Laboratory investigation of cryofracturing potential to stimulate geothermal reservoirs in Kazakhstan

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Thesis submitted to the School of Mining and Geosciences of Nazarbayev University in Partial Fulfilment of the Requirements for the Degree of
Master of Science in Petroleum Engineering

Nazarbayev University
29/04/2024

ORIGINALITY STATEMENT

I, Dastan Begaliyev, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

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ABSTRACT

Following the adoption of the Concept of Transition to Green Economy, Kazakhstan's renewable energy sector continues to expand. Shift to renewable energy is of key importance since it will help lower the amount of greenhouse gases which are emitted. The geothermal energy, including the HDR (Hot Dry Rocks), is a renewable source of power, though the low permeability is a challenge. EGS (Enhanced Geothermal Systems) are a promising technology which can widen geothermal energy use by creating reservoirs through stimulation practices, solving permeability problems in HDR formations. Methods like hydraulic fracturing and thermal stimulation have been suggested by researchers to enhance the productivity of hot dry rock reservoirs, however, these can cause environmental pollution and formation damage and not applicable in dry countries like Kazakhstan because of water scarcity. One way of solving the problem of water-related issues in Enhanced Geothermal Systems (EGS) is to use cryogenic fracturing, which with liquid nitrogen is not only efficient, but also environmentally friendly. This research project entails investigation of influence of elevated temperature with LN_2 cooling on granite strength as a destructive and non-destructive experiments.

There were selected 2 different granites from the outskirts of Akmola region to make comparative analysis. The analysis was made through 16 destructive experiments with unconfined compression and Brazilian tests, as well as by 2 non-destructive measurements with the help of XRD (X-ray diffraction) and CT Scan. The tests were conducted to identify the structural modifications and the mechanical behaviour of the granites affected by the thermal shock process performed in the cryogenic environment. The variable temperatures with LN_2 treatment during the compression and Brazilian tests were applied.

The analysis revealed several key findings. A compression and Brazilian tests showed that the breaking strength gradually diminished with the rise of temperature and LN_2 cooling while the granite was heated, leading to the conclusion that the granite's strength is reduced. It was shown that Young's modulus decreased with increasing thermal shock, while there is a positive correlation between Poisson's ratio and thermal shock. Even though both granites showed similar incrementing trends regarding damage factor curves, granite 1 exhibited a more affected response after heating and LN_2 fracturing, and it was more damaged compared to granite 2 in both the compressive and Brazilian tests. Therefore, it can be inferred that granite 1 achieved superior results compared to granite 2.

DEDICATION

I dedicate this work to my beloved father, whose memory continues to inspire me, my resilient mother, and my cherished sisters, whose unwavering support has been the cornerstone of my academic journey.

ACKNOWLEDGMENT

I'd like to express my gratitude to my supervisor, Professor Randy Hazlett, for his consistent support, guidance, and professionalism demonstrated throughout the completion of this thesis. His wealth of experience and profound expertise were indispensable in bringing this work to fruition.

Also, my deepest gratitude to Dr. Sotirios Longinos, my thesis co-supervisor, for his invaluable advice and support during my studies. Dr. Longinos was both a supervisor and a mentor to me, and his influence on my personal development was tremendous. Furthermore, I am deeply grateful for the invaluable assistance provided by my esteemed research group. I also thank the members of my thesis committee for their substantial contributions.

Furthermore, I would like to thank Nazarbayev University's School of Mining and Geoscience which provided us with an opportunity to study and carry out research under remarkable circumstances.

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1. INTRODUCTION

1.1 Problem Definition

The transition to a sustainable energy system is essential to reduce greenhouse gas emissions and mitigate climate change. Decarbonization, reducing CO_2 emission and a shift towards cleaner sources of energy, such as geothermal energy, are critical to achieving this goal. Kazakhstan's renewable energy sector has been expanding steadily since the implementation of the Transition to Green Economy Concept. By promoting a plan targeting 3 % renewable energy sources by 2020, 10 % by 2030, and ultimately aiming for 50 % low-carbon alternative and renewable energy sources (RES) in total power generation by 2050. Tokayev underscored Kazakhstan's efforts to fulfill its commitments under the Paris Agreement by implementing long-term plans to minimize greenhouse gas emissions. Moreover, despite being an oil, gas, and coal producing country, Kazakhstan's government just inked a deal with the European Union for raw materials and lower CO_2 emissions. Geothermal fields are another alternative with a low environmental impact because they use comparable technology to oil and gas operations. On the one hand, these geothermal energies correspond to hot dry rocks (HDR) (e.g., granite), which have reduced injection capacity due to non-contiguous cracks and extremely low permeability for extracting geo-energy. Kazakhstan, on the other hand, is one of the world's driest nations, therefore water consumption must be limited, such as in hydraulic fracturing and acidizing (both of which need a significant quantity of water) in geothermal energy extraction. As a result, there is an obvious need for a unique stimulation strategy that addresses both difficulties.

1.2 Objectives of the Thesis

1.2.1 Main Objectives

While Kazakhstan is on the course of a green energy system transition, an energy transition is expected to take place in the country in the next couple of decades. The geothermal energy sector stands out as a vital player in this transition, being appreciated as a renewable and harmless-to-the environment energy source. Destined for the fact that Kazakhstan's economy rests on the petroleum industry with a lot of people employed, it is possible to make a direct transition to the geothermal sector without any interruption of employment. Lastly, the technology related to the geothermal industry shows a lot of similarities to the technology in the oil and gas industry. Hence, workers in oil and gas can easily adapt to the sustainable geothermal industry, and this can avoid the problem of unemployment.

Several of the ways, which are a means of improving geothermal reservoirs, are known to us; but none of them can take care completely of both destruction of formation and water-related problems, which cause trouble for arid countries like Kazakhstan. Among all the new methods, cryogenic fracturing is the only one that can take all these problems by their horns. The method with uses almost no water and lower pumping pressure is more effective in controlling water-related issues such as contamination and formation damage. Having said that, the cryofracting technology appears as one of the effective methods of geotherm mal reservoir development in Kazakhstan.

In this context, this thesis is aimed at examining cryogenic fracturing to stimulate geothermal reservoirs in Kazakhstan through practical laboratory studies. Based on the preceding discussion, the main objectives of the thesis are outlined as follows:

- to diminish the environmental damage connected with geothermal resource exploitation in the territory of Kazakhstan.
- to avert the unemployment risks when the energy transition occurs.
- to tackle the water-related issues that come with hot geothermal energy extraction process in Kazakhstan.

1.2.2 Specific Objectives

As this thesis is going to make laboratory investigation of cryofracturing potential of 2 different granite rocks from the periphery of Astana, there are some specific objectives that must be achieved:

- to assess the effect of LN_2 treatment on the maximum load values of granite 1 and granite 2 rocks at elevated temperatures under a uniaxial compression test.
- to examine the LN_2 treatment effect on the maximum load values of granite 1 and granite 2 rocks at elevated temperatures under an indirect tensile stress (Brazilian) test.
- to identify the temperature range that will show the best outcomes after treatment by LN_2 and its relationship to the depth.
- To determine which type of granite is most affected by cryofracturing.

1.3 Scope of Work

The scope of this research is the comparison of two distinct varieties of granite present in the Akmola region's surroundings, exposed to higher temperatures corresponding to medium and high enthalpy reservoir conditions, respectively. The goal is to investigate their feasibility for ecologically friendly applications such cryogenic fracturing using a number of destructive and non-destructive testing such as compression, Brazilian, and CT-Scan tests. This project represents the first phase of unconfined tests, which will be followed by confined examinations in the second stage, with the ultimate objective of determining their potential for geothermal applications in Kazakhstan.

2. LITERATURE REVIEW

2.1 Geothermal Energy

2.1.1 Overview

Geothermal energy is categorized as a renewable and limitless source of heat and electricity. Geothermal energy can be delivered at all hours of the day and through every season, which is in the best interest of the environment and the unpredictability of the weather. On a human time, scale, geothermal energy is also seen as limitless or unbounded. The water injected into the reservoir through wells for heat extraction does not reduce heat resources below the surface [1]. The earth's core, which is more than 6.400 kilometers deep, has been radiating heat for more than 4.5 billion years [1,2]. Scientists predicted that approximately 42 million megawatts (MW) of energy flow from the earth's core to the surface, primarily through conduction [1]. Additionally, the geothermal energy source typically extends thousands of kilometers down into the Earth's subsurface from shallow reservoirs. Geothermal energy is also adaptable to a variety of uses and sources, from low thermal heat for district heating and agricultural demands to high temperature suitable for steam power plants to meet an area's or even a town's electrical needs [2].

2.1.1.1 Modelling and Systems for Geothermal Energy

A geothermal system typically consists of three main components: a heat source, a reservoir, and a fluid that carries heat and can also be referred to as the heat medium from the subsurface to the surface. As shown in Figure 1 below, the geothermal system can be explained methodically by heating water with thermal energy from the earth's upper crust in a constrained space and then transferring that heat to a heat sink on the earth’s surface. Additionally, as seen in Figure 1, the geothermal energy system's heat source in this case is magma.

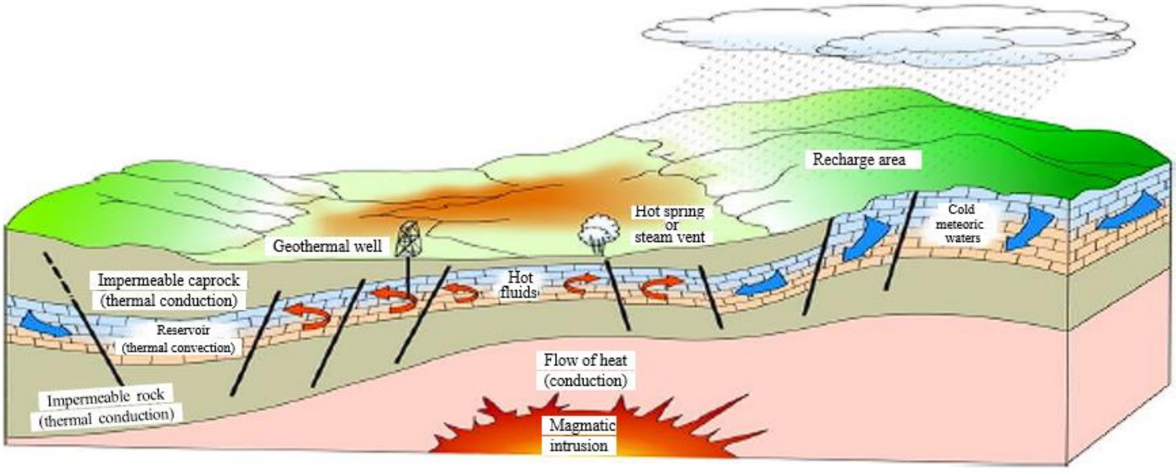


Figure 1. Ideal Geothermal Energy System [3]

Water trapped between impermeable rock layers heats up as a result of the magma's thermal conduction through intervening layers. Both impermeable matrices serve separate purposes; the upper matrix serves as a caprock and the lower one conducts heat [3].

If the heat from the hot rock volume can be transported to the surface to generate electricity, the geothermal reservoir might be economically attractive. There are four geothermal reservoir categories based upon temperature:

1. *High-Temperature Reservoir:* Usually, the high-temperature reservoir has enough thermal energy to convert the steam to electricity. These reservoirs often exist in volcanically active locations and have temperatures of more than 150 °C.

2. *Middle-Temperature Reservoir:* This type of reservoir has temperatures between 90 and 150 °C, which is a lower range than the first. Although the capacity is substantially lower than high-temperature reservoirs, the middle-temperature reservoir, nevertheless, enables sufficient extraction of power using fluid volatility. The reservoir is typically found in areas with higher-than-average geothermal gradients or unusual geological settings. Urban heating and industrial activities can benefit from the deployment of middle-temperature heat.

3. *Low-Temperature Reservoir:* A low-temperature reservoir can range from 30 °C to 100 °C. This type of reservoir is typically found in an advantageous geological setting with deep aquifers. The extraction of heat involves pumping hot groundwater from the aquifer and reinjecting it into the earth once the heat has been removed. The heat gradient is between the domain's averages, and heat extraction involves draining hot groundwater from the aquifer and

re-inoculating it into the earth once the heat is supplied. Both direct district heating and industrial processes can use this sort of heat.

4. *Very Low-Temperature Reservoir:* Heat exchangers can still extract heat at a temperature lower than 30 °C. The application can be utilized for agricultural and home air regulation. Since the efficiency under typical geothermal gradient settings is only governed by the subsurface thermal inertia, these sorts of reservoirs may be found at well-known locations [4].

The fluids produced by geothermal energy can be a combination of liquid and steam phases or simply liquid. The geothermal production technique can be impacted by the kind of steam system [5].

2.1.1.2 Power from geothermal sources

Because the ground has a broad range of potential energy variants from the horizontal surface to the shallow to deep subsurface, geothermal energy retains a variety of energy possibilities and sources from various levels of the earth.

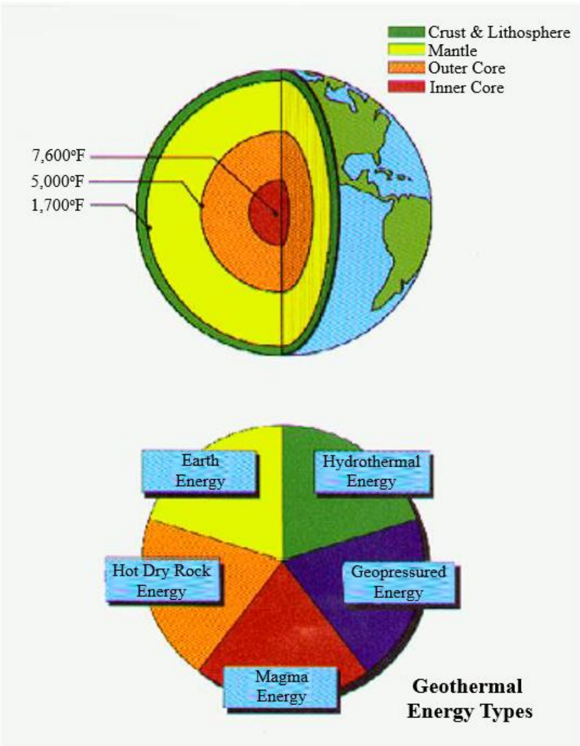


Figure 2. Geothermal Energy Types [5]

Geothermal energy is distinguished and categorized in Figure 2. Earth energy, hydrothermal energy, hot dry rock energy, magma energy, and geopressured energy are the five distinct subtypes of geothermal energy. The earth's layers, from the crust and lithosphere to the ultradeep inner core with its extremely high temperature, classify the geothermal energy seen in the above diagram. The energy derived from the hydrothermal energy system is the most developed and used of the five geothermal energy options mentioned above because the matrix's pores typically contain fluids and the reservoir depth is relatively reachable, both of which have an impact on the economics of using geothermal energy [5]. The hydrothermal system makes use of fluids with a high or low enthalpy level that has a high heat capacity and is embedded in a porous matrix. Advanced geothermal gradients and high volcanic activity zones are primarily associated with high enthalpy systems, which may be used to power electricity-generating power plants. A low enthalpy system, on the other hand, is often employed for direct geothermal energy generation in ordinary areas with average to moderate geothermal gradients [6].

2.1.1.3 Common Uses for Geothermal Energy

Geothermal energy uses may be broadly divided into direct and indirect (power generating) applications. Both categories often distinguish themselves based on demands, geothermal potential, and climate. Direct uses of geothermal energy make use of the underlying thermal resource and surface manifestation of the geothermal capabilities to achieve a particular energy goal. Direct geothermal energy is mostly used in subtropical and cold areas to meet the need for environmentally friendly space heating.

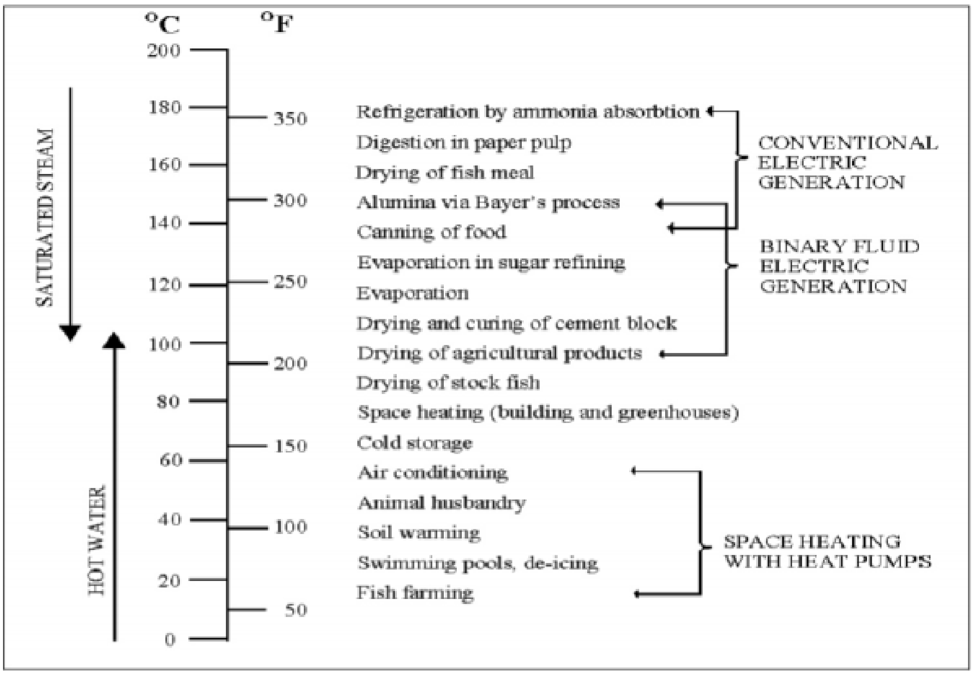


Figure 3. Lindal Diagram [7]

According to the Lindal diagram above, fluids with thermal contents below 100 °C are mostly used for agricultural and urban heating requirements, whereas fluids over 100 °C are primarily used for industrial purposes like drying and evaporating. The primary instruments for using geothermal energy directly are often heat pumps, heat exchangers, and pipes [7]. Indirect geothermal usage also refers to the use of hydrothermal resources systems that need a high temperature (greater than 150 °C) from dry steam wells and water wells and is frequently associated with geothermal power plants. The electrical turbine is powered by high thermal water or steam. The 14 locations that use this type of geothermal energy are often found in volcanic regions with considerable activity [2].

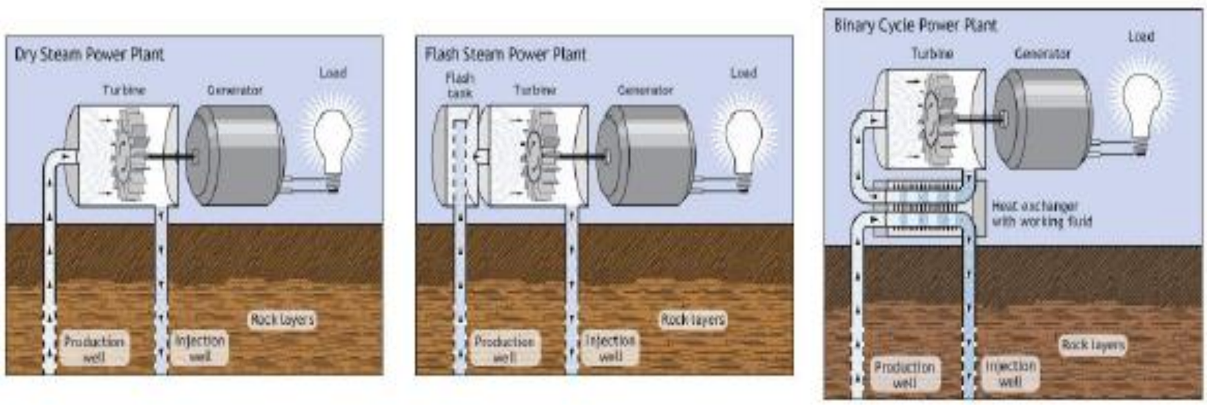


Figure 4. Type of Geothermal Power Plant [2]

There are three central systems of geothermal power plants, as shown in the kind of geothermal power plant diagram above:

1. *Dry Steam Power Plant:* Among the various geothermal power plants, this one is the simplest. The minimal quantity of fluid and steam is injected again after the heat is created into the generator while the heating steam produced from the production well enters the turbine and drives the electricity generator.

2. *Flash Steam Power Plant:* as the fluid is saturated as it enters the wellhead, this power plant is utilized. The liquid is released into a flasher where it is heated until it evaporates, at which point the vapor enters the turbine to generate energy.

3. *Binary Cycle Power Plant:* Typically, the subsurface fluid used for this type of power plant needs to be heated to roughly 200 °C or until it is adequate. The fluid from the subsurface is used to heat the organic fluid that powers the electrical turbine [8].

2.1.2 Geothermal Resources

Geothermal energy is a vast resource that is mostly found underneath the earth's surface. The geothermal energy resource's heat source transfers energy by conduction to the reservoir fluids inside the pore matrix. Since the use of geothermal energy should not exceed a specified point of economic limit, the subsurface heat contained in shallow or even deep reservoirs should be harvested appropriately economically. In addition to the underlying geothermal resource, certain volcanic sites with high levels of activity also include surface geothermal energy resources, such as geysers and heated earth [9].

Figure 5. Map of the World's Geothermal Energy Facilities [10]

Geothermal energy generator electrical power plants are now being used successfully in hilly and volcanically active locations (as shown in Figure 5 above) with the application of current technology. For instance, Indonesia established the "Sarulla Geothermal Project", the largest geothermal power plant in the world, thanks to locations that are surrounded by predominantly active volcanic volcanoes and situated in the ring of fire. Three distinct power plant units, each with an estimated 110 MW capability to produce energy, make up this geo-thermal project. Additionally, the geothermal well may be shallower (1000 meters) than in non-volcanic areas (>2000 meters) to get the necessary heat to be extracted from the geothermal energy in the volcano's active area because the resource for surface manifestation can be used there and the thermal gradient is higher [11].

2.1.2.1 Resources for Geothermal Surface Manifestation

When fluids rise from the subsurface to the earth through a fracture via permeable rock pores, this is the most obvious sign of geothermal reservoirs. There are several ways in which the surface manifestations might arise, as will be detailed below:

1. Hot or Warm Spring

This type of surface manifestation is one of the signs that some places have the potential for geothermal energy. Thermal fluids from the subsurface seep through the stone matrix and into the surrounding region to create a hot or warm spring. Warm and hot springs are classified according to the fluid temperature in the surface area; warm springs normally have temperatures around 30 °C, while hot springs have temperatures over 50 °C. The spring may also be a sign that hot water or steam predominates inside the geothermal reservoir [5].

2. Fumarole

The fumarole is a tiny hole in the earth with either dry or wet steam coming from it. Furthermore, the steam-dominated hydrothermal reservoir system typically contains fumarole that streams high-speed steam. Additionally, this steam could contain SO_2, which can only be stable at extremely high temperatures greater than 500 ºC. In the end, nearly every fumarole on the surface releases a hot, moist vapor that is typically not hotter than 100 °C [5].

2.1.2.2 Subsurface Resources for Geothermal Energy

Most geothermal energy resources are underground. As previously indicated, several geothermal energy forms may be employed for large-scale energy extraction, including earth energy, hydrothermal, hot dry rock, magma, and geopressured energy. Contrarily, given that the application of exploration and exploitation of hydrothermal systems is mostly used with advanced oil and gas technology, hydrothermal energy is the most widely utilized primary energy source globally [5].

Most geothermal systems, in contrast to hydrothermal systems, are still in the early stages of technical development. For instance, Chinese scientists are now exploring China's potential geothermal resources for hot dry rock energy systems. With the current state of technology, engineered geothermal systems in the hot, dry rock could potentially recover energy with a temperature greater than 150 °C to be used for both power generation and heating sources. A group of scientists drilled a well with a depth of 3,705 meters and reached the sources of the hot, dry rock with an estimated temperature of 236 °C. Additionally, a preliminary study suggested that the world's potential hot dry rock system resource is comparable to 10 times the combined amounts of oil, natural gas, and coal [10].

The same route of development is presently being followed for magma rock energy, which is still in the R&D stage of development. In one specific instance, a research team from the USA attempted to dig a defunct geothermal energy source on an active volcanic mountain in Iceland. The crew discovered a high-quality geothermal well after drilling a well right into the magmatic region. Additionally, the team's testing of the well revealed that it could generate dry steam at 400 °C; as a result, the high-temperature steam could generate a 25 MW power plant, which is greater than a normal geothermal well's 5 MW to 8 MW capability [2]. Since most geopressured resources contain three energy types-thermal, hydraulic, and methane gas-they appear to be less developed than other forms of geothermal energy. Most energy that relies on geopressured is combined with other energies, such as oil and gas or hydrothermal energy [12].

2.1.3 Geothermal Power Generation

2.1.3.1 Technology for Exploration

Most of the geothermal exploration technology has been adopted from oil and gas exploration technologies. Geochemistry, drilling, remote sensing, geology/stress analysis and modeling, potential field geophysics, and seismic activity are the five stages of the thermal potential exploration process. Geology and geophysics (GnG) activities account for most exploration efforts in the quest for geothermal energy potential. The exploration survey, particularly GnG mapping, can be beneficial to and is primarily in the upstream area of geothermal energy because the variety of geothermal types and utilization of this energy is volatile. With the map from the survey, the specific types of exploration and utilization can be predicted and adjusted with the needs of utilization. Seismic surveys, mapping, remote sensing, stress analysis, modeling, geophysics, and geochemistry are all examples of GnG operations. Having the exception of the geochemical activities, the instruments employed in this GnG phase are mostly those having a mapping objective, such as seismic tools. Most of the geochemical efforts during the exploration phase focus on evaluating the fluid contents of the surface and subsurface steam.

The drilling procedure is the most costly, dangerous, and important step in the exploration phase, after the GnG process. Borehole construction for heat extraction from the earth might cost millions of dollars without any assurance of hitting the same reservoir on the first try. Most of the drilling applications have been modified from the oil and gas drilling phase; the borehole and pipe sizes are the primary differences in the geothermal drilling procedure. The size of a geothermal well can range from being very small (a 2" well) to having a large diameter hole (> 8.5"). While the huge hole was successfully utilized for efficiency in geothermal energy heat extraction, the micro-size hole of the geothermal is mostly used for the exploration hole to find the estimated temperature in the reservoir below the surface [13].

2.1.3.2 Utilization and Production Technologies

Geothermal energy production technologies may be divided into two distinct processes: direct use and use in electrical power plants. As previously said, direct use is the major method employed, and the potential for geothermal energy in each region is not as substantial as the needs of an electric power plant.

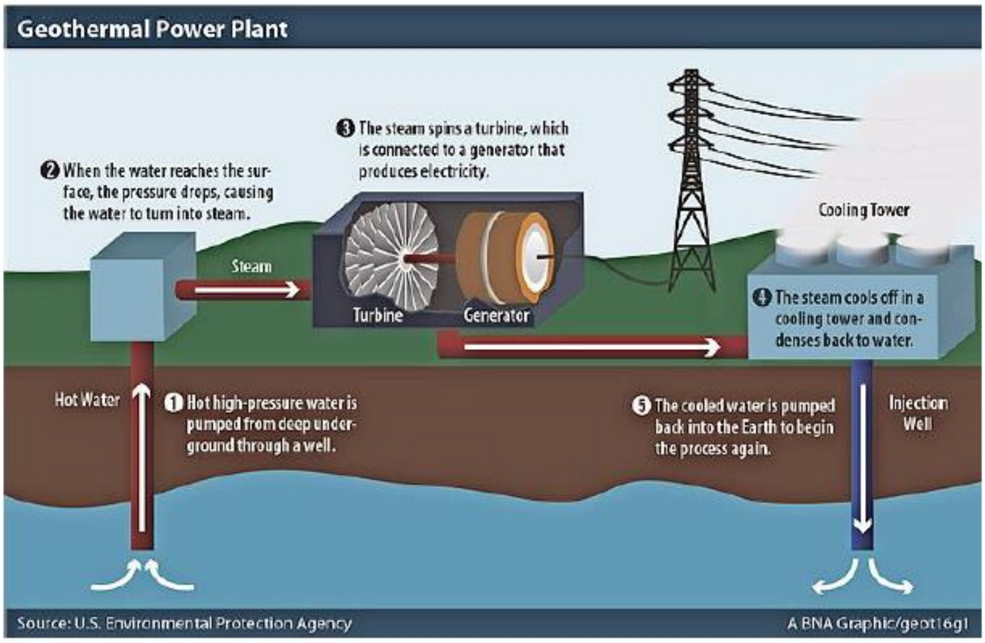


Figure 6. Geothermal Electricity Power Plant [2]

Figure 6 above explains the geothermal energy generation plant. This sort of geothermal energy is thermally extracted from the steam that circulates through the producing well. The turbine that is attached to a power generator to generate energy is spun by surface-produced steam. The fluids and steam enter the cooling tower after the heat from the fluids has been removed, and the cooled water is then injected back into the reservoir via an injecting well. As was also mentioned in the subchapter on electricity generation above, the most common technologies used in the electricity generation of geothermal energy are dry steam plants, flash steam plants, and binary steam plants.

Direct heating employs more volatile and varied technology in its applications than power plant use. First, the use of ground-source heat pumps is considered the most direct heat usage. The consistent temperature below the earth is what this geothermal heat pump depends on. Since the subsurface temperature is generally warmer in the winter and colder in the summer, ground-based heat sources can be used in the winter and can transfer thermal energy away from buildings in the summer. Geothermal heat pumps do not have the same excellent geological conditions as hot springs to be used daily. In addition to being ecologically benign, ground-source heat pumps (GSHP) may lower emissions 66 % cleaner than conventional thermal systems that are powered by fossil fuels. Three additional system types are also included in the GSHP: open, closed, and others. The systems themselves can be chosen based on the characteristics of the heated or cooled regions as well as the geology, hydrology, area, and use of those areas [14].

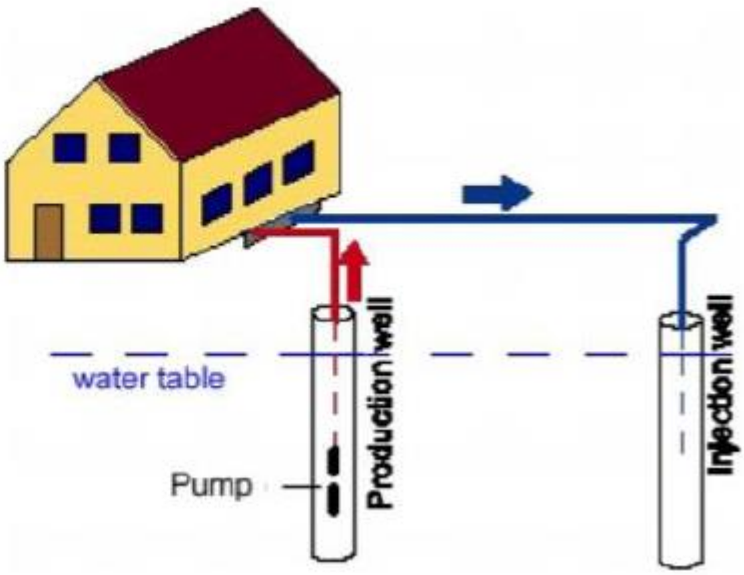


Figure 7. Doublet for an open loop groundwater heat pump [14]

Groundwater or surface water is used as the heat exchange medium in open-loop systems. The systems consist of surface water systems, reinjection wells, and extraction wells. After that, water availability and quality are the two most important considerations, since poor water quality can cause pipe fouling, corrosion, and blockage, while 1.5 to 3.0 gallons of water per minute should be circulated between the heat exchanger and refrigerant as a minimum. On the other hand, the ground heat exchanger is mostly used in closed systems for direct heat geothermal usage. The pipes can also be used as heat exchangers or collectors for ground heat. Although the heat exchanger is connected in series or parallel for greater land efficiency in certain smaller nations like Western and Central Europe owing to limits, an American version uses more space across a wider region. These pipes are buried horizontally below beneath the top layer of soil.

Last, but not least, "other systems" refer to those systems that do not perfectly follow the same principles as both open and closed systems. Other systems can relate to anything that already exists and might be exploited as a thermal source, including standing column wells, mine water, or tunnel water. The system may alternatively be characterized as a system that occurs when there is no legitimate delimiter for the separation between the subsurface water and the heat carrier liquid. It may be stated that geothermal resources can be categorized as surface and subsurface resources. Geothermal energy resources on the surface may be a sign that enormous heat potential from geothermal energy is stored underneath and may be utilized to generate power and serve other dual purposes. Second, the electric power plant is the most desired use of geothermal energy in daily operations, because it requires the least amount of heat to convert geothermal energy into electricity, whereas direct use of geothermal energy heat extraction would allow it to be used not only for household heating but also for the needs of commercial applications like drying and agriculture. Finally, the technology behind geothermal energy is essentially modified oil and gas exploration and production instruments. Petroleum drilling technologies are employed during the exploratory phase, particularly when digging geothermal wells, anticipating extremely high temperatures and high pressures [14].

2.1.4 Geothermal Energy Applications

2.1.4.1 Generation of electricity

As previously said, mountainous and volcanically active regions are where geothermal energy applications (mostly hydrothermal energy) that are sufficient to provide the quantity of heat needed to operate the power plant are most frequently found. The heat from the subsurface well, either using dry or wet steam is transferred by pipe straight to the electricity-producing power unit. Additionally, the remaining water and chemicals from the subsurface are injected once more using the injection well once the heat from the steam has been removed. Because geothermal energy only uses the heat from the subsurface, the remaining water and chemicals from the steam are returned to the subsurface. This is why geothermal energy is classified as renewable.

There are three different types of hydrothermal energy-producing power plants in use today: binary steam plants, flash steam plants, and dry steam plants. Although the technology of flash steam is more complex than that of dry steam, the energy generator plant is the type of geothermal power plant that is currently being used the most. This is because leftover water and any condensed steam are injected back into the ground, maintaining pressure and resource sustainability [15]. Later, a more advanced geothermal energy technology was created for the Sarulla geothermal energy project in Indonesia. The Geothermal Combined Cycle Units (GCCUs) technology claimed to build more efficient technology and sufficiently catch the steam from the subsurface before producing heat sustainably without any interference and evading the reservoir system from the exhaustion of gas [16].

2.1.4.2 Direct Heating

The simplest things that geothermal energy may be used for are direct heating applications. Direct heating may be used for a variety of purposes, from drying and heating in homes to heating and drying in large sectors. The Lindal Diagram [7] divides the geothermal direct heating temperature needs into three ranges, ranging from the lowest 15 ºC to 200 ºC. The majority of uses for this relatively modest heat source range from air conditioning to space heating using heat pumps in the fish farming industry, with temperatures ranging from 15 °C to 60 °C. Since the technology is simply basic and may be used with a heat pump for home and small community heating, this low geothermal energy can be employed in most subtropical and cold areas.

Furthermore, the binary fluid electricity generation technology can used for building and greenhouse heating but is also useful to medium industries such as drying and canning of agricultural products, stock fish incubation, and cement block manufacturing with heat sources in the moderate temperature scale from 80 °C to 150 ºC. Later, a small quantity of electricity may be generated using the capability of mild temperature, which is employed for direct heating. The quantity generated may not be sufficient for widespread commercial power generation, but the heat extracted using present technology might be fully utilized for space heating and improving the energy efficiency of various sectors.

The highest temperature that geothermal energy is often utilized for direct heating is from 140 °C to 200 °C. The traditional electric generation that is mostly used for direct heating is also capable of producing electricity in power plants. At these temperatures, direct heat is typically combined with the steam that is produced in power plants to produce electricity. In terms of the number of countries generating geothermal energy, the United States is the one that uses it the most for both direct heating and power production. In terms of geothermal energy power generation for direct heating and electricity production, the nation produces more than 3.5 GW equivalent of electricity [7].

2.1.4.3 Greenhouse Heating

One of the most practical direct geothermal energy heating applications that helps agricultural sectors move toward widespread usage of renewable energy for commercial purposes is greenhouse heating. In the global ranking of geothermal capacity without and with heat pump application, the use of geothermal energy for greenhouse heating came in third and fourth, respectively. Following the data, the proportion of greenhouse heating not utilizing heat pump technology is ranked third with 8.96 % of the total global share in worldwide capacity, while the utilization of heat pumps in greenhouses only accounts for 2.6 % of the total global ranking of heat pumps geothermal world capacity. In this instance, geothermal energy is being used for direct heating, which has a very low-temperature requirement and is appropriate for frigid climates where plants cannot flourish. Low enthalpy from shallow to deep wells is used to heat greenhouses using geothermal energy, often with the assistance of a pump and heat exchanger. Depending on the thermal gradient of the area, the system from a single well might be used for not just one greenhouse but possibly for two or even more.

For instance, Greece has been using low-enthalpy geothermal energy for greenhouses for more than ten years. The heat exchanger helps the farmers use the geothermal fluid's heat. The equipment can assist the farmer in heating water to a temperature of about 95 °C. Heavy-duty steel pipes may be used to distribute the heat from the exchanger to the plants in the greenhouse, and the temperature can be lowered from 95 °C to around 50 °C to avoid overheating the plants. Overall, the heating system can keep the greenhouse's interior temperature at 20 °C even when the outside temperature is 7 °C; even when the temperature drops to 2 °C, the system can keep the temperature steady at 15 °C. When the temperature starts to drop due to the winter weather, which lasts from October to April, low enthalpy geothermal energy is most useful. Additionally, since the use of heat is advantageous to farmers, many of them in the subtropics are beginning to investigate their options for using geothermal energy to break their dependence on traditional heating systems that rely on limited resources like fossil fuels [17].

2.1.4.4 Bathing and Swimming

It may not be widely known or frequently mentioned why geothermal energy is used to directly heat water for bathing and swimming. The geothermal application, which is mostly used for bathing and swimming without the use of heat pumps, came in first place among all other geothermal applications with 44.74 % of the overall market share. If it is practicable, the resources in this situation can also be extracted from surface manifestations in addition to subsurface ones. Since some surface manifestations, like natural hot spring water in some areas, may be utilized immediately for bathing and swimming, the majority of surface geothermal manifestations take the form of fluids like geysers and hot pools. However, bathing and swimming may also be done using geothermal energy that is stored beneath the earth's surface. To maintain a comfortable temperature for swimming, a heat exchanger may transfer the heat from the earth. The geothermal system may also be used in conjunction with a binary system to provide bathing facilities for homes as well as communities. This system may be trusted for both heating and cooling reasons [18].

2.1.4.5 Heat Pumps and Space Heating

Geothermal heat pumps, which may also be utilized for building and space heating, account for most of the dominance in geothermal utilization for direct heating. Around 70.95 % of the global capacity for geothermal heat pumps is utilized for geothermal heat pumps with multiple uses (primarily for buildings), while 10.74 % of the global capacity is devoted to space heating. On the other hand, according to another statistic on the global capacity of geothermal utilization without heat pumps, 36.98 % of the world's utilization is utilized for space heating, which is ranked second only to bathing and swimming, which accounted for 44.74 % of the world's total share. Geothermal district heating is being used in 12 different countries and provides more than 44.772 TJ of energy annually [18].

One of the earliest geothermal direct usage applications might also be referred to as space and district heating. The first district heating system was installed at Chaudes-Aigues Cantal, France, around the beginning of the 14th century, and it is still in use today. Later, as technology advanced and demand increased, heat exchangers and pumps were utilized to raise the temperature to predetermined levels. Even though the standard temperature needed is roughly 50 °C, geothermal heat pumps enable the utilization of resources with lower temperature requirements, down to 40 °C in some circumstances [20].

2.1.4.6 The use of agriculture and aquaculture

These applications in the direct use of geothermal energy are less common than the other uses. Agriculture drying and aquaculture pond heating are currently not extremely frequent and popular uses, with a global share of less than 4 %. The primary goals of agricultural drying are to reduce the risk of spoilage during storage, speed up the harvesting process, and raise the price and quality of agricultural products [19], whereas the primary goals of aquaculture pond heating are to increase freshwater or marine living organisms in a controlled environment to increase the production ratio [20].

Air is most often used as a heat transfer fluid. There are two options for heating the air as the medium: first, the fluid in the heat exchanger can heat the air; second, the fluid in the heat exchanger can circulate the air in the more sophisticated systems. The low hydrothermal temperature might be utilized as the heat source for the air that is simultaneously being used to dry the crops because the thermal requirements for this purpose are quite low (from 35 ^{o}C to 80 ^{o}C). On the other side, the aquaculture method is more frequently utilized in colder locations where the conventional heater is not cost-effective. The required temperature range for this pond heating application is only 10 ^{o}C to 30 ^{o}C. The geothermal heat fluid may also be combined with a heating system powered by fossil fuels and utilized to control the pond's environment [21].

2.1.4.7 Industrial Uses

In terms of worldwide share, both with and without heat pumps, industrial applications of geothermal energy come in last with less than 3 % of total capacity (even in terms of overall proportion with heat pumps, it accounted for less than 1 %). Many industrial operations, including process heating, industrial space air conditioning, food and fish drying, pulp and paper processing, textile washing, even fuel manufacturing, and oil upgrading, may be used with this application. Industrial uses just require a heat source, which may be supplied by low to medium-geothermal fields. While most companies now utilize traditional heat sources, such as gas and coal, the heat may be required most frequently between 10 ^{o}C to 149 ^{o}C and can be provided by geothermal. Geothermal energy can be one of the alternative sources that can be utilized by enterprises, with a broad range of applications, given that the industrial sector consumes 54 % of all energy and still employs renewable resources as their primary source of energy in most cases [21].

2.1.5 Effects on the Environment and Society

Geothermal energy development does not just rely on its benefits. The biggest problem with geothermal development projects is how to deal with the contradictory nature of the technology itself. In actuality, the difficulties in harnessing geothermal energy are not just constrained by physical difficulty. Economic, technological, and societal difficulties associated with geothermal development might potentially provide a hurdle for the development of hydrothermal systems. Since the development of geothermal energy, especially in electricity power generators, mostly implicates the upstream and downstream process, the involvement of stakeholders in this energy development (from external and internal) also could be complicated and bring challenges [2].

Table 1. Summary of Geothermal Sustainability Issues [22]

Theme	Positive impacts	Negative impacts
Poverty	- Increased per capita income - Increase in salaries - Social development initiatives - Affordable energy supply - Higher living standards - Improved food security - Access to drinking water	- Rising property prices - Community displacement
Health	- Improved sanitation - Improved medical facilities - Lower indoor air pollution - Therapeutic uses	- Odor nuisance - Toxic gas emissions - Water contamination risk - Noise pollution
Education	- Improved education facilities - Improved school attendance	- Sudden or unprecedented cultural change
Natural hazards		- Induced seismicity - Subsidence - Hydrothermal eruptions

Demographics	- Positive social change - Increased tourism	- Negative cultural impacts - Resettlement - Livelihood displacement
Atmosphere	- Displacement of greenhouse gas emissions from other energy sources	- Greenhouse gas emissions - H_2S pollution - Toxic gas emissions
Land	- Small land requirements relative to other energy sources	- Habitat loss - Soil compaction - Conflict with other land uses
Forests	- Replacement of traditional biomass	- Deforestation - Ecosystem loss
Freshwater	- Low lifecycle water consumption relative to other energy sources	- Conflict with other energy uses - Contamination of shallow aquifers and other water bodies
Biodiversity		- Habitat loss or disturbance - Loss of rare geothermal ecosystems
Economic development	- Increased energy security - Low climate dependence - High-capacity factor - Direct, indirect, and induced economic activity and employment	- Few direct long-term jobs
Consumption and production patterns	- Waste heat can be cascaded or recaptured	- Waste may cause environmental contamination - Risk of overexploitation - High cost of turbines may compromise efficiency

Referring to Table 1, there are 11 issues or challenges related to geothermal development that can be categorized as physical, technical, social, economic, or environmental (e.g., poverty, health, education, demographics, and environmental hazards), as well as technical (e.g., consumption and production patterns). Although not all the aforementioned effects may affect geothermal energy users or producers, the majority of major geothermal producers would confront these difficulties when establishing geothermal energy systems [22].

2.1.5.1 Problems with Geothermal Energy Currently

The development and deployment of geothermal energy may have several benefits and drawbacks that may be divided into three categories: physical, technological, and societal concerns. This is because geothermal energy is not currently implemented and is used everywhere on a big scale like fossil fuels. There are more than ten key concerns and problems with geothermal development and utilization, according to Shortall et al. [22]. The author also mentions the good side of impacts while explaining the bad effects.

2.1.5.2 Physical Problems

Since geothermal energy is located beneath the earth's surface and is being exploited during the exploration process, there is a high risk of negative effects on the environment and the area around the proposed locations. As a result, the physical problems of geothermal development are the biggest concerns regarding the impact. Natural hazards, the atmosphere, land, freshwater, forests, and biodiversity are the key concerns that geothermal energy production is now facing [2].

2.1.5.3 Natural Hazards

Seismicity induction, landslides, and hydrothermal eruption are negative effects that might result from the development of geothermal energy. The danger of these adverse effects is most likely to occur during the discovery phase of geothermal energy, with a small chance of accident occurring during the exploitation phase. First, one of the contentious issues surrounding the Enhanced Geothermal Systems (EGS) is the relationship between induced seismicity and micro-seismicity. This issue has resulted in the cancellation of at least two EGS projects globally. Even though there are no physical hazards for communities, as a result of micro-seismicity in the reality and application of EGS development, the public is still concerned when there is a geothermal project in a specific area, such as the Soultz Geothermal Development Project in France. To increase the public's acceptance of geothermal energy, more technological advancements must be made since induced seismicity is an essential technique of reservoir management that is particularly significant in the period of showing the potential of geothermal regions in specific locations [23].

Second, one of the problems that primarily affected the geothermal exploration and production phases that took place mostly in volcanic geothermal zones was subsidence or landslides. As has already been established, places with high inclination mountains have the greatest potential for geothermal energy, particularly hydrothermal energy. Although widespread irrigation and community usage of subsurface water caused most of the sinking, extensive geothermal development might possibly result in dangerous subsidence. For instance, the Wairakei geothermal project in New Zealand caused a subsidence of about 15 M. Despite this project's minor impact, a systemic disaster may have occurred in the area's vicinity, necessitating the use of specialized technical surveying systems to avert a larger catastrophe [24]. Finally, even though hydrothermal eruptions frequently occur in both exploited and unexploited geothermal regions, geothermal activity on a certain scale can trigger an eruption when pressures exceed lithostatic, steam and/or gas buildup occurs, flashing progresses, and the rare occurrence of additional magmatic heat or gas. Later, even if the situation is rather uncommon, the corporation or organizations should do a hazard assessment while constructing the geothermal fields to avoid hydrothermal eruptions [25].

2.1.5.4 Atmosphere

Additionally, air pollution brought on by geothermal exploration and extraction operations is included as an atmospheric issue. The actions may release H_2S pollutants, greenhouse gas emissions, and other harmful gas emissions. First, most energy-related activities, including those involving renewable energy sources, can produce some harmful greenhouse gases. However, by reducing reliance on fossil fuels, the negative effects that CO_2 gas can have on the environment can be reduced.

Table 2. Environmental Impact of Energy Sources [26]

	CF (%)	Efficiency (%)	CO_2	Water	Land
PV	8-20	4-22	90	10	28-64
Wind	20-30	24-54	25	1	72
Hydro	20-70	>90	41	36	750
Geoth	90+	10-20	170	12-300	18-74
Coal		32-45	1004	78	
Gas		45-53	543	78	

According to Table 2 above, even though geothermal energy doesn't create as much greenhouse gas as fossil fuel sources (coal and gas), it still produces the most CO_2 when compared to other renewable energy sources (PV, wind, and hydro). Later, with efficiency and water consumption also being the primary drawbacks of geothermal energy activities, the main benefit is land efficiency, as shown in the table above [26]. One of the main risks to the extraction of geothermal energy's heat is hydrogen sulfide or H_2S gas. Together with CO_2, H_2S gas may be created, and this corrosive gas is hazardous, especially if the geothermal source and power plant are situated in a shared region. The level of hydrogen sulfide in these areas, such as the City of Bjarnarflag, is engineered into specific models to distribute and predict the concentration of H_2S to avoid disadvantageous and even life-threatening conditions, as is the case with most of the geothermal power plants in Iceland [27]. The extraction of geothermal heat may also result in the production of another gas. Along with CO_2 and H_2S, the other gases that are often generated by geothermal fluid and steam include H_2, N_2, CH_4, and Ar. Fortunately, under some circumstances, the H_2 gas concentration of geothermal gas might be used as a different source of energy. Directly from the geothermal fluids, hydrogen may be obtained by a few chemical procedures. Additionally, since gases like CH_4 are combustible and might harm the surface if there is a fire, the surplus gases in small amounts of geothermal fluid, such as N_2, Ar, and CH_4, are often injected back into the subsurface within the injection well [2].

2.1.5.5 Land

There are some issues with the land impact of geothermal energy development and utilization such as habitat loss, soil compaction, and conflict with other land uses, even though some other renewable energy sources like solar panels and wind energy claim that the use of geothermal energy only requires a small amount of space or land. The development of this energy might put certain local animals in jeopardy since some geothermal energy deposits are in protected zones. Take the development of geothermal energy in Kenya as an example. While the Olkaria geo-thermal power plant project has the potential to increase Kenya's electricity costs, the present geothermal region also must be preserved. The Olkaria project is in Kenya's Hells Gate National Park, which has an endangered habitat. As a result, the government must be concerned with both the development of renewable energy sources and the preservation of the park's delicate natural ecosystem [28].

Along with soil erosion, cases of soil compaction are also possible. throughout pre-lease exploration and even throughout the post-lease exploration, development phase, and production activities, the soil may become more compact than usual. In other words, as geothermal sites are developed, the heavy machinery used to dig the sites may have an influence on the soil in those places. Additionally, these activities have the potential to degrade the soil's structural integrity, compress the ground in certain regions, and loosen it in others. Conflict with other land usage is the last prevalent issue. Before geothermal power facilities were established, the area was used for a wide range of purposes. For instance, in some volcanic areas, the property might be utilized for local housing, community and local usage, tourist, and environment and forest protection. Because the subsurface resources of geothermal energy cannot be relocated like the surface condition, the conflict with other land use purposes may still be an issue in the future of geothermal energy, because the development area of geothermal energy must be "clear" in a specific size [29].

2.1.5.6 Fresh Water

One of the important topics now being debated in many scientific and governmental forums is the availability of fresh water. Some types of geothermal power plants require large volumes of fresh water to function, which is one of the weakest areas in the use of geothermal energy. In comparison to other types of fossil and nuclear power plants, geothermal power plants may need more water. In the case of the Imperial Valey geothermal power plant, it is predicted that the plant will require more than 300.000-acre feet of water to maintain the production of 5.500 MWe of electricity [30]. Additionally, throughout the development and production stages of geothermal energy, water pollution is an issue. Surface and underground water might get contaminated by interactions between the drilling operation and the steam produced by the power plant [31].

2.1.5.7 Forests

When the development of this thermal energy might create such a complex issue as deforestation and ecosystem loss when creating the energy, geothermal energy utilization can still conserve forests and their biodiversity by substituting conventional biomass. Geothermal energy with deforestation is an ancient problem. While geothermal energy is renowned for being environmentally friendly and has many benefits, in some cases of geothermal development, the energy is found are in the middle of forests, such as in Indonesia. Numerous geothermal power plants may be found in the mountains and woods, including the Kamojang project. Although the Kamojang project is located within a protected conservation forest, more than 200 hectares of wood have been destroyed since the power plant's construction began to keep the electricity project on track due to the necessity of energy [32]. Like the deforestation issue, the ecosystem loss issue would make geothermal development more challenging, particularly if mass thermal resource usage occurs in a location with a remote and vulnerable ecology. Once more, the deforestation issue would bring about the next challenging step, ecosystem destruction. The wildlife ecology in a specific region of the forest may be in risk due to development, and the effects of a variety of non-condensable gases, as well as other elements like arsenic and mercury, may have a long-term, systemic influence on the ecosystem [33].

2.1.5.8 Biodiversity

The Sustainable Development Goals (SDGs) include protecting biodiversity and raising the proportion of renewable energy sources, but some projects to develop geothermal energy may put biodiversity at risk by promoting habitat loss and upsetting rare eco-systems in the geothermal potential areas. One of the current concerns for several governments, like Indonesia, is the damage of the ecosystem in some geothermal areas. To assure the development of geothermal fields, the Indonesian government must lease "virgin" forest preservation on Slamet Mountain, which is also known as the home of the Javanese Puma, an endangered animal that once roamed the region [2].

2.1.5.9 Technical Problems

Technical perfectionism would lead a geothermal energy project to a certain goal of success, while poor engineering performance could lead the project into technical failures that also lead to other problems in physical and social dimensions. The biggest technical challenge with geothermal energy, as stated by Shortall et al. [22], relates to the topic of consumption and production patterns. The complexity of the energy project might increase due to poor waste management, overproduction, and exploitation, as well as turbine costs for geothermal power plants. First off, poor waste management in the generation of geothermal energy might transfer the environmental issue to another account. As was indicated in the section on physical issues, subsurface steam may include hazardous chemicals and corrosive gases that might damage the local people who reside close to the geothermal project site as well as the surrounding environment. Second, since most geothermal projects are anticipated to last a long time, it is important to maintain and carefully monitor the hydrothermal reservoir component. This is because a loss of pressure in the geothermal reservoir might affect the efficiency of power production.

Thirdly, the turbines themselves play a major role in the use of steam to generate energy. One of the most expensive initial investments in the development of geothermal energy is made by steam turbines, which turn steam into electricity. Since focusing on reducing geothermal operation capital and initial cost is currently the issue faced in the plan of development geothermal energy, there is a conundrum of choosing the right options between worrying about capital efficiency or focusing on maximizing the engineering design which will directly affect the performance of the power station for an extended period [34]. Additionally, most geothermal power plant operations are now dealing with the maintenance problem of geothermal power stations to maintain the electricity production performance within a specified limit. For instance, the Olkaria II power plant in Kenya output capacity decreased from 35.0 MWe to 34.3 MWe after producing energy for two years in a row. This is concrete proof that the geothermal power plant needs regular maintenance to maintain output levels, since a loss of MWe production might result in a significant financial disadvantage [35].

2.1.5.10 Social Problems

In addition to the physical and technical aspects, the social dimension of geothermal energy issues is the most challenging. Since the economic side is also an essential component of the social context in this exposition of society's challenges with geothermal energy development, the social problems may also include poverty, health, education, demographics, and economic development.

2.1.5.11 Poverty

Poverty is a typical issue that developers encounter, especially for the local people who have lived in the areas for a long time. This is because the vast geothermal potential is mainly situated in distant and underdeveloped areas. While the rising aspect of income, salaries, and higher living standards may be a positive aspect in addressing poverty in the geothermal power plant development surrounding areas and community, the developed site of geothermal power plant areas also would raise property prices, which would affect a certain kind of people who can afford to buy a property in the surrounding areas. In the meantime, a situation of community displacement in the geothermal energy development zones nearby may also result in poverty. As has been mentioned, a massive potential of geothermal areas mostly located in rural and some residents may not legally own the land upon which they live, since the geothermal developer company could force the local communities to leave with the legal permit that they have to develop the site like what happened in the relocation of Maasai families caused by Kenya Electricity Expansion Project (KEEP) geothermal operations [36].

2.1.5.12 Health

In addition, the negative effects of air pollution, toxic gas emissions, water contamination, and noise pollution would have a significant negative influence on society's health. When there are problems with geothermal wells, such as hydrogen sulfide accumulation, people surrounding the geothermal power plant may be put at risk. Even a larger volume of this gas might be dangerous. An impact assessment with AERMOD (Atmospheric Dispersion Modeling System) was required before the construction of the geothermal power plant, notably in the inhabited regions, to ensure and reduce the possibility of a subsequent H_2S gas leak and air quality [38]. Since a high level of noise disturbance might affect hearing loss or even a hearing breakdown, further assessment of the noise level is necessary to prevent disruption of the loudness in geothermal production activity [39]. Like how poisonous gas emissions may pollute the air, geothermal waste from production and exploration can contaminate ground and surface waters, which can be dangerous for human health. Given that harmful substances like arsenic, mercury, and boron that might contaminate the groundwater reservoir that is mostly utilized for daily living could be present in geothermal fluids [40].

2.1.5.13 Education

An advanced explanation of the geothermal energy business with the benefits to the surrounding area should be promoted to educate the locals about the energy itself and increase social acceptance of geothermal energy. Education, especially in formal sectors, in the geothermal energy activity area improves with the possible allocation of CSR allowance in education facilities. Most of the time, education levels in distant and rural areas are lower than in metropolitan areas, and as was already noted, the areas with the highest geothermal energy potential are often volcanic mountains with sparsely populated areas. In certain remote areas, a minimal level of comprehension and communication issues causes the populace to oppose geothermal development. Lack of knowledge about energy and its technology from the company, coupled with a lack of local community involvement, would cause local stakeholders to lose trust and acceptance. As a result, education formal and informal-is the key to fostering local acceptance, along with other crucial factors like public involvement and communications [41].

2.1.5.14 Demographics

Geothermal energy demographics are crucial for driving positive social change in the way that energy is used, as well as for other applications like eco-tourism that may help the local economy. Despite the positive aspects of demographic demographics, greater geothermal development may undermine residents' traditional ways of life. Construction and extraction activities after exploration may result in physical disturbances that lead to noise and dust pollution. Also included in the assimilation of the site employees might be the culture and way of thinking of the locals in the neighborhood. Participation in education may be important, for a consistent supply of power might also alter the local community's way of life.

Other factors, such as livelihood relocation and resettlement, which also had a significant part in this demographic development, should not be disregarded. As was noted in the sections on poverty, the relocation situation can also provide difficulties. Community relocation brought on by resettlement once occurred in Kenya and may do so once again when this energy is developed in other regions of the world. Both positive and negative effects might result from a shift in livelihood. From a positive perspective, new employment may be secured, and people might be inspired to find new ways to make money and use their creativity. From a different angle, the new jobs provided by geothermal energy activities may cause the old livelihood that was also a signature of their cultural identity to vanish since the locals may be more focused on the new sources, such as retail, food services, and lodging [42].

2.1.5.15 Economic

In addition to the previously listed variables, the economic component is the final one that may be named as the most crucial. The development goal is significantly impacted by two connected factors, including energy and economic expansion, on a particular scale. The energy trilemma principle states [42,43] that the keys to decreasing conflict in energy production are energy security, social equality, and environmental sustainability. While the development of geothermal energy in some areas may also help the area develop with the availability and security of electricity, the job differentiation between the highly skilled workers and the local inhabitants would widen the gap between the locals and the newcomers because most projects do not always involve and recruit the locals in their surrounding site due to the lack of skill problem. As a result, the direct long-term jobs would predispose the locals and the newcomers to the disadvantages associated with the lack of skill [42].

2.1.6 Geothermal Energy in Kazakhstan

During deep well drilling for hydrocarbons, regional geological research, and other work/studies in Kazakhstan, geothermal waters have been discovered [43,44]. Although there was some geothermal research done in Kazakhstan during the Soviet era, there was little done after the country gained its freedom. However, some studies have been done throughout the later period, as will be briefly discussed below. Comprehensive assessments of Kazakhstan's geothermal resources were carried out in the 1980s in the most prospective areas of South Kazakhstan. This comprised exploration and appraisal work for space heating and hot water supply in Turkestan, Arys, and the Almaty Oblast (Ily and Usek) from 1982 to 1991. The findings suggested significant geothermal reserves. A feasibility study was presented in 2006 after 40 existing deep wells in the south and southeast of the nation were examined. The most prospective sites for additional prospecting and exploration were determined by the research. The Zharkent subbasin in Southeast Kazakhstan underwent prospecting and exploration in 2008, and exploitable geothermal reserves were estimated. This included research on a deep well (2800 m), which produced 90 °C water and afterward provided thermal energy to a sizable greenhouse complex. To determine if the region has enough geothermal reserves for immediate use, prospecting, and deep exploratory drilling for geothermal energy at the Zharkunak site in the Zharkent basin were conducted in 2015-2016. After the completion of this project, hot water from two to three wells is presently utilized for space heating, hot water supply, greenhouse heating, fish aquaculture, and other purposes [43].

2.1.6.1 The characteristic of thermal needs of Kazakhstan

Two different types of aquifers-hydrogeological massifs and artesian basins are formed in Kazakhstan due to the country's physical-geographical, geological structural, and hydrodynamic circumstances [44]. The aquifers in the hydrogeological massifs are primarily local in development and match tectonic zones. Due to this, the hydrogeological massifs' geothermal resources were not assessed. Nearly 60 % of Kazakhstan's land is covered by artesian sedimentary basins, which are where most of the country's geothermal resources are located. Drill holes have reached various aquifers with temperatures ranging from 40 to 100 °C in the Mesozoic-Cenozoic deposits of those basins at depths between 200 m and 5000 m (assumed technically accessible depth) [43]. These aquifers varied in region, frequency of occurrence, depth, and thickness.

Geothermal characteristics, such as temperatures at depths of 1 km to 5 km, geothermal gradients in sedimentary rocks, the temperature of the intermediate layer, and the thickness of the water-saturated basin or a portion of it, are used to evaluate geothermal resources. The results from publications and temperature measurements taken by drilling and servicing firms were systematized and generalized. The heat transporter (fluids) and consumer requirements (power capacity) dictate the many ways geothermal resources are used. Different categories were offered by both domestic and international studies [43,44]. Five groups may be created by combining the heat loads in industry, agriculture, and district heating (Table 3).

Table 3. Consumers of geothermal energy, divided into groups [44]

Groups of consumers	Heat carrier, T °C		Heat load, GJ/h
	Name of group	T °C	
1	Extremely low T°	<20	0,01-0,5
2	Low T°	20-60	0,5-50
3	Medium T°	60-90	50-500
4	High T°	90-150	500-5000
5	Extremely high T°	>150	>5000

2.1.6.2 Conditions for Geothermal Systems

A map of Kazakhstan's geothermal resources was created using information from sedimentary basins (Table 4). Maps were created to depict the distribution of Earth's crustal temperatures in Kazakhstan at 1, 2, and 5 km and the average depth of isotherms of 20, 40, 60, and 90 °C for each sedimentary basin (Figure 8).

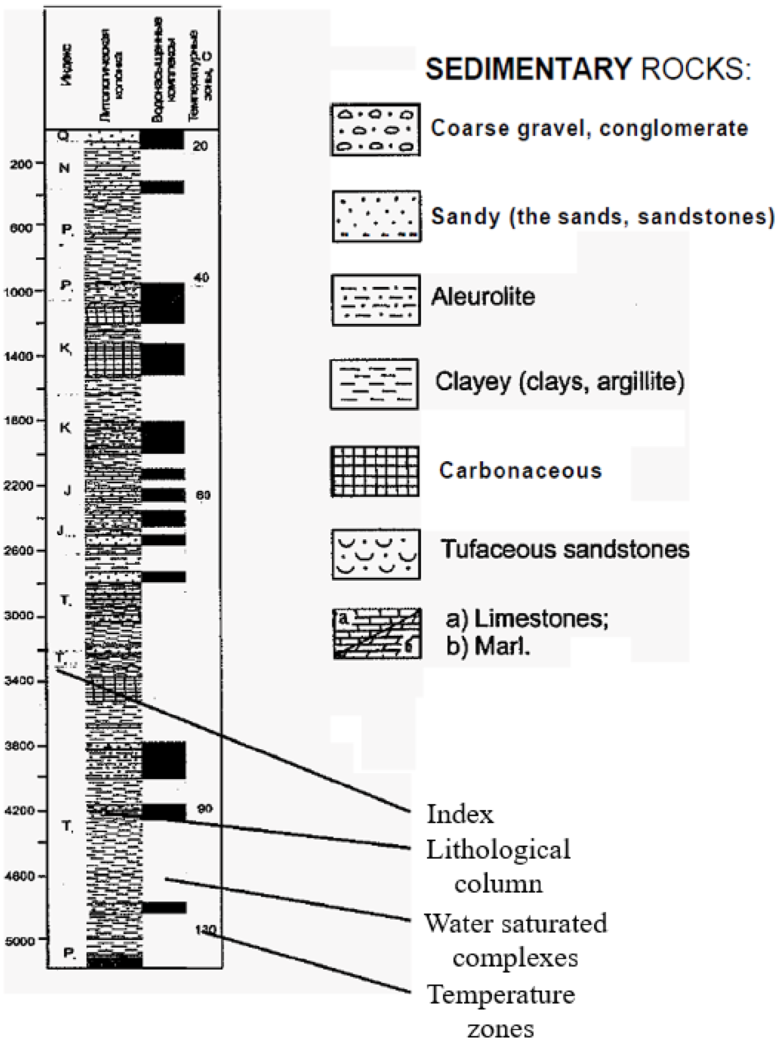


Figure 8. The distribution of Earth's crustal temperatures in Kazakhstan

Based on geological information from regional Mesozoic–Cenozoic geological–structural element investigations, the thickness of water-saturated formations was calculated. These investigations allowed for identifying areas with similar lithological and facies conditions of sedimentation, which made it possible to locate sediment sequences with the same composition within specific basins and across all structure tectonic zones [43,44].

2.1.6.3 Forecasted Geothermal Resources

The 20 °C zone's geothermal resources are estimated to be 280,7*10^9 tons of equivalent (toe). The next zone's (20 °C - 40 °C) geothermal resources are 332,2*10^9 toe. Throughout the basins, the unit potential ranges from 0,10 to 1,01 (on average - 0.47 toe/m^2) (Table 4). The amount of the next zone's (T= 40 °C - 60 °C) geothermal resources is 903,3*10^9 toe. The unit potential ranges between 0.52 and 1.75 toe/m^2 (Table 4). T= 60 °C - 90 °C zone has 1239,0*10^9 tons of toe geothermal resources. It has a potential unit of 0.48 to 6.56 toe/m^2. The Prikaspiy, Ustyurt-

Buzashin, Mangyshlak, Syr-Daria, Sbu-Sarysuy, West, and East Iliy basins contain the zone with T> 90 °C. The zone's geothermal resources are $1356,6*10^9$ toe. Its unit potential ranges from 0.60 to 8.47 toe/m^2. The total energy potential of the Kazakhstan basins as a technically feasible and environmentally sound alternative energy source is 4.2 trillion toes [44].

Table 4. Density of geothermal resources of the Kazakhstan sedimentary basins, toe/m^2 [44]

	Sedimentary basins	Temperature zones (°C)					Total
		<20	20-40	40-60	60-90	>90	
I	Prikaspiy	0,27	0,15	1,75	1,26	1,4	4,83
II	Ustyurt-Buzashin	0,02	0,11	0,63	3,22	7,49	11,47
III	Mangyshlak	0,04	0,1	0,31	3,36	8,47	12,28
IV	Aral	0,03	0,21	1,35	4,34	0,6	6,53
V	Syr-Daria	0,18	0,41	0,52	0,52	1,01	2,64
VI	South-Torgay	0,33	1,27	1,14	0,48	-	3,22
VII	North-Torgay	0,22	0,18	-	-	-	0,4
VIII	North-Kazakhstan	0,11	0,39	-	-	-	0,5
IX	Teniz	0,09	-	-	-	-	0,09
X	Shu-Sarysuy	0,16	0,61	1,17	1,87	2,04	5,85
XI	West-Iliy	0,16	0,27	0,52	6,56	2,03	9,54
XII	East-Iliy	0,15	0,58	1,37	4,62	7,77	14,49
XIII	Balkhash	0,26	0,75	0,61	-	-	1,62
XIV	Alakol	0,13	0,82	1,34	-	-	2,29
XV	Zaisan	0,03	1,01	1,28	-	-	2,32
XVI	Priirtysh	0,02	0,24	0,8	1,04	1,86	3,96
	AVERAGE	0,14	0,47	0,98	2,73	3,63	7,95

2.1.7 Geothermal Energy's Future

Geothermal energy is derived from the Earth's outward heat flow, caused by the decay of radioactive isotopes in the mantle and crust of the planet and by internal heat left over from the planet's formation. The Earth's crust contains geothermal systems, which are places where this flux and the resulting energy storage are abnormally high. Water is typically the energy transmission medium in such systems, which is why they are hydrothermal systems. These geothermal resources are found all over the world. Even though tectonic plate borders are where most geothermal systems and geothermal energy are concentrated, geothermal energy may be found in most nations. Although geothermal activity is mostly centered in volcanic areas, heated groundwater may also be found in sedimentary rocks worldwide. Geothermal energy is frequently found in populous or accessible places. However, geothermal activity may also be observed at tremendous depths on the ocean floor, in hilly areas, and beneath glaciers and ice caps. Since many geothermal systems lack surface activity, many more are likely still to be found [45,46,47].

Compared to how they are used and how much energy humanity will require in the future, the Earth's geothermal resources have great potential. The technically feasible electrical generating potential of known geothermal resources was estimated [45] to be 240 GWe (1 GW = 109 W), which is most likely a minor portion of hidden or undiscovered resources. Additionally, he stated that the most likely direct usage potential of resources at lower temperatures (150 °C) is 140 EJ/yr (1 EJ = 1018 J). However, with the current state of knowledge and technology, it is difficult to precisely assess the Earth's total geothermal potential. Even while the use of geothermal energy has increased significantly in recent years, it is still minuscule in comparison to the potential of the planet. Global installed geothermal energy generating capacity was estimated by Bertani [46] to have been around 10.7 GWe in 2010 and by Lund et al. [47] to have been 438 PJ/yr (1 PJ = 1015 J) in 2009 [47]. Fridleifsson et al. [48] predicted that 2050 direct usage may be 5.1 EJ/yr and electricity generation capacity might reach 70 GWe. Therefore, plenty of room exists for further utilization of geothermal resources globally.

Understanding the nature and features of the geothermal system and clearly describing it are essential for effective exploration, development (including drilling), and exploitation of any sort of geothermal system. The ideal way to do this is to create a conceptual model of the system, a descriptive or qualitative model that incorporates and unifies the key physical characteristics of the system. Examining geological and geophysical data, temperature and pressure data, reservoir property data, and data on the chemical composition of reservoir fluids constitute the foundation of conceptual models. Additionally, once they are accessible, monitoring data that indicate reservoir changes during long-term extraction helps refine conceptual models [49].

2.2 Hydraulic fracturing (HF)

2.2.1 Overview of HF and its applications

As a result of pressurized situations, which may arise from fluid at high pressures or a reduction in the minimum primary stress to magnitudes smaller than the fluid pressures, openings inside the rock/soil materials are created during hydraulic fracturing. During petroleum exploration activities, hydraulic fracturing may occur intentionally or accidentally. It may also occur due to naturally occurring geological processes that cause significant increases in fluid pressures or decreases in the magnitude of the minimum principal stress below threshold values [50]. Hydraulic fracturing is utilized more frequently in the petroleum sector because it improves the material's conductivity, which has several engineering uses and environmental effects. It is possible to use hydraulic fracturing on wells to mitigate damage to the area around the wellbore, extend flow paths into deep formations located at greater depths to increase productivity, and reroute fluid flow as part of reservoir management strategies [51].

Additional uses for hydraulic fracturing include the following in addition to enhancing the permeability of formations to raise well productivity:

- Using 'Frac and pack' techniques, the pressure drops in damaged areas close to well bores can be reduced [50].
- Stimulation of groundwater wells, where the groundwater serves as a vital conduit for the transportation of contaminants from waste deposited below the surface (by regulating the size and shape of apertures, stress distribution within fractures plays a significant role in groundwater flow since fractures serve as potential conduits for transmission and even assist the transportation of injected waste into safer rock formations at greater depths) [52].
- As an alternate method of evaluating in-situ rock stresses, prolonged leak-off experiments can be used to determine the lowest primary stress [53].
- As a method for cleaning up polluted soils, which is particularly useful for releasing trapped volatile pollutants from thick formations [54].
- To encourage rock caving for mining purposes [55].

2.2.2 HF in Enhanced Geothermal Systems

Across a range of scales, hydraulic-driven fractures are essential to subsurface energy systems. These frequently have the same aim in mind. In hydraulic fracturing, the in-situ stress field and fracture formation pattern may be identified by repeatedly injecting fluid at high hydraulic pressure into rock with limited intrinsic permeability [56]. To determine the maximum horizontal stress direction using the analysis of imprint packer records or borehole televiewer logs, hydraulic fracturing is used as a stress measurement technique. This approach also entails determining the minimum stress and fracture characterization by shut-in pressure analysis [57].

At the reservoir scale, hydraulic fracturing is an effective approach to enhance the rock's hydraulic permeability and generate a fracture network for transport pathways in tight rock. This applies to unconventional oil shale gas and deep geothermal reservoirs [58]. Depending on the existence of high enthalpy fluid in the rock formation, the hydraulic stimulation of unconventional reservoirs at a depth of two to five thousand meters is referred to as hot dry rock (HDR) systems or enhanced geothermal systems (EGS) in the geothermal application [59]. Additionally, building underground nuclear waste repositories, for example, demands the highest level of trust in the safety evaluation of geological risks at tunnel size geotechnical and mining engineering. These are frequently tied to the opening of fractures caused by groundwater seeping via connecting cracks in deteriorated subterranean man-made structures or seismic occurrences in deep crustal rock [60]. Laboratory investigations may be carried out to understand better micromechanical mechanisms during hydraulic fracture development [61].

A commercially accepted method for increasing oil and gas output from tight rock reservoirs is hydraulic fracturing. However, induced seismicity, also known as earthquakes, generated unintentionally due to fault reactivation and large enough to be felt on the surface or to cause damage to infrastructure and structures, is a significant geological problem in using EGS [62,63]. Therefore, significant induced seismic occurrences may force the suspension or termination of a project [64]. Creating a fracture network with inadequate permeability and flow velocity may also render an EGS project unprofitable [65,66]. Determining hydraulic stimulation treatments that permit safer and more profitable production is the focus of current geoscientific research programs like DESTRESS and GEMEX [67,68]. Additionally, for all the rock engineering issues discussed above, accurate interpretation of hydraulic fracturing tests for stress measurement is crucial [69]. Tools that may provide a detailed understanding of the hydraulic fracture development process and relate it to the recorded pressure history for joint interpretation are becoming increasingly necessary [70].

Fracture initiation, fracture propagation, and shut-in or flow-back are the three basic processes that make up hydraulic fracturing or hydraulic stimulation [71]. Between fracture propagation and shut-in, fracture coalescence and crack arrest-stopping phases can extend the three primary processes [72]. Several variables affect how difficult it is to forecast the fracture network that results:

1. Rock deformation and fluid movement within the crack are correlated. It is known as a hydro-mechanical connection [73].

2. Several multi-physics phenomena include hydraulic and natural cracks and leak-off interplay. Multiple length and time scales result from these processes' interaction and competition [74].

3. Due to the inconsistent availability of verifying data and the sometimes-high related expenses, geological and operational circumstances are difficult to estimate effectively [71].

2.2.3 Hydraulic Fracturing Process Systems and Fluids

2.2.3.1 Hydraulic Fracturing Systems

To increase productivity and the operator's return on investment, hydraulic fracturing fluid systems are developed to apply treatment in line with the design. The type of the frac fluid, the viscosity requirements, the rheology of the frac fluid, the economics of the fluid, the knowledge of the local formations, the laboratory data on the formation, the availability of fracking fluid materials, and the choice of proppant are used to create designs. Fluid systems optimized to these parameters can minimize formation and fracture face damage for maximum results [75-79]. There are several distinct types of fracking fluid systems, including friction-reduced water, linear gels, crosslinked gels, and foam. Moreover, Table 5 shows the various fracking systems, including the kind of polymer used for fracking, the crosslinker, and the highest temperature that could be applied in Fahrenheit degrees. The following is a list of fracking fluid techniques:

Water Fracking System: It comprises water, a friction-reducing compound, and a clay control ingredient. To lessen any diffusion coefficient or impacts of the water block, a water recovery agent (WRA) is occasionally applied. The main advantages of employing the Water Frac technique are its low cost, simplicity in mixing, and potential for water recovery and reuse. This system's low viscosity, which results in a fracture with a small breadth, is a drawback [80-82].

Linear Gel Fracking System: It is primarily made of water, a clay-controlling agent, and a gelling ingredient like guar, hydroxypropyl guar, or hydroxyethyl cellulose (HEC). These substances, frequently employed as bactericides or biostats, are vulnerable to bacterial growth. Additionally, chemical breakers were applied to lessen the impact on the sand (proppant) pack. A liner gel's lower viscosity makes it less expensive and improves its ability to limit fluid leakage. This is due to the fractured face having a filter cake developed to stop liquids from flowing into the formation. The linear gel has low viscosity like the water frac system, and the leftover water contains a breaker that renders it not reusable [80,83,84].

Crosslinked Gel Fracking System: The linear gel's components are also present, along with a crosslinker that raises viscosity. This kind of gel has a variety of uses, including lowering fluid loss and enhancing proppant transfer. Its greater viscosity may also aid in enhancing the fluid's effectiveness. The crosslinking increases the liquid's elasticity and the proppant's movement. The filter cake that builds up on the fracture surface controls the fluid loss as fluid is lost to the formation. A thorough explanation of the cross-linking agents utilized, and the chemistry and process of cross-linking is available [84-86].

Oil-Based Fluid System: It is utilized in formations susceptible to substantial damage from contact with water-based substances. The base fluid, palm oil as a gelling agent, and naphthenic acid as a cross-linking agent make up the first fracking fluid to shatter the commonly used gasoline. napalm. Although certain crude oils include particles that can create filter cakes, viscosity is widely thought to be the factor that regulates liquid loss. C-II. The use of gel oils has several disadvantages. Using high-viscosity crudes or crudes with many naturally existing surfactants might cause gelling issues [81,82,87].

Foam/Poly-emulsion fracking system: It consists of substances immiscible with water. Examples include nitrogen, carbon dioxide, or hydrocarbons like propane, diesel, or condensate. These liquids are extremely clean, have truly little liquid loss, transfer proppants very well, and separate readily by gravity. When a hydrocarbon, such as condensate or fuel, is emulsified with water, the result is a poly-emulsion in which the hydrocarbon is the outer phase. Varying the hydrocarbon/water ratio affects viscosity [88-91].

Table 5. Frac Fluid Systems

Fluid System	Polymer	Crosslinker	Maximum Temp [F]
CleanStim	Non-Guar	Al	225
PermStim	Non-Guar	Zr, Al	275
EZ-Stim	Guar	B	160
Sirocco	CMHPG	Zr	400
DeepQuest	HPG CMHPG	B, Zr	325
Hybor	Guar, HPG	B	320
SeaQuest	HP	B/Ti	300
Pur-Gel III	CMHPG	Zr	275
pHaserFrac	CMHPG	Zr	275
Delta Frac	Guar, HPG	B	200
Silver Stim LT	Guar	B	100

2.2.3.2 Hydraulic Fracturing Fluids

Water, sand (proppant), and additives are mixed and pumped into the well at high pressures during the hydraulic fracturing process to fracture the nearby formations, create pathways, and enable increased hydrocarbon and gas production as the flow from the created fracture to the production well increases. The fracking fluid's basic components are 99 % water, 0.51 % sand, and 0.49 % chemical additions [82,88,92]. Figure 9 depicts the many chemical additives used in hydraulic fracturing, including gelling agents, crosslinkers, friction reducers, corrosion inhibitors, scale inhibitors, and biocides. The purpose of each additive is also shown in Table 6, along with the types of additives and primary chemical compounds used for each role in the fracking process [89-91,93-97].

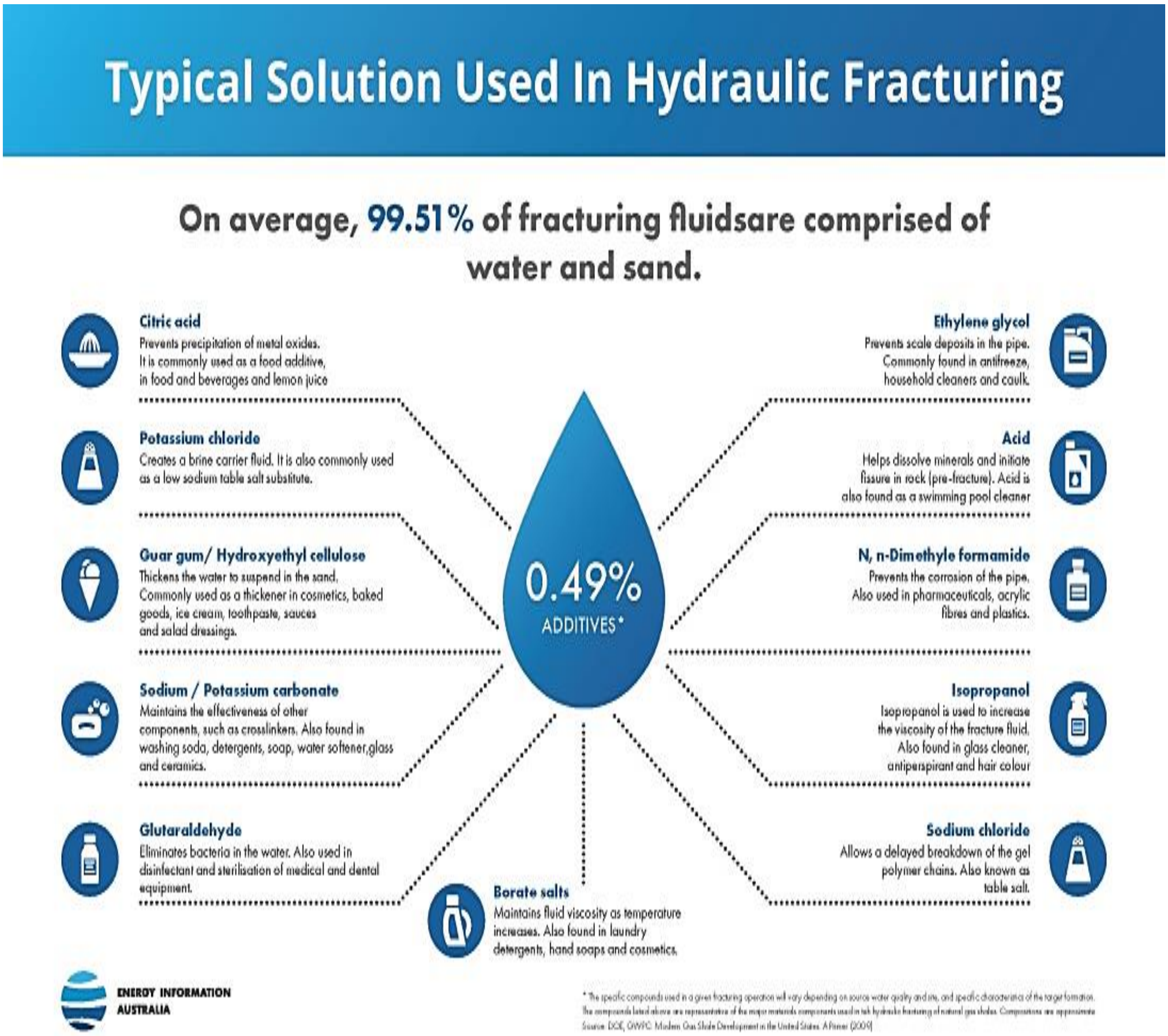


Figure 9. Fracking fluid chemical additives [91]

Table 6. Fracturing Fluid Additives [89,93-97]

Additive Type	Main Compound(s)	Purpose
Diluted Acid (1.5%)	Hydrochloric acid or muriatic acid	Help dissolve minerals and initiate cracks in the rock.
Biocide	Glutaraldehyde	Eliminate bacteria in the water that produces corrosive byproducts.
Breaker	Ammonium persulfate	Allows a delayed breakdown of the gel polymer chains.
Corrosion Inhibitor	N,n-dimethyl formamide	Prevents the corrosion of the pipe.
Crosslinker	Borate salts	Maintains fluid viscosity as temperature increases.
Friction Reducer	Polyacrylamide, Mineral Oil	Minimizes friction between the fluid and the pipe.
Gel	Guar gum or hydroxyethyl cellulose	Thickens the water in order to suspend the sand.
Iron Control	Citric acid	Prevents the precipitation of metal oxides
KCL	Potassium Chloride	Creates a brine barriers fluid.
Oxygen Scavenger	Ammonium Bisulfite	Removes oxygen from the water to protect the pipe from corrosion.
PH Adjusting Agent	Sodium, potassium carbonate	Maintains the effectiveness of other components such as crosslinkers.
Proppant	Silica, quartz sand	Allows the fractures to remain open so the gas can escape.
Scale Inhibitor	Ethylene glycol	Prevents scale deposits in the pipe.
Surfactant	Isopropanol	Used to increase the viscosity of the fracture fluid.

2.2.4 Environmental Impacts

2.2.4.1 Water usage and management: Sourcing, treatment, disposal, and potential water contamination

Wells may be flowing right away after stimulation or left for a length of time, termed the shut-in period (sometimes called "soaking time") [98]. During this time, water can imbibe into the shale rock, which causes the shale matrix to release hydrocarbons into the fissures and enhance the rate at which they are produced [98,99]. The wells are turned on after the shut-in period. The volume and chemical makeup of the water used for hydraulic fracturing during this period vary on the kind of stimulation, the initial source of the water (fresh, salty, or recycled), the geology, and the stage of the well [100,101]. Like conventional produced waters, this water, known as flow back, may contain salts, metals, metalloids, organics like benzene and aromatics, or naturally occurring radioactive materials (NORMs), constituents that are leached from the formation during the fracturing process and may pose environmental hazards [102,103]. Advanced geochemical techniques are frequently required to deconvolute the component fluids that make up flowback, because the chemistry of the flowback water from a specific well will change with time and the well's stage, including chemical contributions from the stimulation chemicals, the formation, and the formation fluids [104-106]. The salinity of the early-time flowback water is often lower than that of the later-time flowback water. Flowback may be hyper-saline, leading to the precipitation of salts that might obstruct the well's ability to produce, depending on the geology and state of the reservoir. As a result, over the well's entire production life, wells with such saline conditions (such as those in North Dakota's Bakken) can need periodic flushing with fresh water, often known as maintenance water. According to Kiger's estimations, the 6000–11,000 m^3 of water necessary to fracture a conventional well might be used for maintenance during its 30- to 40-year lifespan [107].

Water may still be generated with oil and gas after the flow back procedure (often the first two weeks of the production period), referred to as produced water. This water may contain minute amounts of formation water, also known as in situ brine and maintenance water, both of which were previously described. Like flow back water, generated water may also contain compounds initially present in the fracture fluid and novel chemicals created by inter-well interactions and potentially dangerous pollutants leached from the reservoir [108-111]. Although industry and/or regulators frequently see flow back and generated waters as distinct forms of water, in the end, regulators and industry view all these fluids as wastewater that must be treated or disposed of. Any produced water is referred to as "wastewater" moving forward. Variable wastewater management procedures exist within North American shale plays because of variables such as the variety in a region's geology, available facilities, laws, and differences in the volume and chemical composition of wastewater among wells [112]. According to Annevelink et al. (2016), inadequate wastewater treatment may provide the greatest potential environmental dangers of all hydraulic fracturing-related activities [113].

2.2.4.2 Air quality concerns: Emissions of methane and volatile organic compounds

The two main issues with hydraulic fracturing emissions are the unexpected loss of methane, a gas with significant potential for global warming, the release of volatile organic compounds (VOCs), and other air quality problems. Shale gas wells are thought to leak anywhere between 30 % and 200 % more methane to the environment than conventional gas wells, according to 2011 research by Howarth et al. [114]. Howarth and others hypothesized that shale gas may have a higher global warming footprint than coal even though burning natural gas emits far less carbon dioxide than burning coal because methane has a global warming potential roughly 33 times greater than carbon dioxide over 100 years. This discovery prompted several follow-up investigations, although they typically found significantly smaller methane losses than

Howarth's initial estimate [115–117]. According to the most current analysis, only 0.42 % of total output losses is - methane, which tracked methane emissions from 190 wells spread across multiple shale plays [118]. Additionally, capturing or burning (flaring) this methane to prevent it from escaping into the atmosphere can cut emissions by 80 % or more. As a result, the literature contends that the original overstatement of the harm posed by significant methane emissions [119].

Natural gas wells can discharge several additional air pollutants in addition to methane losses. They include dangerous air pollutants, including benzene, ethylbenzene, toluene, and xylene, which can influence human health even at low concentrations [120]. Under the Clean Air Act, the US Environmental Protection Agency (EPA) is tasked with evaluating technology and revising rules to reduce harmful emissions. Oil and gas operators must use reduced emissions completions (RECs), also known as "green completions," which make use of machinery to reduce the loss of methane, volatile organic compounds (VOCs), and other atmospheric pollutants during well construction. The EPA signed new regulations requiring their use in April 2012, and they must be fully implemented by January 2015 [121]. According to the EPA, the new regulations should be able to cut well-site emissions by 95 % [122].

2.2.4.3 Seismicity and induced earthquakes: Connection to injection of fracking fluids and wastewater disposal

The surge in unconventional oil and gas exploration has created a significant amount of wastewater, raising the need for deep-well injection of wastewater and, in some cases, triggering seismic occurrences. For instance, Hornbach et al. [123] attribute a substantial increase in seismicity in Azle, Texas, in the Barnett play, from 2011 to 2012, to a combination of brine production and wastewater injection. The most likely cause of a significant increase in seismicity between 2011 and 2014, which coincided with injection times, was the injection of Marcellus hydraulic fracturing wastewater in a disposal well close to Youngstown, Ohio [124,125]. However, recent investigations have demonstrated a connection between the act of hydraulic fracturing and produced seismicity. In Ohio, Skoumal et al. [125] recorded 77 earthquakes within less than 1 km of the horizontal legs of two hydraulically fractured wells, barely 18 km from the injection well investigated by Kim [124,126]. These occurrences reached up to local magnitudes (M_L) 3. Eaton and Mahani in Alberta linked the hydraulic fracturing of the Duvernay play to atypical earthquakes of up to ML in 2014 and 2015. Governments and the public are concerned about generated seismicity because of events like these. While deep-well injection reduces the possibility of wastewater leaks during surface storage or the expense of treating wastewater on-site for reuse, operators may be encouraged to enhance wastewater reuse/recycling efforts due to worries about seismicity [127].

2.2.4.4 Land disturbance and habitat disruption

Shale gas wells exhibit exceptionally high production rates during the first few months, followed by a sharp fall within only the first few years, in contrast to conventional natural gas wells, which frequently produce natural gas at a slower but more stable long-term rate [128]. As a result, maintaining shale gas production necessitates continuous drilling and an increasing number of access roads, wells, and pipelines. According to Goellner's assessment, the nation's natural gas infrastructure is expected to grow by over 450,000 kilometers over the next 25 years [129]. In contrast to traditional wells, shale gas wells rely on directional drilling, which may push the wellbore up to two miles deep into the underlying deposit. Additionally, directional drilling enables the drilling of eight or more wells from a single pad [130]. In contrast to traditional gas wells, shale gas production may thus require fewer well pads, access roads, and collection pipelines per unit of land area, even though it necessitates continuous drilling [130-131]. Additionally, due to the extended reach of horizontal drilling, it is possible to locate shale wells where they won't disturb large sections of forest or other delicate ecosystems on the surface while allowing production of subterranean resources [132].

In contrast to many other human land uses, Slocknecker and others note that the cumulative landscape disturbance caused by shale gas well pads, access roads, and pipelines is rather low [133]. However, these features have a strong propensity to split or fragment ecosystems, such as continuous stretches of forest. Kiviat points out that many species vulnerable to ecosystem disturbances share their entire habitat ranges with areas of active shale gas development and that, as a result, their very existence may be threatened by shale gas activities even though there is not enough data to determine how this fragmentation may affect other organisms. More investigation is required to comprehend better these creatures' susceptibility to shale gas operations and the extent to which landscape fragmentation and disruption may be prevented by careful well placement to spare sensitive habitats. Although some writers refer to articles on natural resource law, the physical scientific literature on fracking often does not draw from the social science literature [134].

2.2.5 Alternative Energy Sources and Transition

2.2.5.1 Role of hydraulic fracturing in the context of transitioning to renewable geothermal energy

The applications of geothermal heat sources (heating for aquaculture and agricultural purposes, bathing, and swimming etc.) were projected to eliminate 148 million tons of greenhouse gas emissions and replace 350 million barrels of oil equivalent in 2015 [135,136]. According to statistics data, the installed capacity of geothermal power plants for energy generation was already 12.729 MW in 2016 and is predicted to quadruple by 2020. Considering this, geothermal energy is an important sustainable energy option to fossil fuel energy that has the potential to lower greenhouse gas emissions [137]. Granite that is hard and has little permeability typically makes up hot dry rock (HDR) geothermal formations. Because of the high temperature, the formations have very little or no water. As a result, the creation of HDR geothermal deposits necessitates constructing an improved geothermal system that can effectively transform geothermal energy into electricity [138]. Injection and production wells are finished in an upgraded geothermal system, allowing fluids to collect geothermal energy. Hydraulic fracturing is one of the most important methods for creating reliable flow channels for geothermal energy extraction. Therefore, it is crucial to comprehend how hydraulic fracturing produces cracks as flow pathways in HDR formations [139].

2.2.5.2 Potential challenges and opportunities for replacing fracking with cleaner energy technologies

Although top experts in world trends and global processes convincingly demonstrated the incommensurability of the real potential of renewable energy generation with the global energy crisis more than 50 years ago, the idea that renewable sources can solve the world's energy crisis has permeated people's minds [140-143]. Supply issues for traditional energy carriers and significant price swings on the global market drive interest in alternative energy sources. Along with changes in the price of crude oil worldwide, this interest can occasionally grow drastically or fall somewhat. The interest is sustained by environmental movements and organizations and by technological intimidation from nations that use a lot of crude oil and attempt to convince countries that produce a lot of crude oil that they don't need their resources. The interest of the agriculture and science lobby in industrialized nations in subsidies and grants, as well as the media's attention on different "scientific" sensations produced by informal science and passionate amateurs, play a notable part in the speculations on this topic. Because of this, alternative energy has consistently held the top spot in both popular and scholarly magazines [144].

There is no question that mankind cannot continue to rely on fossil hydrocarbon fuels, which have helped to build and sustain the industrial civilization. However, various expert groups have varied ideas about how long the "hydrocarbon civilization" will continue and what will take its place. Unfortunately, just like every other topic of public interest, examination of the trends in energy production - a perfectly logical area of human endeavour has always entailed and still incorporates emotions, real-world knowledge, and even fantastical ideas. These feelings and beliefs, which may run counter to common reason and even the laws of nature, can sometimes significantly impact the advancement of specific sections of the energy business as well as other fields of research and technology [145]. As a significant consumer of new scientific discoveries that continuously accumulate cutting-edge and promising technical solutions, energy engineering is nevertheless a very traditional field of technology due to its size. It takes several decades to replace fundamental technology in the energy production industry. Therefore, even the outcomes of significant technical revolutions are applied on a big scale in energy engineering only many decades after they occur, unlike, for instance, information technology, where new ideas and technological solutions may drastically alter the market in just one or two years. Due to this delay, energy engineering projections may be rather accurate, at least for the next 20 to 30 years, or until the service life of existing or future big power generation facilities is exhausted.

The generation of energy based on all the currently available sources will rise in the medium term (25 to 30 years), according to predictions made by experts from the most reputable energy organizations. Despite some redistribution of their contributions to the global energy balance, crude oil, coal, and natural gas consumption quantities will be larger than they are presently (Figure 9). This will mostly be connected to a gradually declining oil percentage and a gradually rising natural gas proportion. According to IEA predictions, annual growth in total energy consumption will average 1.6 %, from 10 579 million toe in 2003 to 22 112 million toe in 2050. This is substantially slower than the 2.1% annual average global energy growth rate from 1971 to 2003. Nevertheless, global energy consumption will have doubled by the middle of the twenty-first century. The three main fossil energy sources are expected to contribute almost similar amounts of energy by 2035, or 25 % for each (Figure 10); in other words, after 20 years, the conventional fossil resources will still be responsible for at least 3/4 of the energy generated on Earth. The IEA basic scenario predicts that despite advancements in nuclear energy engineering and using renewable energy sources, the percentage of fossil fuels will remain at least 85 % of all energy sources in 2050 [146].

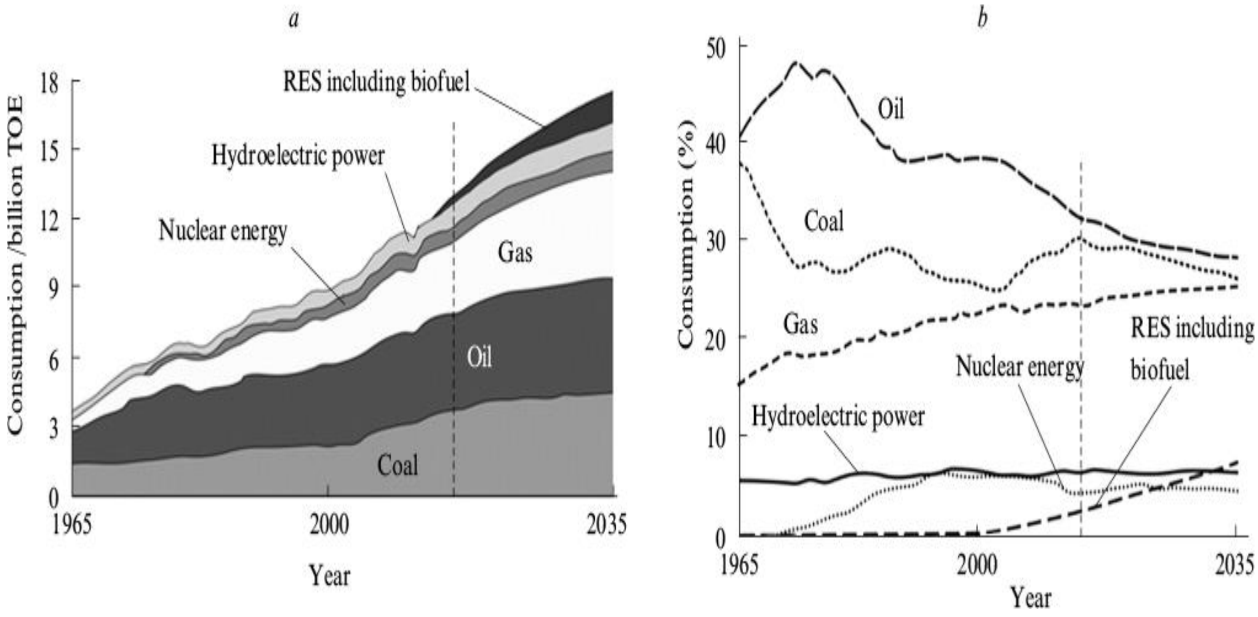


Figure 10. Current and predicted consumption of various sorts of primary energy sources in the world energy balance [146]

2.3 Application of Liquid Nitrogen for Hot Dry Rock

2.3.1 Introduction

A new area of global energy growth is anticipated to be geothermal energy, a tactical alternative energy that has been steadily developed in recent years [147–150]. A unique geothermal resource with widespread distribution, significant deposits, and no negative effects on the environment is hot dry rock (HDR) [151]. Properly creating a flow channel in HDR reservoirs is one of the major challenges to developing geothermal energy systems [152,153]. Hydraulic fracturing [154–156], thermal stimulation [157,158], and chemical stimulation [159-161] are the three techniques for reservoir stimulation that are most often utilized. The most popular and efficient stimulation method currently being employed in the oil and gas sector is hydraulic fracturing [162,163]. Hydraulic fracturing, however, frequently results in simple cracks [164], making it less effective for enhanced geothermal systems (EGS) projects [165]. An alternative to traditional anhydrous fracturing techniques for exploiting geothermal resources is liquid nitrogen (LN_2) stimulation [166]. In addition to pore pressurization brought on by nitrogen's phase transformation (from liquid to gas) when it meets HDR, a high differential thermal stress brought on by a significant temperature difference between the rock surface, and LN_2 may also cause many fractures in the reservoir [167].

Three main categories, namely heating, cooling, and a combination of heating and cooling, can be used to classify the effects of thermal shock on the physical (microstructure, porosity, and permeability) and mechanical properties (compressive strength, tensile strength, elastic modulus, and Poisson's ratio) of rocks. Rocks can typically weaken during heating, especially over the threshold temperature. LN_2 cooling is frequently used in the single cooling technique. After the LN_2 chilling procedure, the rock's permeability is noticeably increased, but the extension of the microfractures and the formation of pores cause the rock's strength qualities to decrease. Three coolants, namely air, water, and LN_2, have been employed to explore various variations of the damage analysis of rock after the combination of the cooling and heating techniques. Kim et al. [168] investigated the effect of air-cooling on the mechanical characteristics of the heated sandstone (100 ^oC, 200 ^oC, and 300 ^oC). They discovered that wave velocity, tensile strength, and fracture toughness are unaffected. According to Brotons et al. [169], compressive strength and elastic modulus of heated San Julian's calcarenite are reduced more by water chilling than by air cooling. Researchers Shao et al. [170], Zhang et al. [171], and Zhu et al. [172] discovered a threshold temperature for the water-cooling effect and a strong relationship between the heating temperature and the mechanical properties of granite. The more severe thermal damage is brought on by water cooling, according to Zhu et al.'s systematic investigation of the modification of the thermomechanical characteristics of heated granite with air and water cooling [173]. According to Wu et al. [174], the fast-cooling rate caused by LN_2 cooling causes the mechanical characteristics of the heated rock to degrade more quickly with LN_2 cooling than with air or water cooling. According to these findings, HDR's physical and mechanical properties are directly related to the cooling rate, and greater cooling rates result in a higher degree of structural degradation inside HDR. Therefore, the stimulation of geothermal reservoirs can greatly benefit from LN_2 cooling fracturing [175].

2.3.2 Experimental analyses and results

Zhang et al. [176] examined granite specimens' characteristics at initial temperatures ranging from 200 ^oC to 300 ^oC after cooling using a low-pressure liquid nitrogen (LN_2) jet. There was a quantitative analysis of the fractal process of the connectivity and complexity of fractures. Permeability and ultrasonic velocity tests were also used to examine the failure due to thermal stress. Last, there was optical analysis and observation by scanning electron microscope (SEM). The outcomes indicated that over this range of starting temperature, specimen heating has a minor influence on thermal fracture formation in comparison with cooling by LN_2 treatment. As granite temperature augments, the quantity and the magnitude of thermal fractures enhance. The fractal analysis showed that the crevices formed by thermal shock have a beneficial fractal feature. The fractal dimension is enhanced with the increment of granite temperature, which shows that the connectivity of influenced samples is ameliorated. The thermal fractures were allocated on the impaction surface of influenced granite with a moderately small temperature (200 ^{o}C). When the granite temperature increased to 300 ^{o}C, the thermal fractures prolonged for a specific range. The fractures significantly increased the granite permeability, and the maximum augmentation was 228.6 %. Furthermore, the tests for p-wave velocity indicated a decrease with the enhancement of granite temperature. The damage factor reached 0.55 for the granite temperature of 300 ^{o}C, showing that the granite has been severely compromised by the LN_2 treatment jet. The SEM examination indicated that the thermal fractures in impacted granite are primarily caused by tensile and shear stress.

A numerical and experimental examination of the hot dry rock fracturing stimulation using a high-pressure, abrasive liquid nitrogen jet was also conducted by Zhang et al. [177]. Numerical simulation was used to analyze the fluid flow, heat transfer, and thermal stress distribution during HRD fracturing with an abrasive LN_2 jet. A transient three-dimensional simulation model was used. The low Reynolds number - model precisely predicts the near-wall flow. The heat transfer between LN_2 and heated rock at the solid-liquid interface was calculated using a conjugate heat transfer inverse approach. The distribution of thermal stresses in rock is calculated using a thermo-elastic model. According to numerical findings, the abrasive LN_2 jet outperformed the abrasive water and supercritical CO_2 jet in perforation. A significant amount of tensile stress was dispersed in the area at the contact, while its depth was impacted little. This tension was anticipated to favour the formation and propagation of fractures in the direction of perforation. Short hole lengths facilitate heat transmission at the interface. The original rock temperature significantly influences thermal stress levels. The impact of the LN_2 jet on hot granite specimens with a tiny hole in the center was used in experiments to confirm the effects of thermal stresses on fracture. The fractal approach was used to quantitatively characterize the capacity of rock masses to flow and move materials. According to experimental findings, the interface experienced many thermal fractures. An advantage to fracture initiation during LN_2 jet fracturing is that rising rock temperature can considerably increase the number and size of thermal fractures and enhance the connectivity of fragmented rock.

Huang et al. [178] investigated how hot dry rocks with semi-circular bend (SCB) fracture toughness mode I will respond to high temperature and liquid nitrogen cooling. The rock samples were collected from ShanDong, China, called “LuHui” granite. The outcrop was transformed into 16 disks, each measuring 100 mm in diameter and 35 mm in thickness. Before and during the high temperature and liquid nitrogen chilling treatment, the mode I fracture toughness, tensile strength, and p-wave velocity were assessed. All tested parameters' fluctuation regularity before and after treatment was discovered. According to experimental findings, the treatment altered the p-wave, tensile strength, and mode I fracture toughness. Figure 11 displays the fracture toughness test failure scenarios for granite specimens at various temperatures. Most of the damage was a brittle fracture, mainly in the same direction as the pre-existing crack. The displacement of the granite specimen during fracture steadily rose with rising temperature. In other words, the granite became softer due to the high temperature.

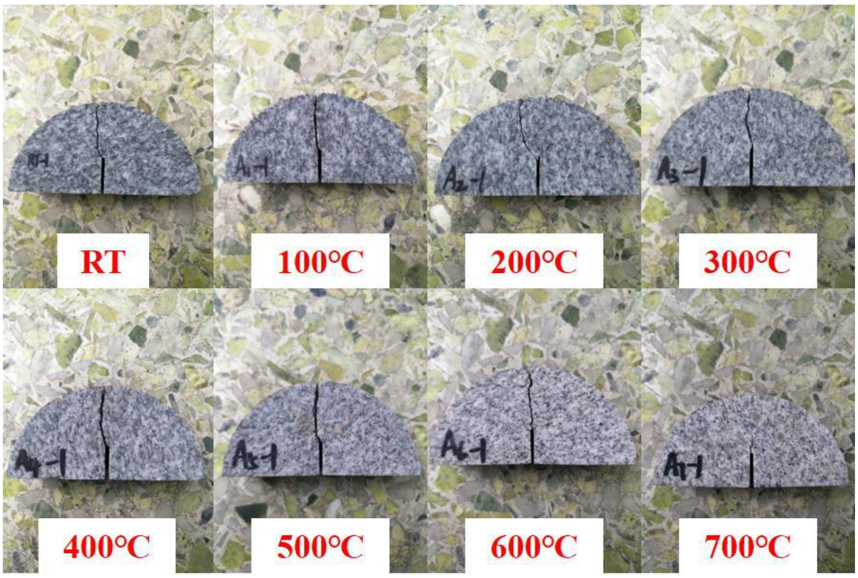


Figure 11. Fracture states of granite at different temperatures

The relationship between the p-wave and mode I fracture toughness and treatment temperature was positive. As temperature rises, P-wave velocity steadily falls and practically exhibits linear declining features at 500 °C. At 700 °C, the P-wave velocity was only 38.44 % of that at 100 °C. Granite's water evaporation and the resulting heat stress are to blame.

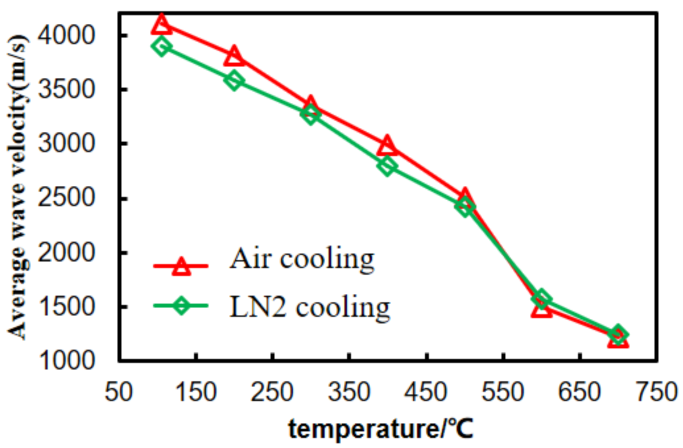


Figure 12. Velocity comparison of air and LN_2 cooling

Figure 12 demonstrates that the LN_2 cooling group's P-wave velocity is consistently lower than that of the air-cooling group. It is primarily caused by the larger thermal stress created by the liquid LN_2 group's higher temperature differential compared to air cooling. This shows that chilling with LN_2 makes granite weaker and more brittle. In other words, LN_2 is believed to make fractures in HDR reservoirs more likely to form, spread, and enlarge [178].

Rock samples were subjected to a series of lab studies by Yang et al. [179] under triaxial-confining forces. The two strategies used were gas fracturing with and without LN_2 (196 °C) treatment. High-temperature granitic specimens were submerged in LN_2 for several hours before the fracture tests. The rock specimen's temperature (100 °C - 600 °C), axial tension (5 MPa to 20 MPa), and lateral stress (5 MPa to 20 MPa) were all considered. The fracture patterns were then discovered to forecast the breakdown pressure based on the experimental data, and correlations for both LN_2 rapid-cryogenic and natural-cryogenic stimulations were constructed. A thermal-hydraulic coupled transient numerical model was constructed after discussing the field applications for LN_2 cryogenic stimulation in HDR reservoir to provide a plan for LN_2 injection for a successful cryogenic stimulation. According to the findings, LN_2 cryogenic stimulation lowered breakdown pressure levels by 9 % -51 % greater than untreated specimens. Particularly on rock specimens over 200 °C, LN_2 offers higher fracture efficiency. This may be ascribed to a strong local tensile stress expanding the micro-pore structures inside the high-temperature rock samples due to a severe thermal gradient caused by LN_2. Larger fracture apertures and more cohesive fracture networks may also be created inside the rocks with the help of LN_2. Additionally, when high-temperature rocks are exposed to greater anisotropic stresses, LN_2 treatment, or fast cryogenic fracturing, assumes an ever-increasing significance.

The main conclusions of this research may offer a practical method for investigating HDR resources for geothermal development [179].

A crucial issue for the technical use of the cyclic LN_2 fracturing approach in HDR geothermal was examined by Wu et al. [180] in their analysis of the impact of cyclic heating and liquid nitrogen (LN_2) cooling on the physical and mechanical characteristics of granite. They collected the granite from Yantai in Shandong Province, China. The primary minerals in granite, as determined by X-ray diffraction (XRD) examination, included quartz (26.6 %), orthoclase (22.7 %), albite (35.1 %), biotite (6.8 %), and others. Figure 12 displays changes in mass M, volume V, and density. Granite loses density following heat treatment (see blue1 curve in Figure 13). The combined effects of mass loss and volume expansion during heat cycles cause the change in density.

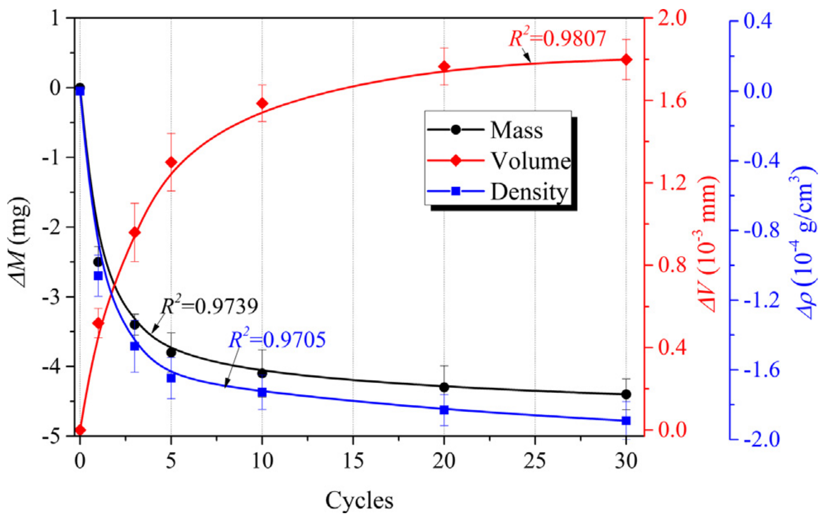


Figure 13. Changes in M, V, and density after different heating and LN_2-cooling cycles

Fine- and medium-grained granites were compared to ascertain the impact of grain size on rock reactions to heat cycles. The fine-grained granite had a modal particle size of 355 m and a median particle size of 178 m, respectively. However, the medium-grained granite's N_{mode} and N50 are 1310 m and 1268 m, respectively, which are much bigger than those of the fine-grained granite. The medium-grained granite has better permeability and lower V_p because rock with bigger particle sizes has more void space. According to the experimental findings, the heating and LN_2-cooling cycles can exacerbate granite degradation by amplifying the rise of permeability and mechanical deterioration. However, the first few cycles are when granite is most likely damaged. Changes in the physical and mechanical properties become less noticeable after around ten cycles. Granite damage is accelerated, and its decay rate is improved due to the cycles' higher heating temperatures. Additionally, granite's mechanical and physical properties are significantly influenced by the size of the rock particles. The LN_2 chilling and heating cycles are particularly sensitive to granites with lower particle sizes [180].

In addition, Wu et al. [181] tested Shandong granite samples physically and mechanically to ascertain the impact of liquid nitrogen (LN_2) cooling on the destruction of heated rock. These granites were rapidly cooled using a coolant after being rapidly heated to the required temperatures (25 °C - 600 °C) and kept for 10 hours. In their experiment, air, water, and LN_2 were employed as three coolants and were contrasted. After thermal treatments, physical and mechanical characteristics were evaluated. Optical and scanning electron microscopes were also used to detect microstructural alterations. The findings of the experiments show that following LN_2 cooling, the permeability of the heated granites greatly rises while the density, P-wave velocity, strength, and elastic modulus decrease. Changes in these qualities are increasingly noticeable as the heating temperature rises. LN_2-cooling causes bigger changes in the physical and mechanical qualities at any target temperature than air- or water-cooling. This suggests that LN_2-cooling has a greater potential to harm hot pebbles than the other two chilling methods. Microscopic research reveals that intergranular cracking was the main form of failure following thermal treatment, and most of these fractures were distributed near the borders of quartz.

Liquid nitrogen, an eco-friendly and super-cooling fluid, was studied by Yang et al. [182] as a viable alternative fracturing fluid for use in enhanced geothermal systems. They investigated how well liquid nitrogen fractured high-temperature granites under real triaxial confining forces. Samples of granite were taken from outcrops in Shandong, China. The "Pearl Flower" and "Five Lotus" varieties of granite were utilized. Cryo-scanning electron microscopy and 3D X-ray micro-computed tomography were used to shed light on the fracture-network patterns. According to the findings, liquid nitrogen fracturing had the lowest breakdown pressure compared to nitrogen gas fracturing and water fracturing. The 3-D volumetric pattern of the fracture morphology was comprised of branching fractures and thermally stimulated zones. More complicated fracture networks resulted from greater differences in fluid-rock temperatures and reduced stress anisotropy. This work opened the door to waterless fracturing in the Enhanced Geothermal System by demonstrating the possible advantages of liquid nitrogen fracturing in high-temperature crystalline rocks. It is anticipated to offer a practical solution for the effective clean, sustainable development of deep geothermal resources.

The Cracked Straight Through Brazilian Disc (CSTBD) granite specimen (Figure 14) was heat-treated in Ge et al.'s studies [183] at various temperatures to investigate the granite's mode-I fracture toughness following fast cooling by LN_2. Meanwhile, granite deformation and failure were observed using acoustic emission (AE) and digital image correlation (DIC) methods. According to their findings, the internal thermal damage to granite increased when the heating temperature exceeded 400 ^oC after LN_2 cooling, the plastic features gradually improved, and the fracture toughness considerably decreased. The DIC data demonstrate that, under mode-I loading, fractures began to develop at the two ends of the pre-crack as stress increased and spread to the contact point between the press and rock sample. A high strain band formed along the loading direction as the Von-Mises equivalent strain (Evm) steadily rose near the peak load. The number and breadth of thermally induced fractures in granite rapidly increased after LN_2 cooling when the heating temperature was over 400 ^oC, the fracture track gradually deviated from a straight line, secondary cracks grew, and the plastic properties were improved. Rapid cooling exacerbated thermal damage to the rock that is brought on by high temperatures. When fast LN_2 cooling was present, it may be said that 400 °C was the crucial temperature threshold at which the physical-mechanical behaviour and fracture features of CSTBD granite were altered considerably [183].

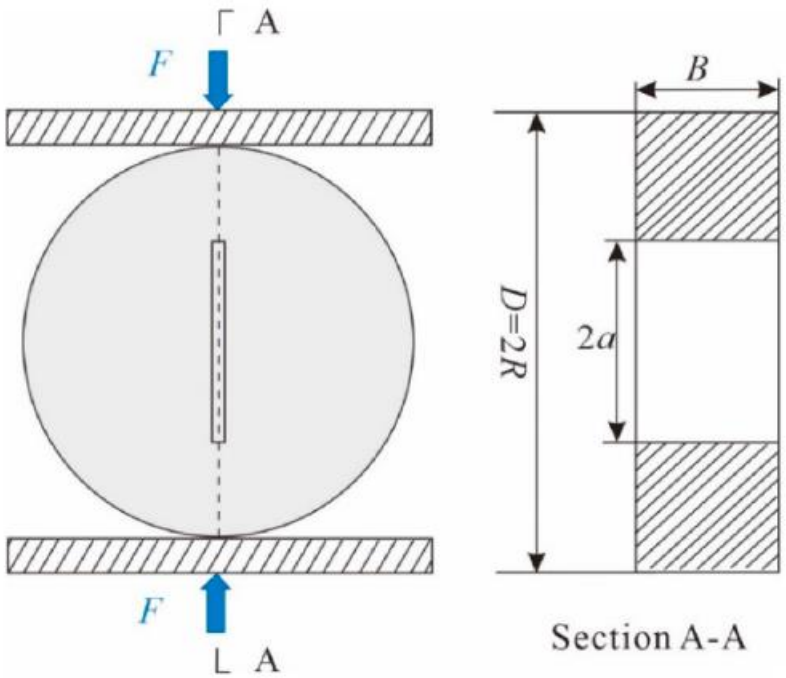


Figure 14. Diagram of the CSTBD granite specimen [176]

Experimental research on the impact of liquid nitrogen cooling on the ability of granite rocks to resist fracturing at high temperatures was conducted by Shao et al. [184]. A series of fracturing experiments were carried out on semicircular bend (SCB) specimens with pure mode-I fracture to investigate the fracture toughness of granite samples following increased temperature treatment and liquid nitrogen (LN_2) chilling. The damage-monitoring procedure was carried out during the test using the acoustic emission (AE) technique. According to the experimental findings, the fracture toughness of LN_2-treated granite samples generally declined with a rise in the sample's starting temperature, except for the region of 25 ^oC - 200 ^oC, where it slightly increased. SEM was used to examine the microstructures of the granite samples following heating and LN_2 cooling. Within LN_2-cooled granite samples at 200 ^oC, isolated, brief, and distributed microcracks were seen. These microcracks may be responsible for the improved fracture toughness by blunting the pre-crack. The earlier AE counts after LN_2 cooling occurred for samples with higher temperatures, indicating that the energy needed for fracture initiation lowers as the heating temperature rises. A transition from brittle to ductile behaviour was seen for samples with higher temperatures (400 ^oC in the present study), whose AE counts can also be monitored in the post-peak stage. Samples with a relatively low temperature (200 ^oC in the present study) after LN_2 cooling still exhibited typical brittle failure, which can be concluded by the straight drop down of the loading curve and intensive release of elastic strain energy. On the LN_2-cooled samples with greater temperature, numerous local failure spots and distinct big AE counts manifest themselves, resulting from the interaction between the pre-crack and the faults brought on by thermal stress. Additionally, compared to samples with greater temperatures, LN_2-cooled samples with lower temperatures will have fracture patterns that are more straight following a three-point bending test.

Shanjie Su et al. [175] used the LN_2 fracturing method in marble from a mine in Xuzhou, Jiangsu Province, China, and the sampling depth was about 280 m above the ground. The marble specimen had a light grey appearance, with dark irregular stripes on its surface. Its mineral composition mainly comprised dolomite (48.6 %), calcite (40.2 %), and periclase (7.5 %) based on the outcome of the X-ray diffraction (XRD) analysis. There was a physical and mechanical examination of marble specimens to define the influence of LN_2 treatment on the failure cooling on the damage behaviour of hot dry rock (HDR). After subjecting them to thermal shock, they evaluated the alterations in the marble specimens' internal structure, mechanical properties, and fracture behaviour. Their results showed a significant augmentation in the porosity of the heated marble after LN_2 treatment. At the same time, there was a reduction in the P-wave velocity, compression strength, and elastic modulus. The alterations in these properties augmented with the enhancement in the marble temperature. Compared to air treatment, LN_2 treatment stimulated bigger alterations in the physical and mechanical properties of the marble. LN_2 treatment increased the formation of secondary and shear fractures under compression experiments compared to air treatment. Moreover, after LN_2 treatment, there was quite a rough crack morphology, creating different intergranular and transgranular fractures.

Li et al. [185] investigated the effects of heating and liquid nitrogen on granite's mechanical and rock burst characteristics. The PIC-2 acoustic emission (AE) testing system, the TAWD-2000 electrohydraulic servo rock mechanics testing equipment, and related literature are the basis for this study. Granite samples were subjected to uniaxial compression tests and AE monitoring experiments to examine the granite's properties and AE characteristic characteristics when subjected to liquid nitrogen (LN_2) and to learn more about the granite's fracture mode. It is possible to draw the following results: LN_2 cooling has a deteriorating effect on rock strength, and granite's elastic modulus and peak stress exhibit a declining trend as the number of cycles increases. The granite's AE ring count, frequency, and energy amplitude in each stage show an increased tendency as LN_2 actions' cycle periods lengthen. When a rock enters the failure stage, the energy and ring count at the catastrophe point dramatically rise. Tensile failure and shear failure are two types of rock failure that the RA-AF diagram of AE characteristics may describe. Shear fractures predominate during granite sample fracture, resulting in granite shear failure or compression failure. The elastic energy technique calculates the tendency index of granite sample rock burst under various operating circumstances. As the elastic modulus falls, the likelihood of rock bursts decreases. The tendency of granite samples' rock burst showed a decreased trend under the repeated action of LN_2, and LN_2's activity somewhat lowered the likelihood of rock burst.

2.3.3 Rock Mechanics Characteristics Testing

Rock mechanics characteristic testing refers to a variety of procedures for determining the mechanical characteristics of rocks. These parameters include but are not limited to uniaxial compressive strength (UCS), elastic modulus, and Poisson's ratio [186]. Loading a specimen to failure in uniaxial compression has two apparent purposes: measuring compressive and tensile strengths. Compressive strength, sometimes known as "crushing strength," is simply the stress at failure calculated using the cross-sectional area perpendicular to the load. Tensile strength is assessed indirectly by compressive loading and estimating failure stress using a cross-section that includes the load axis. One such test, called as the "Brazilian," "diametral compression," or "cylinder split" test, is used because it is insensitive to surface conditions, has uniform stress distribution, and findings are less variable than with other techniques [187]. On the compression test stress-strain curve, there is a straight-line elastic deformation stage before to the stress peak. The slope of the nearly straight section represents the stress-to-axial strain ratio, also known as the rock's average elastic modulus. The average elastic modulus E_{av} is calculated using the following formula:

$$\boldsymbol{E_{av}} = \frac{\boldsymbol{\sigma_b - \sigma_a}}{\boldsymbol{\varepsilon_{lb} - \varepsilon_{la}}} \quad (1)$$

σ_a is the stress value of the beginning point of the linear segment on the stress-strain relation curve (MPa); σ_b is the stress value of the end of the linear segment on the stress-strain relation curve (MPa); ε_{la} is the axial strain value when the stress is σ_a, and ε_{lb} is the axial strain value when the stress is σ_b.

The ratio of measured axial strain and radial strain of the linear elastic phase obtained as the average Poisson's ratio of the rock samples. The formula is

$$\mu_{\boldsymbol{av}} = \frac{\boldsymbol{\varepsilon_{db} - \varepsilon_{da}}}{\boldsymbol{\varepsilon_{lb} - \varepsilon_{la}}} \quad (2)$$

where μ_{av} is the average Poisson's ratio of the rock; ε_{la} is the axial strain value corresponding to the previous σ_a; ε_{lb} is the axial strain value corresponding to the previous σ_b; ε_{da} is the radial strain values corresponding to the previous σ_a; ε_{db} is the radial strain values corresponding to the previous σ_b [186,187].

2.4 Statement of Problem

Following the Concept of Transition to Green Economy adopted on May 30, 2013, Kazakhstan continues to grow its renewable energy sector. This proposal called for the use of 3 % renewable energy sources by 2020, 10 % by 2030, and 50 % low-carbon alternative and renewable energy sources (RES) by 2050 in the overall power generation. Although it is an oil, gas, and coal production country, recently Kazakhstan's government signed an agreement with the European Union for raw materials and less CO_2 emissions. Due to the similar technology of oil and gas fields, geothermal fields are another option with an acceptable environmental footprint. On the one hand, these geothermal fields refer to hot dry rocks (HDR) (e.g., granite), which have low injection capacity due to non-contiguous fractures and very low permeability to extract the geo-energy. On the other hand, Kazakhstan is one of the driest countries in the world, and water use must not be spent in high quantities, like in processes of hydraulic fracturing and acidizing (huge amount of water use) in the extraction of geothermal energy. Therefore, there is an apparent necessity for a special stimulation method that handles both issues.

This study is part of pioneering research work with laboratory experiments with the waterless method of cryogenic fracturing in granites acquired from a region in the outskirts of Astana. Cryogenic fracturing deals with water-related issues and contributes to the creation of new fractures and enhancement of preexisting fractures, consequently leading to an improved fracture network in HDR. Consequently, the method results in increased contact area for heat transfer and improved permeability for injection and production processes in the enhanced geothermal systems (EGS). Moreover, it leads to the elimination of CO_2 emissions, fewer eco-system hazards, and the extermination of injection-induced seismic activity, which are recognized as unpleasant consequences of hydraulic fracturing methods. Through the implementation of cryo-fracturing, our research aligns with the 2015 United Nations Sustainable Development Goals (SDGs), which represent a universal initiative to eradicate poverty, preserve the environment, and ensure global peace and prosperity for all by 2030. Specifically, it refers to the 1st (no poverty), 3rd (good health and well-being), 6th (clean water and sanitation), 7th (affordable and clean energy), 12th (responsible consumption and production), 13th (climate action) and 15th (life on land) goals.

This study aims to investigate the applicability of cryogenic fracturing in geothermal reservoirs of Kazakhstan. The experimental tests of that research work will include destructive and non-destructive experiments, examining mechanical (stress, axial strain, radial strain, load, displacement, Poisson ratio, young modulus, damage factor) and physical (absorbed energy and reduced modulus) properties of granite rocks from the Akmola region. The decreased values of mechanical parameters such as stress and load, physical parameters like absorbed energy and increased values of physical parameters like permeability and porosity will refer to the success of the cryogenic fracturing method. It is expected from the experimental study that there will be elongation of preexisting fractures, creation of new fractures, and ameliorated fracture network in the utilized granite rocks. Due to that, it will increase the contact area for heat transfer and improve the permeability of impermeable rock containing geothermal fields.

3. METHODOLOGY

3.1 Sample preparation

As it was mentioned before, the specimens for laboratory experiments were taken from the outskirts of Akmola region. It is approximately 50 km away from Astana, as shown in Figure 15. It must be highlighted that 2 different types of granite rocks were chosen to expand the laboratory investigation and make comparative analysis.

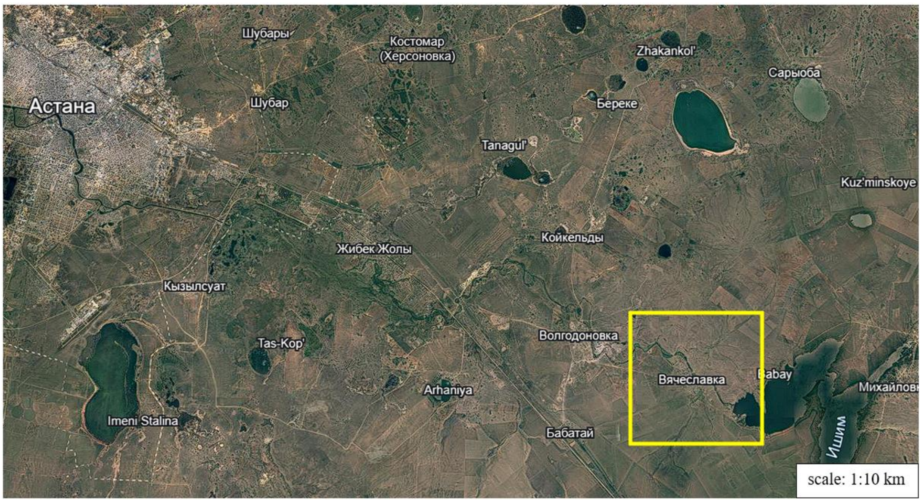


Figure 15. Granite rocks from the outskirts of Akmola region

To prepare granite samples for conducting Brazilian, compression, Computer Tomography (CT) Scan and XRD experiments the granite chunks passed through several stages (Figure 16). First, they were drilled by drilling machine (Heavy Duty Laboratory Coring Machine (RCD-200), GCTS Testing Systems) with 54 mm diameter for both Brazilian and Compression samples and with 32 mm diameter for CT Scan samples. Next, they were cut by cutting machine (Rock Preparation Cut Off Saw RLS-100, ASC Scientific) with certain lengths: for Brazilian samples is 27 mm, for Compression samples is 108 mm and for CT Scan samples is 50 mm. The samples were pre-polished using Bench Polishing Machine 1.03.20 (BROTLAB) and then polished further with Polishing Machine 1.03.17 (BROTLAB) on one side until they achieved a smooth surface. The remaining part of granite rocks after cutting passed through the jaw mill (jaw crusher BB250XL, RETSCH) and disk mill (Disc Mill DM 200, RETSCH) to get powder of granite. To make the powder even smaller it was put into ball mill (Drum Mill TM 300 XL, RETSCH) for 6 hours. The final step was sieving the powder by sieve shaker (Vibratory Sieve Shaker AS 200 Control, RETSCH) to have 250 μm sized powder.

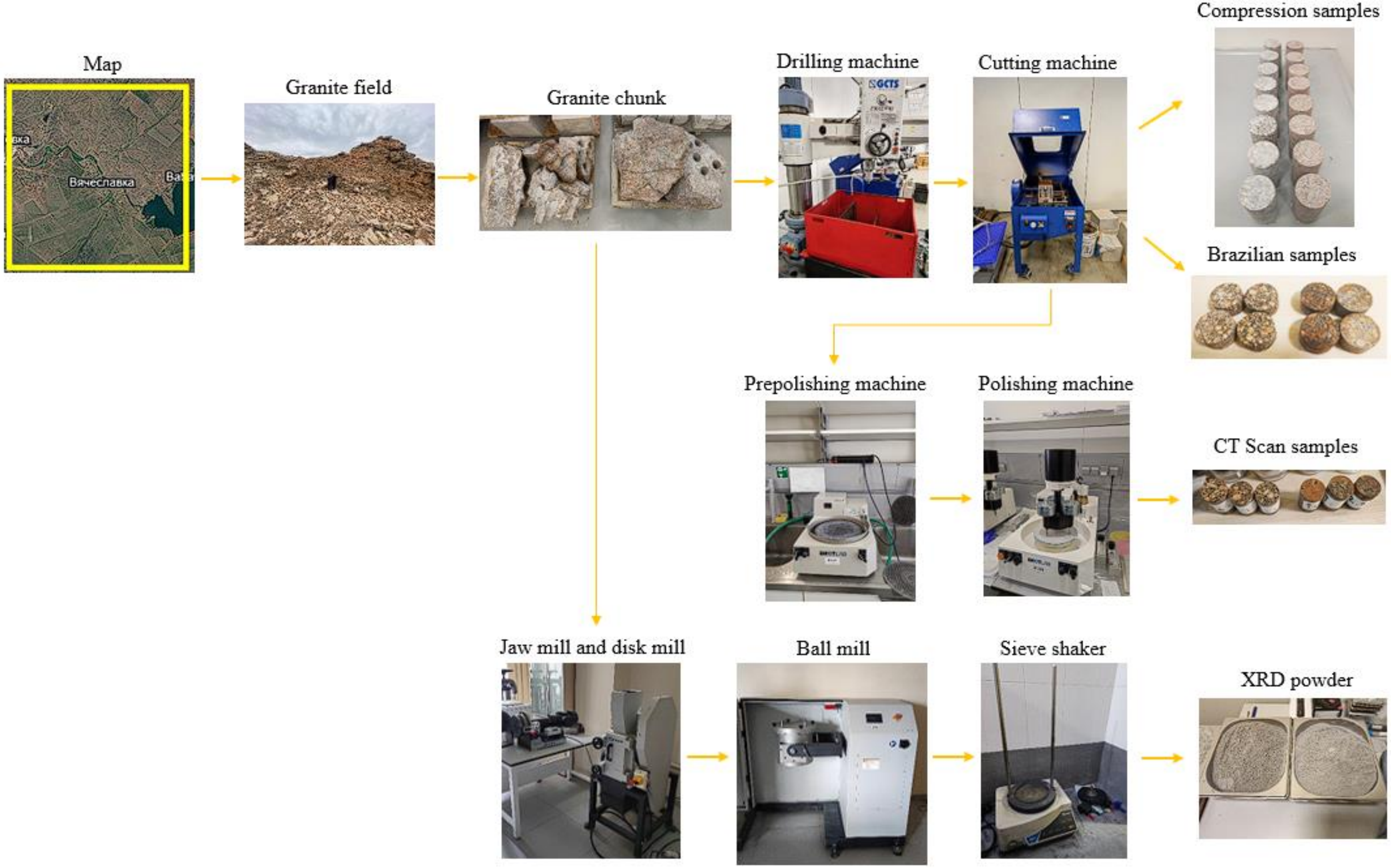


Figure 16. Sample preparation flowchart

3.2 Experimental set-up

After the samples get prepared from sample preparation stage, there is an experimental set-up before conducting any experiment, as shown in Figure 17. There are illustrated dry oven set to 50 ^{o}C, furnace that can be set to desired temperature and heat the samples to reach geothermal reservoir condition, box filled with liquid nitrogen (LN_2) to submerge the treated samples and induce thermal shock. For the furnace set up, there were chosen 3 different temperature range which are 100 ^{o}C, 200 ^{o}C and 400 ^{o}C. The reason for that is to check the effect of liquid nitrogen on granite samples by the double increase of temperature.

First, the samples were put into dry oven with 50 ^{o}C for 24-48 hours to take out humidity from samples. Next, they were placed in furnace for 2 hours. After they were heated, the samples were immediately submerged into LN_2 for 1 hour. Then, they were placed into the dry oven for 1 hour to get prepared for compression and Brazilian experiments. In the case of CT Scan samples, they were initially fully submerged into glass tumblers filled with distilled water and tested without any treatment in the CT Scan device. Subsequently, they underwent the treatment process before being tested again in the CT Scan equipment. For the XRD analysis, the powder was not treated with elevated temperature and LN_2, as it aimed to make mineralogical analysis of 2 different granite rocks.

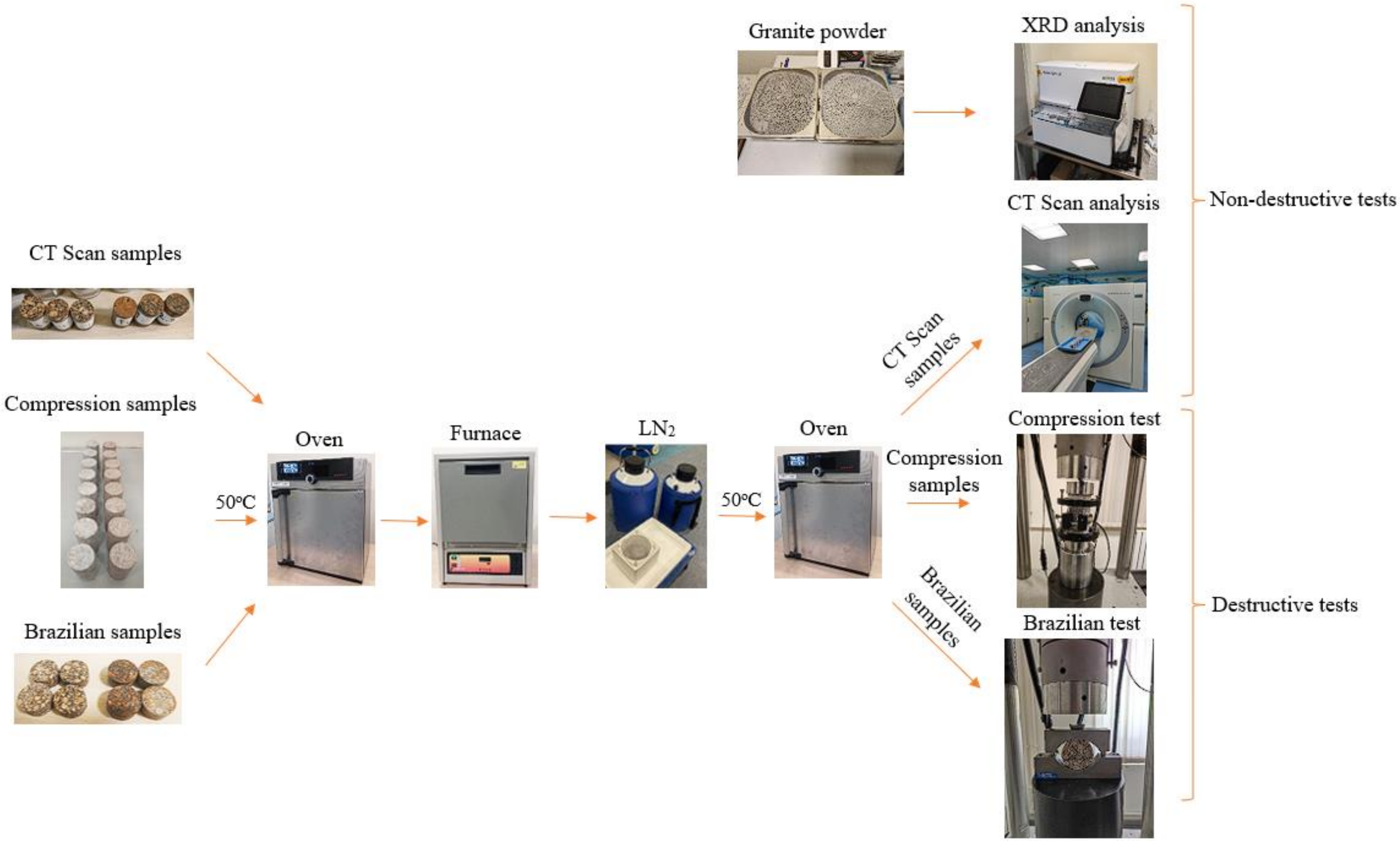


Figure 17. Experimental set-up flowchart

3.3 Granite samples: X-ray diffraction (XRD) analysis

XRD techniques are based on crystals' ability to diffract X-rays in a distinctive manner, which allows for a detailed investigation of the structure of crystalline phases [188]. The selected 2 granite specimens from the outskirts of the Akmola region were tested by an XRD device (Figure 18). The samples were processed as finely powdered, homogeneous material.

Figure 18. XRD device

Figure 19 illustrates the results of XRD analysis for granite 1 powder. There were obtained 3 different compounds including quartz at 37.1 %, albite at 44.4 %, and potash feldspar at 18.5 %.

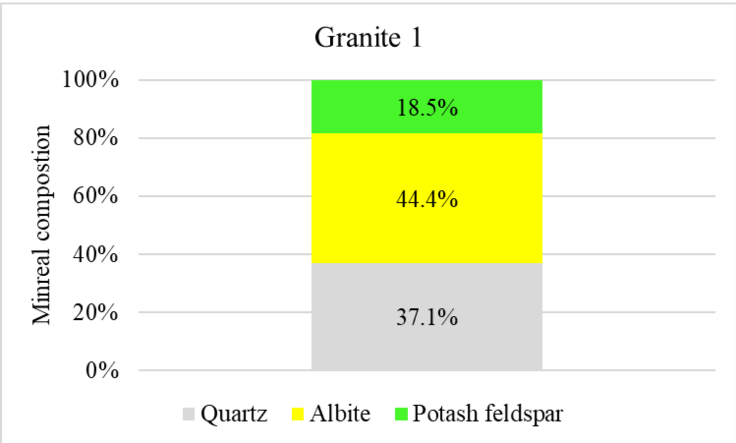


Figure 19. Results of XRD analysis for granite 1

The results of the XRD experiment for granite 2 powder are demonstrated in Figure 20, as shown below. Like granite 1, there were identified 3 distinct compounds which are quartz (47.8 %), albite (40.6 %), and strontium feldspar (11.6 %).

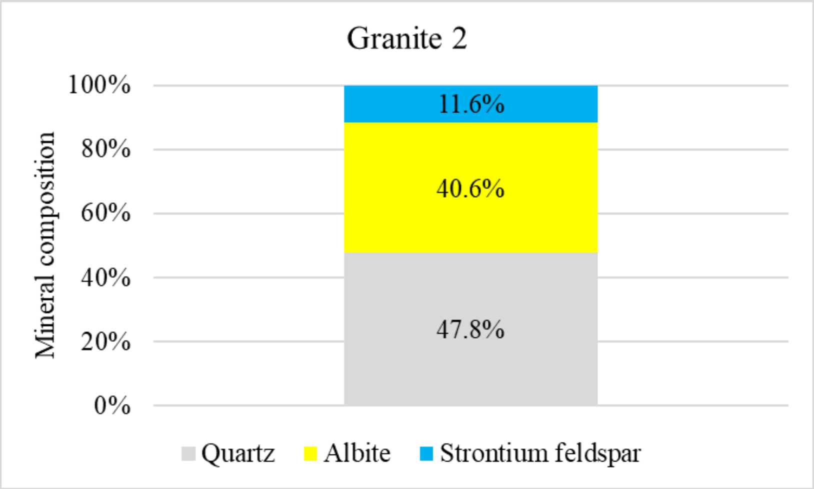


Figure 20. Results of XRD analysis for granite 2

It can be mentioned that in granite 1 the percentage of albite is the highest among the minerals, while in granite 2 results the quartz appears as a dominating mineral. This refers to the concept that the higher the quartz amount in a material, the higher the strength of the material, and the higher the feldspar (e.g. albite) content, the lower the strength of the material [189].

3.4 Experimental process: CT (Computer Tomography) Scan analysis

Figure 21. CT Scan device

CT-scan examination is done by rotating a focused beam of X-rays around the substance and taking a series of measurements. The signals are generated by the X-rays and are then processed by the machine to generate cross-sectional images, often referred to as "slices", giving the machine the ability to identify internal structures. In our study, CT Scan experiment is used to identify visually any new internal fractures in the granite samples which are subjected to high temperatures and then to LN_2 freezing. The examination was carried out with the "Siemens SOMATOM Sensation" device. The granite samples kept in glass tumblers were in an order for inspection, as shown in Figure 21.

3.5 Experimental process: Unconfined uniaxial compression test

The GCTS Unconfined Compression Testing apparatus is a specialized tool designed for evaluating the unconfined compressive strength of cylindrical specimens. Its axial actuator is governed by the SCON-1400 Wireless Servo Controller and Data Acquisition System, complemented by 64-bit Windows-based software (Figure 22). This integrated system facilitates the execution of both static and dynamic closed-loop tests, enabling the manipulation of various parameters including load, deformation, stress, and strain. Test measurements are readily accessible and exportable, streamlining result analysis. With an axial load capacity of 4,500 kN and an axial stroke extending up to 200 mm, it features a four-column load frame with an adaptable crosshead and boasts a frame stiffness of up to 5,000 kN/mm. Additionally, the device is equipped with closed-loop digital servo control, enabling precise management of axial load or deformation [190].

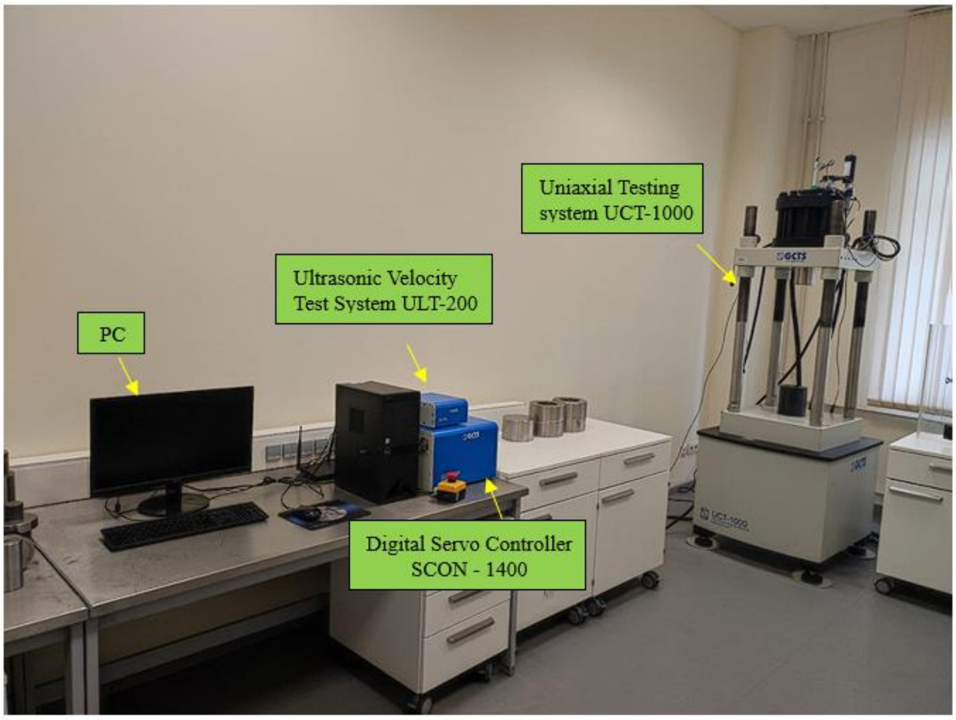


Figure 22. UCT-1000 device

In our compression experiments the rate of 0.01 %/min of axial strain was fixed. Figure 23 depicts sample set-up before running the compression test. There are shown core sample (d=54 mm, l=108 mm) fixed with 2 rings and chain. Into the 2 rings vertically inserted 2 rods with Linear variable differential transformer (LVDT) sensors at tips to measure the axial strain during the experiment. The chain was also fixed with rod and horizontally adjusted LVDT sensor to measure the radial strain.

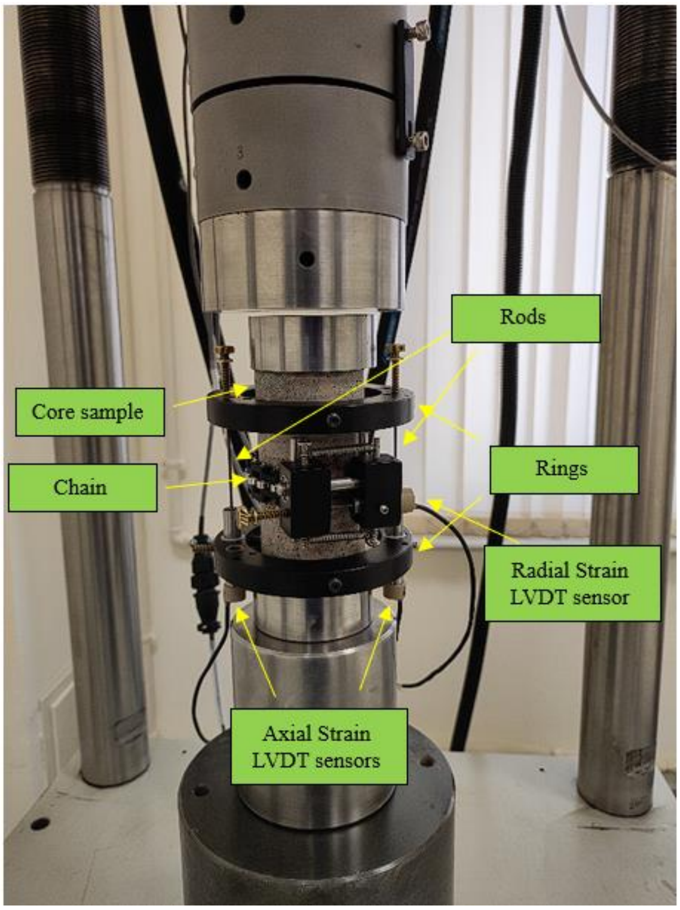


Figure 23. Sample adjusted with LVDT sensors before compression test

The Figure 24 demonstrates the sample after compression test was finished. There are obvious cracks in the sample.

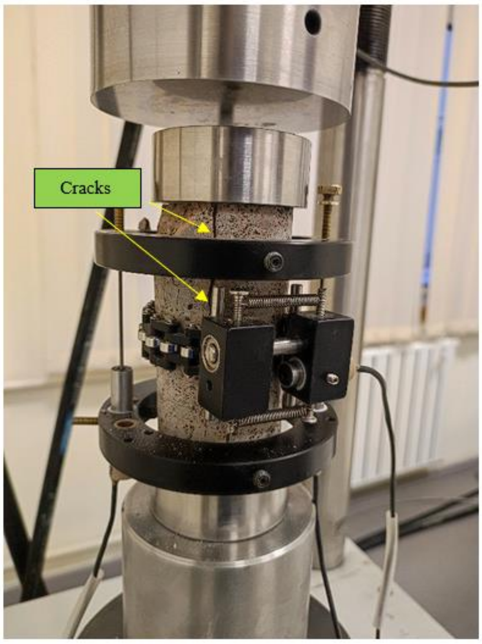


Figure 24. Sample after failure

3.6 Experimental process: Brazilian test

The Brazilian Test is a laboratory procedure commonly employed in rock mechanics to ascertain the tensile strength of rocks through indirect means. The determination of the tensile strength of rock materials holds substantial importance in the design and execution of geotechnical projects, as it typically registers considerably lower values compared to the compressive strength of rocks [191].

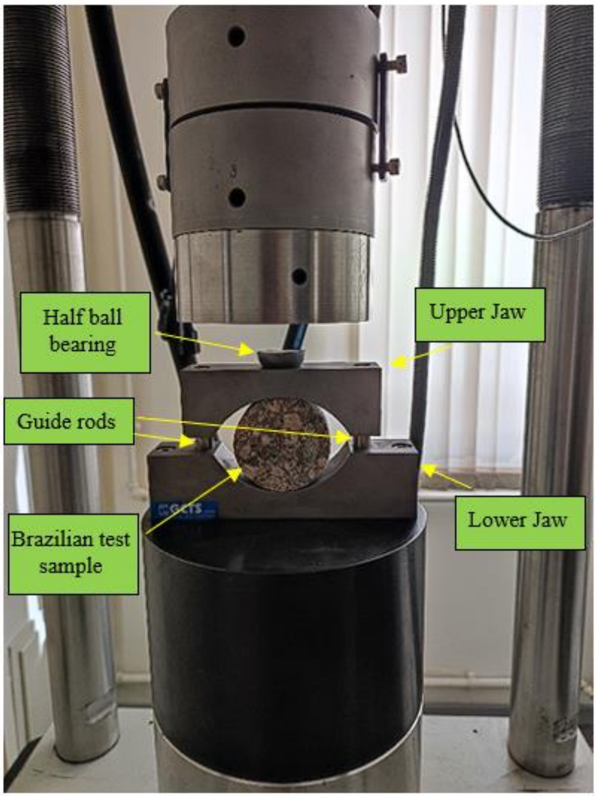


Figure 25. Sample adjusted before start of Brazilian test

The sample's diameter should not be smaller than 50 millimetres, and its thickness should fall within the range of 0.2 to 0.75 times its diameter, ideally approaching half of the diameter (25 mm) for optimal conditions according to International Society for Rock Mechanics (ISRM) standards. The sample's set-up consists of upper and lower jaws connected with guide rods to fix the sample and half ball bearing above that will be pressed to create stress on the specimen. In our case, the Brazilian test had the rate of stress fixed at 2 kN/min (Figure 25). The Figure 26 illustrates the sample at the end of the experiment.

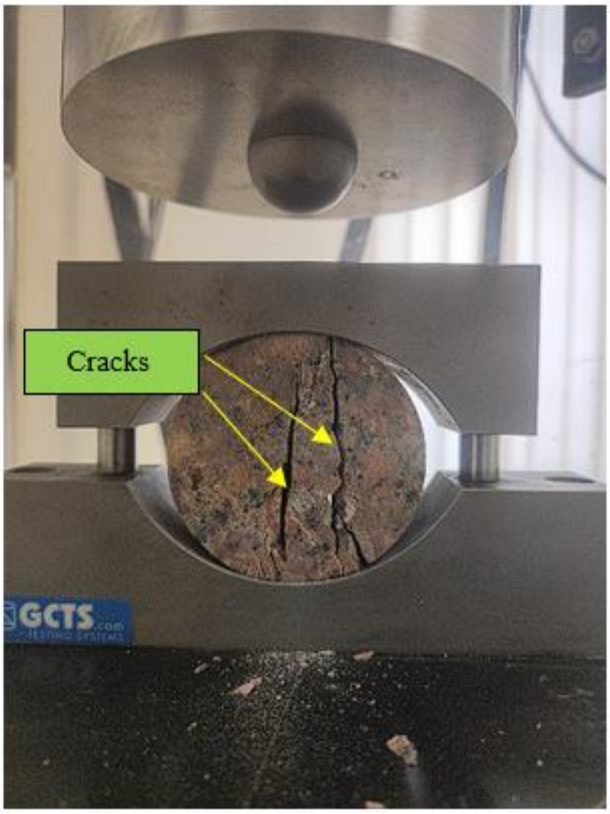


Figure 26. Sample cracked after finish of Brazilian test

4. RESULTS AND DISCUSSION

As discussed in the previous chapter, the thesis contains 2 non-destructive (XRD and CT Scan analysis) and 2 destructive (compression and Brazilian) tests. This chapter will provide results from the experiments comparing both the baseline with higher temperatures subjected to LN_2 and 2 granite differences and make thorough discussion for them.

4.1 Uniaxial compression test

UCS tests were implemented to investigate the strength of heated at elevated temperatures and subjected to LN_2 granite samples. The strength and deformation results have been determined by calculating the axial stress versus axial strain, axial stress versus radial strain, and load vs displacement values. Figure 27 illustrates the axial stress versus axial strain curves. Figure 28 demonstrates axial stress versus radial strain curves for the two different granites, and Figure 29 indicates load versus displacement for the same treatment processes.

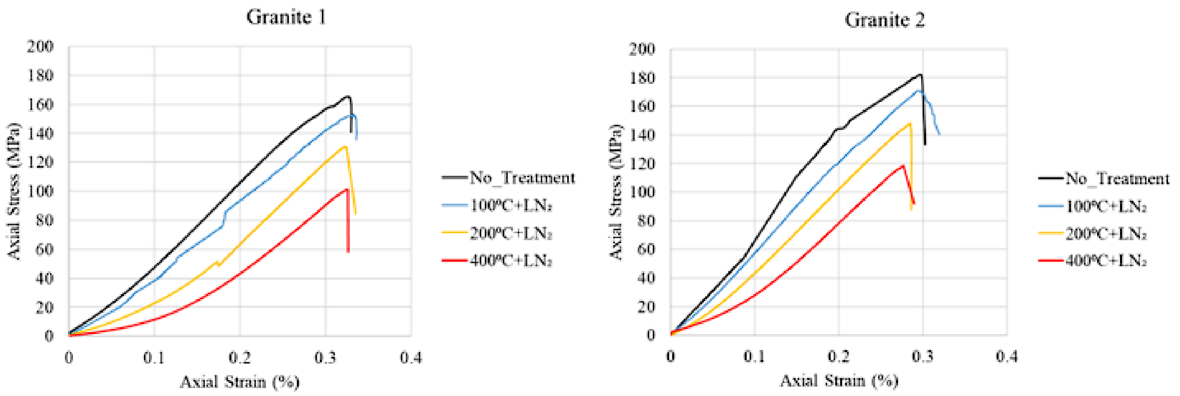


Figure 27. Axial Stress vs Axial Strain for granite 1 (left) and granite 2 (right)

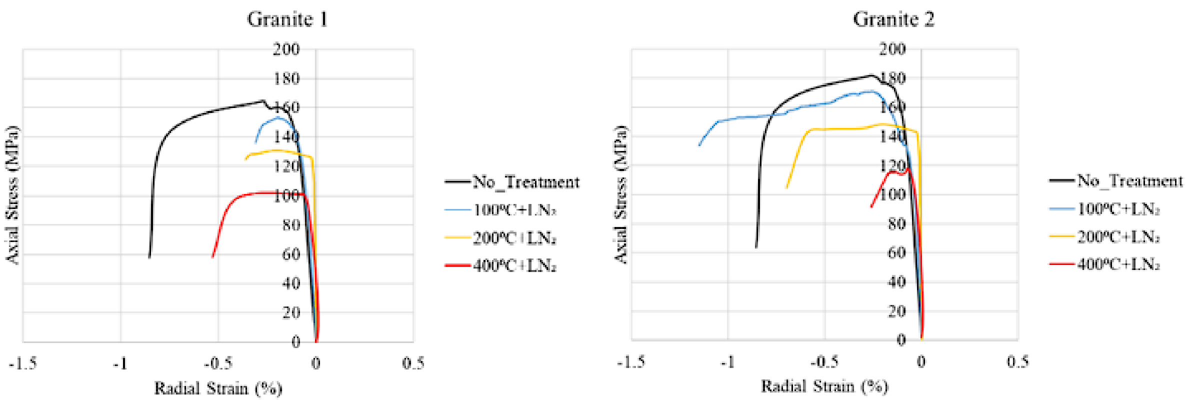


Figure 28. Axial Stress vs Radial Strain for granite 1 (left) and granite 2 (right)

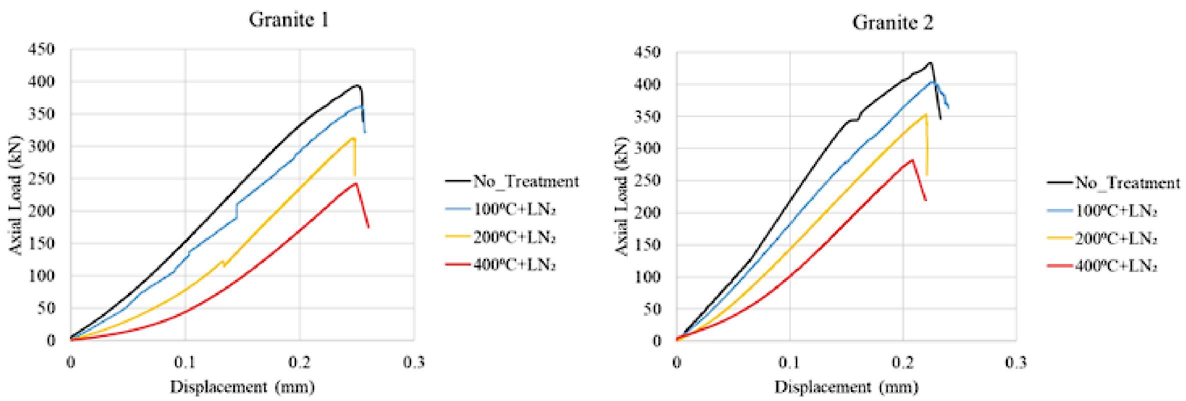


Figure 29. Axial Load vs Displacement for granite 1 (left) and granite 2 (right)

The highest measured stress in the experiment with no treatment was 164.79 MPa for granite 1 and 181.42 MPa for granite 2 (Table 7). The lowest values are achieved at 400 °C with LN_2 treatment, with 101.31 MPa and 118.33 MPa for granite 1 and granite 2, respectively. The peak stress of specimens with ‘no treatment’ and 100 °C after LN_2 cooling is high with minor differences. The difference per experiment (percentage difference in UCS peak stresses between successive temperature increments) varied from 6.92 % (difference between no treatment and 100 °C with LN_2 treatment experiments) to 22.73 % (difference between 200 °C and 400 °C with LN_2 treatment experiments) for granite 1 experiments. For granite 2 experiments, they are 5.84 % to 20.11 %, respectively. On the other hand, the difference per temperature (percentage difference in UCS peak stresses between the baseline and elevated temperature increments) shifts from 6.92 % (difference between no treatment versus 100 °C and LN_2) to 38.52 % (difference between no treatment versus 400 °C and LN_2) for granite 1 experiments and from 5.84 % to 34.78 % for granite 2 experiments, separately. The difference between the reported 2 granites’ experiments is shown in the last column of Table 7 and it is the percentage difference in UCS peak stress between similar tests with successive differences. For no treatment, 100 °C and 200 °C with LN_2 treatment cases, they demonstrated a minor change in the difference per granite (10.09 %, 11.38 %, and 12.97 % respectively), while for 400 °C after LN_2 cooling, it showed the maximum difference value of 16.8 %.

Table 7. Results from UCS test experiments for stress values for both granite 1 and granite 2 experiments

Specimen №	Temperature (°C)	UCS Peaks (MPa)	Difference per experiment (%)	Difference per temperature (%)	Difference per granite (%)
1	50	164.79	-	-	10.09
2		181.42			
1	100	153.38	-6.92	-6.92	11.38
2		170.83	-5.84	-5.84	
1	200	131.12	-14.51	-20.43	12.97
2		148.12	-13.29	-18.36	
1	400	101.31	-22.73	-38.52	16.80
2		118.33	-20.11	-34.78	

Poisson's ratio and Young modulus are essential mechanical properties determined during UCS testing. To properly foresee the beginning of fractures and their propagation, differences in Poisson's ratio and Young modulus must be established. Figure 30 depicts the connection between Young modulus and Poisson's ratio at increased temperatures following LN_2 treatment. Young modulus falls when the starting temperature rises during the LN_2 treatment. As granite specimens were subjected to heating to 400 °C and then treated with LN_2, their Young modulus values were reduced by 73.9 % for granite 1 experiments and 54.4 % for granite 2 experiments when compared to the baseline. The opposite pattern is shown in Poisson's ratio, which grew as the range of the temperature shock expanded. When granite samples were heated at 400 °C and treated with LN_2, the values of the Poisson's ratio increased by 69.4 % and 69.2 % for granite 1 and granite 2 experiments respectively compared to the baseline experiment. Granite is made up of a variety of minerals that include quartz, feldspar, and mica. At higher temperatures, it expands making the rock's volume augmentation due to thermal expansion caused by these minerals. Consequently, there is more intergranular spacing as well as diminished rock stiffness, hence reducing Young's modulus and it is possible for the expansion in one direction to result in a corresponding lateral expansion which leads to an increased Poisson's ratio.

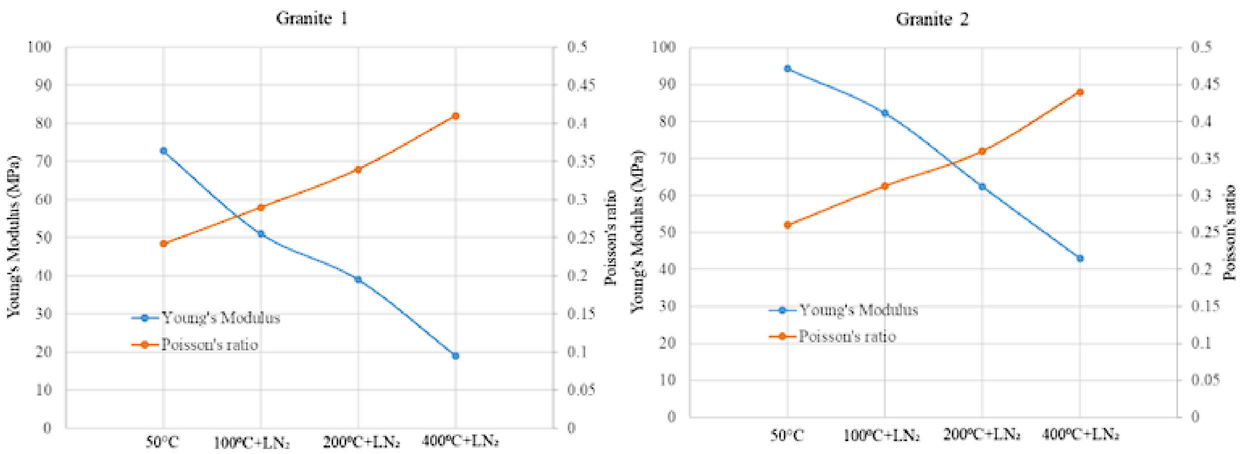


Figure 30. Young's modulus and Poisson's ratio values for granite 1 experiments (left) and granite 2 experiments (right)

The damage factor, which is associated with the fracture stress of the granite, may be determined using the formula below [192-193].

$$D_F = 1 - \frac{F_c}{F_o} \tag{3}$$

where D_F is the damage factor calculated from the fracture load, F_c is the maximum fracture load (kN) at different temperatures, and F_0 is the fracture load at baseline experiment (kN). As can be noticed from Figure 30, The D_F readings show an overall raised trend with increasing temperature and LN_2 cooling. Till the elevated temperature is less than 200 °C, the 2 granites kept the same increasing rate of the D_F values. But after 200 °C, the D_F value begins to rise slightly higher for the granite 1 compared with granite 2, while the second one keeps the constant rate of increasing.

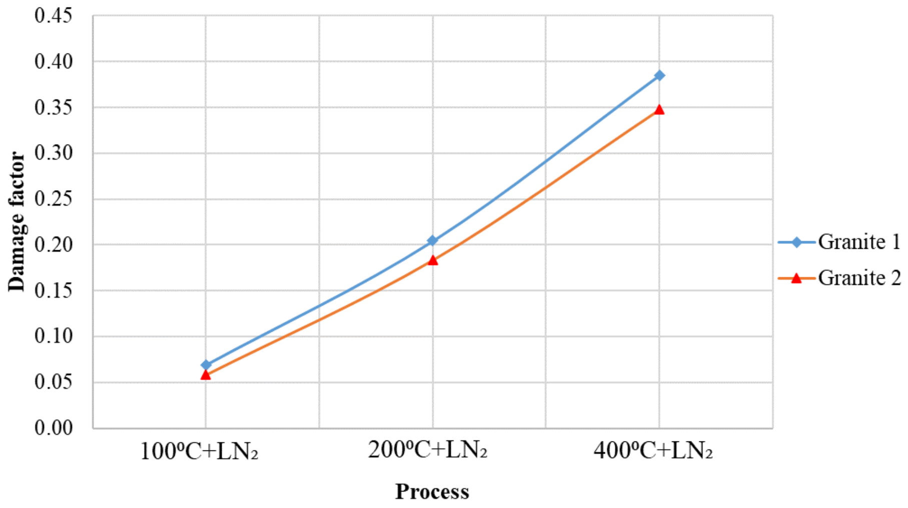


Figure 31. Damage factor values for granite 1 and granite 2

The area below the load-displacement curve is referred to as energy absorption [194], as shown in Figure 32. So, Figure 32 demonstrates how it was calculated on the example of Granite 1 – No treatment case. It is important to mention that the area computed is that until the failure point. The total fracture energy is defined as the work performed due to the axial load, using the equation below.

$$E_{fracture} = \int_0^{\delta_{peak}} P(\delta)d\delta \qquad (4)$$

In this equation, P represents the axial load, δ represents the granite sample's axial displacement, and δ_{peak} represents the maximum load value.

For discrete data, the integration sign is replaced by the summation symbol, and the absorbed energy is calculated using the trapezoidal rule: $\delta_{i+1} - \delta_{i-1}$:

$$E_{fracture} \approx \int_{i=2}^{n-1} \frac{P_{i+1}+P_{i-1}}{2} \bullet (\delta_{i+1} - \delta_{i-1}) \qquad (5)$$

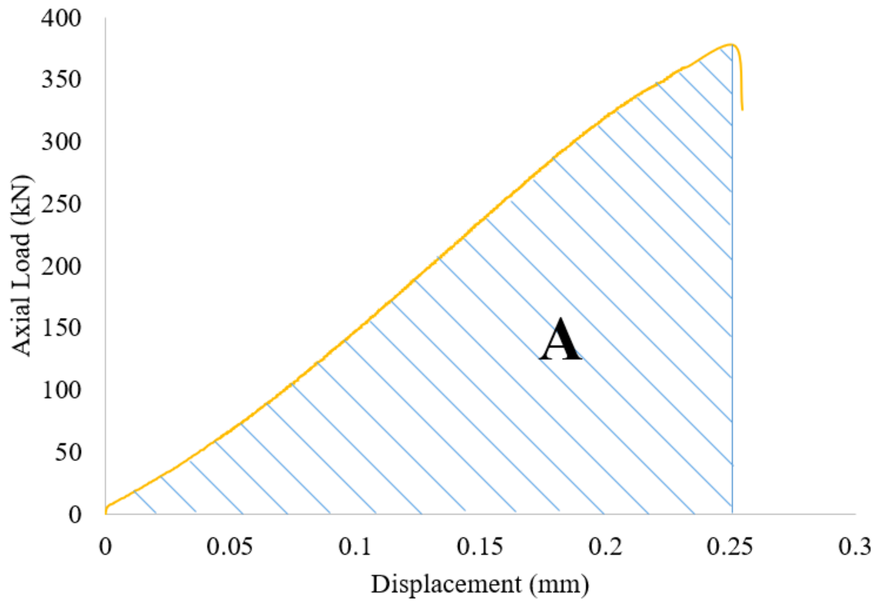


Figure 32. Example plot for calculating the absorbed energy (A – area)

According to axial load vs displacement plot there was built additional plot which is absorbed energy per each process (Figure 33).

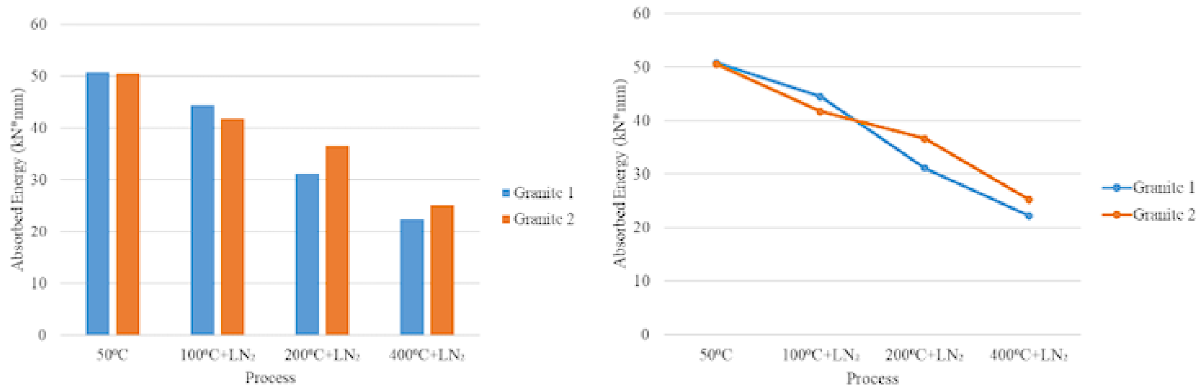


Figure 33. Absorbed Energy per Process for granite 1 and granite 2 (Compression test)

The absorbed energy until failure values shows a general reduction with rising temperature and LN_2 cooling. From no treatment to 100 °C treated with LN_2 there is a slight decrease for granite 1 and a moderate decrement for granite 2 (Figure 33). However, the slight decline shifted to a sharp decrease for the granite 1 line while the granite 2 line shows an inconsiderable diminishing rate from 100 °C treated with LN_2 to 200 °C treated with LN_2. The rate between 200 °C treated with LN_2 and 400 °C treated with LN_2 demonstrates a modest reduction in the granite 1 line and rapid diminution for granite 2 curve.

As the initial temperature increases, the distinct features of mechanical and physical characteristics become noticeable. Thermal shock tends to be the main reason for fractures both between grains (intergranular) and inside of grains (intragranular). The deformation of grain boundaries is a critical element, as it causes cracks, which then contribute to the formation of visible separations between the minerals of the rock sample [192-194]. Such a process is a result of the increasing thermal stresses, that minerals are subjected to when they are heated to a higher temperature, and this causes the distortion of the minerals. The compressive stresses that are induced inside of the specimen by the warmer interior section cause alterations in thermal stress patterns, which, eventually result in thermal fractures [195,196].

4.2 Brazilian test

Brazilian tests were used to assess the strength of processed granite specimens and discover how they distorted under particular experimental settings when compared to untreated specimens. The force and deformation findings were obtained by calculating load versus displacement for granites 1 and 2. Brazilian testing (indirect tensile stress) used samples that were 54 mm in diameter and 27 mm in length. Figure 34 shows the load-displacement curves for two distinct granites tested in Brazilian. The load decreases as the temperature increases in conjunction with LN_2 treatment.

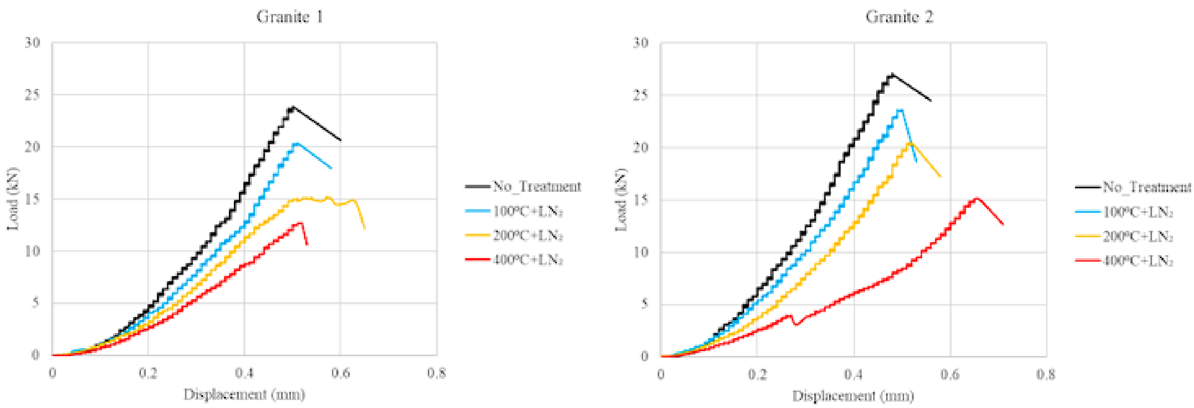


Figure 34. Load vs Displacement for granite 1 (left) and granite 2 (right)

The highest recorded load in the tests was with no treatment (50 °C), which was 23.9 kN for granite 1 and 27.1 kN for granite 2 (Table 8). The lowest values were recorded at 400 °C for both the granite 1 and granite 2 trials, with 12.7 kN and 15.09 kN, respectively. The load of specimens with temperatures (till 200 °C in the current experimental work) after LN_2 cooling is high, with minor differences between experiments, ranging from 14.64 % (difference between no treatment and 100 °C with LN_2 treatment experiments) to 46.86 % (difference between no treatment and 400 °C with LN_2 treatment experiments) for granite 1 experiments and 12.83 % to 44.33 % for granite 2 treatment process, correspondingly. The difference in maximum load between experiments for successively increasing shock temperature differences (difference between no treatment versus 100 °C and LN_2, difference between 100 °C and LN_2 versus 200 °C and LN_2, and finally difference between 200 °C and LN_2 versus 400 °C and LN_2) varies from 25.49 % to 16.45 % for granite 1 experiments and from 13.22 % to 26.4 % for granite 2 experiments. The last column of Table 8 depicts the difference between two granites that were treated under identical conditions. For no treatment, the difference is 13.39 %, while the difference for 100 °C treated with LN_2 is 15.79 %. For 200 °C treated with LN_2 the contrast is 34.87 % and for 400 °C treated with LN_2 is 18.8 % showing the moderate difference between the 2 granites.

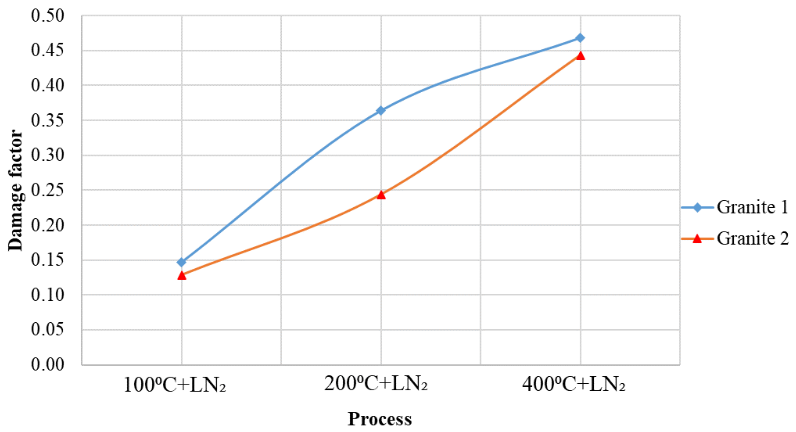


Figure 35. Damage factor values for both granites

As can be noticed from Figure 35, The D_F readings show an overall raised trend with increasing temperature and LN_2 cooling. The granite 1 line illustrates the sharp increasing rate from 100 °C to 200 °C treated with LN_2 and a modest increment from 200 °C to 400 °C cooled with LN_2, reaching the highest value of D_F at the end. In the case of the granite 2 line, it represents slight augmentation from 100 °C to 200 °C treated with LN_2 and then demonstrates a considerable increment rate till 400 °C cooled by LN_2.

Table 8. Results from Brazilian test experiments for load values for both granite 1 and granite 2 experiments

Specimen №	**Temperature (°C)**	**UTS Peaks (kN)**	**Difference per experiment (%)**	**Difference per temperature (%)**	**Difference per granite (%)**
1	50	23.90	-	-	13.39
2		27.10			
1	100	20.40	-14.64	-14.64	15.79
2		23.62	-12.83	-12.83	
1	200	15.20	-25.49	-36.40	34.87
2		20.50	-13.22	-24.35	
1	400	12.70	-16.45	-46.86	18.80
2		15.09	-26.40	-44.33	

Showing a trend of decline, the absorbed energy until failure values decreases gradually with rising temperature and LN_2 cooling (Figure 36). Transitioning from untreated conditions at 50 °C to LN_2-treated states at 100°C, granite 1 exhibits a moderate decrease, while granite 2 displays a significant drop. However, the moderate decline shifted to a rapid decrease for the granite 1 line, while the granite 2 line shows a modest reduction from 100 °C treated with LN_2 to 200 °C treated with LN_2. The rate between 200 °C treated with LN_2 and 400 °C treated with LN_2 demonstrates a minor reduction in the granite 1 line and an inconsiderable diminishing rate for granite 2 curve.

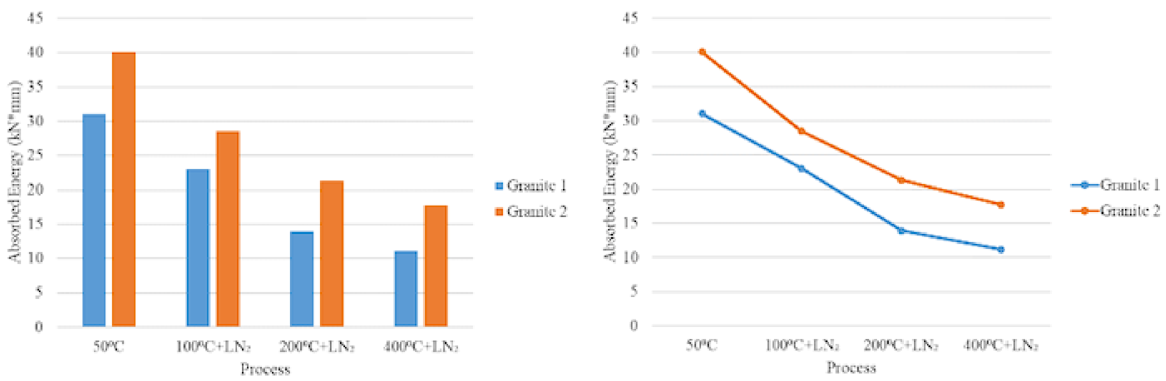


Figure 36. Absorbed Energy per Process for granite 1 and granite 2 (Brazilian test)

According to Feng et al. [197], there are three types of fractures of samples, which are in turn subdivided into eight sub-types. Figure 37 illustrates a schematic of the fracture types. In our case, through running the Brazilian test experiments there were obtained fractures for granite 1 and granite 2 samples for no treated and treated with elevated temperature with LN_2 cases.

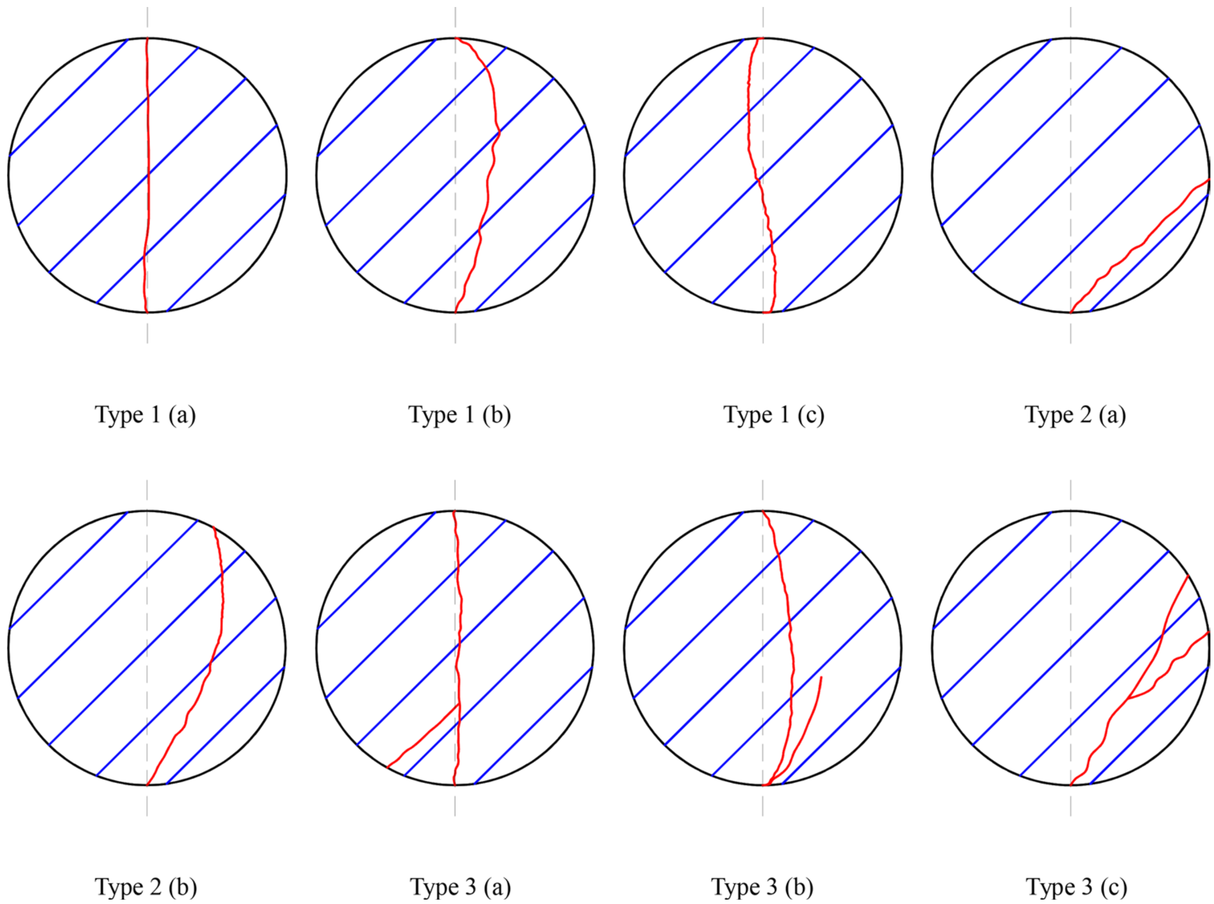


Figure 37. Fracture classification diagram (dotted line indicates the loading direction; blue lines indicate the layering direction; red lines indicate the fractures) [197]

Figure 38 and Figure 39 demonstrate the before and after failure images depicting both untreated and treated cases in Brazilian test experiments conducted with granite 1 and granite 2, respectively, showcasing the impact of treatment on the test results. In the "untreated condition (no treatment case)" granite 1 and granite 2 show a Type 1 (c) fracture, which is an S-type fracture pattern that is extended through the upper and lower loading ends without significant lateral deviation. 100 °C followed by LN_2 cooling for both granite 1 and granite 2 resulted in a transition of the Type 1 (b) fracture with a non-central fracture line extended through the upper and lower loading ends. In the 200 °C and 400 °C temperatures at LN_2 treatment, both granite 1 and granite 2 are moving in the direction of Type 3 (a) fractures. These cracks end with a main central fracture line that also has branched fractures, which are characterized by a more complex crack structure. Finally, the two granites that were left untreated and treated with 100 °C + LN_2 pertain to Type 1 fractures, while both the 200 °C + LN_2 and 400 °C + LN_2 treated cases correspond to Type 3 fractures.

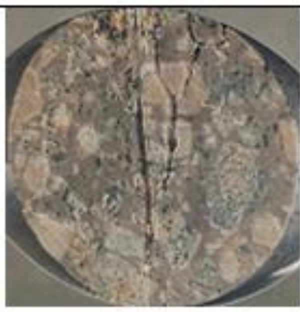
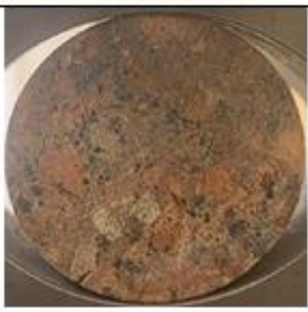
Treatment	Before failure	After failure
No treatment (50 °C)		
100 °C + LN_2		
200 °C + LN_2		
400 °C + LN_2		

Figure 38. The before and after failure images depicting both untreated and treated cases in Brazilian test experiments conducted with Granite 1, showcased the impact of treatment on the test results.

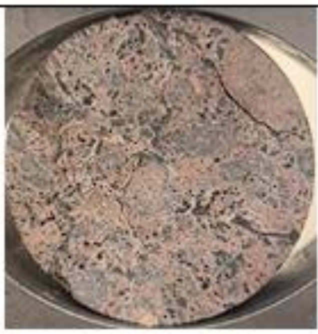
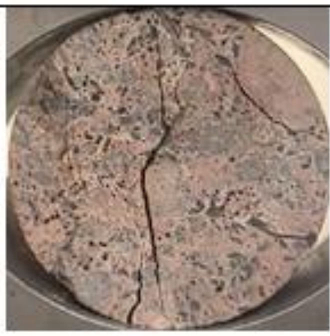
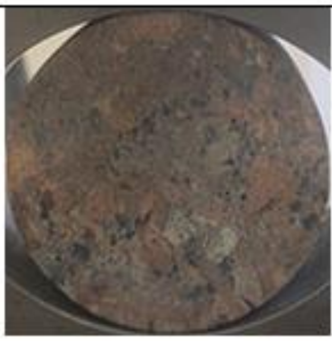
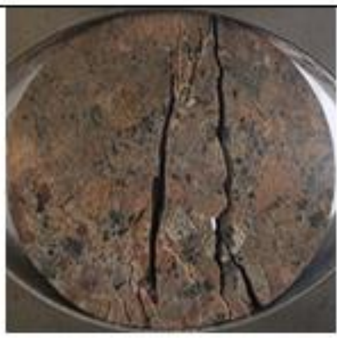
Treatment	Before failure	After failure
No treatment (50 °C)		
100 °C + LN_2		
200 °C + LN_2		
400 °C + LN_2		

Figure 39. The before and after failure images depicting both untreated and treated cases in Brazilian test experiments conducted with Granite 2, showcased the impact of treatment on the test results.

Tensile stresses on the samples' less warm exterior surfaces cause changes in thermal stress distributions, which eventually lead to the production of thermal fractures [195,196]. Microfracture is facilitated by the stresses that occur at the grain boundaries which are, in turn, caused by higher initial temperatures and the LN_2 cooling process. Therefore, this increase influences the quality of granite which is expressed by the non-uniformity and non-continuity of the granite specimen. The structural integrity can be affected [198,199].

4.3 CT Scan analysis

As it was mentioned before, the CT Scan analysis was done to see the new internal fractures, fracture network, and the elongation of the pre-existing ones after treatment of granite with elevated temperature supported with LN_2. For the evaluation of these parameters, the top view and horizontal view cross-sections of the specimens were checked. To investigate different regions, 3 separate cross-sections (left side, centre and right side of the sample) were selected. Moreover, it must be mentioned that in the illustrated black and white images, the density decreases along from white to black. White areas have higher density, grey areas have medium density, and the black areas have the lowest density.

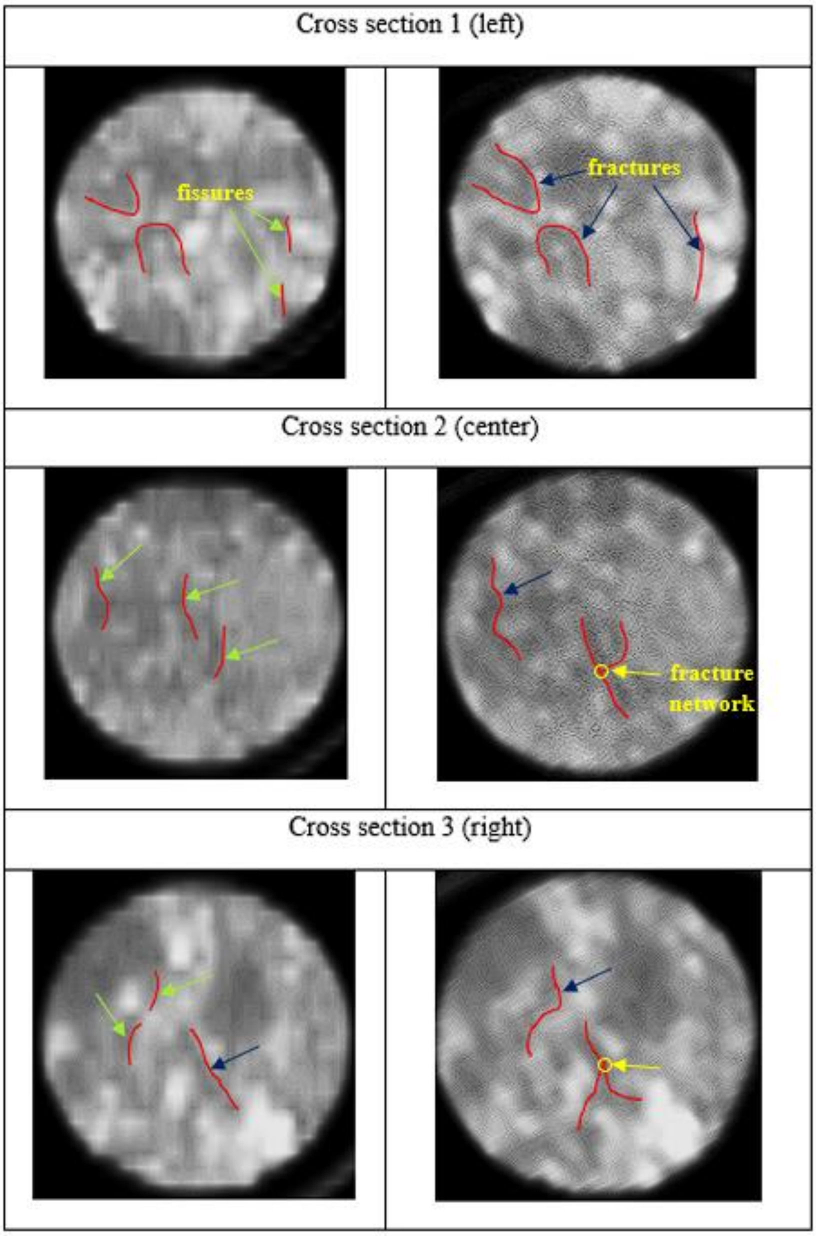


Figure 40. Top view cross sections for granite 1 before (left) and after (right) treatment with 100 °C + LN_2

The fractures in the cross-sections were depicted with red lines and they can be obtained next to the fractures (not to cover the real ones). For distinguishing the fissures (small cracks), fractures (big cracks) and fracture networks, green, dark blue and yellow arrows were used, respectively. For the fracture network case, they are occurring in “Y” shaped forms and the connecting points of primary and secondary fractures were illustrated with yellow circles.

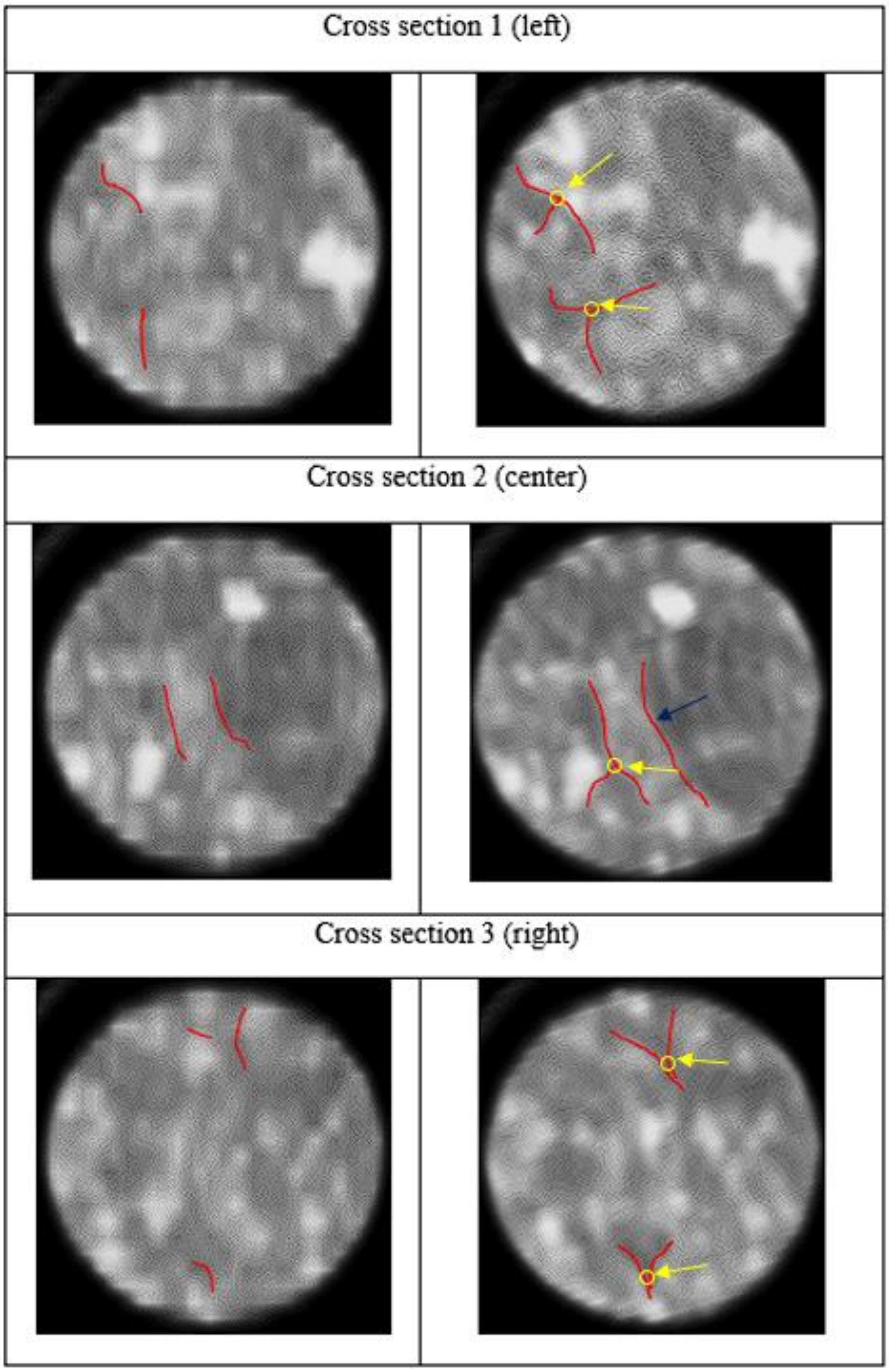


Figure 41. Top view cross sections for granite 1 before (left) and after (right) treatment with 200 ºC + LN_2

Figures 37 and 40 (top views of granite 1 and granite 2), as well as Figures 43 and 46 (horizontal views of granite 1 and granite 2), depict the fractures detected before and after treatment with 100 °C + LN_2. Initially, just a few fractures were seen, with rare cases of fracture networks. While new fractures were minor after treatment, pre-existing fissures and fractures grew noticeably. This shows a notable structural change, defined by elongated characteristics rather than the development of new fractures.

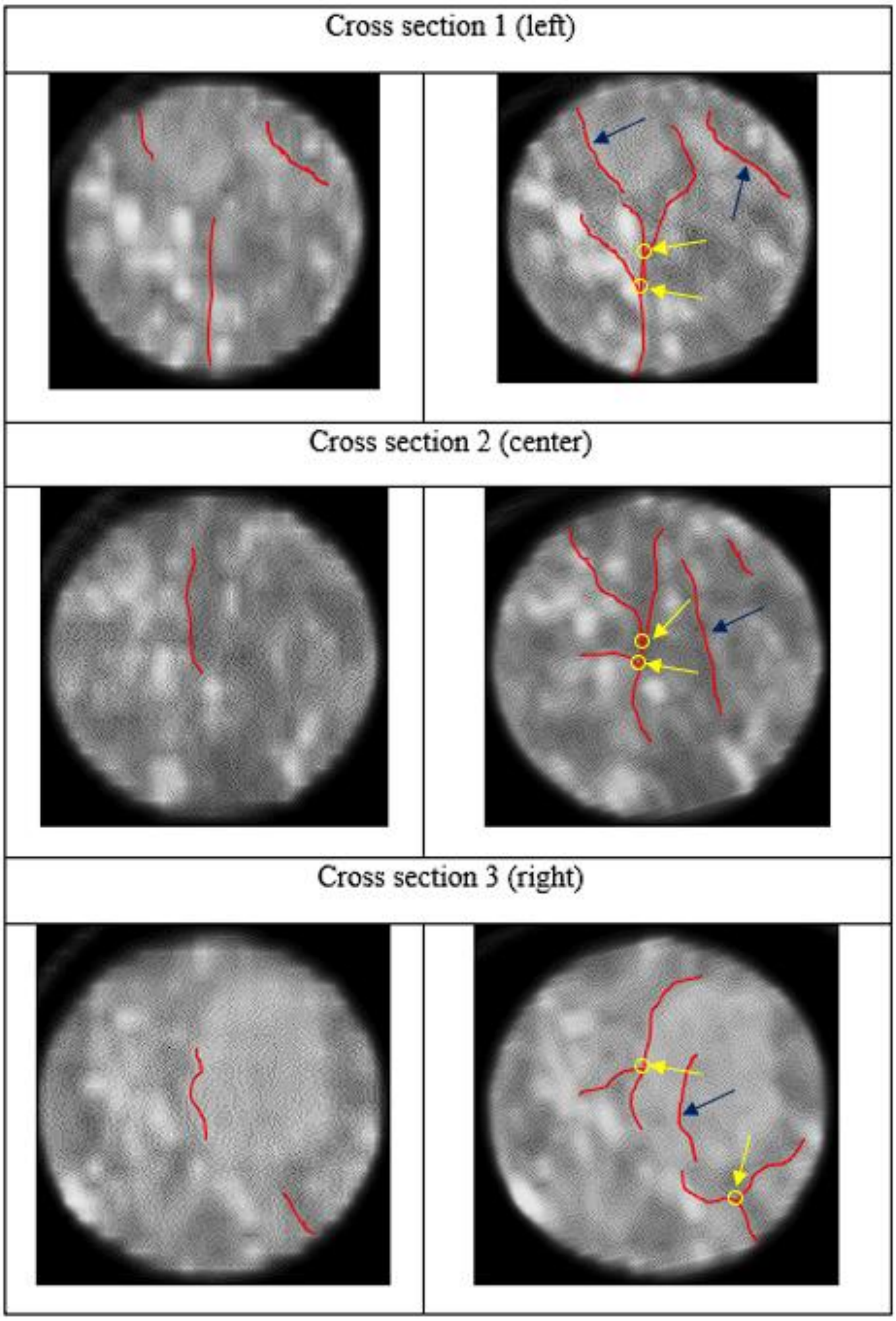


Figure 42. Top view cross sections for granite 1 before (left) and after (right) treatment with 400 °C + LN_2

The fractures detected before and after treatment with 200 °C + LN_2 are illustrated in Figures 38 and 41 (top views of granite 1 and granite 2), as well as in Figures 44 and 47 (horizontal views of granite 1 and granite 2). Notably, the number of fissures and fractures, as well as the creation of fracture networks, has increased notably when compared to the 100 °C + LN_2 treatment. For instance, in Figure 44, the third cross-section shows two elongations of pre-existing fissures that turned into fractures, as well as the advent of new fractures and the formation of two "Y"-shaped fracture networks. This suggests a more profound structural change, as seen by a greater incidence of fracture development and network creation after the 200 °C + LN_2 treatment.

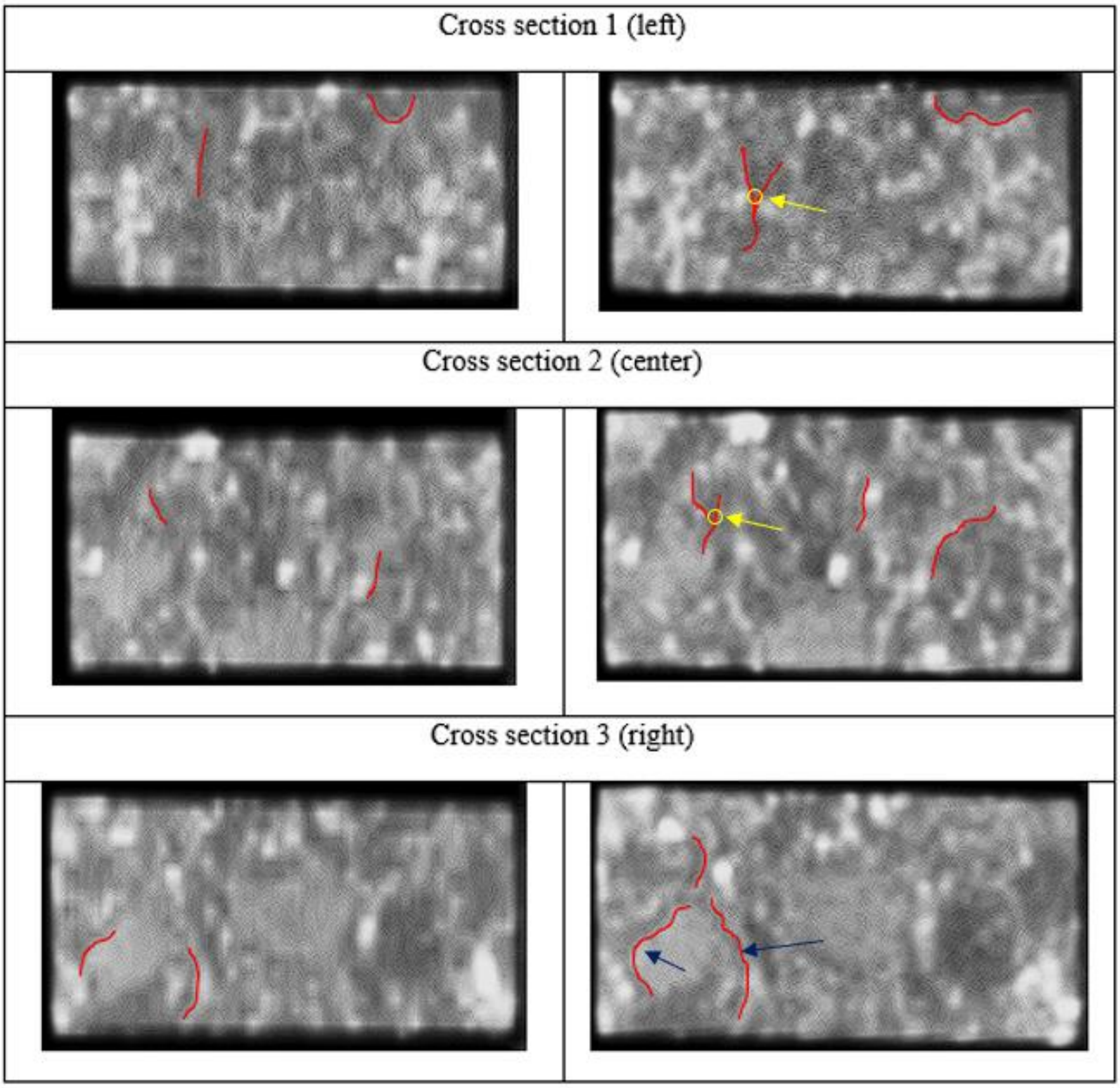


Figure 43. Horizontal view cross sections for granite 1 before (left) and after (right) treatment with 100 ºC + LN_2

However, the 400 °C + LN_2 case produces the most noticeable effects when compared to the 100 °C + LN_2 and 200 °C + LN_2 instances, as evidenced in Figures 39 and 42 (top views of granite 1 and granite 2) and 45 and 48 (horizontal views of granite 1 and granite 2). This treatment resulted in an enormous increase in new fractures, many occurrences of extended pre-existing fractures, and, most importantly, the creation of numerous fracture networks, as seen in Figure 42, especially in cross-section 3. This implies a better outcome than in the previous two cases, with a more significant change in structural integrity and the desired creation of widespread fracture networks.

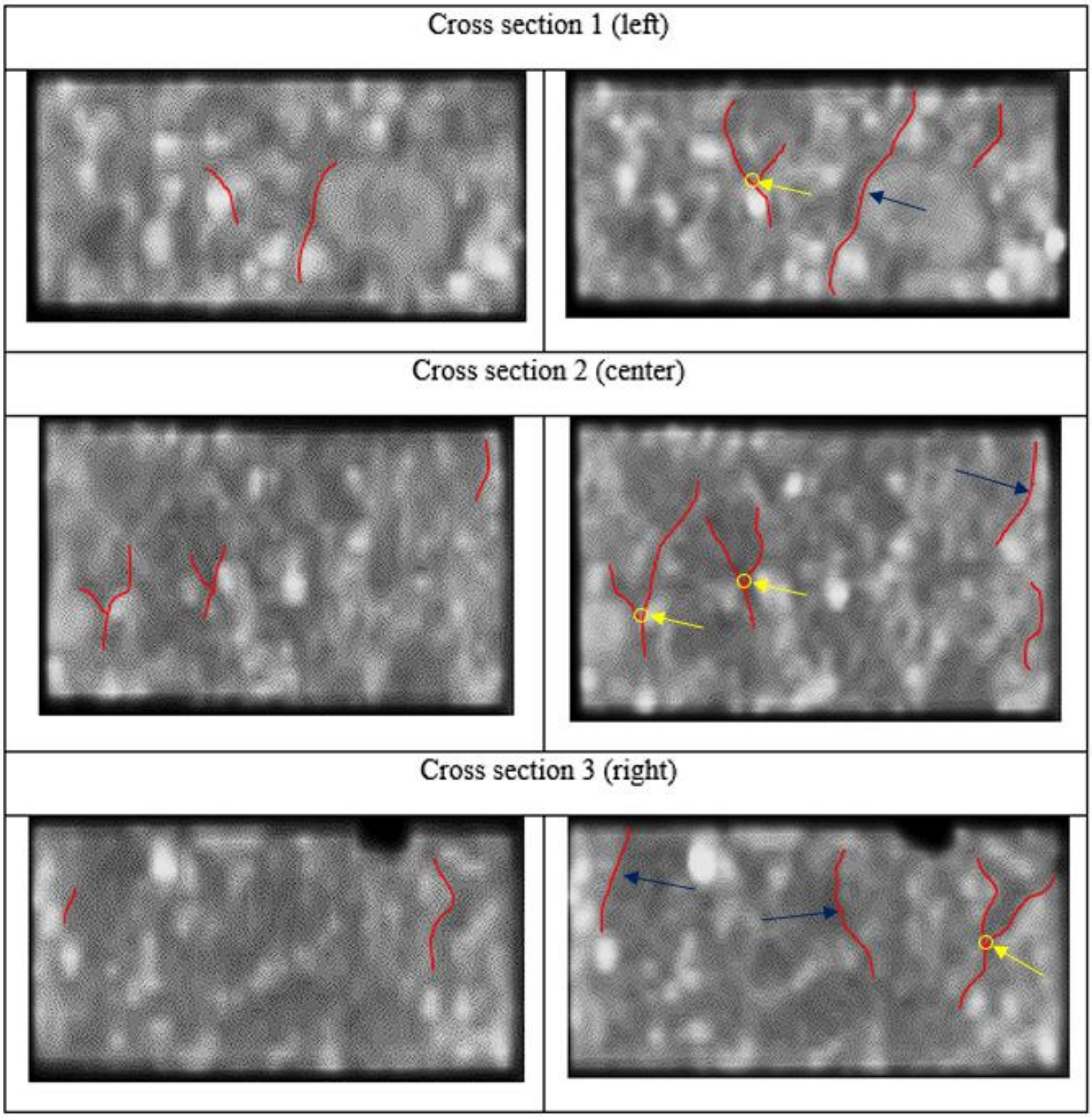


Figure 44. Horizontal view cross sections for granite 1 before (left) and after (right) treatment with 200 ºC + LN_2

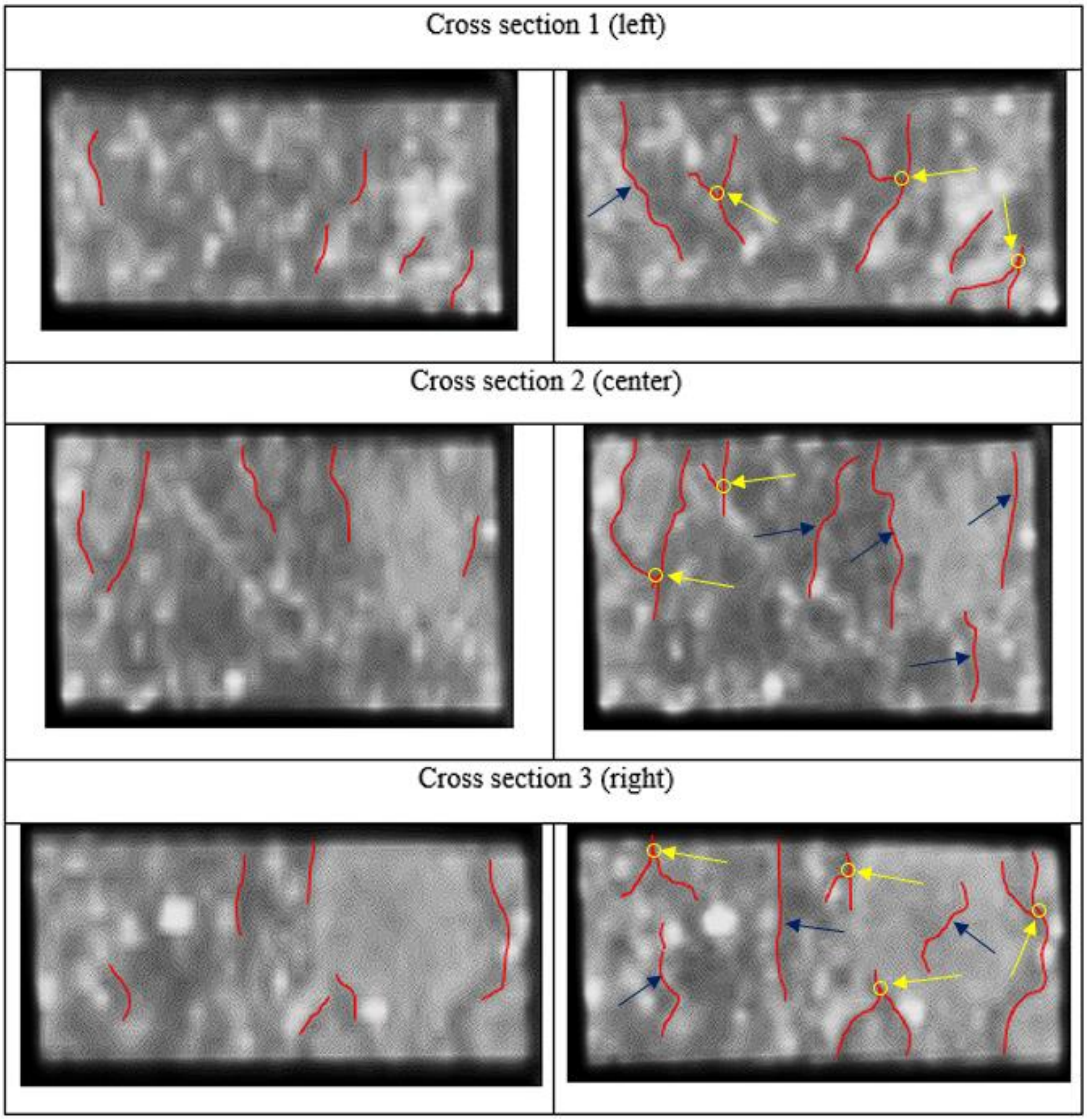


Figure 45. Horizontal view cross sections for granite 1 before (left) and after (right) treatment with 400 ºC + LN_2

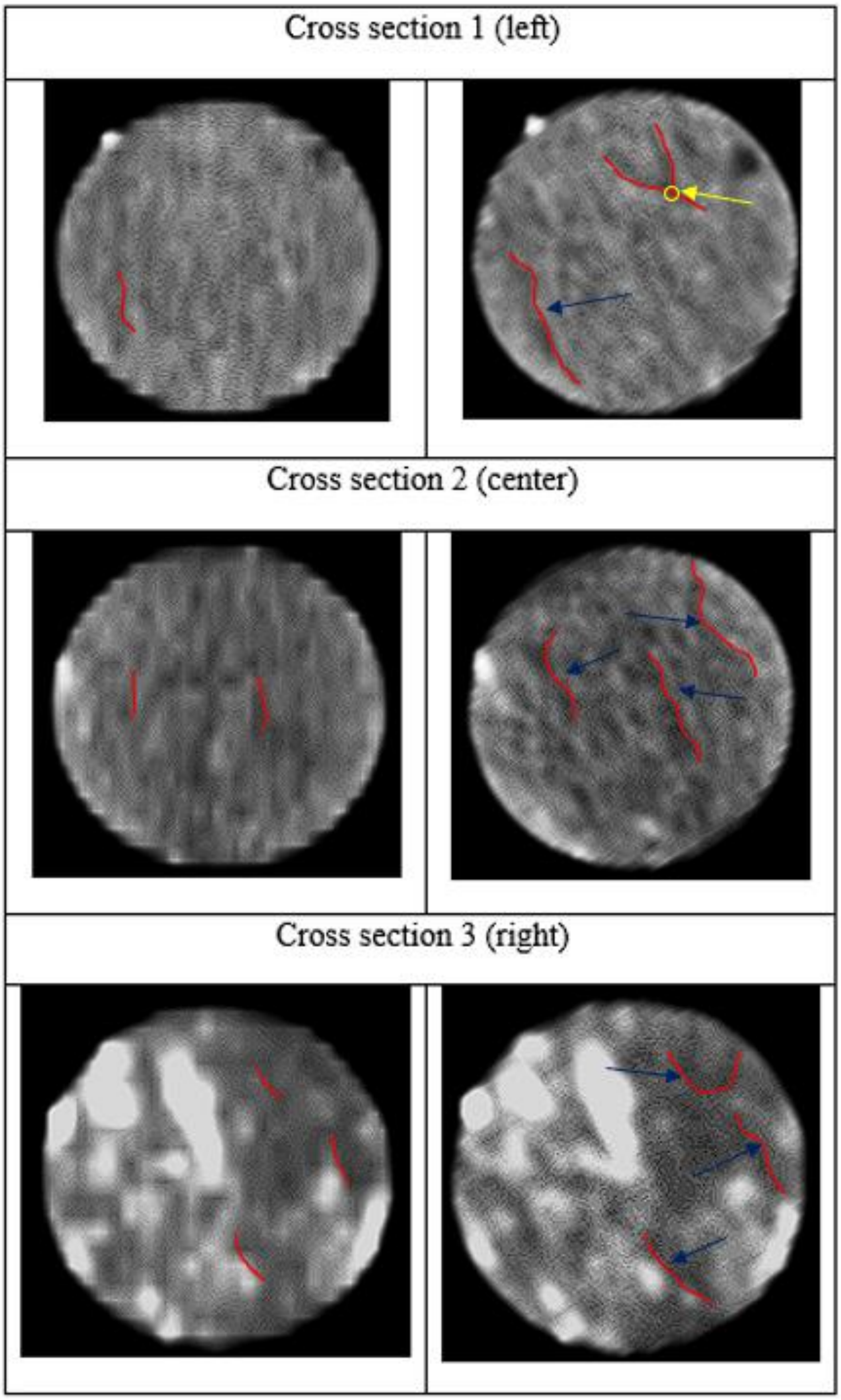


Figure 46. Top view cross sections for granite 2 before (left) and after (right) treatment with 100 ^{o}C + LN_2

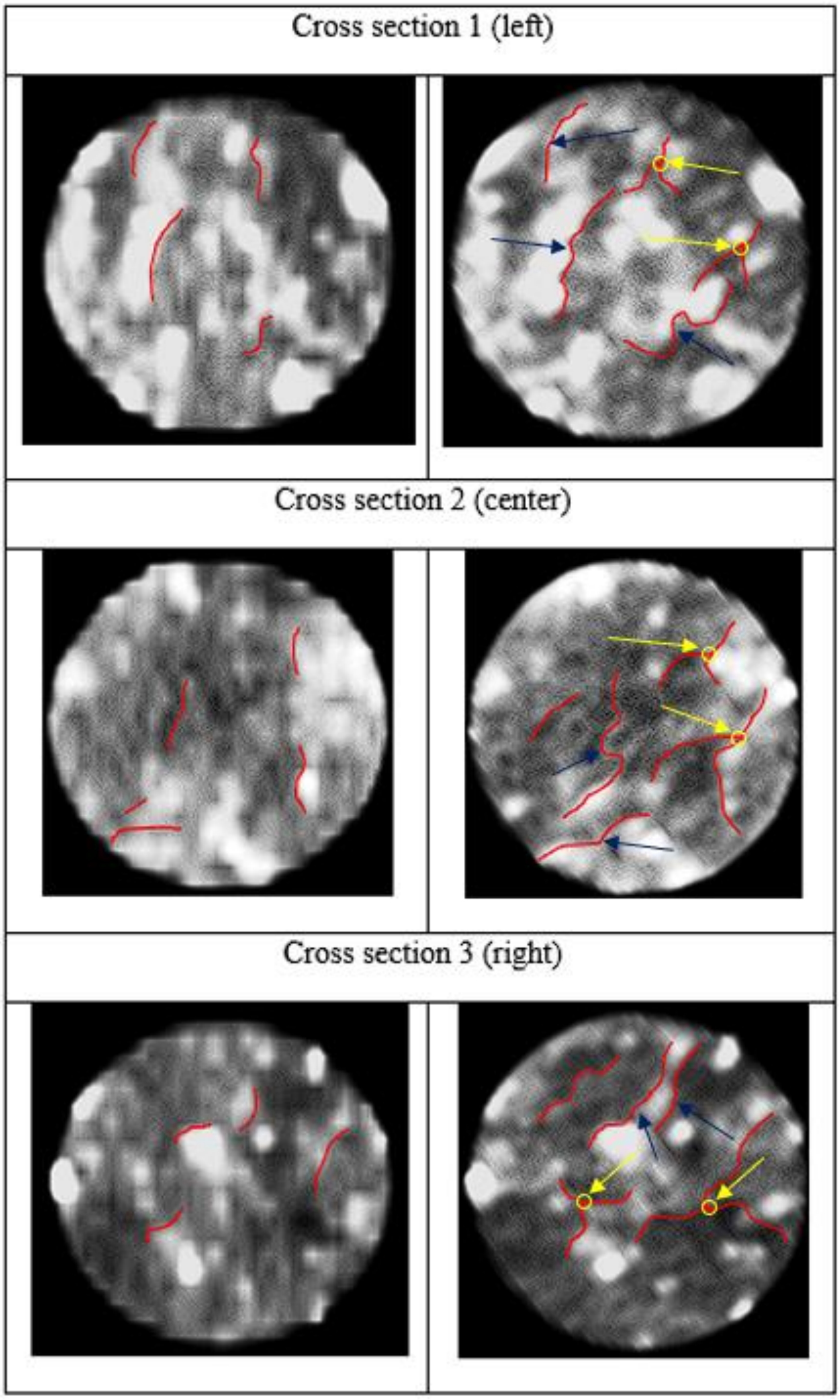


Figure 47. Top view cross sections for granite 2 before (left) and after (right) treatment with 200 ºC + LN_2

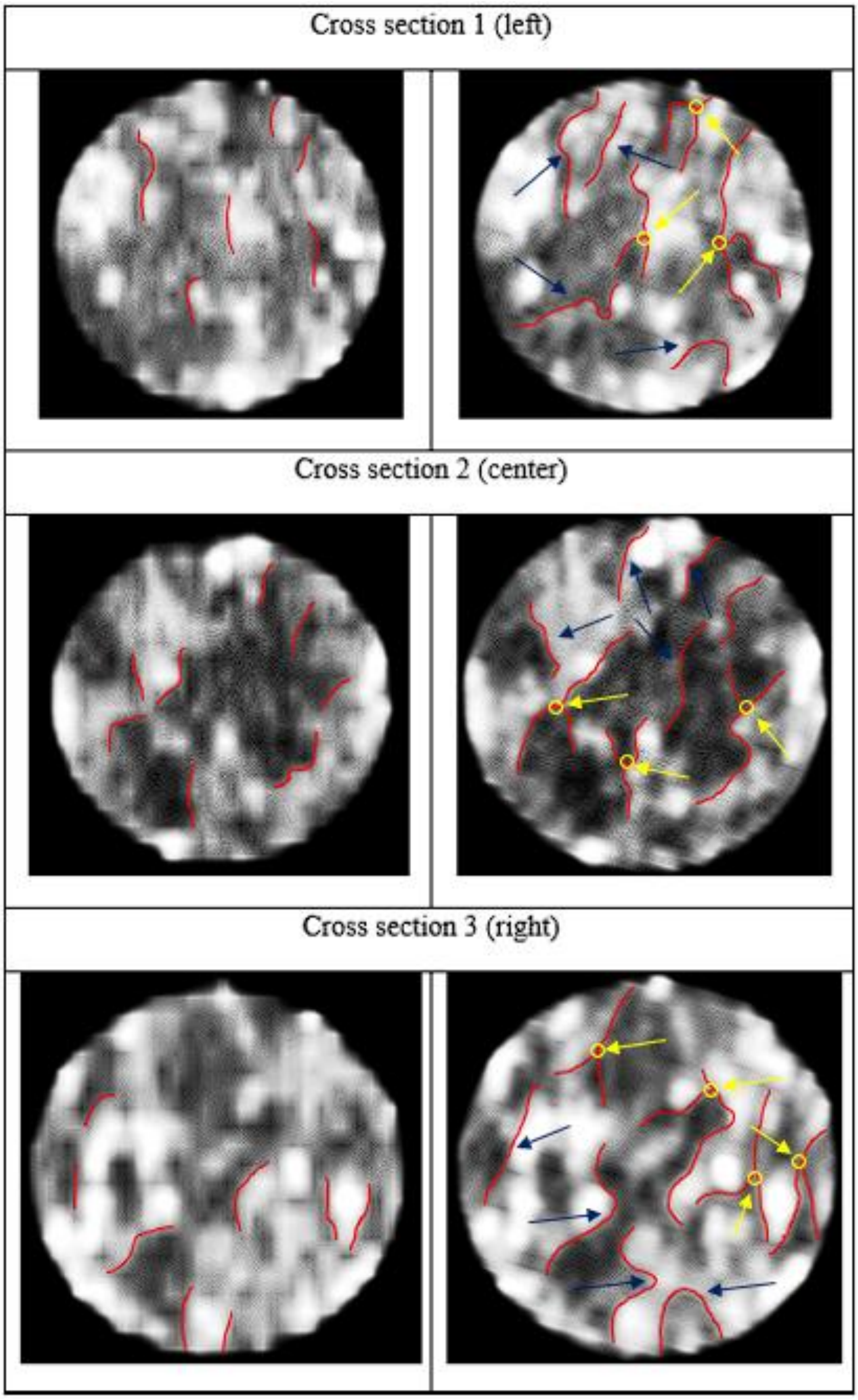


Figure 48. Top view cross sections for granite 2 before (left) and after (right) treatment with 400 ºC + LN_2

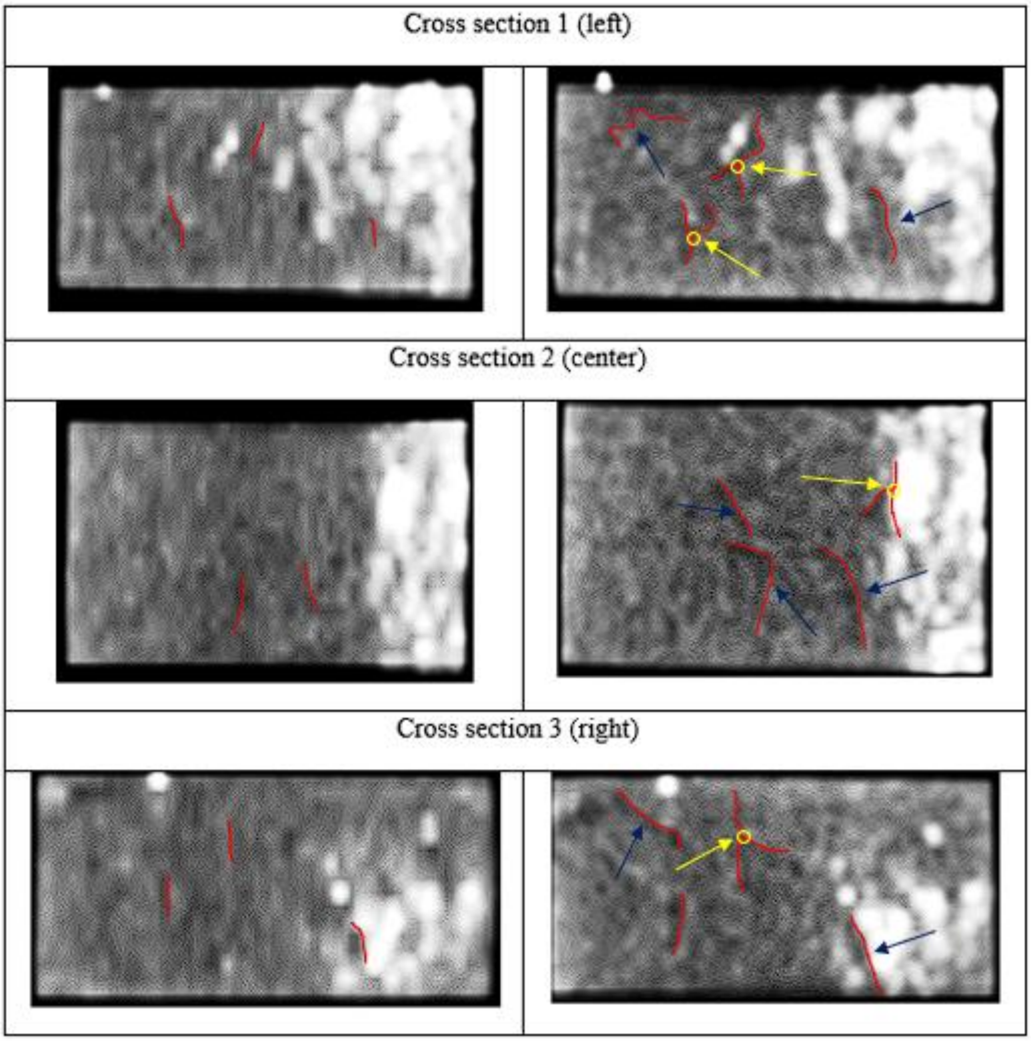


Figure 49. Horizontal view cross sections for granite 2 before (left) and after (right) treatment with 100 ºC + LN_2

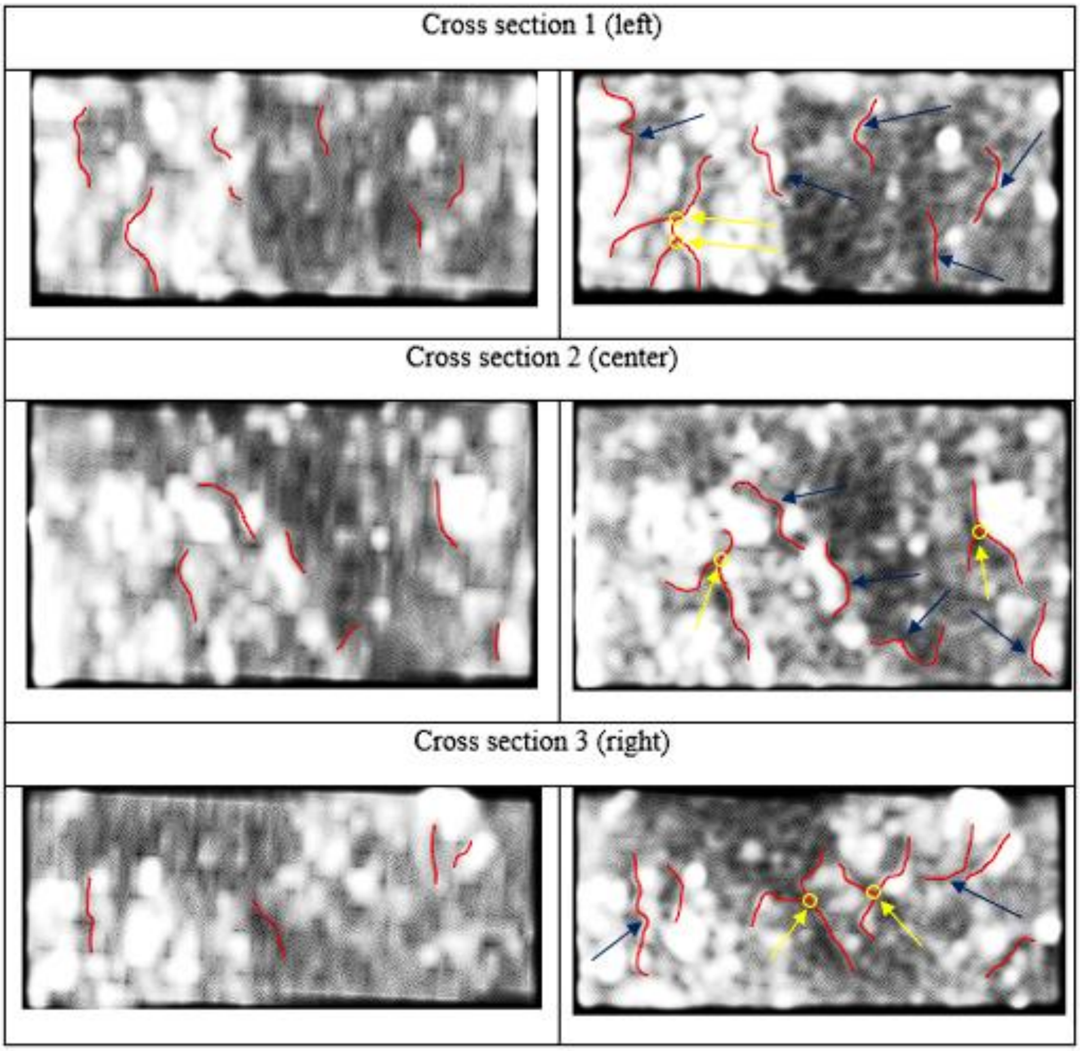


Figure 50. Horizontal view cross sections for granite 2 before (left) and after (right) treatment with 200 ºC + LN_2

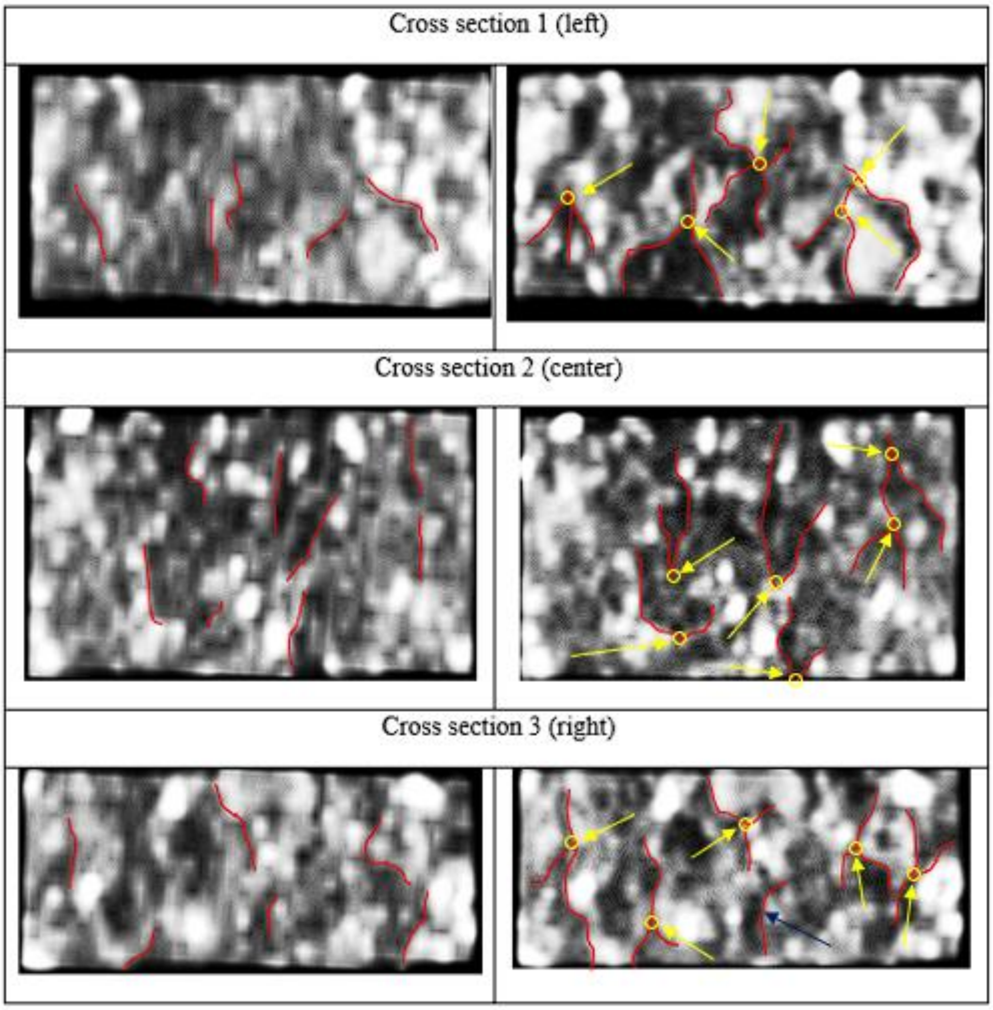


Figure 51. Horizontal view cross sections for granite 2 before (left) and after (right) treatment with 400 ºC + LN_2

The presence of LN_2 cooling at 400 °C, leads to an enhanced probability of fracture in the examined specimens and suggests a higher susceptibility to thermal shock-induced fractures at higher temperatures. At the same time, the growth of the secondary cracks in addition to the crack growth is the result of the plastic behavior of the samples which is a result of the sample's deformation. The involvement of these microfractures is a critical contributor to the overall instability of the specimen through the enhancement of thermal stress, fracture development, and material properties interaction [193,200,201]. In addition to that, these cracked zones merge to form a complex fracture network which can result in the compromised strength of the sample and the increase in its permeability.

5. CONCLUSION

Over 16 destructive experiments involving uniaxial compression and Brazilian tests, coupled with 2 non-destructive measurements using X-ray diffraction (XRD) and CT Scan analysis, were employed to thoroughly assess the impact of liquid nitrogen (LN_2) exposure on the strength properties of granite specimens. In this experiment, a range of mechanical testing was used to explore changes in the internal microstructure and mechanical behavior of thermally treated granites under LN_2 cooling. The starting temperatures for compression tests and Brazilian tests were systematically varied before undergoing LN_2 cooling. Based on the analysis of the experimental investigation, the following conclusions were derived:

• The compression tests revealed a decrease in stress as the temperature increased with LN_2 treatment. Specifically, for granite 1, stress values decreased for 38.52 % from 164.79 MPa without treatment to 101.31 MPa after treatment at 400 °C with LN_2, while for granite 2, the stress values decreased for 34.78 % from 181.42 MPa to 118.33 MPa under similar conditions.

• In the compression tests, there was a negative correlation observed between Young's modulus and the degree of thermal shock, whereas a positive correlation was noted for Poisson's ratio.

• The Brazilian tests demonstrated a gradual reduction in the load to failure of the investigated granite specimens by the increment of temperature supported with LN_2 cooling. Particularly, there is a decline from 23.9 kN without treatment to 12.7 kN for granite 1 (46.86 %), and from 27.1 kN to 15.09 kN for granite 2 (44.33 %) experiments, respectively.

• The CT Scan analysis illustrated that as the temperature incremented from 100 ^{o}C to 400 ^{o}C with the use of LN_2, there was obtained a perceptible increase in the number of elongations of preexisting fractures, creation of new fractures and formation of fracture network, which is a desired outcome.

• Throughout all experimental procedures, specimens subjected to an elevated initial temperature of 400 °C followed by treatment with liquid nitrogen consistently exhibited more favourable results characterized by the noticeable emergence of new fractures or extension of preexisting ones, leading to the formation of fracture networks, a desirable outcome. Deeper granites, with higher temperature gradients, are more easily subjected to thermal shock, which leads to increased fracture development. This phenomenon enhances to the formation of fracture networks, which is a desired result in well stimulation procedures.

• Both examined granites exhibited comparable behavior in terms of compressive and tensile strengths and displayed analogous incrementing trends regarding the influence of the elevated temperature subjected to LN_2. Nonetheless, their sensitivity to thermally induced fracturing varied. Looking at the damage factor curves, granite 1 depicts higher damaged values compared to granite 2 in both compression and Brazilian tests. Hence, it can be concluded that granite 1 performed better results than granite 2.

• According to the classification of cracks for Brazilian tests, no treatment and 100 ^{o}C + LN_2 experiments belong to Type 1, while 200 ^{o}C + LN_2 and 400 ^{o}C + LN_2 belong to Type 3 classification.

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