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Morariu D.
Independent Petroleum Geologist, Geneve, Switzerland, morariu45@gmail.com
Averyanova O.Yu.
Independent Petroleum Geologist, St. Petersburg, Russia, info@ngtp.ru

THERMAL CRACKING - KEY PARAMETER FOR INCREASING ROCK PERMEABILITY

The thermal cracking and rock permeability enlarging are important key parameters controlling the flow capacity. Strictly impermeable rocks (igneous rocks, gneiss, quartz sandstone, etc) during the burial type of deformation (yo-yo tectonics with multiple cycles of burial and exhumation in several tectonic settings like orogen, collisional orogen, wrench area, back-arc depression, back-arc rift and intercontinental rift) can reach temperatures exceeding 350-400^{0}C. Within this thermal range the thermal cracking metamorphism can become very active and intensive. At this stage affecting rock can even reach permeability values characteristic of semi-pervious rocks.

During exhumation, the fabric and PT adaptation process (retromorphism like) begins in the buried rock. As the retromorphism like process is rarely complete we can observe some rocks on the field that at first glance seem to belong to impervious class. The same rocks after being tested in laboratory during petroleum or other exploration activity may show specific permeability values that lead us to place them in the semi-pervious permeability class.

Keywords: *permeability, thermal cracking, yo-yo tectonic, retromorphism like process, semi-pervious rock.*

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Rock permeability – capacity of a rock to transmit a fluid – is an important hydrogeologic parameter determined by stress hydrostatic pressure, fluid viscosity, temperature, porosity, fracturing connectivity and by degree to which the rock openings are interconnected. Generally, the permeability can be enhanced or inhibited by several processes: inhibited by changes in stress or pore pressure or enhanced by thermal cracking.

The directly measured permeability of common geologic media varies by approximately 16 orders of magnitude, from values as low as 10^{-23} m^2 in intact crystalline rocks, intact shales and fault gouge, to values as high as 10^{-7} m^2 in well – sorted gravels [Ingebritsen, Gleeson, 2015].

The thermal stress is caused by differences between mineral thermal expansion coefficient as well as mineral thermal decomposition. The thermal cracking and permeability changes are mainly driven by the difference between mineral thermal expansion coefficients; the changes in thermal properties can be significant [Liu et al., 2018].

Under a high temperature, high pressure and eventual hot mineral - rich fluids, a series of physical and chemical changes occur in the rock, processes having a significant influence on rock permeability too. Following a high temperature treatment the changes in pores and the cracks of the rock are related to the thermal expansion and structural transformation in the rock [Qian et al., 2015].

The changes in the rock openings and cracks of the rock are related to structural transformation of the rock under different confining pressure; all these changes will affect the rock permeability [Ge, Sun, Li, 2018].

Data about permeability are needed to predict flow and solute transport characteristics especially in non-homogenous rocks.

Permeability of sedimentary rocks - introduction

The oil and gas reservoirs can be divided in term of their accessibility into conventional and unconventional reservoirs. The classification of oil and gas reservoirs as conventional and unconventional may be strongly dependent on the permeability contrast too.

Petroleum reservoirs can have primary permeability known as the matrix permeability and secondary permeability. Matrix permeability has been produced during deposition and lithification time. Secondary permeability is the consequence of the rock matrix permeability changes by compaction, cementation, fracturing and solution. Generally, compaction and cementation activity reduce the permeability, while solution trend to increase it.

Nelson P.H. indicated that pore-throat sizes (diameters) are generally greater than 2 μm in conventional reservoir rocks, ranging from about 2 to 0.03 μm in tight-gas sandstones and from about 0.1 to 0.005 μm in shales [Nelson, 2009] (Fig. 1).

Loucks et al. found that matrix-related pore networks in mudrocks contain a very important number of pores with size dimensions ranging from nanometre to micrometre [Loucks et al., 2012]. In shale-gas systems, these pores along with natural fractures form the flow-path permeability network that allows flow of the gas from the mudrocks to induced fractures during production.

Porosity allows us to estimate oil and gas quantity in place and reserves, while permeability makes it possible to estimate production rate and predict reservoir fluid performance. Intrinsic permeability is a key parameter controlling the flow capacity of rock. However, its magnitude may vary over several orders of magnitude, even for a single rock type (Fig. 2).

Permeability of sedimentary rocks - overview

Generally, the sedimentary rocks are composed of several minerals. When a sedimentary rock undergoes temperature change, new cracks can be created and /or pre-existing cracks will be activated to reopen owing to thermal stress. Such thermal stress is caused by differences between mineral thermal expansion coefficients as well as mineral thermal decomposition [Liu et al., 2018].

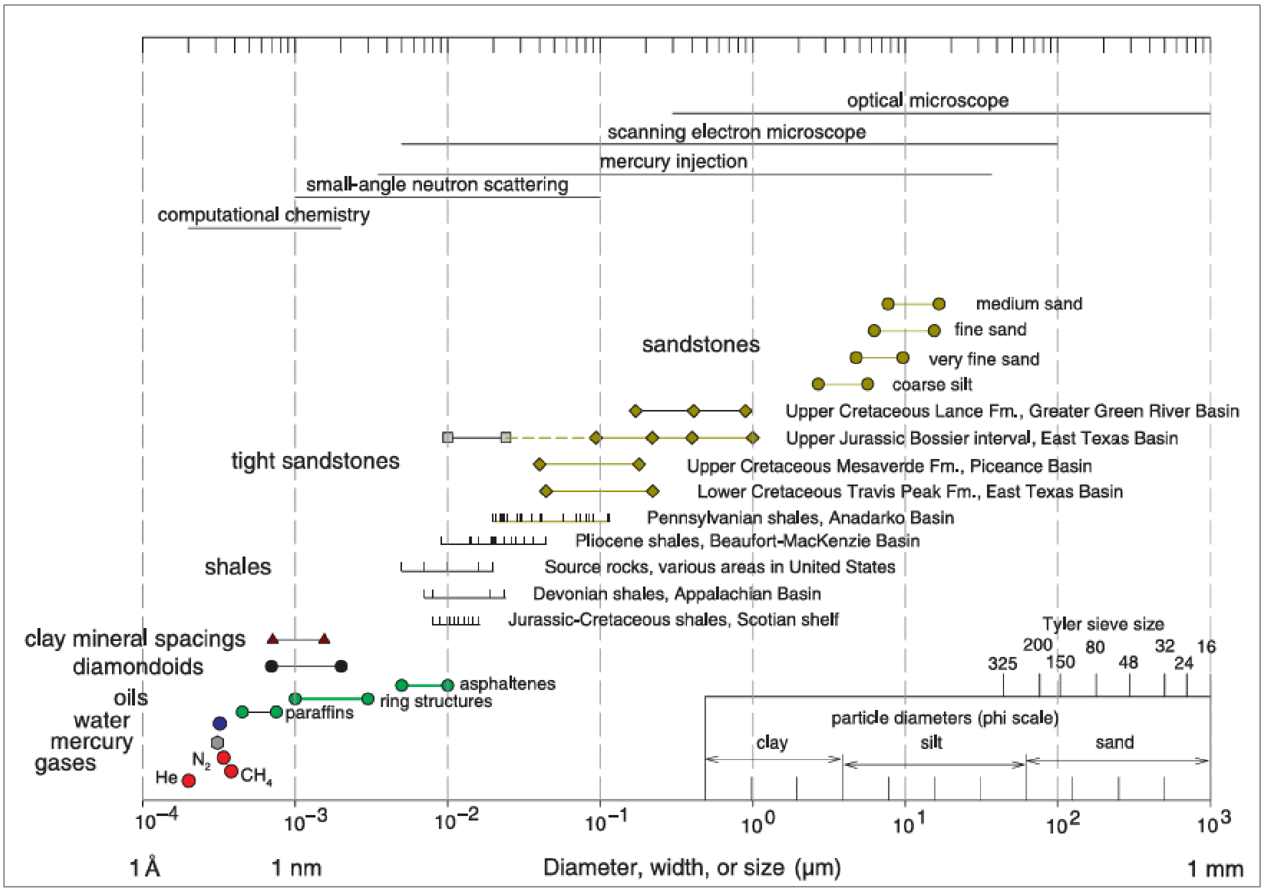
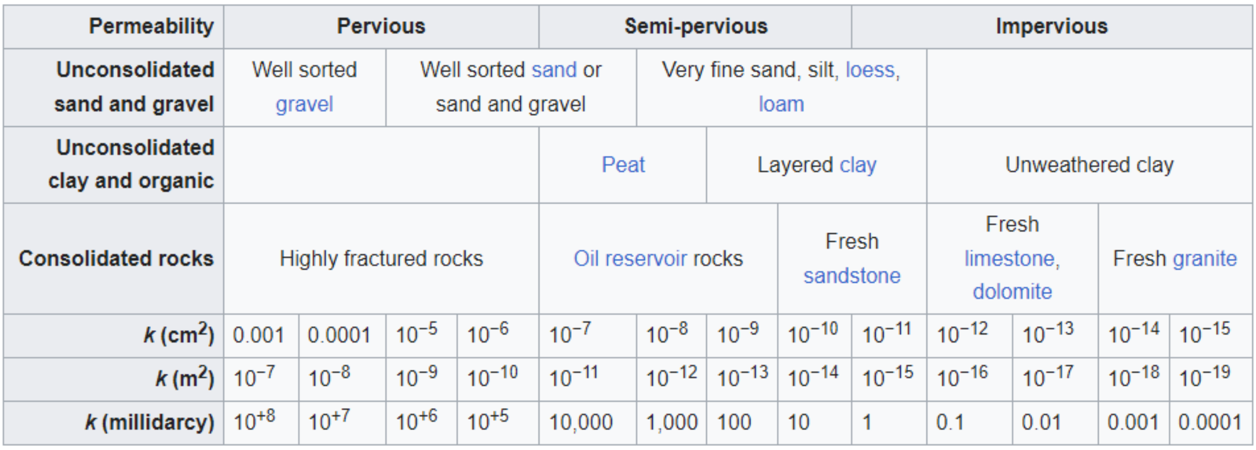


Fig. 1. Sizes of molecules and pore throats in siliciclastic rocks on a logarithmic scale covering seven orders of magnitude [Nelson, 2009]

Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diamondoids, and three oils, and molecular diameters of water, mercury, an d three gases are also shown.



Permeability	**Pervious**				**Semi-pervious**				**Impervious**				
Unconsolidated sand and gravel	Well sorted gravel		Well sorted sand or sand and gravel			Very fine sand, silt, loess, loam							
Unconsolidated clay and organic					Peat		Layered clay			Unweathered clay			
Consolidated rocks	Highly fractured rocks				Oil reservoir rocks			Fresh sandstone		Fresh limestone, dolomite		Fresh granite	
***k* (cm^2)**	0.001	0.0001	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}
***k* (m^2)**	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-16}	10^{-17}	10^{-18}	10^{-19}
***k* (millidarcy)**	10^{+8}	10^{+7}	10^{+6}	10^{+5}	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001

Fig. 2. Ranges of common intrinsic permeabilities [Bear, 1988]

Ni H.Y. et al. studied the gas permeability characteristics of tight sandstones under temperature - stress coupling and reported that the gas permeability increases with the temperature under the same confining pressure [Ni et al., 2019]. The tight sandstone is usually characterized by a low porosity less than (10%), a low permeability (less than 10^{-16} m^2) and a strong sensitivity to in situ stress. SEM images show that as the temperature increases, the sandstone particles expand to cause the primary cracks and pores to be closed. When the temperature reaches 400^0C, some large cohesive particles peel off resulting in sharply increase in the number of smaller particles. The formation of new cracks and development of initial cracks can be observed.

Ni H.Y. et al. reported that the initially maximum gas permeability of the investigated sandstone was less than $1.2x10^{-17}$ m^2 [Ni et al., 2019]. The authors remark that the gas permeability increases with temperature under the same confining pressure and finally it is approximately 2.4 times as large as the initial value, when the temperature rises from 20 to 400^0C.

Somerton W.H. and Gupta V.S. used dried cores to investigate the impact of temperature on sandstone permeability and their experiments revealed that the gas permeability of the rocks increased at least 50% after thermal treatment [Somerton, Gupta, 1965].

Ge Z. et al. assembled a large amount of experimental data about the Chinese sandstone and studied the changes in the permeability of sandstones, siltstones, and conglomerate too [Ge, Sun, Li, 2018]. The temperature and confining pressure have great influence on permeability of rock, especially for sandstone.

There is a threshold temperature and when the heating temperature is higher than the threshold temperature the water in the rock channel evaporates improving the rock permeability; consequently, the permeability of sandstone gradually increases with an increase in temperature. When the heating temperature is higher than 300^0C (especially around 400^0C) the permeability rapid increases and sandstone expands when heated and this expansion behaviour is mainly caused by the phase transition of quartz.

The high temperature also changes the thermal stress in the rock and transforms the rock structure which produces many small thermal cracks inside the rock and enhances the flow capacity of the fluid, thus increasing the rock permeability. The physical-chemical and structural-textural properties (such as decomposition, oxidation, dehydration and evaporation) of rock are obviously changing, which significantly affects the rock permeability. As the strain increases new fissures occur in the rock, the internal fissures are reopened and expand, thereby increasing the permeability.

The effects of thermal factor on the rock permeability are:

A. increased interconnectivity between pre-existing and newly formed cracks or pore,

B. new-microcracks provide additional flow path,

C. widening of crack aperture reduces impedance to fluid flow resulting from boundary friction [Ge, Sun, Li, 2018].

The first two effects (A plus B) are expected to be more important at low cycle temperatures, whereas crack widening is expected to domine at higher temperature [Bauer, Johnson, 1979].

Ge Z. et al. considered that the changes in the pores and cracks of the studied rocks are related to the deformation of the rock under different confining pressure [Ge, Sun, Li, 2018]. All these changes will affect the rock permeability.

Based on an average geothermal gradient of crustal rock of 3^0C/100 m the maximum temperature may reach about $100\text{-}150^0$C at a depth of 3000-5000 m which is relevant depth for geothermal resources, deep mining and petroleum exploration. For magmatic intrusion and deep volcanic area, the temperature will be more than 150^0C [Zuo et al., 2010]. The same paper presented experimental data indicating that when the temperature is lower than 125^0C there are no thermal cracks. When the temperature is higher than 150^0C the thermal cracks initiate. As the temperature rises above than 200^0C the number of thermal cracks increases dramatically. Most of the cracks are intergranular thermal cracks (Table 1).

Table 1

The number of thermal cracks at different temperatures [Zuo et al., 2010]

Temperature, ^{0}C	**The number of thermal cracks**
100	0
125	0
150	9
175	25
200	164
250	364
300	536

Several thermal cracking models have been observed, namely grain boundary, intergranular and mixt thermal cracking.

The first threshold temperature of thermal cracking of Pingdingshan sandstone is about 125^0C dominates by the grain boundary behaviour in which thermal cracking occurs at interface between particle and mineral grain boundaries.

The second threshold temperature is a temperature of about $250\text{-}300^0$C, and the number of thermal cracks increases dramatically. Most of the cracks in this regime are intergranular or transgranular thermal cracking occurring in the middle of an intact mineral grain. Interlaced thermal cracks network might develop at free surfaces after a period of time at 200^0C (Fig. 3).

The second threshold temperature is around $250\text{-}300^0$C. Most of thermal cracks in this regime occur in the middle of an intact mineral grain, as intergranular thermal cracking. The second threshold - a large number of thermal cracks are observed on the surface of clay minerals and mineral grain. Both the number and density of thermal cracks increases as the temperature increases over about

150^0C. Most of the thermal cracks belonging to the threshold occur in the middle of an intact mineral grain, as intragranular thermal cracking (Fig 4).

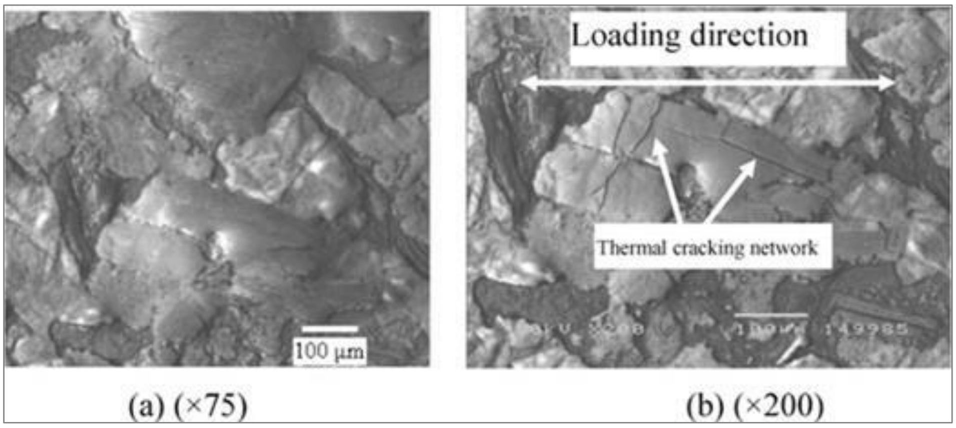


Fig. 3. Surface topography of sample at 150°C (a) and thermal cracking network of sample at 200°C (b) [Zuo et al., 2010]

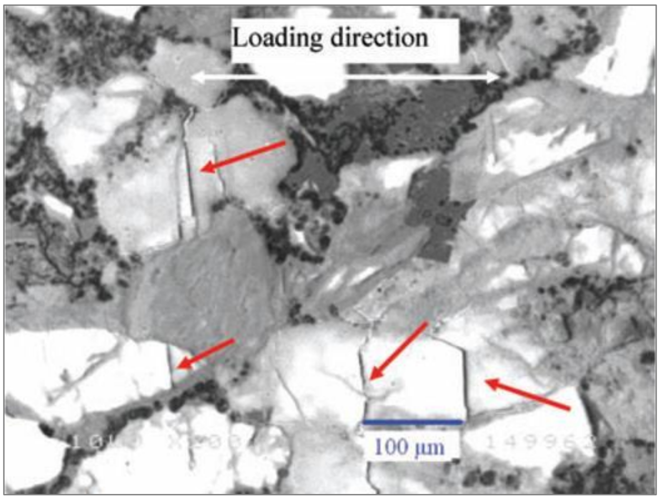


Fig. 4. Thermal crack in mineral grains of sample at 300°C [Zuo et al., 2010]

The permeability of sandstones, siltstones and conglomerate increases slowly when the heating temperature is lower than 400^0C, when the heating temperature is higher than 400^0C the permeability increases sharply. The threshold of sandstones, siltstones and conglomerates is between 400 and 600^0C (Fig. 5). Permeability of Chinese siltstones, sandstones and conglomerate increases with an increasing temperature; the change in the permeability indicates that a threshold temperature exists and marks the temperature at which the rate of growth in permeability increases considerably [Ge, Sun, Li, 2018].

Moreover (between 300 to 400^0C) the water reaches its critical temperature (i.e. 374^0C) at which the water may turn into supercritical fluid [Ge, Sun, Li, 2018], causing changes in the rock internal stress and increasing the rock thermal damage.

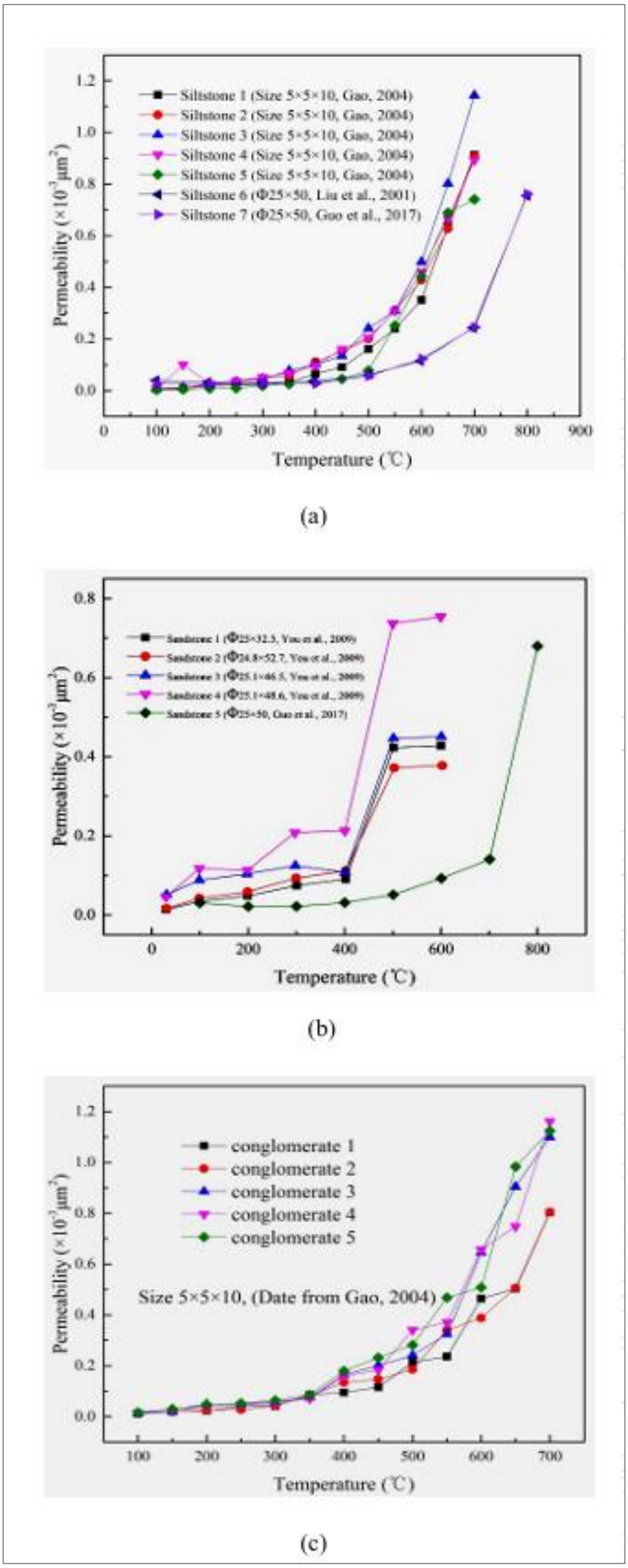


Fig. 5. Influence of high temperature on the permeability of siltstones (a), sandstones (b) and conglomerates (c) [Ge, Sun, Li, 2018]

Igneous rock permeability

Le Ravalec M. and Guéguen Y. built a model to simulate how permeability and connected porosity vary with temperature by combining poroelastic theory and fracture mechanics theory [Le Ravalec, Gueguen, 1994]. Their model showed that permeability change was influenced by several factors, including intrinsic permeability, intrinsic connected porosity, crack geometry, rock composition (bulk modulus affecting critical cracking temperature), and temperature. With increasing temperature, pre-existing cracks propagate and new cracks are formed; together, these phenomena generate well-connected crack networks, thus enhancing rock permeability.

Meng X. et al. considered that the Pingyi granite (Shandong Province, China) nearly impermeable rocks, can show a severe increase of permeability from heating beyond the critical temperature [Meng, Liu, Meng, 2018]. A coupling triaxial testing system was applied to study thermal cracking and permeability evolution of granite specimen with different damage at different inlet gas pressures and temperatures (ranging from 100 to 650^{0}C). The test results show that granite, practically impermeable rocks, can show a striking increase of permeability by heating beyond the critical temperature.

When the initial axial pressure is 60 or 70% of the uniaxial compressive strength the growth of granite permeability exhibits three stages during 100-650^{0}C heating process. The important thermal cracking occurs in a short time (200-250^{0}C). With increasing initial damage, permeability shows a sharp increase. When the temperature is lower than the critical temperature, the magnitude of permeability is 10^{-18} m^2 (impervious rock) with a slight increase. When the temperature is higher than the critical temperature, the magnitude of permeability is 10^{-15} m^2 (semi-pervious rock) with a sharp increase. By thermal expansion the permeability of granite increases by orders of magnitude from heating beyond the critical temperature compares with permeability at 100^{0}C.

When the temperature reaches 250^{0}C, the cracks in the granite are fully connected. The permeability of granite experiences a significant increase and the rate of permeability is high. The structure undergoes a qualitative transformation, and the completed fracture network is formed (Fig. 6a, b).

The increase in the crack population inside a granitic rock can alter its mechanical and transport properties, including Poisson`s ratio, P and S velocities, bulk sample density, Young’s modulus permeability, porosity compressive strength, tensile strength and fracture toughness [Brace, Walsh, Frangos, 1968].

Siratovich P.A. et al. described thermal stimulated granite and basalt cores to 375^{0}C at a confining pressure up to 35MP and rapidly quenched them with cold water to return them to the ambient temperature [Siratovich et al., 2015]. Results indicated that porosity increased, density decreased and permeability of the rocks significantly enhanced. The observed permeability change was approximately four orders of magnitude higher than the original permeability in these tested samples (granite, rhyolite and basalt). The transformation characteristics are related to the intrinsic properties of rocks such as the mineral composition, texture, particle size, degree of pore development during the cracking process and the integrity of its internal structure.

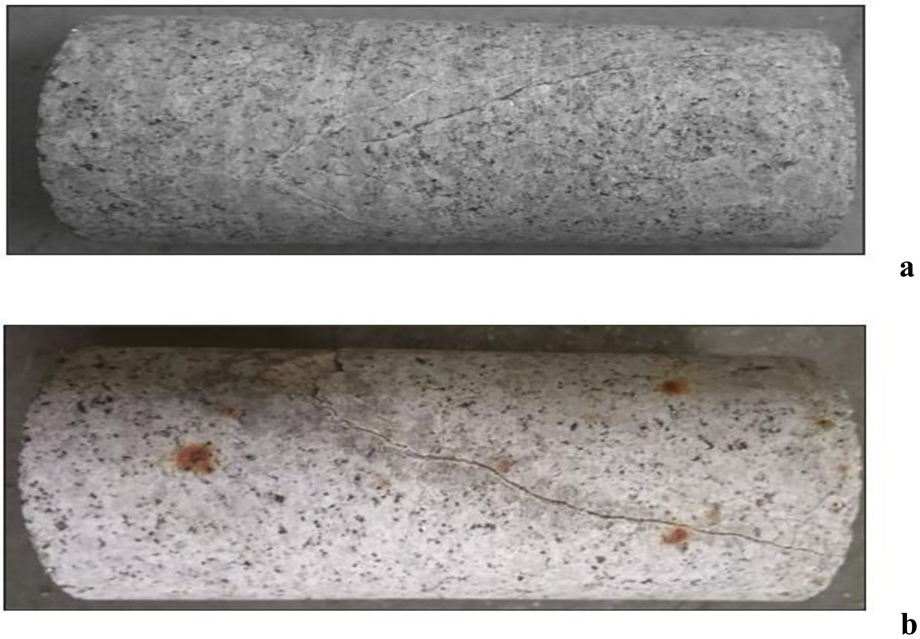


Fig. 6. Thermal cracking images of granite specimens with the low initial damage
[Meng, Liu, Meng, 2018]
a) Initial axial compression is 60% of uniaxial compression strength, b) Initial axial compression is 70% of uniaxial compression strength.

Zengchao F. et al. measured the Luhui granite permeability at triaxial stresses end elevated temperature [Zengchao et al., 2014]. It was found that 300^0C is the critical temperature of permeability changing with temperature in thermally cracked granite. The magnitude of permeability is 10^{-19} m^2 with a low increase below Tc and the permeability whose magnitude is 10^{-18} m^2 increases drastically with high amplitude at 300-400^0C while the magnitude is 10^{-17} m^2 at 400^0C.

The permeability of Luhui granite was measured at triaxial stress and elevated temperature by Feng Z. et al. [Feng et al., 2018]. It is found that 300^0C is the threshold temperature of permeability change with temperature in thermally cracked granite. Two peaks of micro-crack quantity with the length of more than 5 μm and 10 μm respectively exist at temperature up to 400^0C. The quantity of microcrack whose length is more then 10 μm increases sharply at the rate of one per ten centigrade at temperature above 300^0C. The drastic increase of micro crack above 300^0C is the main reason that permeability increases sharply at temperature above 300^0C in thermally cracked granite. The thermal and mechanical coupled effect can more heavily affect granite permeability than only thermal effect.

Jiang G. et al. studied the mechanical properties of Maluanshan granite before and after heating

[Jiang et al., 2018]. The evolution of the cracks in Maluanshan granite was inverted through the change rule of the cracks, wave velocity anisotropy and permeability with temperature. Conclusions – the thermal cracking occurred in four stages: first stage between 50 and 250^{0}C, the crack stabilisation stage between 250 and 300^{0}C, an accelerated development stage of the cracks existed between 300 and 350^{0}C and finally from 350 to 700^{0}C the cracks continued into a further development stage.

The structures of cracks change before and after 300^{0}C. From 50-200^{0}C permeability was determined by the microcracks between 200-400^{0}C was the transition stage and between 400 and 700^{0}C the permeability was determined by the macrocracks.

Fan F. et al. studied the thermal effects on micro-properties of granite collected from Shandong province (China) and noticed in real time permeability evolution of thermally cracked granite [Fan et al., 2018]. The study shows that temperature significantly influences the micro-porosity of granite. The micro-porosity increases as temperature increases between 400 and 800^{0}C. The heterogeneity and anisotropy of granite are mainly dominated by initial cracks below 200^{0}C. The thermal induced cracks are mainly in the regions of lower density mineral grains below 400^{0}C, boundary cracks and transgranular cracks generate significantly above 500^{0}C.

Liu J. et al. described experiments showing that the threshold temperature of Lijin granites (China) is around 300^{0}C and the permeability can improve by approximately 2 orders and porosity can increase more than 5 times when heating over 600^{0}C [Liu et al., 2020]. Both crack length and width increase about 10 folds under experiment conditions.

An investigation on thermal effect on micro properties of granite were experimentally studied [Fan et al., 2018]. The results show that micro-porosity of granite significantly increases with the increase in temperature from 400 to 800^{0}C and the granite heterogeneity and anisotropy were mainly dominated by initial cracks below 200^{0}C. The thermal induced cracks are mainly in the regions of lower density mineral grains below 400^{0}C. Boundary cracks and transgranular cracks generate significantly above 500^{0}C.

Thermal stress remarks

The are several mechanisms that can initiate thermal stress in rocks during heat treatment including the difference between minerals thermal expansion coefficients, anisotropic thermal expansion of minerals thresholds and heterogeneous temperature gradients [Liu et al., 2018].

Mineral phase change, desorption and decomposition along with increased temperature can also induce thermal cracking. Among these mechanisms differences between mineral thermal expansion (or contraction) coefficients as well as mineral thermal decomposition are known as a primary factor that causes thermal cracking or thermal fracturing. It can extend and widen existing cracks and create new inter and intragranular cracks.

Moreover, both old and new cracks could be further connected to form crack networks thus changing rock permeability. With increasing temperature at about 400-500^{0}C in the tested siltstone, limestone and conglomerate samples the pre-existing cracks propagate and new cracks are formed; together, these phenomena can generate well connected cracks networks, thus enhancing rock permeability.

The SEM images revealed that the length, width and density of cracks increased gradually with increases in temperature. The cracking of rock is a complex process involving the development of inter-, intra and transgranular cracks with variable shapes.

It was noticed from the SEM images [Liu et al., 2018] that there were some pre-existing cracks gradually inside the initial rock specimen. They were relatively narrow and poorly connected. After the rock was heated to a higher temperature some new cracks were generated and the cracks length and width increased. The formation of the crack network results in sharp variation in permeability especially when samples are heated above threshold temperatures thermal cracking leads to an increase in rock permeability.

Many hypotheses have been proposed in the literature to address the alteration of rock properties by heating. The primary reason for thermal cracking is assumed to be thermal stress. The thermal stress can be initiated in rocks during heat treatment, including the difference between mineral thermal expansion coefficients, anisotropic thermal expansion of minerals, temperature thresholds and heterogenous temperature gradient.

Therefore, understanding and evaluating how rock thermal cracking influences permeability and how to enhance or avoid permeability variation are imperative in geoengineering applications such as underground disposal of nuclear waste, geothermal energy extraction and in situ oil shale retorting process.

The prediction shows that the difference between mineral thermal expansion coefficients is the key factor in thermal cracking. However, mineral decomposition will significantly affect crystal structure and pore properties and definitely enhance rock permeability [Liu et al., 2018].

Chen Y. et al. found that the cracking thresfold of Westerly granite is 60-70^{0}C [Chen, Wu, Zhang, 1999]. When the microscopic fracturing connected like a network, the macroscopic permeability and the fluid transport changed remarkable.

The thermal cracking models have been observed in sandstone namely grain boundary, intergranular and mixt thermal cracking. The thermal changes in rock structure may produce many cracks increasing the rock permeability, especially when the threshold temperature was exceeded.

Fault zone permeability

The permeability of fault zone is an aspect of particular interest of economic geology and seismogenesis and an important parameter for understanding the role of faults within petroleum systems in both exploration and production field.

Caine J.S. et al. considered that the primary components of upper-crustal fault zone are fault core (gouge, cataclasite and mylonite), damage zone (small faults, fractures, veins, folds) and protolith (regional structures) [Caine, Evans, Forster, 1996] (Fig. 7).

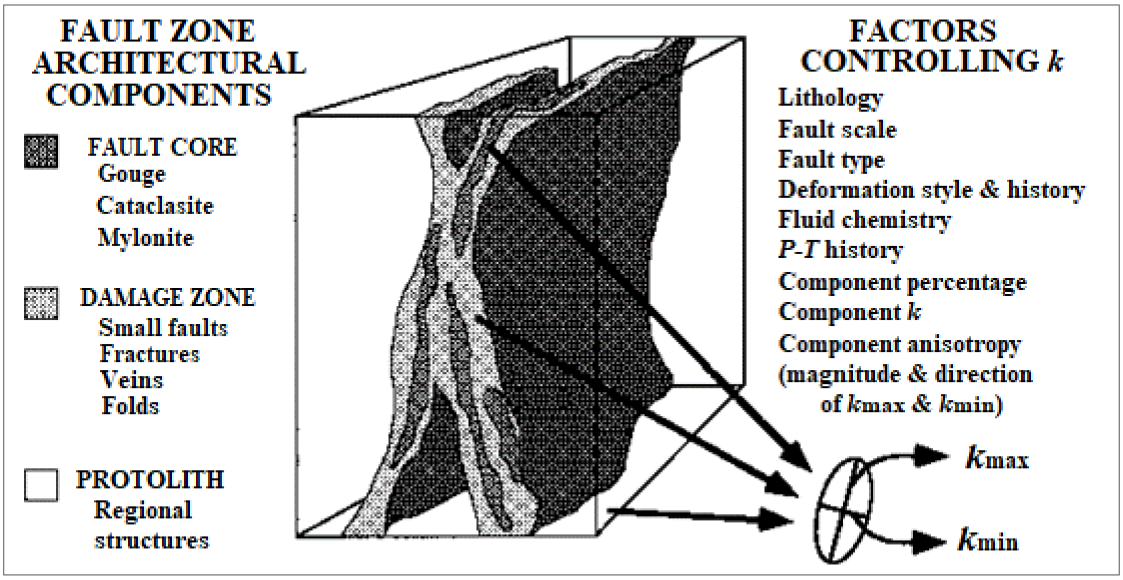


Fig. 7. Conceptual model of fault zone with protolith removed [Caine, Evans, Forster, 1996]
Ellipse represents relative magnitude and orientation of the bulk two-dimensional permeability (k) tensor that might be associated with each distinct architectural component of fault zone.

Fault core was defined by authors as the structural, lithologic and morphologic portion of a fault zone where most of displacement is accommodated. The damage zone is the network of subsidiary structures that bound the fault core and may enhance fault zone permeability relative to the core and the undeformed protolith. The fault zone permeability is dominated by the hydraulic properties of the fracture network [Caine, Evans, Forster, 1996]. The fault core and damaged zones are distinct structural and hydrogeological units and are surrounded by relative undeformed protolith. This is the country rock where fault related permeability structures are absent. Field observation of unfractured fault core materials suggest that they are dominated by grain-scale permeability. The permeability of the fault core may be dominated by the grain-scale permeability of the fault rocks whereas the damage permeability is dominated by the hydraulic properties of the fracture network.

Laboratory determined permeabilities for several fault core materials show a range of variation of approximately 10 orders of magnitude (10^{-12} to 10^{-22} m^2 - from semi-pervious domain to impervious domain) [Caine, Evans, Forster, 1996]. These data suggest that the permeability of fault core materials depends in part on lithology and the degree to which that lithology has been chemically altered (rocks with phyllosilicate content tend to highest permeability).

Fault zone structure and permeability data from the Median Tectonic Line (MTL) in South-West Japan suggest that the fault permeability models are too simplistic for such large structurally complex fault zone macroscopic permeability and the fluid transport changed remarkable fault zone.

It is increasingly apparent that fault zone is typically not discrete planes but zones of deformed rocks with a complex internal structure and three-dimensional geometry. The complex fault contact area has cataclasite up to 4 m wide and is cut by narrow central planar slip zone that probably represents the most recent seismogenic displacement zone [Wibberley, Shimamoto, 2003].

Fault permeability models and the fluid flow behaviour in and around the Japan MTL fault zone should take into account asymmetry where widely contrasting protolith lithologies exist and large permeability variations with a complex central fault zone «core» (Fig. 8).

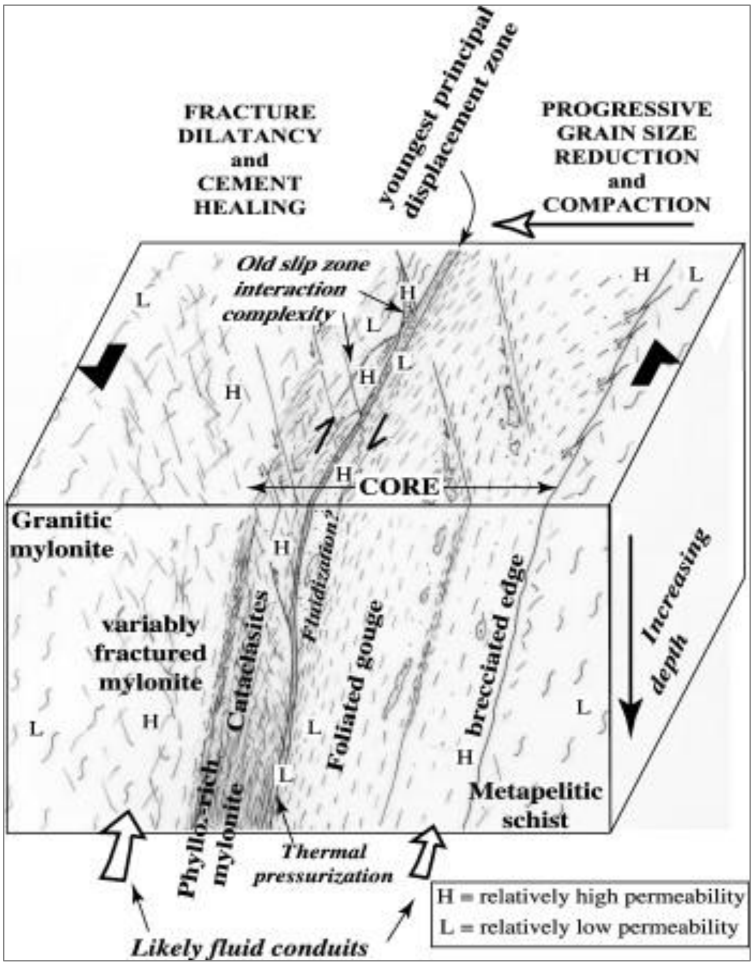


Fig. 8. Summary model of fluid flow behaviour in the shallow crust in and around the Median Tectonic Line fault zone (Central Japan) Note that the central portion is exaggerated in scale
[Wibberley, Shimamoto, 2003]

Central slip zone gouges have the lowest permeability of all of the fault rocks studied. Fracturing and cataclasis of Sambagawa schist also resulted in enhanced permeability as evidenced by high permeability of foliated gouges adjacent to the Sambagawa schist protolith. Fault zone of the Japan MTL permeability structure is controlled by the interplay between fracture dilatancy, cementation, shear-enhanced compaction and clay formation.

In the variably fractured rocks, mylonite and cataclasite sections of very heterogenous permeability, characteristics permeability is high in the fractured veined rocks, and also in incohesive cataclasites whereas is low in cemented fault rocks, that have not been refractured [Wibberley, Shimamoto, 2003].

The different deformation behaviours of contrasting protolith lithologies control the fault zone fabrics and hence final permeability structure (foliation parallel permeability increases steadily as grain size increases from the central zone towards the edge of the fault zone). In situ permeability data for crystalline rocks probable fractured range between 10^{-13} m^2 (semi-pervious rocks) and 10^{-18} m^2 (impervious rocks) for depth of up to 2 km [Brace, 1984].

Wibberey C. et al. presented data about the fault permeability structure models and underline the presence of two types of fault rock components: fractured conduits parallel to the fault plane and granular core barriers to flow [Wibberley, Yielding, Di Toro, 2008].

The permeability of fault zone is an important issue because bulk fluid rates through or along a fault zone are dependent on permeability variations, anisotropy, fracture dilatancy and tortuosity of flow path.

Wibberley et al. shows the porosity-permeability relationship for the suite of clay-rich granular fault gouge from the Japan MTL [Wibberley, Yielding, Di Toro, 2008]. The porosity of clay-rich granular fault gouge varies by a factor of 2-2.5, ranging from 10% down to 4% and permeability varies by 4-5 orders of magnitude from 10^{-16} m^2 (in low cemented fault rocks that have not been refractured) down to around 10^{-21} m^2 parallel to foliation. Permeability is high in the fractured veined rocks and in incohesive cataclasites.

Permeability is anisotropic, so porosity-permeability relationship will be different for permeability in different directions with respect to the foliation. To understand and predict permeability behaviour during active deformation, knowledge of the fault and their response to (anisotropic) stress changes and deformation is critical. Fault zone system containing sufficient lenses of fracture-dilatant cataclasis may drain fluid easily up the fault during deformation depending on whether or not these lenses are sufficiently connected [Wibberley, Yielding, Di Toro, 2008]. Generally, nature of fault rock and the mode of behaviour depend on three key factors: the composition of faulted sequence, the stress conditions at the time of faulting and the post-faulting burial history (especially temperature).

Evans J.P. et al. investigated the permeability structure of a fault zone into granitic rocks, especially in the two principal zone components: the fault core and the damaged zone [Evans, Forster, Goddard, 1997]. Tests performed at low confining pressure indicate that the highest permeability was found in the damaged zone (10^{-16} to 10^{-14} m^2, from impervious to semi-impervious rock domain). The lowest permeability was found in the fault core (10^{-20} to 10^{-17} m^2) and the intermediate permeability was found in protolith (10^{-17} to 10^{-16} m^2). These results are consistent with previous field in situ investigations of fluid flow in faults formed in crystalline rocks.

Uehara S.I. and Shimamoto T. reported the permeability measurements of fault gouge and tonalitic cataclasite from the fault zone of the MTL Ohshika (Central Japan) and presented a schematic sketch showing internal structure of the MTL fault zone at Ohshika Mura [Uehara, Shimamoto, 2004]. The fault zone itself is variable from place to place, but overall, it comprises mylonite (about 1000 m wide), cataclasite (about 50 to 100 m wide) and incohesive fault rocks (5 to 30 m wide) as schematically shown (Fig. 9).

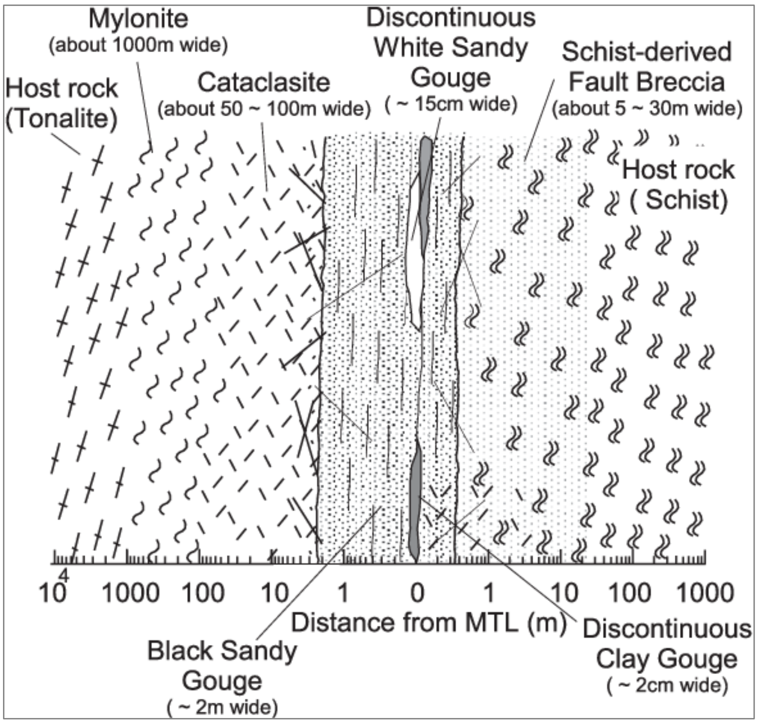


Fig. 9. A schematic sketch showing internal structure of the Median Tectonic Line fault zone at Ohshika Mura, Central Japan [Uehara, Shimamoto, 2004]

Horizontal scale indicates typical widths of representative fault rocks.

The cataclastic zone fractures during and after a large earthquake may change into an even more permeable zone than the fault gouge zone. The permeability of gouge may increase somewhat owing to the release of stress (or reduction in the mean pressure) but a fractured cataclasite zone may become the most permeable portion in a fault zone during and after an earthquake. The permeability cataclasite sample AK0916C is greater than of sample AK0916A by nearly three orders of magnitude, despite the fact that the latter is fractured into fine fragments than the former (Fig. 10). This fact suggests that fluid flow along through going fractures is more effective than through fragmented portions.

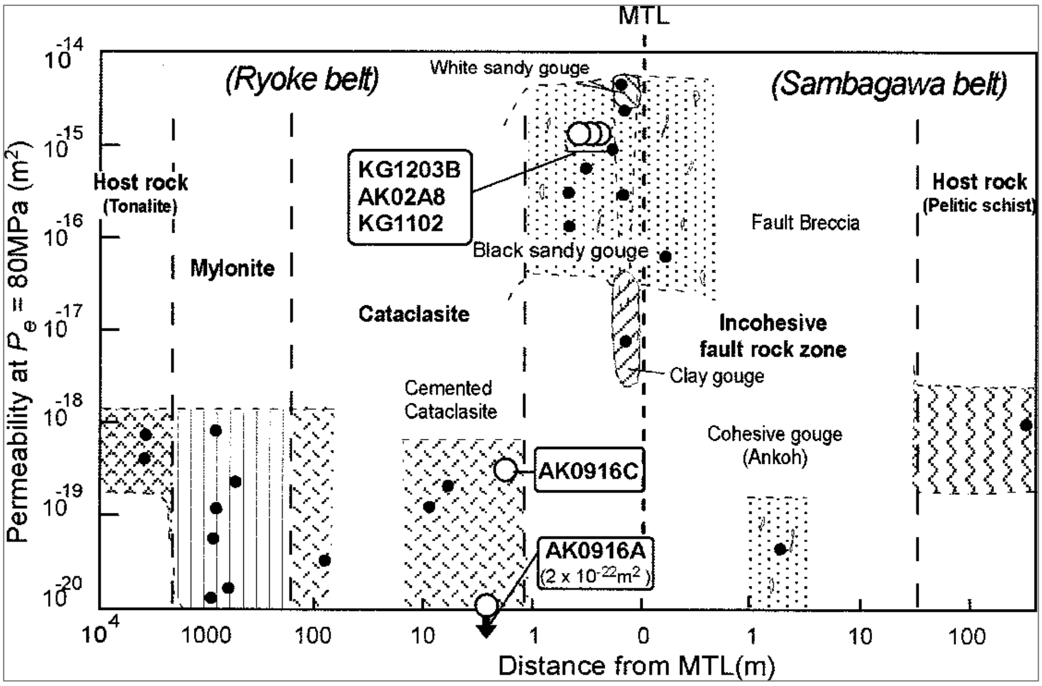


Fig. 10. Permeability structure of the Median Tectonic Line fault zone [Uehara, Shimamoto, 2004]
The circles show the locations and permeability values of the samples, the black dots show the locations of measurement of the permeability values of nitrogen gas at an effective hydrostatic pressure of Pe 80 MPa. The horizontal scale of this open circles shows locations and permeability values of the samples.

Tanikawa W. et al. measured permeability in sandstone and granite sheared at slip rates from 10^{-4} to 1.3 m/s under low normal stress at confining pressures up to 120 MPa [Tanikawa et al., 2010]. The host-rock permeability that separated reductions and increases in permeability was about 10^{-16} at 10 MPa effective pressure. As the slip rate increased, the permeability of Berea sandstone decreased by an order of magnitude, whereas that of Indian sandstone and Aji granite increased by 3 orders of magnitude at high slip rates microcracks and mesoscale fractures formed at slip rates above 0.13 m/s. The slip surface temperature (numerical modelling) increased by several hundred degrees for slip velocities above 0.13 m/s and exceeded the alfa-beta phase transition temperature of quartz at 1.3 m/s numerical modelling. The permeability in all samples decreased with increasing effective pressure.

Changes in the permeability caused by friction in fault vary with slip rate and rock type. The permeability values measured in Aji granite and Indian sandstone changed when slip rate increased; the abrupt permeability increases brought the tested rocks belonging to the large domain of the impervious rocks from 10^{-20} m^2 into the semi- pervious rocks domain 10^{-16} to 10^{-15} m^2 [Tanikawa et al., 2010]. After heating almost impermeable rocks to 300^0C at various lithostatic pressure, thermal expansion increased the permeability by factors of between 2 and 5. An abrupt permeability increase in low-permeability at high slip rates was caused by heat-induced cracks (Fig. 11).

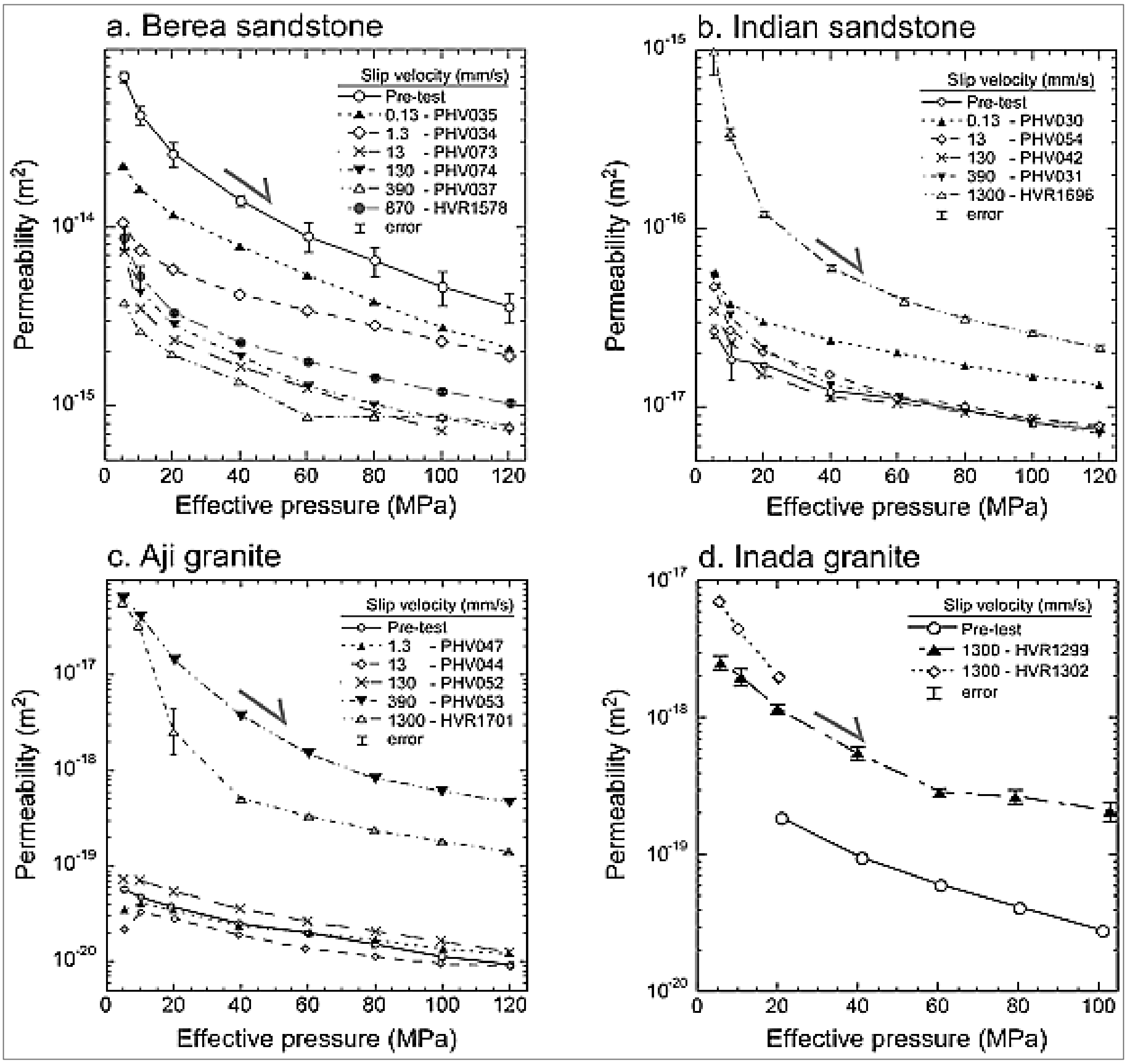


Fig. 11. Permeability as a function of effective pressure for specimens of Berea sandstone (a), Indian sandstone (b), Aji granite (c), and Inada granite (d) before testing and after friction tests at various slip rates [Tanikawa et al., 2010]

Data from the pressurization path are plotted.

Tanikawa W. et al. described a heat-induced cracks relative increase evolution in permeability occurred in most specimens, sandstone and granite sheared at slip rates from 10^{-4} to 1.3 m/s with an initial permeability lower than 10^{-16} m^2 [Tanikawa et al., 2010]. These results suggest that for sedimentary rocks or cohesive fault rocks (cataclasite), an initial permeability of about 10^{-16} m^2 marks the boundary between the permeability decrease attributed to intrusion of gouge into cracks and permeability increase attributed to the development or enhancement or fractures. The abrupt permeability increase at high slip rates in low permeability rocks agrees with hydrogeochemical phenomena observed after earthquakes.

Tanikawa et al. suggest that permeable rocks become relative impermeable after frictional sliding, whereas the permeability of less impermeable rocks increases abruptly at high velocities characteristics of seismic event [Tanikawa et al., 2010].

Oil shale permeability

Kang Z. et al. investigated the thermal cracking inside an oil shale sample using a micro - CT system [Kang et al., 2011]. The oil shale sample was heated to different temperature from 20 to 600^{0}C. It was found that the critical temperature of Chinese Fushun oil shale is 350^{0}C. In the range 20 to 300^{0}C a few small and narrow micro-fissures were formed. When the temperature exceeded 350^{0}C the permeability coefficient of the oil sharply increased and a large number of new fissures were instantly generated, linking with each other to form extensive network and leading to a rapid increase in permeability.

The permeability coefficient changed from 0.008×10^{-3} to 2.040×10^{-3} cm/s. After reaching 350^{0}C all sites of the sample reveal fissure whose number, length and width increase dramatically, resulting in the formation of an enormous network of fissures. Therefore, thermal cracking can be regarded as the decisive factor to affect the change of permeability in oil shale strata.

Zhang H. et al. led thermal shock tests on coal specimens by using a constant temperature drying oven (105^{0}C) and a SLX program controlled cryogenic tank [Zhang et al., 2020]. Results showed that the thermal shock improve the coal permeability significantly. Notably, the permeability of coal after thermal shocks increased from 211.31 md to 368.99 md and was positively correlated with temperature difference. CT scanning images revealed that thermal shocks increased the crack number, crack volume and crack width as well as smoothed and widened the gas flow path enhancing the coal permeability.

Chen X. et al. heated oil samples from Maoming area (China) to a certain temperature (up 50 to 450^{0}C) [Chen et al., 2021]. In the process of oil shale cracking, shale will gradually produce cracks and eventually fracture, so its porosity, permeability and thermal diffusion coefficient will be significant changed. The permeability first increases and then decreases. The variation trend of permeability of oil shale with pyrolysis temperature at different final pyrolysis temperature is presented (Table 2, Fig. 12). The pores of oil shale after 300^{0}C are extruded and deformed and a part of kerogen decomposition products such as asphalt are gradually produced so as to block up and reduce the permeability. The asphalt and other products decomposition continue to develop after 400^{0}C and produce oil and gas which makes the reservoir pressure rise, resulting in increase of oil shale pores, which makes the permeability increase rapidly. After 400^{0}C the pores of oil shale have strong compression deformation, resulting in permeability reducing (Table 2, Fig. 12).

Table 2

Permeability measurement data of shale in Maoming area [Chen et al., 2021]

Temperature, ^{0}C	**Permeability, md**
50	0.0100
250	0.0100
300	0.1373
350	0.0631
375	0.0388
400	2.1110
450	4.2800

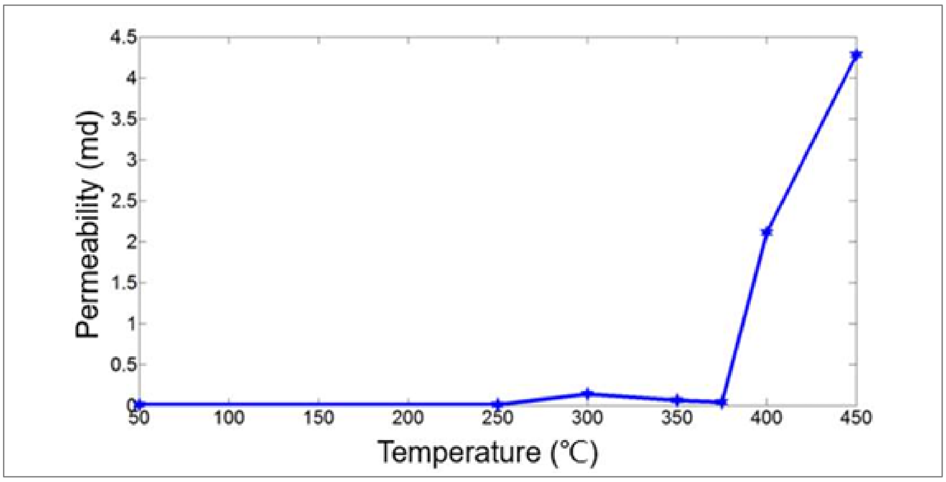


Fig. 12. Permeability changes with temperature in oil shale in Maoming area [Chen et al., 2021]

Yo-yo tectonics – general view

Yo-yo tectonics represents cycles of burial and exhumation occurring in wrench zones in response to switches between transpression and transtension or to changes in the geometries of faults during these types of deformation [Whitney et al., 2008].

The Niğde Massif (Central Anatolia Turkey) is a spectacular example of a tectonic yo-yo in a wrench zone; it experienced two complete cycles of burial and exhumation in a zone of oblique displacement. The two cycles, one regional and one more local occurred over 80 m.y. from Cretaceous burial to Miocene exhumation and cooling [Whitney et al., 2008] (Fig. 13).

Burial of Niğde basin sedimentary rocks and reburial of basement started in the middle Eocene (about 50 Ma). Metamorphic temperature for the buried metaconglomerate (Late Cretaceous age) about 82 Ma did not exceed around 350^{0}C. If the rocks reached the surface prior to 5 Ma, as seems likely, exhumation rates were about 1.5-2.5 mm yearly [Whitney et al., 2008]. Multiple cycles of burial and exhumation are rarely observed in the geologic record because evidence is removed by erosion or because basement-basin pairs have not been examined in an integrated way to reveal records of burial-exhumation cycles.

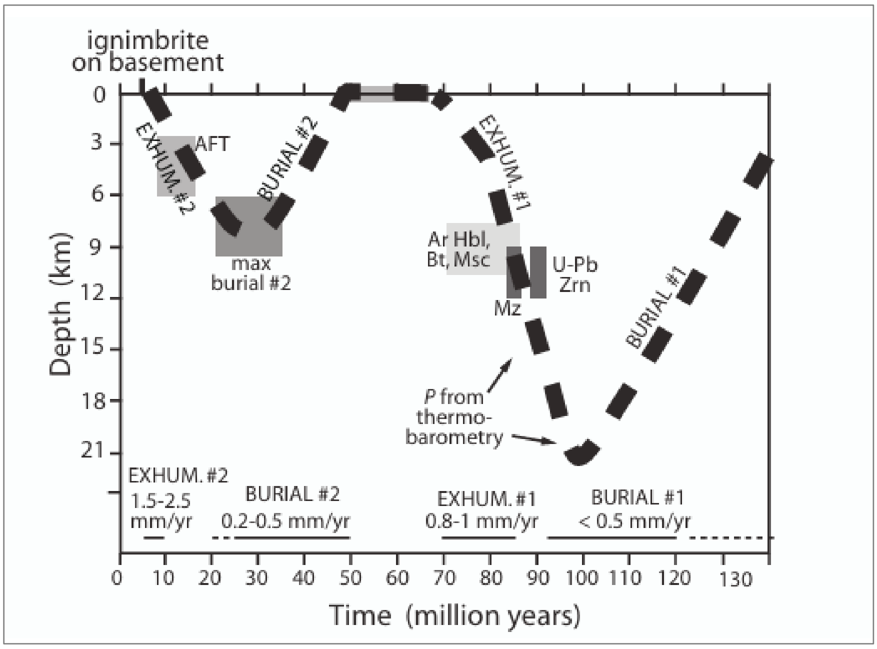


Fig. 13. Depth-time path and rates for the Niğde Massif, Turkey [Whitney et al., 2008]
Dashed black line indicated path for rock exposed in exhumation #1.

Whitney et al. considered that yo-yo processes are expected to occur in the following tectonic settings [Whitney et al., 2008]:

- orogen (e.g. North American Cordillera),
- collisional orogens (Appalachians, Alpine-Taurus belt, Himalayas),
- orogen with a significant component of oblique displacement (wrench).

In addition, the occurrence probability of the yo-yo tectonics processes, in the following types of sedimentary basins classification [Dou, Wen, 2021] should not be eliminated:

- ✓ back-arc depression (Sumatra basin) - current geothermal gradient 50-60^{0}C,
- ✓ back-arc rift (Malay basin) - current geothermal gradient 40-60^{0}C,
- ✓ intercontinental rift (West Siberia) - current geothermal gradient 38-45^{0}C.

The yo-yo tectonics can be applied to multiple complete or incomplete cycles of burial and exhumation occurring in continental crust in wrench zone. The rocks that reached temperatures of approximately 350-400^{0}C during the burial phase adapted to these PT conditions in terms of fabric, porosity, permeability and prograde metamorphic reactions. During the exhumation phase, the rocks in question reach lower PT conditions (retromorphism like process) holding back though a part of previous fabric and petrographic characteristics.

Conclusions

The rock permeability is a dynamic parameter that can change in response to tectonic activity and geochemical regime. Under a high temperature, high pressure an eventually in the presence of hot minerals - rich fluids a series of physical and chemical changes may occur in the rock, processes having a significant influence on the rock permeability too. Following a high temperature treatment, the changes in pores and cracks morphology and density are related to the thermal expansion and structural-textural changes in the rock [Qian et al., 2015].

The high temperature that the rock reached during a burial phase (especially around 350-400^{0}C or even more) changes the thermal stress in the rock and can produce many small thermal cracks inside enhancing consequently the flow capacity of a fluid, and simultaneously increasing the rock permeability. The thermal cracking even in granite can show a severe increase in permeability up to 3 orders of magnitude from 10^{-18} to 10^{-15} m^2 Meng, Liu, Meng, 2018].

Practically impermeable rocks (granites, basalts, gneisses, quartz sandstones, limestones etc) within the burial type deformation yo-yo tectonics [Whitney et al., 2008] with multiple cycles of burial and exhumation can reach temperatures that can exceed 350-400^{0}C, a thermal range where thermal cracking metamorphism can become very active and consequently the same rocks in question can even reach permeability values characteristic of semi-pervious rocks (10^{-15} to 10^{-11} m^2).

During exhumation (within yo-yo tectonics) the affected rocks through retromorphism like process will adapt as much as possible to the surface PT conditions of a geometrically superior structural level.

The rocks in question that were subjected to yo-yo type tectonics could become rocks which at first glance on the field seem to have an impervious permeability. Petrographic and geotechnical analysis in the laboratory could show the presence of permeability values as typical for semi-pervious permeability (partial adaptation to the retromorphism like process). This permeability has been generated in the tectonic stage marked by a large burial-type movement. During the exhumation stage this rock permeability system has been partly transported as a relict structure.

The opportunity of a possible petroleum prospecting activity in such regions (deformed by yo-yo tectonics) should involve associated petrostructural and geotechnical studies of the interesting rocks for determining the specific permeability of the rocks involved in this type of deformation.

Therefore, understanding and evaluating how the rock is influenced by thermal cracking and how to enhance or avoid permeability variations are also imperative for the study in situ oil shale retorting or to petroleum exploration for tight oil or gas reservoirs in relatively impermeable reservoirs rocks [Morariu, 2012].

The rocks reaching the critical level with temperature about 350^{0}C or more during the cycles of burial and exhumation [Whitney et al., 2008] adapt in term of fabric, chemistry, permeability and porosity to the typical conditions for the burial cycle in which they evolve. Part of these transformations can be preserved as relicts transported during exhumation within the retromorphism like process.

Finally, the petrostructural transformations undergone by the structural level involved in the burial deformation followed by exhumation (yo-yo tectonics) could under certain conditions increase the prospective potential for various fluids by improving the permeability of some rocks from this structural segment.

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Морариу Д.
Независимый эксперт – нефтяной геолог, Женева, Швейцария, morariu45@gmail.com
Аверьянова О.Ю.
Независимый эксперт – нефтяной геолог, Санкт-Петербург, Россия, info@ngtp.ru

ТЕМПЕРАТУРНОЕ РАСТРЕСКИВАНИЕ – КЛЮЧЕВОЙ ПАРАМЕТР ПРОНИЦАЕМОСТИ ГОРНЫХ ПОРОД

Рассмотрены различные подходы к вопросам температурного растрескивания и увеличения проницаемости горных пород, которые являются важными параметрами, контролирующими их флюидопропускную способность. Непроницаемые горные породы (магматические породы, гнейс, кварцевый песчаник и прочие) подвергаются термодеформациям при захоронении («йо-йо тектоника» с несколькими циклами погружения и воздымания в различных тектонических обстановках, таких как ороген, коллизионный ороген, область сдвига, задуговая депрессия, задуговой рифт и межконтинентальный рифт), когда достигаются температуры, превышающие 350-400^{0}C. В таком температурном диапазоне метаморфизм температурного растрескивания пород может стать очень активным. На этой стадии воздействие на горную породу может увеличить значение проницаемости до характерного для полупроницаемых пород. Так в процессе воздымания в захороненной породе начинается процесс адаптации к новым PT-условиям (процесс аналогичный ретроморфизму). Поскольку процесс подобный ретроморфизму редко бывает полным и очевидным, некоторые типы пород на первый взгляд могут быть отнесены к классу непроницаемых. Эти же породы при лабораторных исследованиях, выполненных, например, в ходе разведки месторождений углеводородов, соответствуют классу полупроницаемых.

Ключевые слова: *проницаемость, температурное растрескивание горных пород, «йо-йо тектоника», аналог ретроморфизма, полупроницаемая горная порода.*

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