for in the thermal conductivity value, measured in the laboratory (Clauser & Huenges, 1995; Banks, 2008; Dalla Santa et al., 2020).

Knowledge of the thermal properties of rocks and sediments is also increasingly important in various human activities, such as in mining, geotechnical, civil and underground engineering. According to Popov et al. (2016), this knowledge has a crucial role in environmentally sensitive projects such as the disposal of high-level radioactive waste in deep underground sites and repositories, or various engineering projects such as the design of buried high-voltage power cables, oil and gas pipelines and ground modification techniques employing heating and freezing. Much attention in the past years was dedicated to the studies of thermal properties of geologic materials due to growing interest in underground storage. Heat transfer is namely an important consideration when building underground structures (tunnels, subway stations), for underground storage of natural gas and energy and in mining engineering (problem of ventilation for deep mine operation). Detailed data on the thermal conductivity and volumetric heat capacity for relevant geologic formations are needed for thermo-hydrodynamic models to evaluate oil recovery from heavy oil reservoirs and for thermo-hydrodynamic modelling including basin and petroleum systems (Popov et al., 2016).

Thermal conductivity of rocks and sediments – worldwide compilations

For the large number of different rocks thermal conductivity data are available and classified according to rock name and origin in several extensive compilations (Birch, 1942; Clark Jr., 1966; Desai et al., 1974; Kappelmeyer & Haenel, 1974; Roy et al., 1981; Čermák & Rybach, 1982; Robertson, 1988; Sundberg, 1988; Schön, 1996, 2011). It is important to realize that these compilations comprise rocks which are heterogenous in many aspects, such as mineral composition, porosity, water saturation and experimental conditions (Clauser, 2006). Consequently, the great variability of thermal conductivity exists within most rock types. Indeed, rock type as such is a rather poor descriptor for thermal and most other physical rock properties. This limits the usefulness of such tabulations, except for the rare instance when they comprise data for the exact location of particular interest. In all other cases, predictions based only on data collated according to general rock type may be in error. For all practical applications, it is therefore strongly recommended to obtain genuine, representative data of thermal conductivity, either by direct measurement or by inference from geophysical logs. When no measured data are available or no direct measurements can be performed, thermal conductivity can be inferred indirectly, either from data on mineralogical composition together with data on saturating fluids (e.g. Beck, 1988; Horai, 1991; Somerton, 1992; Schön, 1996), or from correlations with other physical properties, in particular those measured in well-logs (e.g. Vacquier et al., 1988; Blackwell & Steele, 1989; Brigaud et al., 1990; Hartmann et al., 2005; Goutorbe et al., 2006). While some of these methods are based on well-defined physical models, others are purely empirical (Clauser, 2006).

Clauser & Huenges (1995) extended their complementary approach of thermal conductivity data compilation with new data. In his attempt to adequately collect and arrange data of the measured thermal conductivity of rocks, Clauser (2006) supplemented data from earlier compilations (Birch & Clark, 1940; Clark Jr., 1966; Touloukian et al., 1970; Desai et al., 1974; Kappelmeyer & Haenel, 1974; Roy et al., 1981; Čermák & Rybach, 1982; Buntebarth, 1984; Robertson, 1988) by a large amount of new data. The data have become available (e.g. Kobolev et al., 1990; Popov et al., 2002, 2003; Mottaghy et al., 2005), and arranged as in the article by Clauser & Huenges (1995) according to four basic rock types: sedimentary, volcanic, plutonic and metamorphic. It is worth noting that older and more recent databases exist on the measured thermal conductivities in several countries or regions, for instance, by Lyubimova & Popova (1967), Lyubimova (1968), Majorowicz & Jessop (1981), Reiter & Tovar (1982), Gable (1986), Robertson (1988), Dövényi & Horváth (1988), Kobolev et al. (1990), Pandey (1991), Fuchs & Förster (2010), Pasquale et al. (2011), Di Sipio et al. (2014), Hamza et al. (2020), Gomes et al. (2021) and others. The thermal conductivity of minerals is much better constrained than that of rocks, due to the well-defined crystal structure and chemical formula for each mineral (Clauser, 2011). Substantial collections of mineral thermal conductivities were compiled, for instance, by Birch (1942), Clark Jr. (1966), Horai & Simmons (1969), Touloukian et al. (1970), Horai (1971), Roy et al. (1981), Čermák & Rybach (1982), Carmichael (1984), Popov et al. (1987), Diment & Pratt (1988), Somerton (1992), Clauser & Huenges (1995), Romushkevich & Popov (1998) and Clauser (2006). Thermal conductivity measurements were also carried out on rock and sediment samples from lakes and seabeds, and also as *in situ* sea-floor and lake-floor measurements around the world (e.g. Haenel, 1979; Fujisawa et al., 1985; Davis, 1988; Dorofeeva & Duchkov, 1995; Dorofeeva, 1998). Thermal conductivities of common rocks measured at room temperature are given also in suitable graphs and tables, for instance, by Kappelmeyer (1979), Zoth & Haenel (1988), Kappelmeyer & Haenel, (1974), Jessop (1990) and a comparison of published compilations of thermal conductivities by Beardsmore and Cull (2001). Recently, Dalla Santa et al. (2020) developed the thermal properties database by integrating and comparing data (a) provided by the most important international guidelines, (b) acquired from an extensive literature review and (c) obtained from more than 400 direct measurements, mainly of thermal conductivity of rocks and sediments. On the other hand, for closed-loop system designers, the most common thermal conductivity values are available from standard tables, such as the German standard VDI 4640 (VDI, 2001). However, they do not list values for all known types of rocks.

Overview of thermal conductivity measurement methods

Thermal conductivity can be measured in the laboratory on rock (cores or cuttings) and sediment samples. It can also be measured *in situ* either in boreholes or with shallow penetration needle probes (e.g. marine heat flow probes 3 to 20 m long). The available and commercial methods for measuring thermal conductivity can be classified into *steady-state* methods (guarded hot plate, heat-flow meter, divided-bar) and *transient* methods (plane source, hot wire, needle probe, laser flash, optical scanning, modulated DSC, thermocouple method, 3ω method – the last three are important for thermal energy storage materials), presented in Figure 1. All of them are also suitable to determine the anisotropy of thermal conductivity of rocks (Clauser, 2006, 2011). These methods are discussed and described in detail in numerous textbooks and review articles, e.g. by Parker et al. (1961), Beck (1965, 1988), Lyubimova (1968), Kappelmeyer & Haenel (1974), Roy et al. (1981), Davis (1988), Kobolev et al. (1990), Somerton (1992), Popov et al. (1999, 2012), Beardsmore & Cull (2001), Blumm & Lemarchand (2002) and Palacios et al. (2019). Among these techniques, the transient ones are also suitable for determining thermal diffusivity (Drury et al., 1984; Clauser, 2011). The laser flash method can be used for very low (down to -150 °C) and very high (above 500 °C) operating temperatures.

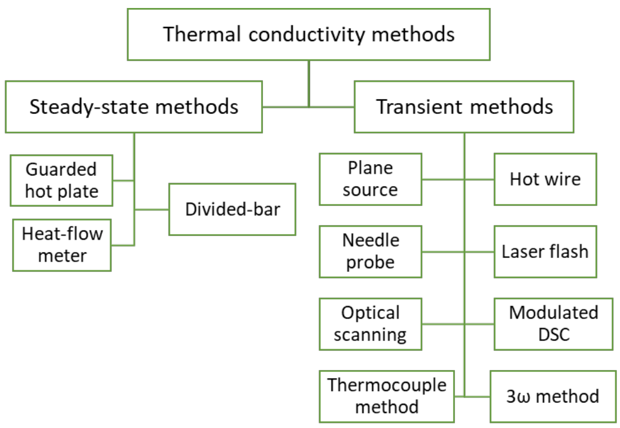

Fig. 1. Thermal conductivity measurement methods classification (modified after Palacios et al., 2019).

Steady-state thermal conductivity measurements are usually made using a divided-bar apparatus – a device designed to measure the thermal conductivity of discs or cylindrical plugs of material (Beardsmore & Cull, 2001). The device, first described by Benfield (1939), is easy to construct and operate, and results are usually accurate to within 5 % (Beck, 1957; Beck, 1988; Beardsmore & Cull, 2001). A similar device, used by scientists, notably from the former Soviet Union, especially in Siberia, is called a thermal (conductivity) comparator (Kalinin, 1981). The thermal conductivity λ is defined as (Carslaw & Jaeger, 1959; Kappelmeyer & Haenel, 1974; Haenel et al., 1988):

$$q = -\lambda \cdot grad\,T = -\lambda \cdot \frac{\partial T}{\partial z} \qquad (1)$$

where q is heat-flow density, and T is the local temperature in the sample. With the known geometry of the sample, which is usually plane-parallel, and the known constant power of the heater, the thermal conductivity λ is determined from the measured temperature differences (Prelovšek et al., 1982). Steady-state methods have few disadvantages, consequently, faster transient methods flourished in the 1970s (Prelovšek et al., 1982). Besides, steady-state techniques are unsuitable for loose sediments or *in situ* measurements. Yet in many cases, especially sea-floor measurements, such situations are encountered where a thermal conductivity estimate is required to convert temperature data into a heat flow measurement. For these cases, a technique for *transient* measurement has evolved (Beardsmore & Cull, 2001). Initially, the transient hot wire method with radial heat flow was developed. The beginnings of this absolute method date back to 1949, when it was used to measure the thermal conductivity of liquids (Van der Held, 1949). Later, the use was extended to solids as well (Ravnik & Uran, 1984). The most commonly used transient device is the *line-source needle probe*, first described by DeVries & Peck (1958), and then by Von Herzen & Maxwell (1959). Among transient methods, the *line-source hot wire* method has become established because it determines the thermal conductivity directly (Carslaw & Jaeger, 1959; Cull, 1974). This method is also the basis of an *improved hot wire* method developed by experts from the Japanese company Showa Denko K.K. (Sumikawa & Arakawa, 1976). Among the transient linear heat flow techniques also few other methods have been developed, such as the method with an *instantaneous source* (Hanley et al., 1978), the "Mongelli" method with a *constant plane heat source* (Mongelli, 1968) and the Ångstrom method using a *periodic heating technique* (Drury et al., 1984). Among the techniques using radial (2-dimensional) heat flow the one with an *instantaneous line-source* was used especially by Lyubimova et al. (1961), while the method with *constant linear or cylindrical heat sources* is the one with typical *needle* probe arrangement (Beck, 1988). One of the more recent methods is the *optical scanning* technology developed by prof. Yuri Popov in the 1980s (Popov, 1983; Popov et al. 1983, 2012, 2017).

The studies comparing the results between the steady-state and transient line-source method of thermal conductivity measurements showed a very good agreement (Čermák et al., 1984; Sass et al., 1984; Galson et al., 1987; Popov et al., 1999). The advantages and disadvantages of both groups of methods are listed in Table 1. Popov et al. (1999) also compared the results between the transient line-source method and the optical scanning method, which showed good agreement. Many studies on the thermal properties of rocks and sediments have taken place with the main goal to increase the number of heat-flow density determinations worldwide (e.g. Roy et al., 1981; Clauser & Huenges, 1995).

However, several difficulties exist when measuring the thermal conductivity of rocks and sediments, since the values are extremely dependent on mineralogical composition, porosity, density, water content (degree of saturation), anisotropy of the material under investigation and pressure and temperature of the surrounding environment. Recent studies have also confirmed the strong influence of solar radiation, soil texture and soil moisture on the soil (or sediment) thermal conductivity down to a depth of 3 m (Dédeček et al., 2012; Di Sipio et al., 2014; Čermák et al., 2016). At a laboratory scale, thermal conductivity measurements are usually performed on samples belonging to rock cores or surface outcrops. Each specimen is non-homogeneous and anisotropic on a scale of a few centimeters, according to its orientation, due to changes in the mineralogical composition, porosity, foliation, bedding, filling of discontinuities and weathering. A difference in thermal conductivity is registered if data are collected between directions parallel (λ_{par}) and perpendicular (λ_{perp}) to the layering, where the former is usually greater than the latter (Davis et al., 2007; Clauser, 2011; Di Sipio et al., 2014).

Upscaling the laboratory data from mesoscale to macroscale entails considering the various lithologies that make up the stratigraphic formations represented on a geological map along with their variability with depth. A geological model must be created where the thermophysical properties of the main lithologies are defined on the basis of real data, obtained from laboratory measurements and supplemented by literature and well-log data (Di Sipio et al., 2014).

Short history of measurements of thermal properties and on geothermal maps in Slovenia

Geothermal research in Slovenia began in the 1950s with hydrogeological studies focusing on hot springs mainly for balneological needs, and to

Table 1. Advantages (A) and disadvantages (D) of thermal conductivity/thermal diffusivity measurement methods (after Palacios et al., 2019).

Steady-state methods		**Transient methods**	
Complex sample preparation	D	Simple sample preparation	**A**
Long measuring time	D	Short measuring time	**A**
Complex realization, thermal constant resistance	D	Small samples	**A**
Clear mean value & simple evaluation of thermal conductivity (simple theory)	**A**	Complex evaluation, solution of heat equations	D
Low cost	**A**	High cost	D

a lesser extent for recreation. They were carried out by the Geological Survey of Ljubljana - GZL (predecessor of today's GeoZS). During their research on hot springs, hydrogeologists obtained a lot of data on water temperature (usually at the source or the wellhead), water yield, chemistry and pressure. However, the results of the temperature measurements were only described descriptively. Geophysical methods, especially geoelectrical soundings and well loggings, soon began to be used in research (Ravnik, 1991). The first systematic geothermal measurements were initiated in Slovenia in 1982–1984 with the manufacture of electric thermometers and equipment for measuring the thermal conductivity of rocks. One of the first results of thermal conductivity measurements on rock samples from a geothermal borehole in Slovenia, using the MTP-1 meter, were presented by Ravnik et al. (1982). Later the results of thermal conductivity measurements on rock samples from the boreholes at four Slovenian geothermal locations, using both line-source meters, were presented by Rajver (1986). These geothermal measurements were supplemented by analyses of the concentration of radiogenic isotopes of elements U, Th and K^{40} at the Jožef Stefan Institute in Ljubljana on prepared (properly ground) rock samples (Ravnik, 1991). In research already done by Ravnik et al. (1995), no clear relationship was found between near-surface heat-flow density and radiogenic heat generation, which was probably due to the predominantly Cenozoic age of the samples, and the irregular vertical distribution of heat producing elements in the near-surface layers.

In 1985, the GZL took over the editing of the preparation of geothermal maps of the former Yugoslavia for the new Geothermal Atlas of Europe. These maps were completed in the first phase in 1987 (Ravnik et al., 1987) and finally in 1989-1990 (Ravnik et al., 1992) and present the results of all previous research, supplemented by new data. The Atlas was published in 1992 under the auspices of the International Association for Seismology and Physics of the Earth's Interior (IASPEI) (Hurtig et al., 1992).

The report by Ravnik & Rajver (1990) was the first transparent result of geothermal research in Slovenia up to that time. The basic research methodology was established and the first two basic maps were produced: 1) a map of formation temperatures at a depth of 1000 m and 2) a map of surface heat-flow density (HFD). Even then, it was planned to create several similar geothermal maps, containing data up to a depth of 5000 m. The aim of the research was to enable the assessment of the geothermal potential of the entire Slovenia as soon as possible, which also required appropriate hydrogeological data. Both aforementioned maps were updated and presented by Ravnik et al. (1995). Every few years, the maps were updated and corrected according to new data (Ravnik, 1991; Rajver, 2018).

Methods

Thermal conductivity measurement methods at GeoZS

The thermal conductivity of rocks has been measured at GeoZS since 1982, when we acquired the first measuring device, based on the transient hot wire method. Considering the basic idea of the Japanese Sumikawa and Arakawa (1976), this method was used also in Slovenia based on the initiative of the Department of Geophysics at GZL (Uran, 1982; Prelovšek & Uran, 1984). At the same time, in cooperation with geophysicists from GZL, the first thermal conductivity meter MTP-1 was produced for GZL at the Department of Physics (Faculty of Natural Sciences at University of Ljubljana) (Prelovšek et al., 1982). It was the first meter of its kind produced in former Yugoslavia (Fig. 2). The results of thermal conductivity obtained with our MTP-1 meter were compared by prof. Prelovšek on the same samples measured with a similar meter at the Department of Geophysics of the Eötvös Loránd University in Budapest (dr. Horváth), then with a similar Japanese QTM (Quick Thermal conductivity Meter) device in the geothermal laboratory of prof. Rybach at ETH in Zurich, and with especially detailed measurements by the standard divided-bar (DB) method (Kappelmeyer & Haenel, 1974; Haenel et al., 1988) at the Geophysical Institute of the Czechoslovak

Fig. 2. Thermal conductivity meter MTP-1 (photo taken in 2022 during measurement on silicified brick).

Academy of Sciences in Prague (dr. Čermák), described by Ravnik & Uran (1984) and Ravnik (1988). Later, controls were also made at the International Institute for Geothermal Research in Pisa (Rajver, 1990) on samples from two deep Slovenian boreholes and during the 4th International Heat Flow meeting in Czechia in 1996, where experts from the State Geological Research Academy in Moscow checked our measurement results with their optical scanning IR device (prof. Popov).

According to these control measurements and according to the literature (Čermák et al., 1984; Sass et al., 1984; Galson et al., 1987), generally insignificant differences were indicated, as the difference between QTM and DB measurements does not exceed ±10 %. Two years later, in 1984 the GZL bought from the same faculty another meter MTP-4 of the same hot wire method, which was slightly improved with more time and power selection options (Fig. 3). At least ten such meters were produced by the mentioned faculty and sold all over former Yugoslavia.

Fig. 3. Thermal conductivity meter MTP-4 (photo taken in 2022 during measurement on lacquered marble).

The proper functioning of both line-source devices was constantly monitored by standard calibration material, like fused quartz and some appropriately prepared rocks, such as marble pieces, limestone and quartz diorite (tonalite). The imprecision of the conductivity data was about 3 %, whereas inaccuracy is estimated to be not more than 10 % (Ravnik et al., 1995). Measurements were performed at normal pressure and room temperature and, if possible, on intact rock samples, using both line-source meters in the period 1982 to 2006. Typically, 10 to 15 individual measurements were performed with the MTP-1 and MTP-4 devices on each rock sample, placing the measuring probes at different positions on the sample.

Since January 2007, we use a TCS device (Fig. 4), which works with the optical scanning method. The *optical scanning* technology is available in the commercial device named "Thermal Conductivity Scanner" (TCS), produced by TCS - Lippmann and Rauen GbR, Germany (Popov et al., 2016, 2017, 1999). The optical scanning technology is based on scanning using a focused, mobile and continuously operated near-point-like heat source in combination with infrared temperature sensors. Infrared sensors measure the temperature before and after focused heating. Determination of thermal properties is based on the comparison of temperature differences measured on *standard samples* (reference samples) with temperature differences measured on one or more *unknown samples*:

$$\lambda = \lambda_R \left(\frac{\Theta_R}{\Theta}\right) \quad (2)$$

where:
λ = thermal conductivity (TC) of sample
λ_R = TC of standard
Θ_R = temperature rise in the standard
Θ = temperature rise in the sample

Fig. 4. The TCS device in a TC+TD mode with a set of rock samples along the scanning line (photo taken in 2022).

The TCS meter also displays the following two values after each TC measurement: G factor (G = standard deviation / mean TC) and Inhomogeneity factor = (max TC – min TC) / mean TC. When the TCS meter is set in the TC+TD mode then also thermal diffusivity (TD) is measured (e.g. Marx, 2014; Haenel et al., 1988):

$$\alpha = \frac{\lambda}{\rho \cdot c} \quad (3)$$

where:
α = TD of sample
λ = TC of sample
ρ = sample density
c = specific heat capacity

The density of rocks were determined by the geomechanics laboratory at GZL by determining the volumetric weight using the mercury method, where the weight of the sample W (in pounds, p) and the weight of displaced mercury W_{Hg} (p) were first measured. Knowing the specific weight of mercury γS_{Hg} (13.546 p/cm^3), the sample volume $V = W_{Hg} / \gamma S_{Hg}$ (cm^3) is calculated, and from this the volumetric weight of the rock sample $\gamma S = W / V$ (p/cm^3). Three such consecutive analyses have been always performed on each sample. The average of the three analyses (p/cm^3) is taken into account, which is multiplied by 10 to get the average in kN/m^3. If this is divided by 9.81 we get the density (g/cm^3). A map of the volumetric (specific) heat capacity (MJ/m^{3}K) of rocks and sediments in Slovenia has also been prepared (Prestor et al., 2018), for which the input data are the basic geological map of Slovenia on a scale of 1:100,000 and average measured values of the volumetric heat capacity of rocks and sediments, which are taken from two standards (SIA and VDI).

Fig. 5. The longer TR-1 single-needle probe and the shorter SH-1 dual-needle probe of the KD2 Pro Thermal Properties Analyzer.

For the TC measurements of the loose sediments, we have been using the KD2 Pro portable device (Decagon Devices, 2016) (Fig. 5) since spring 2017. Depending on the physical properties of the tested sediment samples, two needle probes are used (TR-1 and SH-1).

Comparison of thermal conductivity values by line-source and optical scanning methods on reference standards at GeoZS laboratory

Control measurements of thermal conductivity (TC) were performed with both methods (line-source and optical scanning) on reference standards in the GeoZS geothermal laboratory. The

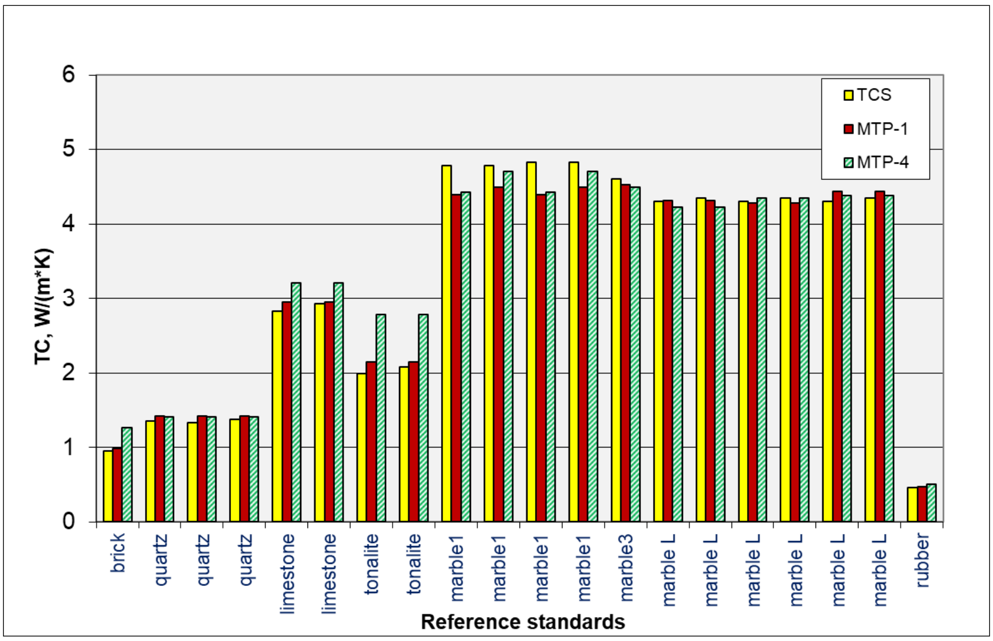

Fig. 6. Comparison of measured TC on reference standards at the GeoZS by the optical scanning (TCS meter) and line-source (MTP-1 and MTP-4 meters) methods.

results showed comparable values of thermal conductivity (Figs. 6 and 7). The measurements on reference standards with the MTP-1 and MTP-4 meters were occasionally carried out over a longer time period (from 1984 to 2007). The used reference standards were (in order from highest to lowest thermal conductivity): polished marble (3 samples), polished lacquered marble (marble L), limestone, tonalite, fused quartz, silicified brick and rubber. Figure 6 shows a comparison between the measured thermal conductivities with the TCS meter (either individual measurements or the averages of 2 to 5 individual measurements, which are different for each standard sample) and the measured TCs with the MTP-1 and MTP-4 meters (averages of a higher number of individual measurements, minimum 4 and maximum 234 measurements on each standard sample), which were performed in different time periods.

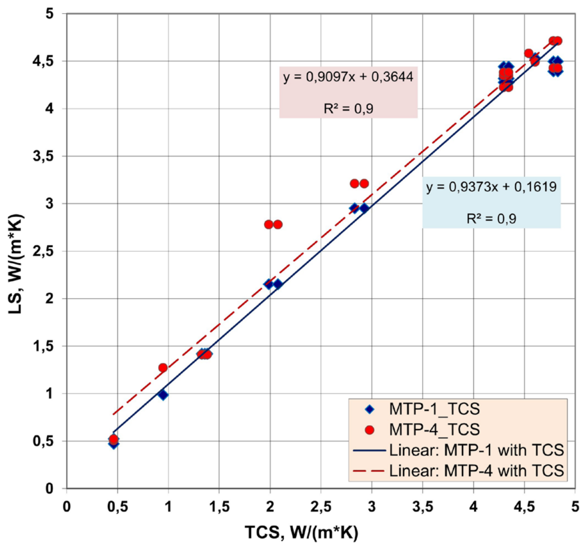

Fig. 7. Correlation between measured TC values (from Fig. 6) on reference standards with the TCS device and the line-source (LS) method (MTP-1 and MTP-4 meters), with trend lines shown.

One may notice a deviation in Figures 6 and 7, showing that higher TC values were obtained by the MTP-4 meter on tonalite, a little higher also on limestone and brick. Perhaps not completely suitable settings of this meter were selected for these particular measurements, or there was some other unexplained reason. Since the TC originally determined by the manufacturer on tonalite was 2.29 and on limestone 2.94 W/(m·K), probably measured with the MTP-1 meter, which were assumed to have declared values, the measurements with the MTP-4 were excluded in further correlation analysis. It turned out that the TCS measured lower TC values on the low conductivity standard (fused quartz) than the two line-source meters (Fig. 8). On the other hand, the TCS measured higher values mainly on the marble 1 standard, especially compared to the results with the older meter MTP-1 (Fig. 7). Of course, more comparative measurements should be made for more appropriate conclusions but both line-source devices don't operate properly anymore or they do only occasionally. Yet, according to Figures 6–8, the agreement of the measured values by both methods is quite satisfactory.

Calculation of radiogenic heat generation

An important source of the Earth's heat is the decay of radioactive isotopes. All natural radioactive isotopes generate heat to a certain extent but only the contributions of the decay series of uranium ^{235}U and ^{238}U, thorium ^{232}Th and of the isotope potassium ^{40}K are geologically significant. In this process, the kinetic energy of the alpha and beta particles and the gamma photons almost entirely convert into heat (Ravnik, 1991). Radioactive heat production H is calculated according to the equation (Rybach, 1988):

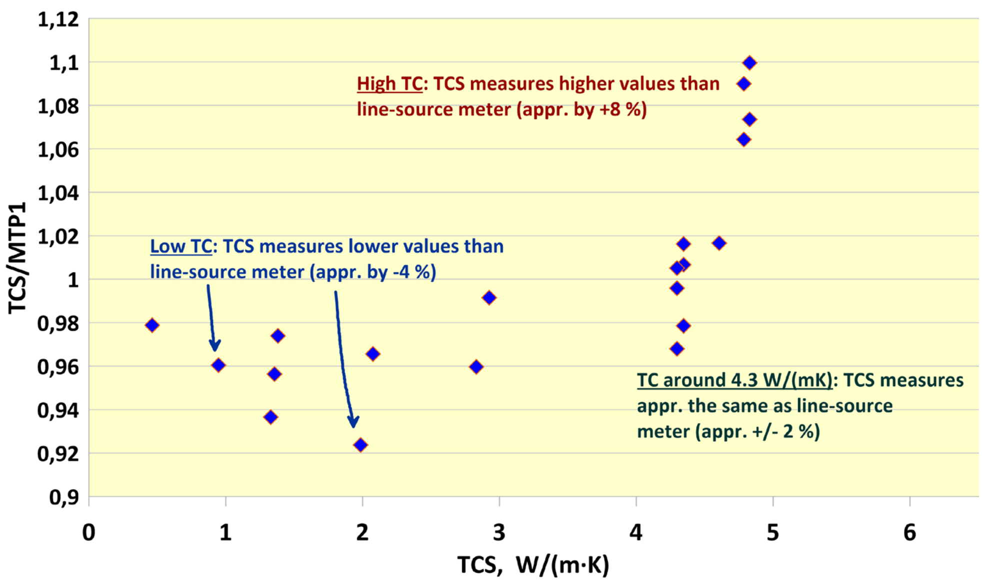

Fig. 8. Correlation between measured TC values (from Fig. 6) with the TCS device and the ratio of values measured with the TCS and MTP-1 meters.

$$H = \rho\,(9.52\,c_U + 2.56\,c_{Th} + 3.48\,c_K)\,10^{-5}\ (\mu W/m^3) \quad (4)$$

where:

c = concentration in ppm for U and Th and in % for K,

ρ = density of the rock (kg/m^3)

μ = micro (10^{-6})

Most samples were analysed at the Institute Jožef Stefan in Ljubljana where the concentration of radioactive isotopes in Slovene rock samples has been determined with a gamma-ray spectrometer equipped with a Ge/Li detector (Ravnik et al., 1995). The remaining 11 samples were analysed at the Geophysical Institute in Bucharest with a gamma spectrometer equipped with a NaI (Ti) detector. All mentioned analyses have been done over the period 1982 to 1995. Knowledge of heat generation is necessary to understand the relationship between geological conditions and the thermal field in the crust.

Results of measurements of thermal properties of rocks and sediments from Slovenia

Thermal conductivity and thermal diffusivity of rocks and sediments

The present paper discusses the results on a total of 606 rock and sediment samples that have been measured since 1982. Of these, 430 were cored rock samples from 119 boreholes, 20 rock samples from two tunnels (17 from the Karavanke highway tunnel and 3 from the Malence highway tunnel SE of Ljubljana) and 156 rock and sediment samples from surface locations (among the latter also four samples from a depth of 1 m in very shallow holes). The rock samples were of different sizes, mostly with a minimum length of 12 or 14 cm (a strict condition for both line-source devices) and minimum thickness of 2 cm, but in most cases, the samples, especially cored samples, were longer (up to 60 cm) and thicker.

The first 35 surface samples and 4 samples from very shallow holes were measured by the line-source method (Appendix A), while the remaining 103 surface samples were measured by the optical scanning method (TCS meter) and 14 sediment samples by the needle probe method (KD2 Pro). Out of 450 samples from the boreholes and two tunnels, 61 samples (13.6 %) were measured by the optical method (TCS meter), 388 samples (86.2 %) were measured by the line-source method, using both meters (MTP-1, MTP-4), and one sample (0.2 %) by the needle probe method (KD2 Pro). The vast majority, 549 measured samples (90.6 %) were sedimentary rocks and sediments, while 23 samples were metamorphic rocks (3.8 %) and 34 samples were igneous rocks (5.6 %) (Fig. 9 and Table 2).

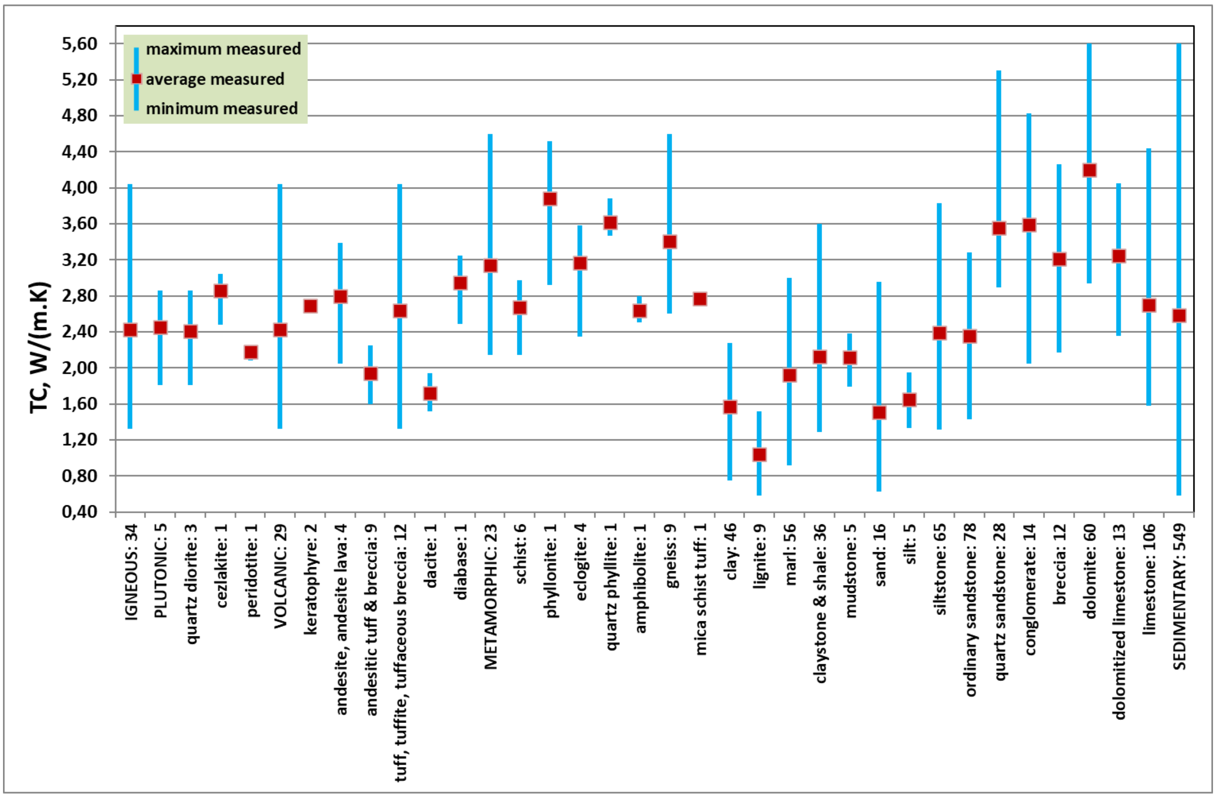

Fig. 9. Thermal conductivity (TC) of total 606 rock and sediment samples from the boreholes, two tunnels and numerous surface locations in Slovenia, with the number of samples by lithology and a total number of samples by main groups of rocks (status: March 2023); red points: mean values; the vertical lines show the range of measured TC values.

Table 2. Values of arithmetic mean TC with standard deviation and median TC of total 606 rock and sediment samples from Slovenia, grouped by lithology and main groups of rocks.

Lithology	No. of samples	Mean TC, W/(m·K)	s.d. TC, W/(m·K)	Me TC, W/(m·K)
Igneous rocks	**34**	**2.43**	**0.66**	**2.27**
Plutonic rocks	**5**	**2.45**	**0.46**	**2.56**
Quartz diorite (tonalite)	3	2.41	0.54	2.56
Cezlakite	1	2.86	/	2.86
Peridotite	1	2.18	/	2.18
Volcanic rocks	**29**	**2.43**	**0.69**	**2.25**
Keratophyre	2	2.69	0.04	2.69
Andesite, andesite lava	4	2.80	0.62	2.87
Andesitic tuff, andesitic breccia	9	1.94	0.22	1.89
Tuff, tuffite, tuffaceous breccia	12	2.64	0.83	2.52
Dacite	1	1.72	/	1.72
Diabase	1	2.95	/	2.95
Metamorphic rocks	**23**	**3.14**	**0.58**	**3.05**
Schist (green, amphibolitic, chloritic, etc.)	6	2.67	0.30	2.74
Phyllonite	1	3.88	/	3.88
Eclogite	4	3.17	0.56	3.36
Quartz phyllite	1	3.62	/	3.62
Amphibolite	1	2.64	/	2.64
Gneiss	9	3.41	0.59	3.31
Mica schist tuff	1	2.77	/	2.77
Sedimentary rocks	**549**	**2.57**	**0.49**	**2.53**
Clay, clay with impurities	46	1.57	0.38	1.57
Lignite, lignite with clay	9	1.04	0.37	0.97
Marl, marlstone with impurities	56	1.92	0.43	1.90
Claystone & shale, with impurities	36	2.13	0.74	1.89
Mudstone	5	2.12	0.26	2.15
Sand, sand with impurities	16	1.51	0.48	1.39
Silt, silt with impurities	5	1.65	0.48	1.68
Siltstone, siltstone with impurities	65	2.39	0.50	2.27
Sandstone (calcareous, marly, silty,...)	78	2.36	0.45	2.38
Quartz sandstone	28	3.56	0.56	3.46
Conglomerate (dolomitic, quartz)	14	3.59	0.88	3.59
Breccia (dolomitic, limestone)	12	3.21	0.70	3.21
Dolomite	60	4.20	0.60	4.11
Dolomitized limestone, limestone grading into dolomite	13	3.25	0.54	3.21
Limestone	106	2.70	0.39	2.68

Localities of the boreholes, two road tunnels and numerous points on the surface where the rock samples have been taken for the thermal conductivity measurements are shown in Figure 10. The boreholes are distributed according to the maximum depth in which the rock sample has been cored. In the GRETA project the rocks were sampled in the Municipality of Cerkno (Casasso et al., 2017, 2018) and in the GeoPLASMA-CE project in the Municipality of Ljubljana - MOL (Janža et al., 2017). Another project focused on geothermal potential assessment in the Municipality of Velenje (Janža et al., 2022). Other groups of rocks were sampled in two distinctive areas for the RockSense project (Jemec Auflič & Šegina, 2022; Rajver, 2022; Research project ARRS PROJEKT

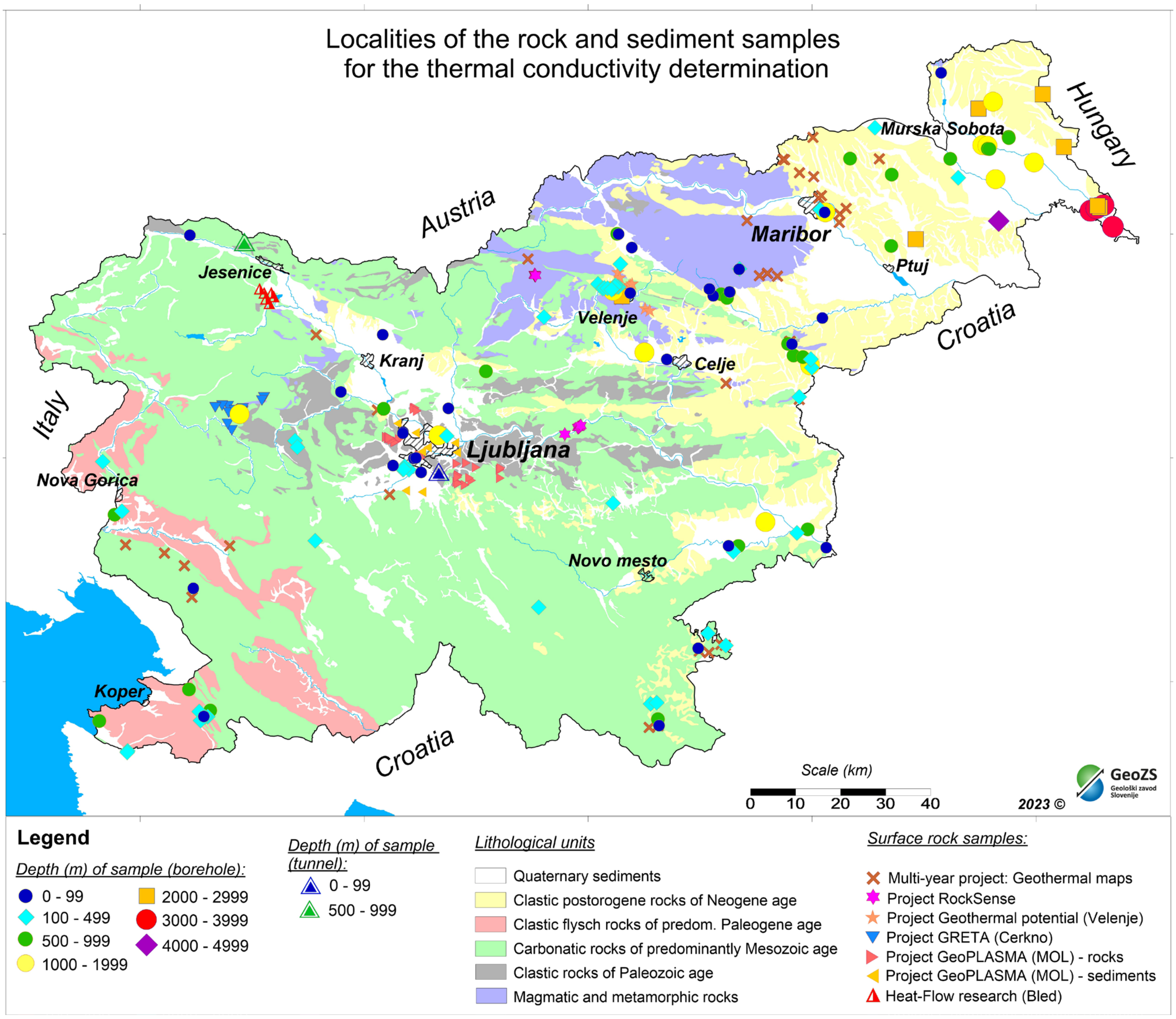

Fig. 10. Localities of the 119 boreholes, two road tunnels and numerous points on the surface where the rock samples have been taken for TC measurements. The boreholes are distributed according to maximum depth of the cored rock samples. The map of lithologic units is simplified after Bavec et al. (2013).

J1-3024) and for the heat flow research (Adrinek et al., 2019; Serianz, 2022). Many surface rocks were already sampled since 1983 for the multi-year project "Geothermal maps of Slovenia" (Ravnik & Rajver, 1990; Ravnik, 1988, 1991; Ravnik et al., 1995).

It should be emphasized that many rock samples and especially sediments, which were cored in boreholes, were brought to the laboratory with mostly preserved pore water content. They were properly wrapped, often even protected with paraffin. So, we took the measurements as soon as we unwrapped them from the protection. For these critical samples, especially samples of sand, sand with impurities, silt and also some sandstones, we characterized the condition of the sediment (and rock) as saturated, semi-dry or dry (Appendix A). It is worth noting that the mean TC values in Table 2 do not show all the diversity of sediments and rocks, for this it is recommended that the user looks at Appendix A and the corresponding graphs for individual rock and sediment types to get a sense that many things affected the larger range of measured TC values, for example, the state of the samples itself (saturated, semi-dry, dry) or whether they were crumbled, fissured and similar.

In the following graphs (Figs. 11–19), the values of measured TC on rock samples, including sediments (such as sand and clay), are shown against the depths of the coring of rocks from the boreholes and depths of sampling below the surface in two tunnels. Samples from numerous surface locations are included (drawn at a depth level of 0 m). In each graph, the arithmetic mean and median of all values together with a range of measured values is presented (Fig. 9, Table 2).

Details of the state of the rock samples and sediments during measurements are shown in Appendix A. It is important to emphasize that thermal diffusivity has only been measured since 2017, when the TCS meter was upgraded. Thermal diffusivity (TD) was measured on a total of 27 rock samples from eight boreholes and on 104 samples from surface locations (Appendix A).

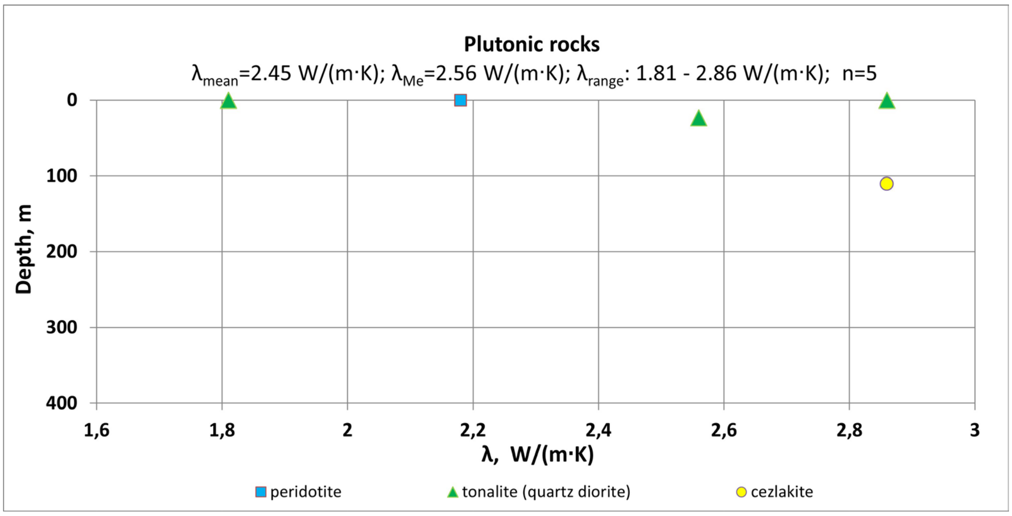

Fig. 11. Thermal conductivity of five samples of plutonic rocks.

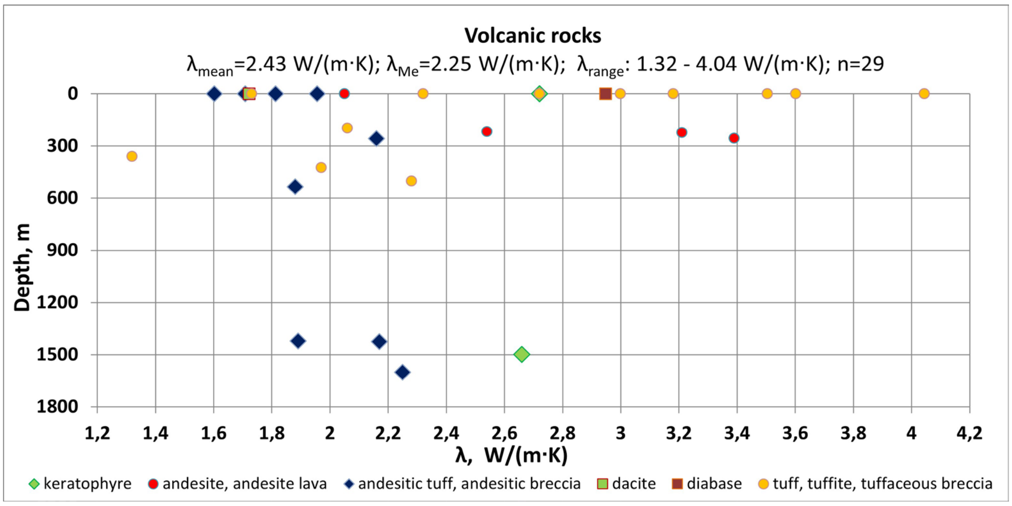

Fig. 12. Thermal conductivity of 29 samples of volcanic rocks.

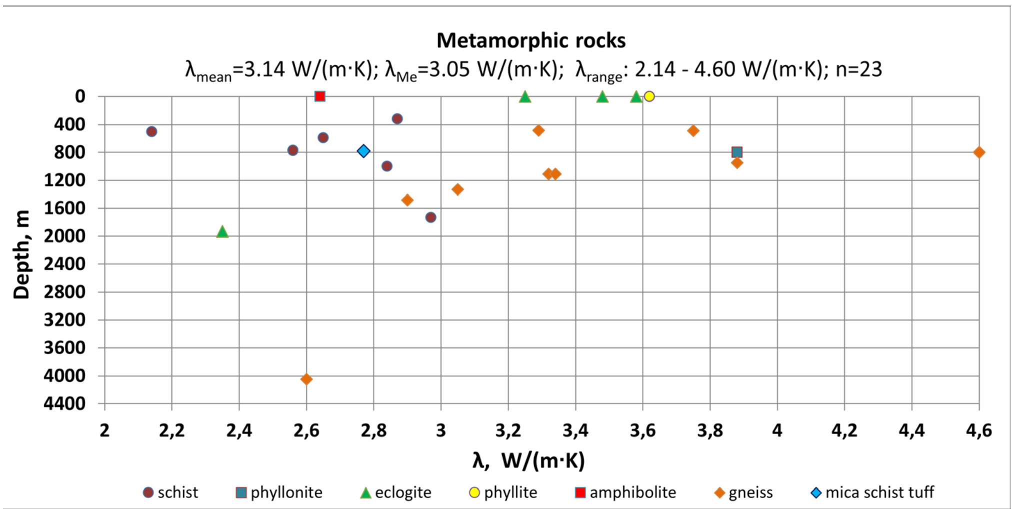

Fig. 13. Thermal conductivity of 23 samples of metamorphic rocks.

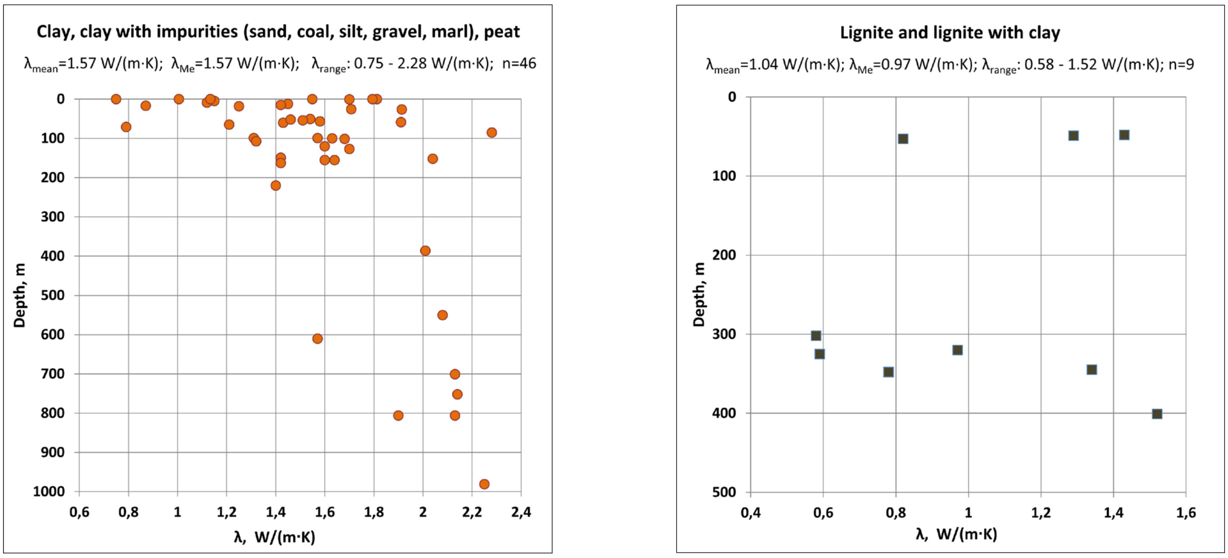

Fig. 14. TC of 46 samples of clay, clay with impurities and peat on the left and on the right TC of nine samples of lignite and lignite with clay.

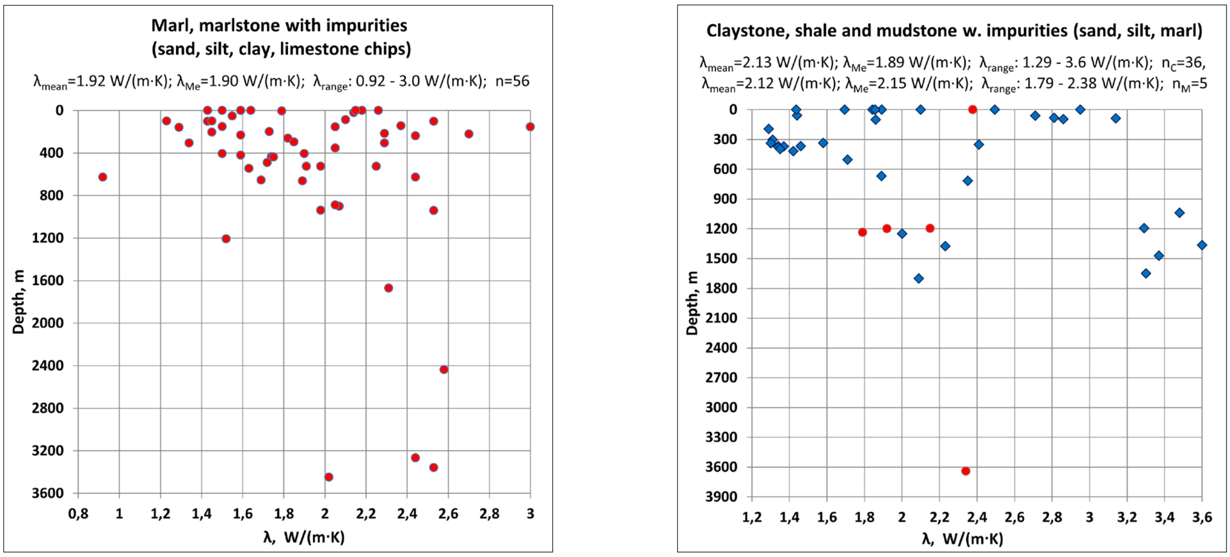

Fig. 15. TC of 56 samples of marl and marl with impurities on the left and on the right TC of 36 samples of claystone and shale (rombs) and five samples of mudstone (circles); some samples also include impurities.

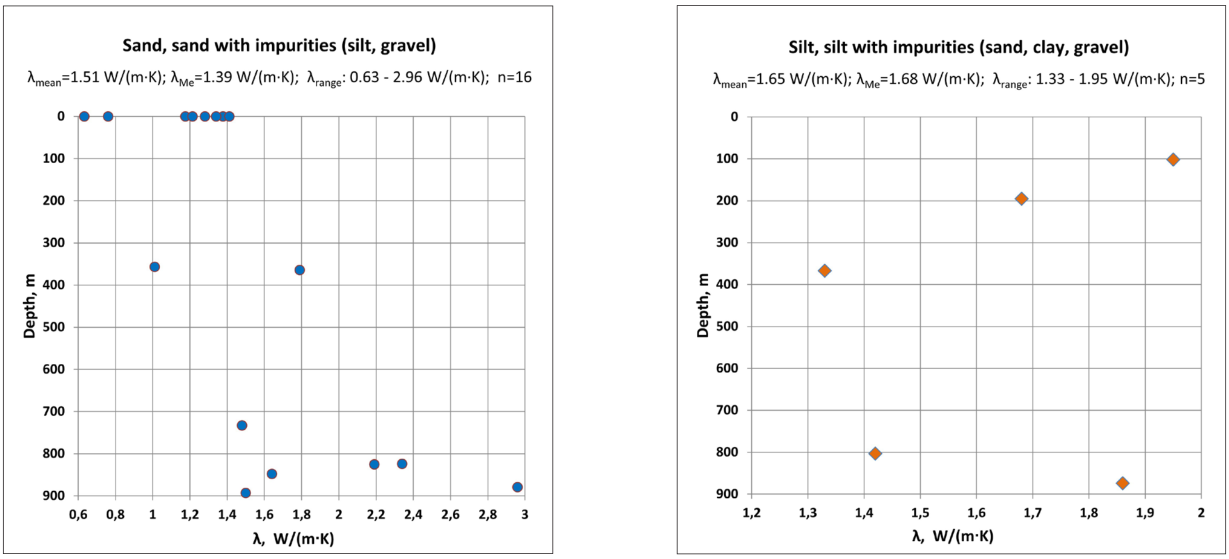

Fig. 16. TC of 16 samples of sand and sand with impurities on the left and on the right TC of five samples of silt and silt with impurities.

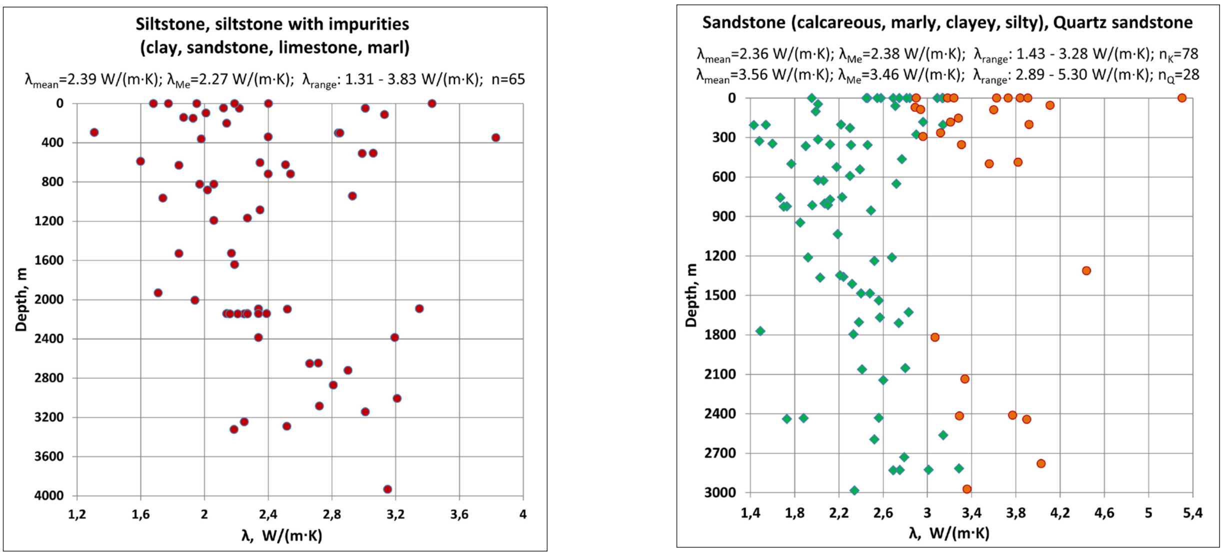

Fig. 17. TC of 65 samples of siltstone and siltstone with impurities on the left and on the right TC of 106 samples of sandstone; of them 78 samples are calcareous or marly, clay, silty sandstones (rombs), some of them with impurities, and 28 are quartz sandstones (circles).

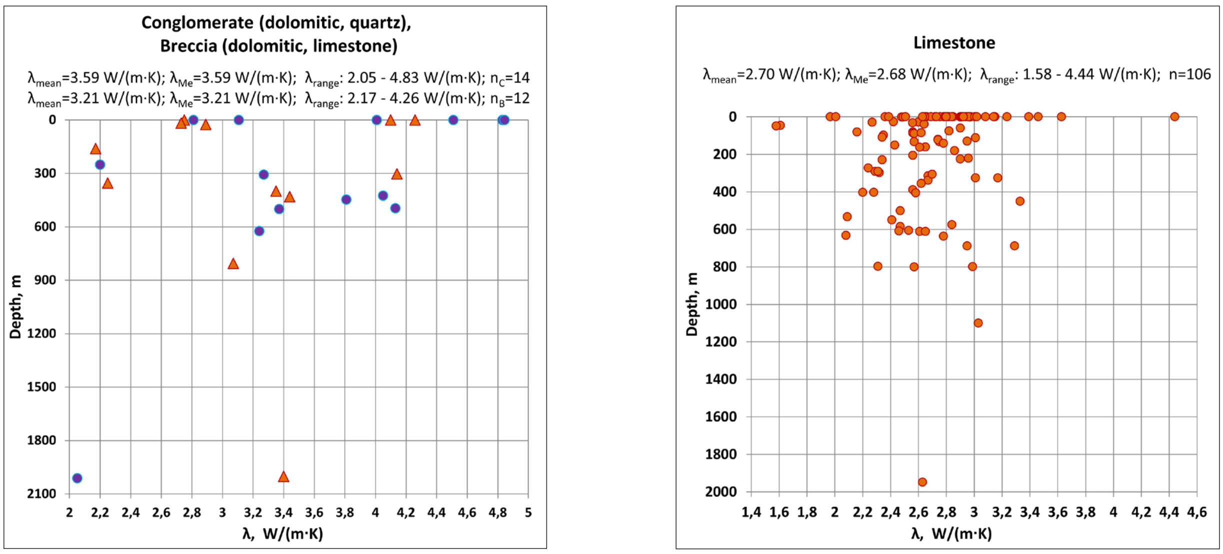

Fig. 18. TC of 14 samples of conglomerate (circles) and 12 samples of breccia (triangles), both of different compositions, on the left and on the right TC of 106 samples of limestone.

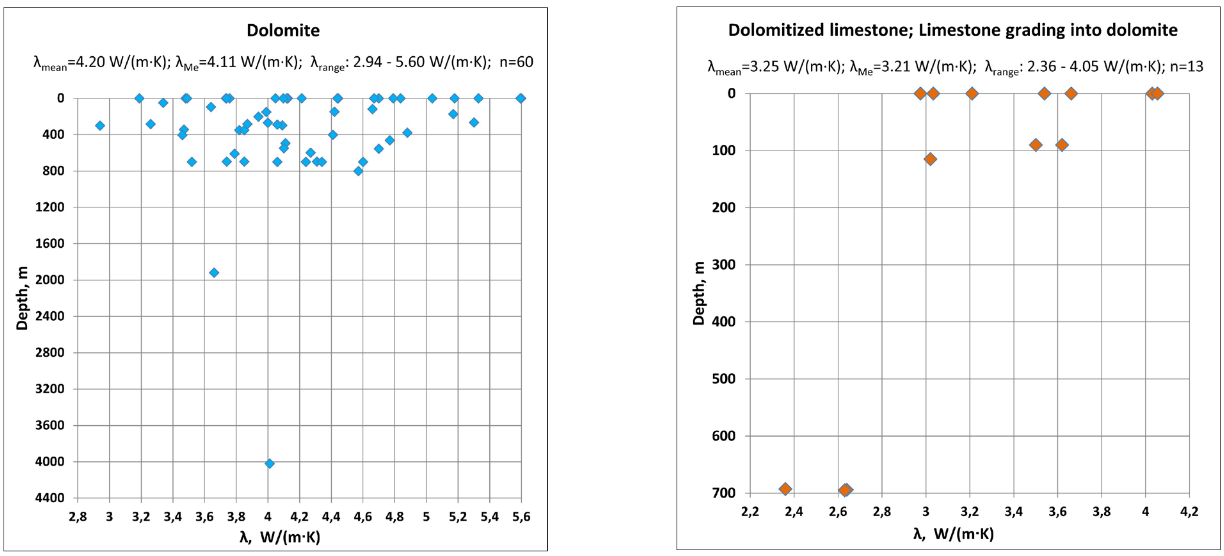

Fig. 19. TC of 60 samples of dolomite on the left and on the right TC of 13 samples of dolomitized limestone and limestone grading into dolomite.

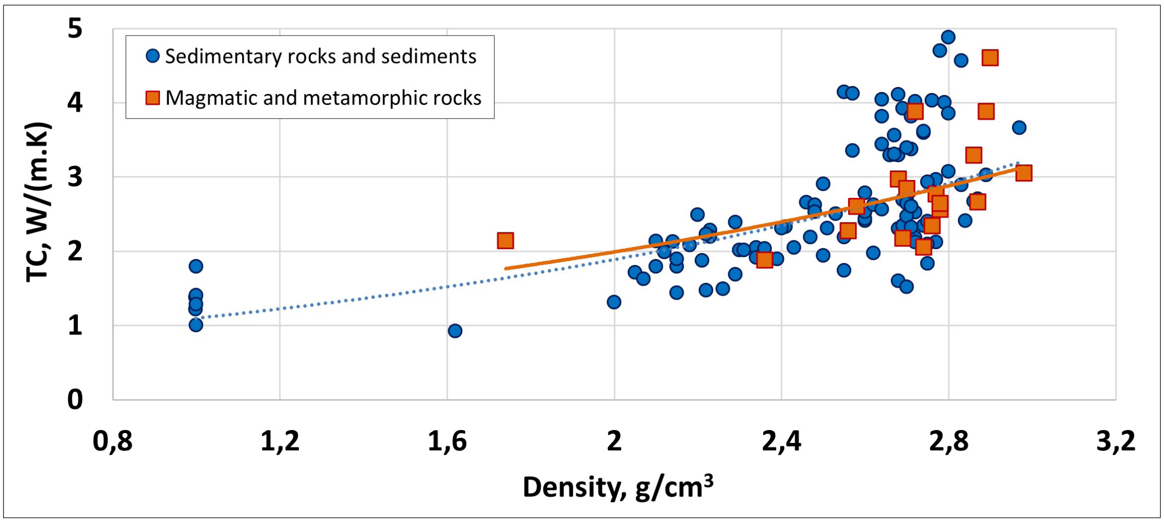

Fig. 20. Relation between TC and density for sedimentary rocks and sediments (blue) and for magmatic and metamorphic rocks (orange).

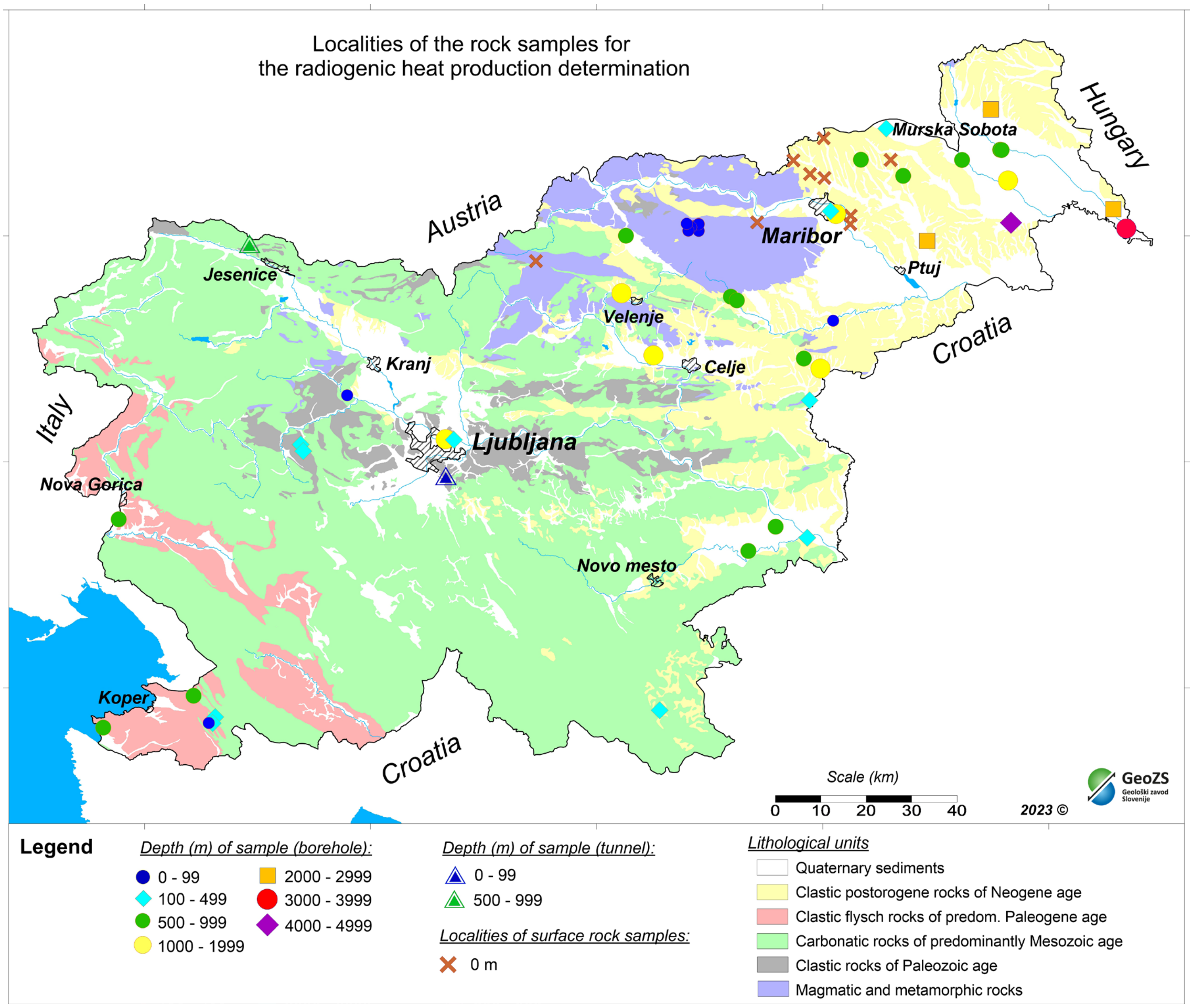

Fig. 21. Localities of the 39 boreholes, two road tunnels, 9 surface localities and 9 very shallow boreholes where the rock samples have been taken for radioactive heat production determination. Boreholes are distributed according to maximum depth of the cored rock samples, and both tunnels are distributed according to maximum depth of extracted rock below the surface (above the tunnel). From very shallow boreholes the samples were taken at a depth of 1 m, and only in one borehole from a depth of 5 m. The map of lithologic units is simplified after Bavec et al. (2013).

A relationship between measured density and TC is shown for 126 rock and sediment samples. Of these, 18 samples are igneous and metamorphic rocks, the rest are sedimentary rocks and sediments (Fig. 20). We found a good relationship between TC and density, with TC increasing with density. Both quartz and olivine play an important role in the relationship between TC and density. In the first case, TC usually decreases with density, and in the second case, TC increases, as already discussed by Pasquale et al. (2015). Also, there is a noticeable scatter in our results. The fact is that not all the samples (in Fig. 20) contain quartz, but only some igneous and metamorphic rocks as well as sandstones and conglomerates. Therefore, TC is not observed to decrease with density in the case of quartz-bearing rocks. At most, we observe that the trend is neutral if we exclude the chlorite carbonaceous schist (phyllite) sample with the lowest density (1.74) and quite low TC (2.14). We can only assume that the relationship is influenced by rock compaction, which is related to mineral composition, as many samples were taken from shallower or greater depths.

Radiogenic heat production of rocks in Slovenia

Localities of the boreholes, two road tunnels and points on the surface from where the rock samples have been taken for the radioactive heat production determinations are shown in Fig. 21. Altogether 144 rock samples were analysed for the concentrations of the mentioned radioisotopes, of them 112 samples from the 39 boreholes, 14 samples from both tunnels (13 from the Karavanke tunnel and 1 from the Malence tunnel SE of Ljubljana) and 18 samples from surface locations, nine of them from depths of 1 m in very shallow boreholes. Their density was first measured and then properly ground into small particles (appr. as small as silt).

In Appendix B, we also show the results of TC measurements of some rock samples (already listed in Appendix A under the same database numbers), which showed distinct layering (sandstone, siltstone, marl) and foliation (gneiss). With this, the effect of anisotropy in heat conduction was verified and, using the same equations as Jorand et al. (2013) have done for TC measured perpendicular and parallel to bedding or foliation, the anisotropy values for certain rock types were found roughly similar to those presented by Kappelmeyer & Haenel (1974) and Di Sipio et al. (2014).

Discussion

It is known that the physical properties of the rocks, such as porosity (e.g. water content), texture and homogeneity of the material, can be significantly modified by tectonic events acting on the territory together with the climate and environmental conditions, for example igneous rocks may be affected by different weathering conditions. All these facts can lead to more or less different TC values from those mentioned in the literature (Di Sipio et al., 2014). Therefore, we strive to create geological and geothermal models, in which the thermo-physical properties of the main lithologies are defined based on real data obtained through laboratory or in-situ measurements and, when necessary, supplemented with data from the literature and well-logging data (Norden et al., 2012). Most of the measured TC values are also accompanied by the standard deviation data, which is a good indicator of the quality of the measurement and how heterogeneous and/or tectonically broken the rock is.

Heat exchanger designers and planners in Slovenia most often use TC values from standard tables in the following standards (Prestor et al., 2020): the German standard VDI 4640 (VDI, 2001), the Swiss standard SIA (Eugster et al., 2010), the British standard MIS 3005 and the American ASHRAE standard. It is assumed that the latter two are less used in Slovenia. The comparison of the results of our measurements on rocks within the projects GRETA and GeoPLASMA with the TC values in four standards (UNI standard 2012 according to VDI 2001, SIA 384/6, MIS 3005 and ASHRAE) is given in the link (page 152 in Prestor et al., 2020). The range of measured TC values complies with those in the cited standards and also with results published in other literature (e.g. Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988; Beardsmore & Cull, 2001). Possible minor deviations between our results and other foreign values of TC are caused due to differences in mineral composition within the samples of the individual lithological types.

We believe that our results could form the basis for a possible future Slovenian standard for thermal properties of measured rocks and sediments, as they also cover some lithological types that are not presented in the existing foreign standards, but appear on the Slovenian territory, like dolomitized limestone, dacite, phyllonite and lignite. For several rock types our results are more constrained than the values in the mentioned standards, as they fall within a narrower range of TC values than reported in other sources.

The results of TC and TD measurements on 32 rock samples from the municipality of Cerkno (project GRETA) have already been presented by Casasso et al. (2017) with maps of shallow geothermal potential intended for the design of closed-loop HP systems with the BHEs. The rock types sampled were claystone and shale, siltstone, sandstone, quartz sandstone, quartz conglomerate, dolomite, dolomitized limestone, limestone, marl and marly limestone, tuff and diabase, all with an age from Carboniferous to Upper Triassic.

In the MOL area, rocks were sampled mainly in the western and eastern parts and on the Ljubljana castle hill (project GeoPLASMA). The rock types of a total of 47 representative measured samples were claystone and shale, siltstone, mudstone, sandstone, sandstone with siltstone and claystone, quartz sandstone, conglomerate, quartz conglomerate, limestone, Dachstein limestone (with grading into dolomite), marl (marly dolomite) and tuff, with ages ranging from Upper Carboniferous to Upper Cretaceous. In addition, in central and southern parts of the MOL, also *in situ* measurements were done using the needle probe method. The measured sediments of Quaternary age were clay with sand and silt, sand with gravel, gravel with sand, river sand, gravel with sand and silt, clay with silt, and peat. The results of all measurements on rocks and sediments from the MOL area have already been presented by Janža et al. (2017).

As part of geothermal heat flow research, six rock samples were measured from the Lake Bled area (Adrinek et al., 2019; Serianz, 2022), comprising the following rock types from Upper Permian to Ladinian age: limestone, massive dolomite, organogenic limestone, massive dolomite with oncoids and stromatolites, dolomite breccia, micritic limestone and marly limestone with mica. The collected outcrop samples were dried in an oven for 24h on 60°C before measuring. Later, the dried samples were saturated by submerging them in distilled water inside a sealed vacuum exsiccator. The values for thermal conductivity and diffusivity fall within the expected values for these rock types.

For the LIFE ClimatePath2050 project, an analysis of the potential of shallow geothermal energy in Slovenia until 2050 was performed. The final report (Prestor et al., 2018) shows two maps – the thermal conductivity and volumetric heat capacity of rocks and sediments on the surface of Slovenia. For the first map, however, it was necessary to upgrade data from laboratory results to lithological units. The TC values of rocks and sediments on the TC map were attributed on the basis of mean TC values obtained from measurements on many different rocks and sediments, mainly from boreholes (435 samples from 118 boreholes and 2 tunnels) and less from surface locations (35 samples). Thus, the mean TC values were used to create the TC map of Slovenia. For Quaternary, Neogene, and Paleogene sediments, different mean values for several different types of sediments were used, from Lower Paleocene to Quaternary in age. They were assigned from different surface locations and boreholes with a proper care as regard to the lithological formations. Therefore, the assigned TC values are not a mixture of different types of sediments. The TC values were assigned to the lithological units of the basic geological map of Slovenia at a scale of 1:100,000. The same basic geological map served as the basis for the second map, where the average values of the volumetric heat capacity of rocks and sediments were taken from two standards, SIA (Eugster et al., 2010) and VDI (2001).

The largest number of measured samples for TC is that of sedimentary rocks and sediments, followed by volcanic rocks, metamorphic and plutonic rocks (Fig. 9). The range of measured TC values for plutonic rocks (Fig. 11) is between 1.81 and 3.04, with a TC mean of 2.45 W/(m·K). Higher TC value is shown by plutonic rock of gabbro group (cezlakite). The range of measured TC values for volcanic rocks (Fig. 12) is between 1.32 and 4.04, with a TC mean of 2.43 W/(m·K). Some rock types show quite high range of values, with the highest TC values measured on andesite, tuff and tuffaceous breccia and diabase. The range of measured TC values for all metamorphic rocks (Fig. 13) is between 2.14 and 4.60, with a TC mean of 3.14 W/(m·K). The highest TC values are shown by phyllonite, some gneisses and phyllite. Among the gneiss samples is also one sampled until now in a deepest (4048 m) borehole LJUT-1/88 at its base.

As expected, the highest range of measured TC values is represented by sedimentary rocks and sediments, being between 0.58 and 5.60, with a TC mean of 2.58 W/(m·K). In the lower part of this range, there are sediments, such as clay and clay with impurities (Fig. 14), with a range of 0.75 to 2.28 and a mean TC of 1.57 W/(m·K), and lignite (Fig. 14) with a range of 0.58 to 1.52 and a TC mean of 1.04 W/(m·K). The samples of sand, when dry, also show low TC values, and in total the range of TC values for all sand samples, also sand with impurities (Fig. 16) is between 0.63 and 2.96, with a mean TC of 1.51 W/(m·K). The samples of marl and marlstone (Fig. 15) were quite numerous (56 in number), showing the range of values between 0.92 and 3.00, with a TC mean of 1.92 W/(m·K). The samples of claystone and shale (Fig. 15) present higher range of TC values, 1.29 to 3.6 W/(m·K), with a mean TC of 2.13 W/(m·K), while the mudstone samples (Fig. 15) show the range between 1.79 and 2.38, with almost the same mean TC of 2.12 W/(m·K). Only five samples of silt (Fig. 16) were measured, showing the range of 1.33 to 1.95, with a mean TC of 1.65 W/(m·K). The samples of siltstone and siltstone with impurities (Fig. 17) were also numerous (65 in number), their TC range is between 1.31 and 3.83, with a mean TC of 2.39 W/(m·K). The range of measured TC values on numerous sandstone samples (Fig. 17) is visibly different for calcareous, marly, clayey and silty sandstones (78 in number) on one side and for quartz sandstones (28 in number) on the other side. For the first ones it is between 1.43 and 3.28 W/(m·K), with a mean TC of 2.36 W/(m·K), while for the quartz sandstone it is between 2.89 and 5.30, with a mean TC of 3.56 W/(m·K). The range of measured TC values for the samples of conglomerate and breccia (Fig. 18) is not so much different. For the conglomerate samples (14 in number) it is between 2.05 and 4.83, with a mean TC of 3.59 W/(m·K), and for the breccia samples (12 in number) it is between 2.17 and 4.26, with a mean TC of 3.21 W/(m·K). The range of measured TC values for the numerous samples of limestone (106 in number, Fig. 18) is between 1.58 and 4.44, with a mean TC value of 2.70 W/(m·K). Samples of dolomite (Fig. 19) were also numerous (60 in number) with a sample from the second greatest depth (4020 m) in the country. Their range of TC values is between 2.94 and 5.60, with a mean TC of 4.20 W/(m·K). Lastly, the range of measured TC values for the samples of dolomitized dolomite and limestone grading into dolomite (Fig. 19) is from 2.36 to 4.05, with a mean TC of 3.25 W/(m·K).

The range for measured thermal diffusivity of rocks and sediments varies between 0.22 mm^2/s for peat with organic clay and 0.42 mm^2/s for clayey sediment of Quaternary (Holocene) age on low side and 2.31 mm^2/s and 3.62 mm^2/s for quartz sandstone of Ladinian and Upper Carboniferous age, respectively, on high side.

The range for determined radiogenic heat generation in the rocks varies between 0.26 $\mu W/m^3$ for milonitized dolomite of Triassic age to 7.09 $\mu W/m^3$ for dark grey sandstone with black shale clasts of Middle Permian age. The latter rock sample was cored in the borehole V-931/88 in the Uranium mine Žirovski vrh (database number 37 in Appendix A), where the production of uranium ore was closed in 1992. The density of the rock was also measured for all those rock samples on which radiogenic heat generation was determined (Ravnik et al., 1995). For one group of surface rock samples with determined radiogenic heat, their density was not measured but only assumed. The measured rock densities vary from as low as 1.651 g/cm^3 for silty marl of Lower Badenian or Karpathian age to 3.042 g/cm^3 for granat-muscovite-biotite gneiss of Precambrian age.

Conclusions

With the presented measurement results on rock and sediment samples from Slovenia, we have presumably covered more than 90 % of all lithological types that occur on the surface of the country. The question is, what other lithological types would be encountered at depths of up to 4 or 5 km, if such boreholes were made in certain areas of Slovenia, especially in areas with metamorphic and igneous rocks, not only as surface rocks but also in the subsurface. For example, thermal conductivity has not yet been measured on any of the following interesting rock types, most of which occur very locally on the surface in Slovenia: poorly metamorphosed slate, quartzite, calc-phyllite, calc-schist, granite gneiss, serpentinite, granite, rhyolite, rhyodacite, syenite and granodiorite.

Nowadays, various users of data on the thermal parameters of rocks and sediments rely on data from the literature. However, direct measurement of thermal parameters on representative samples for a certain territory is necessary to provide real data to energy and infrastructure planners, public authorities and operators involved in the exploitation of geothermal energy resources in low, medium and high enthalpies (Di Sipio et al., 2014). Although it is known that the thermal response test (TRT) is the most reliable method for determining in-situ thermal properties in the shallow underground, as it also includes local hydrogeological conditions and physical parameters of the specific lithological units, it is expensive and time-consuming. Therefore, it is advisable to perform it in cases where large scale closed-loop systems are planned (e.g. more than 10 BHEs), and the use of literature data is sufficient when small scale closed-loop system are planned (individual houses). A good alternative to the field method are precise laboratory measurements, which could be used on a regional scale to provide necessary information for the dimensioning of closed-loop systems with the heat pumps and to better predict the geothermal conditions for the planning of deep boreholes.

We are confident that the thermal property results of Slovenian rocks and sediments are within the expected range for each lithological type, which is confirmed by literature data, thus highlighting the quality of our methodology and measurements. We believe that by presenting the results of TC and TD measurements in a manner as they are in Appendix A, the requirements of the IHFC Global Heat Flow Database Renovation Group (Fuchs et al., 2021) are satisfied also for the compilation and collection of metadata. Our results could be the basis for the possible future Slovenian standard of thermal properties of measured rocks and sediments.

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Appendix A and B: Supplementary data associated with this article can be found in the online version at https://doi.org/10.5474/geologija.2023.005

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