THERMAL CONDUCTIVITY OF SEDIMENTARY ROCKS IN THE LOWER INDUS BASIN, SINDH, PAKISTAN

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Abstract: Thermal conductivity plays a significant role in fields such as oil and gas exploration, geotechnical engineering, and mining industry. Knowledge of thermal properties of rocks is essential in investigating the geothermal gradients and thermal maturity of different reservoir bearing formations. Unfortunately, thermal property data on Pakistan's most producing basin, lower Indus basin, does not exist and is least known. Hence, the study has also carried out thermal conductivity experiments along with other petrophysical properties on sedimentary rocks obtained from lower Indus basin. The experiments conducted include but are not limited to thermal conductivity, porosity, permeability, and X-ray diffraction (XRD) tests. It was observed from experimental results that samples containing a slightly higher percentage of clay have lower thermal conductivity as it acted as insulating to the heat conduction. Results obtained were cross plotted and displayed that there is reasonable relationship between thermal conductivity and porosity values however, no clear relationship appears between thermal conductivity and permeability. XRD showed that the dominating mineral within sandstones samples were quartz with minor quantity of illite and smectite.

Key words: *Thermal conductivity, Eocene strata, Sedimentary rock, thermal properties of rocks, lower Indus basin*

1. Introduction

Thermal conductivity of sedimentary rocks is important in understanding the geothermal gradients, thermal evolution, earth internal dynamics and thermal maturity of different reservoir bearing formations (Tang et al.2018; Tosi et al., 2013). Understanding the mechanism of the earths' internal structure, temperature distribution of the earth underneath and the history of the earth's thermal evolution is also essential and studied by several researchers (e.g. Ray et al., 2007; Geng et al., 2018, and Tang, et al. 2018, Gul et al. 2018; Kovačević et al., 2013; Liu et al., 2012; Abdulagatova et al., 2009). Essentially, the knowledge about thermal conductivity of rocks is beneficial in understanding various scientific, engineering and technical applications including the underground storage of thermal energy (e.g. Kun Sang Lee, 2013; Fridleifsson, 2001; Kovačević et al., 2013), the oil or gas pipelines buried underneath of the earth (Horai, 1971; Zhao et al., 1995, Tang, 2013), underground deposition of nuclear wastes (Somerton and Gupta, 1965, Brace et al. 1968; Kujundžić et al., 2012). Furthermore, the thermal conductivity has importance in understanding and development of the subsurface gasification of coal (e.g. Maugh, 1977, Wen et al., 2015, Yao et al., 2016) and it has also significant standing in geothermal energy techniques and advancements in geothermal energy (e.g. Kun Sang Lee, 2013; Hofmeister, 2014, Verma et al., 2016). The thermal conductivity of sedimentary rocks plays a decisive role in storage and long-term sequestration of CO_2, soil mechanics, geotechnical designs. Thermal conductivity has significant impact on steam injection in subsurface for heavy oil reservoirs productivity enhancement (e.g. Sarma et al. 2017). A comprehensive study of the geological catastrophes and the expansion of geological structures is essential, which requires the detailed knowledge of the thermal behavior of different rocks under different temperature conditions (e.g. Geng et al., 2018). Investigating the effect of thermal conductivity underneath rocks is essential in understanding their thermal characteristics and important for engineering as well as geological research (e.g. Geng et al. 2018). Generally, understanding the thermal characteristics in oil and gas field developments within mature reservoirs is also important to enhance productivity by injecting hot water and steam inside the reservoirs (Sarma et al. 2017).

Further the impact of thermal properties upon different rock forming minerals is well documented (e.g. Christoph, 2011) since the rock specimen are comprised of varying mineral composition hence their conductivities significantly vary. In general, it is seen that the rock forming minerals, and their structures are not well explained due to their complex composition. If it is observed that the type of rock is somewhat does not provide detailed description of their physical properties. The properties of any of the rock are based on their dominating mineral occurrence. Hence, the required properties of rock could be characterized based on the dominating mineral and internal structure of given samples. In order to characterize the thermal conductivity of sedimentary rocks and the factors that could affect the thermal conductivity are the mineral content, the rock porosity, pore fluid occurrence, saturation, rock heterogeneity and anisotropy (e.g.Geng et al., 2018) . The rocks do not possess unique internal structure and their composition varies too, hence aforementioned factors could vary for each rock, such a variation of rock composition leads to varying thermal conductivity. The thermal conductivity could be characterized in a statistical manner in (e.g. Clauser, 2006, 2009) rendering to the rock diagenetic classification. Extensive work on thermal conductivity data collections, analysis and investigations has been compiled by various researchers (Birch, 1942, Clark, 1966, Horai & Simmons, 1969), Dreyer, 1974, Čermák & Rybach, 1982, Carmichael, 1984, Popov et al., 1998, Clauser, 2006, Ray et al., 2007; Kovačević et al., 2013 and Geng et al., 2018). However, the thermal conductivity of the sedimentary basin in Pakistan is least compiled. If thermal conductivity of sedimentary basin is not appropriately predicted, then its implications for analyzing thermal histories and the organic maturation of hydrocarbon generations may become unsuccessful when applied to real basins (e.g. David and Steele,1989). Unfortunately, the thermal property data on Pakistan's most producing basin, Lower Indus Basin does not exist and is least known. Hence, it would be very difficult to predict their thermal maturity and thermal histories effectively. Hence, keeping this fact in view, a detailed study was conducted on thermal conductivity on the samples from various different regions of Pakistan. The interrelationship of thermal properties of different rocks formations from Lower Indus Basin, Sindh Pakistan has been investigated. Thermal conductivity tests were conducted on sedimentary rocks including sandstone formations, limestones which were mainly composed of calcite.

1.1. Field location and Geology of Lower Indus Basin

The study area is present in the southern part of lower of the lower Indus basin as shown in figure 1. The Lower Indus Basin, lying south of 3 out 155,000 square miles of Pakistan and contains in its deepening of Jurassic, Cretaceous and Tertiary Sediments. The present stratigraphy in general is the original subdivisions established many years ago by the (with refinements made in the coiirfe of petroleum exploration. The rocks in lower Indus basin are oldest sedimentary rocks exposed are Permian Triassic strata (Kadri, 1995). The Jurassic consists mainly of limestone and in the western part of the basin may be divided into four formations. The Cretaceous is a dominant marine classic and is divided into six formations. The Lower Tertiary is about half carbonite and half clastic, largely marine, and consists of five formations, a thick sequence of continental outwash deposits. The Lower Indus Basin has an elongated shape and is oriented in northeast-southwest direction and according to Klemme's classification it falls in the category of extra continental down warp trough type (Memon et al., 2005). It is divided into two basins Upper and Lower. The Lower Indus basin starts from Sargodha high and extends southwards to offshore Indus basin. The lower Indus basin covers an area of more than 250,000 km^2 area (Shah, 2009). The lower Indus basin is further subdivided into two basins, central Indus basin and Southern Indus basin (Farah et al., 1984). The lower Indus Basin is comprised of many structural zones suggested by (Kazmi, 1997; Kazmi and Jan, 1997; Kazmi and Rana 1982). These include` buried ridges of Sargodha-Shahpur and Nagar Parkar; Zones of Upwarp include Mari-KandhKot High, Jacobabad-Khairpur High, Thatta Hyderabad High and Tharparkar High; Zones of downwarp and platform slope include Northern Punjab Monocline, Southern Punjab Monocline, Cholistan shelf, Panno Aqil graben, Nawabshah slope, Lower Indus trough, Nabisar slope and finally Sulaiman and Kirthar foredeeps are included. The stratigraphy of the lower Indus basin extends from Triassic to Tertiary (e.g. Memon et al., 2005). Except for some tertiary continental deposits, almost the entire sequence of lower Indus basin is of marine origin (Shah, 2009). Due to Punjab and Sindh Monocline structure dipping east to west, the sedimentary cover above the basement increases towards west in thickness and attains maximum thickness near foredeeps (Memon et al., 2005). According to Memon and Siddique (2005) stratigraphy of lower Indus basin as distributed as, Shales and Sandstones in Triassic followed by clastics in the lower part and shallow marine limestone at the upper part in Jurassic. The cretaceous sediments consist of shales deposited in deep depressions and overlain by shallow marine limestones and thick sandstones in upper part (Memon and Siddique,2005). Palaeocene rocks mostly are shallow water clastics overlain by limestones and at some places basalts are present in the lower Palaeocene strata. Further Memon and Siddique (2005) has stated that the

Eocene strata comprise mostly limestone with subordinate shale, Oligocene rocks are limestone, shale and sandstones. Miocene rocks consist dominantly of shale, limestone and sandstones. Plio-Pliocene rocks consist of coarse grained to fine grained clastic.

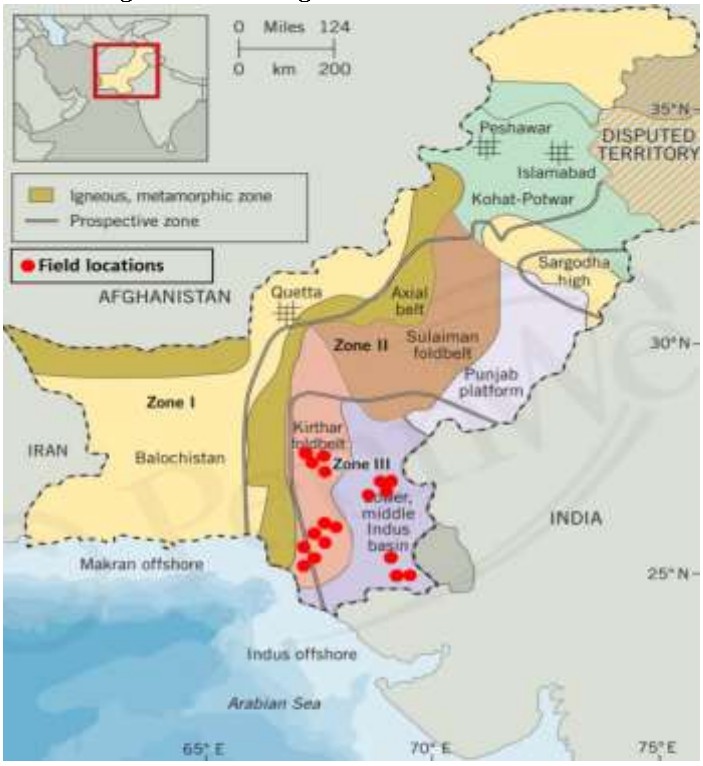

Figure 1 Sketch map showing the sample collection locations of the lower Indus Basin Pakistan (modified from Shar et al. 2016)

1.2. Samples, apparatus and methods of measurement

1.2.1 Sample preparation

In present study, the samples from different locations of lower Indus Basin Sindh Pakistan were collected to measure the thermal conductivity. The required sizes of samples for experiments were cut and prepared to give them appropriate shape to make the measurements. The required sizes of sample as per experiment facility were obtained after cutting it using the marble cutting machine from the local market. Thermal and electrical conductivity tests on samples of varying size ranging from 45 mm diameter and 15 mm with varying thickness were prepared. The samples were then soaked (for two days) and subsequently oven dried at 102± 10 °C for 24 hours prior to conduct of their thermal and electrical conductivity experiments.

1.2.2 Thermal conductivity measurement method

Thermal conductivity could be measured by various methods under normal pressure and high temperature conditions. In general, the methods of measuring thermal conductivity are mainly divided into two categories: the transient methods and steady state methods **(**Hanley et al., 1978; Hofmeister, 2006; Wen et al., 2015**)**. In this study the thermal conductivity measurements were made using the newly developed steady state experimental setup **Error! Reference source not**

found. (Gul et al., 2018). The setup is used for measuring the thermal resistance of various sizes of specimen. The system developed operates at various temperatures of heat source and heat sink. The system has capabilities of measuring the thermal conductivity of even powder unconsolidated and consolidated cemented solid specimens (Gul et al., 2018). The system of thermal conductivity experimental setup designed works on principle of steady state-based methodology. In the first instance the calibration of the system is essential hence prior to rock's thermal conductivity measurement the setup was calibrated with known conductivity of the samples. After performing calibrations, the measurements were made on the prepared specimens of rock samples. The Schematic of the system developed for thermal conductivity is shown in **Error! Reference source not found.** (Gul et al., 2018). The all components of the thermal conductivity experimental set-up used for measurement of their thermal conductivity of present study are listed in Table 1. Furthermore, the system has been designed in such a way that the relative place of the heat flux transmission towards the sample is not fix (the relative position could be on either side i.e. the hot or cold side).

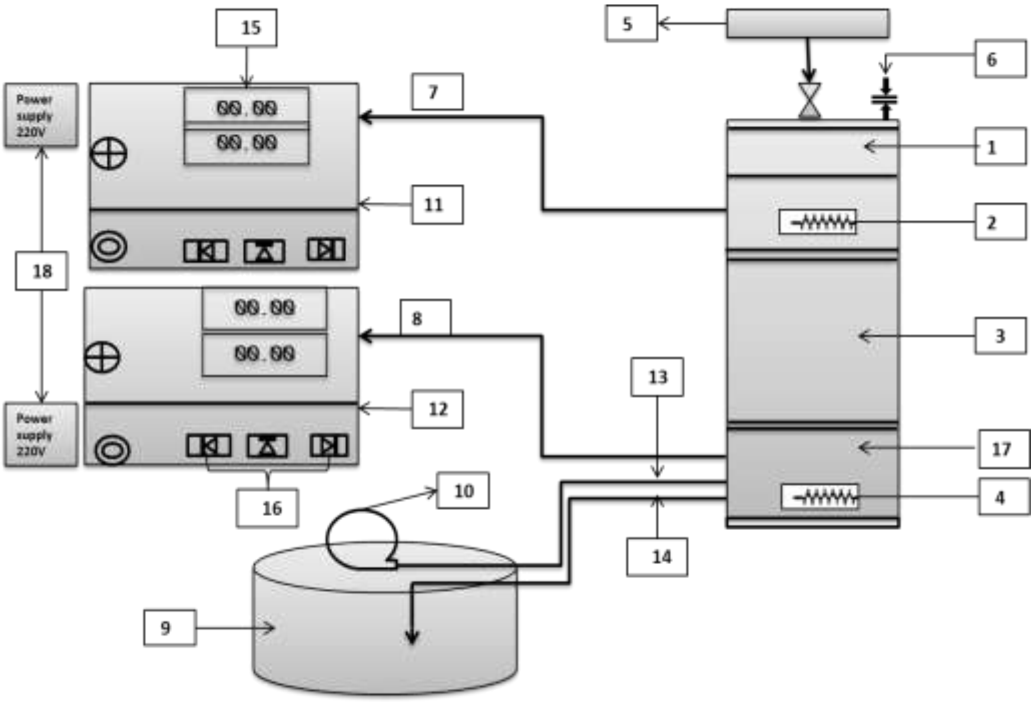

Figure 2. Basic experimental setup layout of thermal conductivity measurement apparatus (taken from Gul et al. 2018)

Table 1 Components of thermal conductivity setup (Gul et al., 2018)

Components			
1	Top plate	10	Pump to discharge fluid for circulation
2	Upper Thermocouple heating coils	11	Upper temperature sensor
3	Soil sample	12	Lower temperature sensor
4	Lower Thermocouple heating coils	13	Fluid Inlet pipe
5	Surcharge weight	14	Fluid outlet pipe
6	Power 110 Voltage	15	LCD display (heat flux transducer)
7	Upper temperature sensor wire	16	Control switch

8	Lower temperature sensor wire	17	Lower plate
9	Cooling bath	18	Power supply [220 Voltage]

1.2.3 Thermal conductivity measurement principle

The working principle of the system is based on typical guarded heat flow technique. The thermal conductivity measurements depend upon the heat flux equation, which is represented as below,

$$K = QL/A\Delta T \quad (1)$$

Where, K is the thermal Conductivity of the tested sample, Q is the flow of heat across the sample, L is the length of the sample, A is the Cross-sectional area of the sample and ΔT is the temperature difference between sensors. To measure the thermal of rock samples tested the following readings were taken:

Q = The amount of heat energy (Watts)
T1 = Heat source temperature (0C or K)
T2 = Heat sink temperature (0C or K)
A = Area cross-section of the specimen (m2)
L = Sample thickness (m)

1.2.4 Samples preparation for permeability measurement and other data collection

The sedimentary rocks of various locations were collected from outcrops in the lower Indus basin for analyses ranging from a typical size of 10 to 20 cm. The cylindrical plugs and cubes were taken for further petrophysical property analysis. The coring and plugging machine present the laboratory of the department was used for taking standard sized plugs. The plugs and cubic blocks of appropriate size were prepared for experiments. The plugs of appropriate diameters taken using the coring facility of the department were 1 inch and one and half inch diameters with the varying plug lengths. The reason to take the samples of size was because of the core holder availability. In addition, the proportions of mineral constituents were determined using X-ray diffraction (XRD) facility present at the material engineering department of NED University of Engineering and Technology. Through X-ray diffraction (XRD) analysis mineral composition of 1 cubic centimetre representative sample was taken. All samples were collected from outcrops and were used to see the impact of thermal properties on different mineral constituents, which could be consistent with data present in literature.

Table 2. Experimental methodologies adopted during this study

NO	Measurement Method	No. of Samples analyzed	Laboratory Facility
1	Thermal conductivity	65	Thermal conductivity measurements were made using the indigenously developed experimental setup as shown in **Error! Reference source not found.** at NED university Civil Engineering department.

2	Quantitative X-ray diffraction (QXRD)	5	QXRD was performed to obtain elemental composition including mineral composition of the samples using the facility available at Materials engineering department NED university.
3	Porosity	12	Porosity measurements were also made at Edith Cowan University located in Perth, Western Australia.
4	Permeability	10	Gas permeability experiments were conducted using core laboratory facility at Edith Cowan University Australian public university located in Perth, Western Australia.

Figure 3. Photographs of representative sedimentary rocks collected from Lower Indus Basin Sindh, Pakistan. Among them KT shows kirthar limestone, LK shows laki limestone, NRA shows nari sandstone and NRB shows nari siltstone

1.3. Results and discussions

The outcrops of sedimentary rocks for measurement of thermal conductivity were collected from different locations of the lower Indus basin Pakistan. These include kirthar limestone, laki limestone, nari sandstone and nari siltstone formations. The preceding names in the samples are of locations from where the samples have been collected. The analysis of thermal conductivity results and their summary of data are presented in table 3. The results from the sandstone, limestone and siltstone were selected for testing to identify their physical features in natural and heat-treated conditions. The rocks of different texture and structural characteristics were chosen for analysis and thermal properties measurement (Table 3). Total number of samples analyzed were 65, all these were prepared in nearly perfect cubic shape (figure 3), out of which 20 were kirthar limestones, 16 were laki limestones, 18 were nari sandstones and 11 were nari siltstones. These cubic samples were cut from large blocks which were collected from several outcrops by sawing in variable dimensions. Considerable attention was paid to perfectly prepare samples which must be free from all noticeable shortcomings and flaws. Generally, the thermal conductivity of sedimentary rocks of lower indus basin ranges from 0.76 to 3.46 W/mK with a mean of 1.20 to 2.54 W/mK (Table 3). It is apparent that thermal properties considerably differ between lithologies (figure 4-6). The thermal conductivities of nari siltstone, laki limestone and kirthar limestone samples are relatively low with value of 0.82-2.24 W/mK,1.19-2.47 W/mK and 0.76-2.67 W/mK respectively (figure 6), while the thermal conductivitie of nari sandstone samples containing higher quartz contents exhibited relatively high values ranging from 1.92 to 3.46 W/mK. This shows that the thermal conductivity of those samples is higher which exhibits higher density and lower porosity vlaues, which is probably representative of the combined effects of discrepancy in mineral composition of rock and pore characteristics on thermal conductivity (Li et al., 2019).

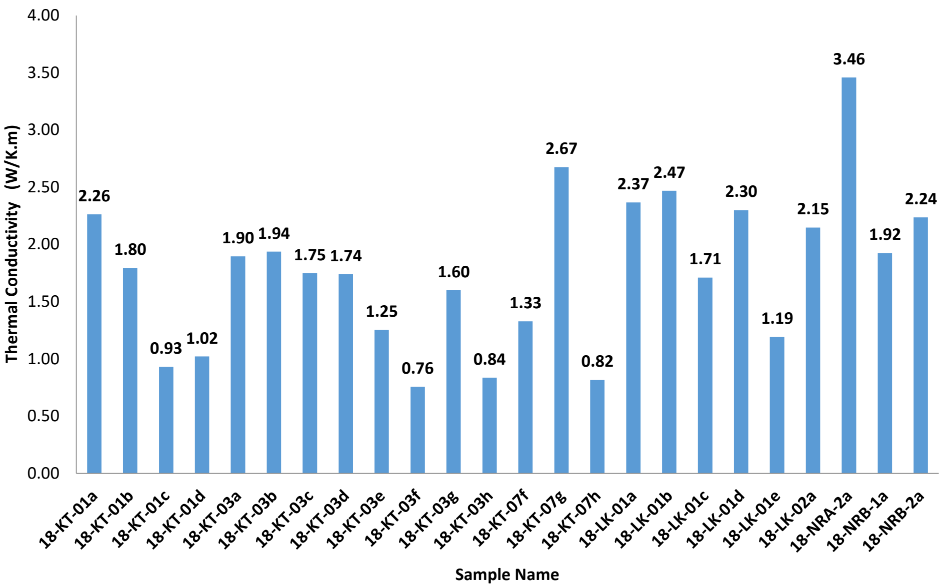

Figure 4 Histograms of thermal conductivity for sedimentary rocks from lower Indus Basin, Pakistan.

Table 3 Thermal conductivity of different rock formations from lower Indus basin Sindh Pakistan

Lithology type	**Number of Samples**	**Range of measured thermal Conductivity (W/K.m)**	**Thermal Conductivity (W/K.m) Mean value + SD**
Kirthar Limestone	20	0.76-2.67	1.51±0.575
Laki Limestone	16	1.19-2.47	2.54±0.489
Nari Sandstone	18	1.92-3.46	2.03±0.811
Nari Siltstone	11	0.82-2.24	1.20±0.792

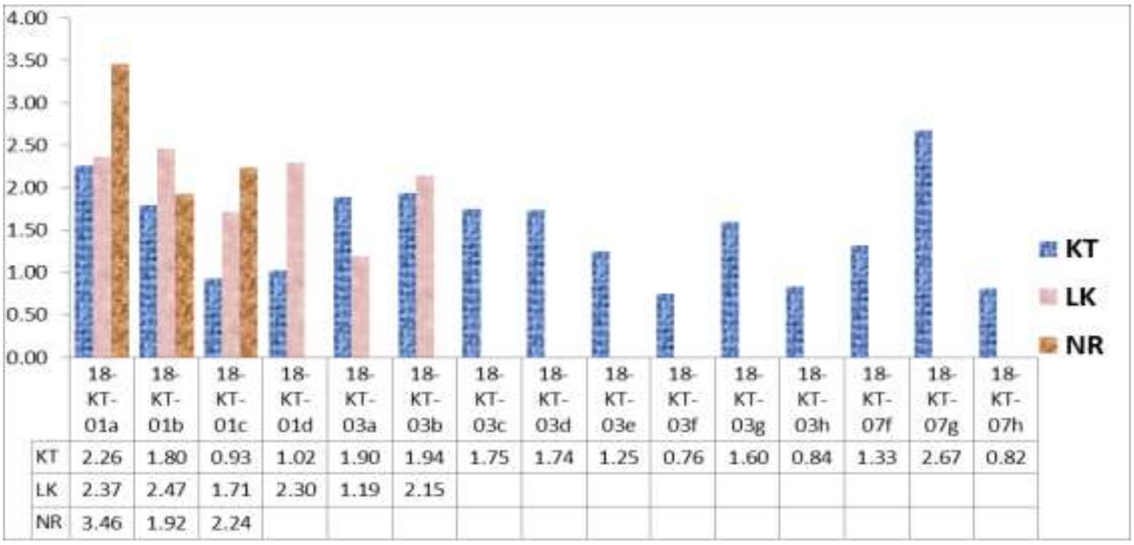

Figure . 5 Histogram of thermal conductivity of different rocks in the Lower Indus Basin.

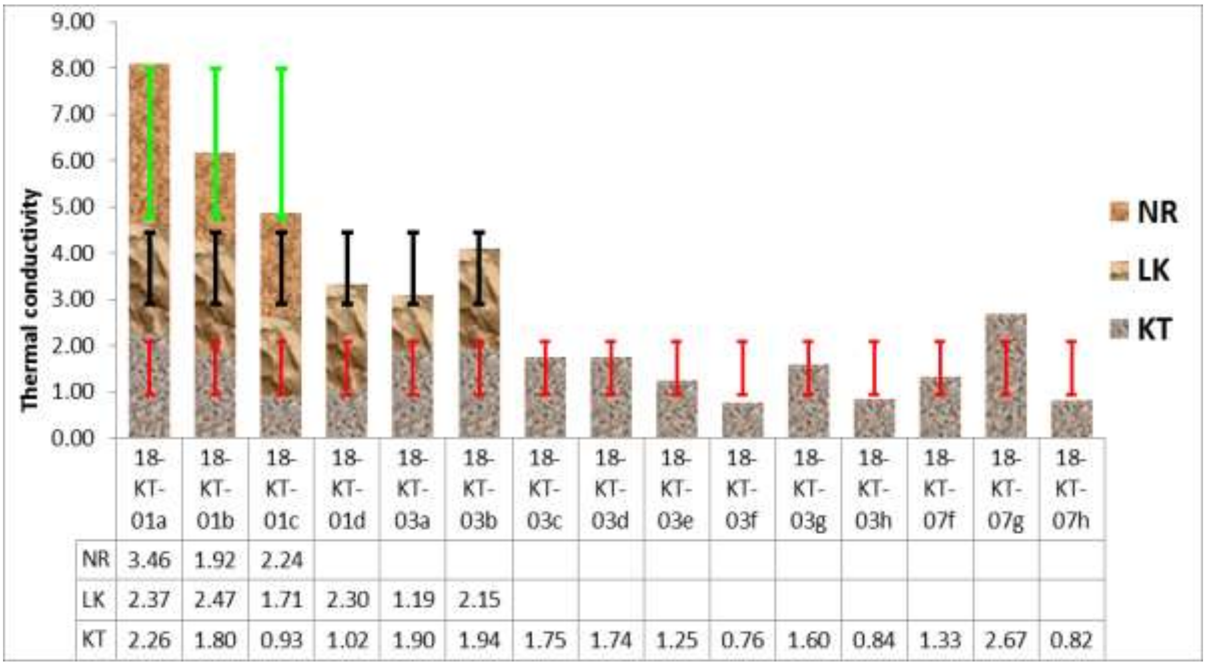

Figure 6. Thermal conductivity distribution of different formations in the Lower Indus Basin.

1.4. Factors that affect thermal properties of Lower Indus Basin sedimentary rocks

1.4.1 Effects of thermal conductivity on rock mineral Composition:

Mineral composition is one of the key factors that influence the thermal conductivity of sedimentary rocks. The thermal properties of rocks is essentially assessed by the thermal conductivity of rock-forming minerals. Through X-ray diffraction analysis the mineralogy of samples from different formation analysed and is presented in figure 7 and figure 8. The sandstone formations of nari sandstones have displayed that it contains quartz content as dominating in all analysed samples of nari sandstones. Kirthar formation is purely carbonate and is dominated by calcite However; quartz is found in high quality in nari sandstones. Some samples of nari sandstone were ranging from 80.20% to 90.60% quartz, which are typically quartz sandstone. The clay content and feldspar content is very small in these analysed samples of nari sandstones and can be considered as negligible. Further, the laki limestones samples analysed were mainly dominated by calcite with some exceptions of quartz in it. The quartz was in very small quantity and could be neglected within these samples of kirthar limestone. The average total Ca.Mg.SiO2 content of kirthar limestone samples (31.56%) in that is larger than the average total content (15%) in laki limestone of Eocene strata of lower indus basin. It is reportred that the quartz mineral possess high thermal conductivity value ranging from 6–7 W/mK, this reported value of thermal conductivity is higher than that of any other rock forming mineral (Clauser, 2006). Although, the sedimentary rocks such as sandstone, limestone and siltstones and their thermal properties are mainly affected by their mineral composition (Clauser, 2006). Mineral composition is one of the crucial factors that affect the thermal conductivity of sedimentary rocks. Thermal conductivities values of sedimentary rocks from lower indus basin have shown diverse range of thermal conductivities values ranging in between 0.76 to 3.46 W/m K. These obvious differences in thermal conductivities could be seen as shown in Table 3 within samples of lithology as well as among diverse lithologies, similar differences in thermal conductivity values are also reported for the rocks from Sichuan basin China (Tang et al. 2018). The sandstone samples of nari sandstone formation exhibit higher thermal conductivities values than other samples such as kirthar limestone, laki limestone and nari siltstone formations in the region (Table 3).

From SEM and petrographic analysis point of view, the influence of clay minerals on thermal properties of rock could not be neglected. In most of the samples, we observed different types of clays. The clays are found to be present in form of illite or illite/smectite mixed layer. Simultaneously, the illite content is the main component in nari sandstone and kirthar formations, while the kaolinite can be observed in siltstones. To sum up, mineral composition is one of the key factors that influence thermal conductivity. Thermal conductivity plays important role on the rocks which contains clay minerals as clay increases the thermal conductivity decreases although it is found that if the content of quartz increases the thermal conductivity of these sandstone significantly increases.

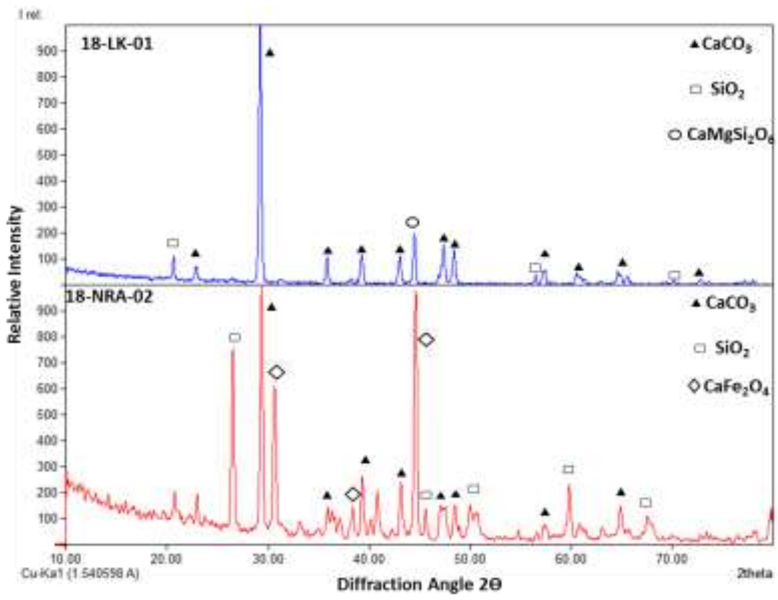

Figure 7. Illustration is the XRD results of two different formation Laki limestone and NARI formation sandstones.

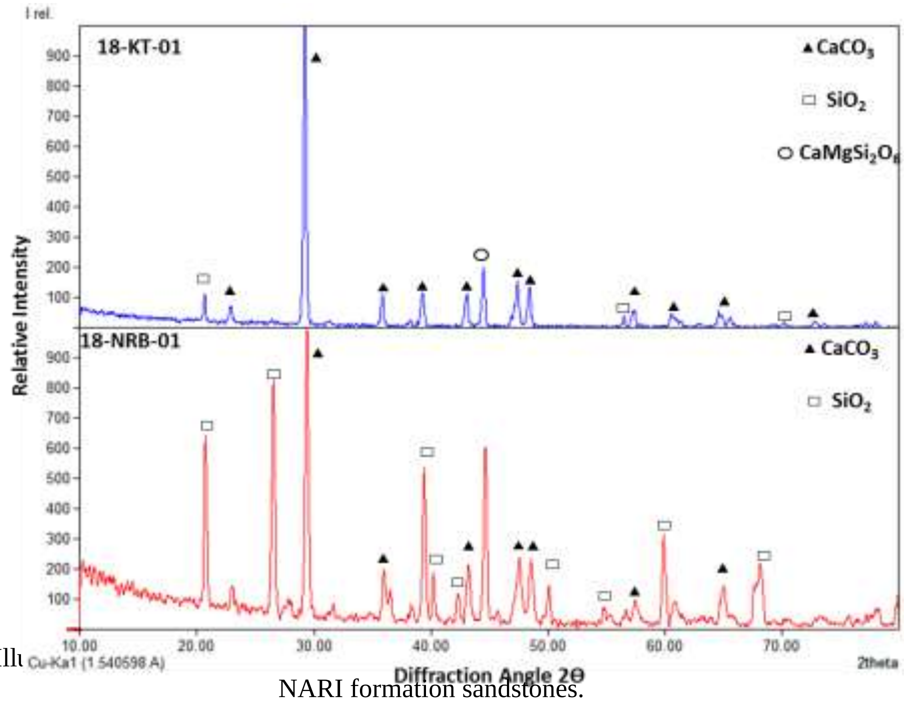

Figure 8. Ill[...] and NARI formation sandstones.

1.4.2 Effect of thermal Conductivity on rock porosity and permeability

High subsurface temperatures could be considered as one of the key parameters of potential damage to porosity of subsurface rocks. Higher temperature may change the rock fabric due to grain particles enlargments and internal thermal expansion of rocks, hence higher temperatures could alter the original porosity of these rocks. The porosity of sedimentray rocks in particular to sandstones varies at large scale ranging from around 2% to 35% due to their diversified arrangement of garins, occurrence of different minerals and cementing compositions (e.g. Fang, 1991; Kadri, 1995;Tian et al., 2012). It has been observed that many rocks, either sandstones or carbonates encompasses several microscopic fractures and their pores are almost occupied with air or other fluids by influencing their thermal properties. Many authors have measured thermal conductivity of porous sedimentary rocks and found that the open cracks and microfractures have significant influence on the thermal conductivity (e.g. Gringull and Sandner, 1979). it has also reported that the rocks if filled with air possesses thermal conducitivity value of 0.025 W/(m·K) or water 0.57 W/(m·K) (e.g. Gringull and Sandner, 1979). The relationship of porosity and thermal conductivity of sedimenetary rocks from lower Indus Basin of Paksitan is shown in figure 9. This shows that if porosity is increased the rock thermal conductivity is decreased. The reduction in thermal conductivity due to increased pore volume is since the disconnected grain arrangements. The samples which posseses higher porosity and result in lower thermal conductivity illustrate that the grains are loosely packed providing detached medium for flow of heat. It is also reported in literarture that as the temperature increases the porosity of those samples increases due to high temperature heating treatments create cracks and small fishers in rock formations (e.g. Gomez-Heras et al., 2016; Sun et al., 2016). In literature, it also has been reported that below temperature of 400^0C the porosity of smaples does not significantly change, although there is small internal grain fabric modification occurs. Thereafter, at higher temperatutres, the rock internal pores would greatly impact the rock by damging the rock morphology (e.g. Tian et al., 2012; Sun et al. 2016). Moreover, the microfractures in sandstones could occur at higher temperatures at about 400^0C (e.g.Tian et al., 2012; Sun et al., 2016).

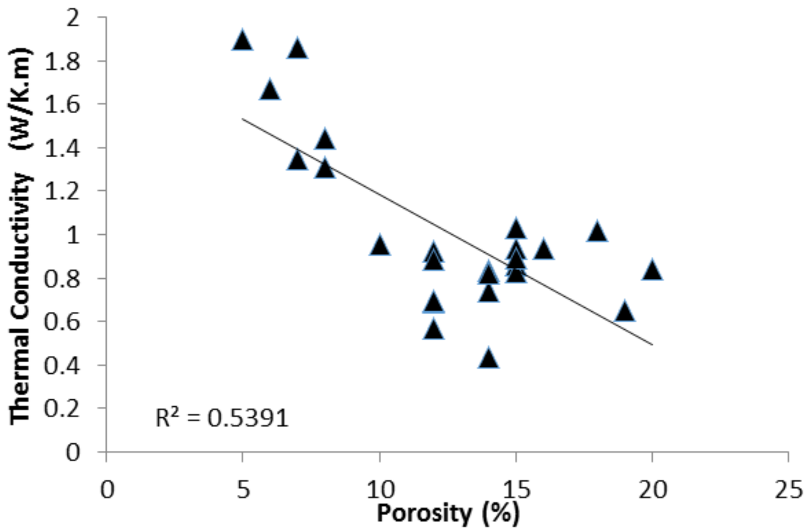

Figure 9. Plot is the relation between thermal conductivity V/s porosity of sediementary rock from Lower Indus Basin. The total absolute error of the porosity measurements is ±0.6%.

Further, the understanding about the permeability and thermal conductivity relationship to each other are the key parameters in estimating the thermal maturity of reservoir bearing formations (e.g. Mielke et al. 2010). Although the correlation between permeability and thermal conductivity could only be conceivable if both properties should be measured on similar samples under analogous conditions. We obtained samples from diferent formations of the lower Indus basin and determined their permeabilities. Samples' permeabilities measured were ranging from 0.012 to 85 mD, and thermal conductivities of these were in range of 0.76 to 3.46 W/(m K). The values of thermal conductivity and permeability cross plotted no correlation was established among two rock property parameters assessed from Lower Indus Basin (figure 10). The data of permeability and thermal conductivity presented in figure 10 demonstrates that the sandstones posseses high permeabilities as well as exhibits higher thermal conductivities. However, the sandstone samples which are dominated by clay mineralogy demonstres lower permeabilities. though the mineral compositions significantly afftects the thermal conductivity of these rocks. clearly, the sandstone samples showed that their thermal conductivity increases with increased content of quartz. While samples dominated by clay minerlas has lower thermal conductivity as it acted as insulating to the heat conduction. Similar observation from various regions of different rock formations determined has been reported (Mielke et al. 2010).

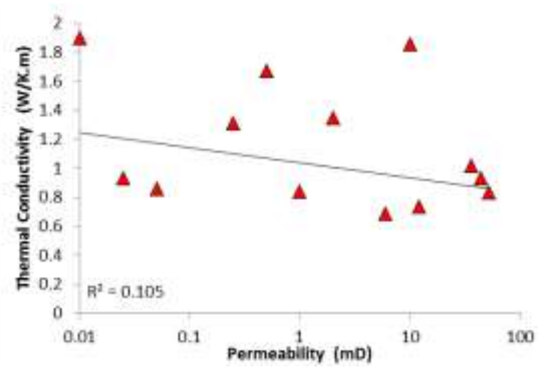

Figure 10. Illustration is the relationship between permeability vs. thermal conductivity for samples from lower Indus basin, Pakistan.

1.5. Conclusion

The measured thermal conductivity of outcrop samples in sedimentary strata of the lower Indus basin are in the range of 0.76-3.46 W/m K, with a mean of 1.20-2.54 W/m K. The thermal conductivities of nari siltstone, laki limestone and kirthar limestone samples are relatively low with value of 0.82-2.24 W/mK, 1.19-2.47 W/m K and 0.76-2.67 W/m K respectively, while the thermal conductivitie of nari sandstone samples containing higher quartz contents exhibited relatively high values ranging from 1.92 to 3.46 W/m K. The thermal conductivity of nari sandstone and kirthar limestone displayed higher values than other Laki limestones of eocence strata. Minerals and their components also significantly afftect the thermal conductivity of these rocks. Obviously, the sandstone samples showed that their thermal conductivity increases with increase content of quartz. It was also observed from experimental results that samples containg slightly higher percentage of clay have lower thermal conductivity as it acted as insulating to the heat conduction. Although the thermal conductivity and permeability data were cross plotted , it appears that there is no consistent relation reveals between two property parameters.

References

[1] Khan, M., Nawaz, S., Shah, M., & Hasan, M. (2016). Interpreting Seismic Profiles in terms of Structure and Stratigraphy, an Example from Lower Indus Basin Pakistan.

[2] Abdulagatova Z, Abdulagatov IM and Emirov VN (2009) Effect of temperature and pressure on the thermal conductivity of sandstone. International Journal of Rock Mechanics & Mining Sciences 46: 1055–1071.

[3] Birch, F., Schairer, J. F., & Spicer, H. C. (1942). Handbook of physical constants: Geol. Soc. America Special Paper, 36, 325.

[4] Brace, W., Walsh, J. B., & Frangos, W. T. (1968). Permeability of granite under high pressure. Journal of Geophysical research, 73(6), 2225-2236.

[5] Blackwell, D. D., & Steele, J. L. (1989). Thermal conductivity of sedimentary rocks: measurement and significance. In Thermal history of sedimentary basins (pp. 13-36). Springer, New York, NY.

[6] Clauser, C., 2006, Geothermal energy, in K. Heinloth, ed., Landolt–B¨ ornstein, Group VIII: Advanced materials and technologies: Heidelberg, Germany, Springer-Verlag, v. 3, p. 493–604.

[7] Khadri, I.B., 1995, Petroleum geology of Pakistan: Karachi, Pakistan Petroleum Ltd., p. 275.

[8] Kazmi AH, Jan MQ (1997) Geology and tectonics of Pakistan, vol 1. Graphic Publishers, Karachi,pp 483–500.

[9] Kazmi, A., 1997, Geology and Tectonics of Pakistan: Graphic Publishers, Karachi, Pakistan, 554 p.

[10] R. S. Carmichael (Ed.) (1984), Handbook of Physical Properties of Rocks, vol. 3, CRC Press, Boca Raton, Fla.

[11] Tang, B., Zhu, C., Xu, M., Chen, T., & Hu, S. (2018). Thermal conductivity of sedimentary rocks in the Sichuan basin, Southwest China. Energy Exploration & Exploitation, 0144598718804902.

[12] Gringull, U., Sandner, H., 1979. Wtirmeleilung. Springer Verlag, Berlin.

[13] Geng, J., Sun, Q., Zhang, Y., Cao, L., Lü, C., & Zhang, Y. (2018). Temperature dependence of the thermal diffusivity of sandstone. *Journal of Petroleum Science and Engineering*, *164*, 110-116.

[14] Clauser, C. (2011). Thermal storage and transport properties of rocks, ii: thermal conductivity and diffusivity. In *Encyclopedia of solid earth geophysics* (pp. 1431-1448). Springer, Dordrecht.

[15] Geng, J., Sun, Q., Zhang, Y., Cao, L., Lü, C., & Zhang, Y. (2018). Temperature dependence of the thermal diffusivity of sandstone. *Journal of Petroleum Science and Engineering*, *164*, 110-116.

[16] Muhammad, G., Marri, A., & Shar, A. M. (2018). Development of Experimental Setup for Measuring Thermal Conductivity Characteristics of Soil. *Mehran University Research Journal of Engineering and Technology*, *37*(4), 559-568.

[17] Kujundžić, T., Korman, T., & Macenić, M. (2012). State of the art of drilling large diameter boreholes for deposition of high level waste and spent nuclear fuel. Rudarsko-geološko-naftni zbornik, 24(1), 49-59.

[18] Lee K.S. (2013) Underground Thermal Energy Storage. In: Underground Thermal Energy Storage. Green Energy and Technology. Springer, London.

[19] Blackwell, D. D., & Steele, J. L. (1989). Thermal conductivity of sedimentary rocks: measurement and significance. In *Thermal history of sedimentary basins* (pp. 13-36). Springer, New York, NY.

[20] Kovačević L, Terek P, Kakaš D, Miletić A, Kukuruzović D (2013) Determination of Metal-Mold Heat Transfer Coefficient During CO_2 Sand Casting. In: Proceedings and Book of Abstracts of Metallurgical & Materials Engineering Congress of South-East Europe, Belgrade, Serbia: 312-319 .

[21] Liu, S., Lei, X., Feng, C., & Li, X. (2016, April). Heat flow, deep formation temperature and thermal structure of the Tarim basin, Northwest China. In EGU General Assembly Conference Abstracts (Vol. 18).

[22] Li, X., Liu, S., & Feng, C. (2019). Thermal properties of sedimentary rocks in the Tarim Basin, northwestern China. AAPG Bulletin, 103(7), 1605-1624.

[23] Maugh, T.H., 1977. Underground gasification: an alternate way to exploit coal. Science 198 (4322), 1132–1134.

[24] Mielke, P., Bignall, G., & Sass, I. (2010, April). Permeability and thermal conductivity measurements of near surface units at the Wairakei Geothermal Field, New Zealand. In Proceedings of the World Geothermal Congress 2010.

[25] Sun, Q., Lü, C., Cao, L., Geng, J., Zhang, W., 2016. Thermal properties of sandstone after treatment at high temperature. Int. J. Rock Mech. Min. Sci. 85, 60–66.

[26] Sarma, P., Kyriacou, S., Henning, M., Orland, P., Thakur, G., & Sloss, D. (2017, May). Redistribution of Steam Injection in Heavy Oil Reservoir Management to Improve EOR

Economics, Powered by a Unique Integration of Reservoir Physics and Machine Learning. In SPE Latin America and Caribbean Petroleum Engineering Conference. Society of Petroleum Engineers.

[27] Tosi N, Yuen DA, Koker N, et al. (2013) Mantle dynamics with pressure- and temperature-dependent thermal expansivity and conductivity. Physics of the Earth and Planetary Interiors 217: 48–58.

[28] Horai K (1971) Thermal conductivity of rock-forming mineral. Journal of Geophysical Research 76(5): 1278–1308.

[29] Ray, L., Bhattacharya, A., & Roy, S. (2007). Thermal conductivity of higher Himalayan crystallines from Garhwal Himalaya, India. Tectonophysics, 434(1-4), 71-79.

[30] POPOV, YU. A. and MANDEL, A. M. (1998), Geothermal Study of Anisotropic Rock Masses, Izvestiya, Physics of the Solid Earth. 34 (11), 903–915.

[31] Shah, S. M. I. (2009). Stratigraphy of Pakistan: Geological Survey of Pakistan Memoir 22.

[32] Tian, H., Kempka, T., Xu, N., Ziegler, M., 2012. Physical properties of sandstones after temperature treatment. Rock Mech. Rock Eng. 45, 1113–1117.

[33] Verma, A.K., Jha, M.K., Maheshwar, S., Singh, T.N., Bajpai, R.K., 2016. Temperaturedependent thermophysical properties of Ganurgarh shales from Bhander group, India. Environ. Earth Sci. 75 (4), 1–11.

[34] Wen, H., Lu, J., Xiao, Y., Deng, J., 2015. Temperature dependence of thermal conductivity, diffusion and specific heat capacity for coal and rocks from coalfield.Thermochim. Acta 619, 41–47.

[35] Yao, X., Xie, Q., Yang, C., Zhang, B., Wan, C., Cui, S., 2016. Additivity of pore structural parameters of granular activated carbons derived from different coals and their blends. Int. J. Min. Sci. Technol 26 (4), 661–667.

[36] Zhao YX, Yang SZ, Zhang WR, et al. (1995) An experimental study of rock thermal conductivity under different temperature and pressure. Progress in Geophysics 10(1): 104–113 (in Chinese with English Abstract).

[37] Somerton, W. H., & Gupta, V. S. (1965). Role of fluxing agents in thermal alteration of sandstones. Journal of Petroleum Technology, 17(05), 585-588.