

## A CONCEPTUAL MODEL FOR GEOTHERMAL ENERGY INVESTIGATION WITH EMPHASIS ON THE CARIBBEAN

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### **ABSTRACT**

Some of the Caribbean islands have great potential for Geothermal Energy. These islands have been formed partially by the subduction of the Atlantic Crustal plate beneath the Caribbean plate, forming volcanic island chains. The North-Eastern islands are older, extinct volcanoes while the Western arc contains younger more active volcanoes. These give rise to volcanic eruptions resulting in geothermal activity, lending huge potential for geothermal energy.

The only operating geothermal plant in the Caribbean is at Bouillante in Guadeloupe with a 15 MW capacity. The island Governments of Dominica and Nevis have initiated exploration work for geothermal energy. Nevis has a potential of 700 MW and the Government is in the process of setting up a geothermal power plant to develop 24 MW of energy for domestic use as well as to sell to neighboring islands.

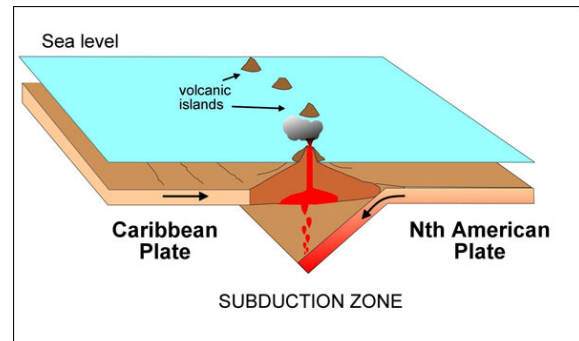
Geophysical surveys, resistivity and seismic, are being investigated to identify fault lines, thus enhancing the possibility of identification of hydrothermal systems. The use of shear-wave splitting (SWS) as a tool for identifying fractured reservoirs is also being investigated. A conceptual model is being developed with the view of better enabling the investigation of hydrothermal systems. This model would be able to describe the fractured density and orientation of the reservoir.

### **INTRODUCTION**

Geothermal energy is present beneath the Earth's surface with the most desirable, high temperature sources being concentrated in regions of active or

geologically young volcanoes. This is the situation with the younger more active Western arc of the

volcanic islands of the Eastern Caribbean chain as shown in Figure 1.



*Figure 1: Interaction of North American and Caribbean plates. (Source: Seismic Research Centre, The University of the West Indies.)*

Developments are being made to exploit these resources in the Caribbean. In particular, exploratory work is being undertaken in the islands of Nevis, Dominica and Saba to develop their geothermal resources for commercial use. This paper focuses on the island of Nevis.

The objective of this paper is to theoretically and mathematically develop a conceptual representation of the fractured zones and the relevant physical processes occurring within them. The geothermal investigations are presented specifically with respect to fluid flow and how it behaves in porous boundaries. Hence the fluid flow and transport processes within the reservoir are conceptually modeled to better understand these hydrothermal

systems thereby making it possible to more easily identify the fracture zones for exploitation of the geothermal energy.

## **THEORY**

Geothermal energy refers to the stored thermal energy in, or heat produced from, the Earth's interior. The geothermal gradient is defined as the rate of increase in temperature per unit depth in the Earth. Although this gradient varies from place to place, it averages 25 to 30°C/km in most regions, but can be several times greater in high-grade geothermal regions. Any fluid produced from a geothermal well is termed a geofluid. Geothermal fluids may be dry or superheated steam, pressurized liquid, or a mixture of liquid and vapor, usually accompanied by dissolved solids and non-condensable gases.

Large quantities of heat that are economically extractable tend to be concentrated in places where hot or even molten rock (magma) exists at relatively shallow depths (<5km) in the Earth's outermost layer (the crust). Such "hot" zones generally are near the boundaries of the dozen or so slabs of rigid rocks (called plates) that form the Earth's lithosphere which is composed of the Earth's crust and the uppermost, solid part of the underlying denser, hotter layer (the mantle).

The high temperatures of these geothermal fluids are enhanced by the friction created as tectonic plates grind against each other, fracturing rocks and thus allowing water to circulate at depth and transport heat toward the Earth's surface. Accordingly, the plate-boundary zones and hot spot regions are prime areas for high-temperature hydrothermal-convection systems.

The existence of a naturally occurring geothermal reservoir, otherwise known as a hydrothermal system, requires three components: heat, fluid and permeability. Most aqueous fluids are derived from surface waters that have percolated into the earth along permeable pathways such as faults. Openings in the rocks are compressed by the weight of the overburden as depth increases, hence the permeability and as a result, the amount of fluid tends to decrease as depth increases.

When extracting geothermal fluids the geological properties of the rocks and, in particular, the rock porosity and permeability, which depend upon the occurrence of pores, fractures, joints, faults, and other openings in the rock, need to be considered. For a

given reservoir temperature, the greater the porosity and permeability of a hydrothermal system, the more efficient its production of available water and thus energy yield will be.

## **ELECTRICITY GENERATION**

Geothermal power plants use superheated fluids from the earth's geothermal sources to generate electricity. The natural heat in the earth which originates from molten rock called magma creates the geothermal resource. The accumulation of rainwater in the earth's surface forms the underground reservoir. When the fluid meets the magma, it becomes a superheated fluid. To reach the superheated fluid (from which the thermal energy is extracted), production wells are drilled 3 to 5 km into the Earth's crust. The relatively high pressure of the superheated fluid naturally propels it from the geothermal resource to the earth's surface where it may be used to generate electricity for homes and businesses. As high pressured geothermal fluid flows towards the surface, the pressure decreases, causing a small portion to 'flash' into steam. This steam is used to drive turbines to generate electricity; all remaining geothermal fluids are injected back into the reservoir for reuse.

## **PLATE TECTONICS & GEOTHERMAL "HOT SPOTS"**

In any geothermal power generation project, whether it a low-or-high enthalpy system, it is very important to understand the geology, structural and tectonic regime of the area, and subsurface characteristics based on surface geophysical methods, as well as geochemical characteristics of the geothermal waters and gases.( Chandrasekharam, D. & Bundschuh, J. 2008).

A map illustrating the "Ring of Fire" is shown below in Figure 2, along which active volcanoes are common and earthquakes occur frequently. Approximately 10,000 MW of commercial geothermal power capacity developed worldwide to date is established almost exclusively within the Ring of Fire. Hence this ring is an area in the Pacific Ocean that is prone to volcanic and earthquake activity. It is also called the "Ring of Geothermal Energy", since numerous high-temperature geothermal systems are associated with active volcanoes. The Caribbean region is part of this ring. The reason for the active volcanism in the Caribbean islands is that they occupy a crustal plate which is

moving eastward along the North and South American Plates whilst at the same time being subducted by the westward moving Atlantic Plate (Huttrer, G.W. 2010).



Figure 2: The Ring of Fire (Source: Sanyal 2010.)

Figure 3 is a map of the Caribbean illustrating areas of subduction and strike-slip faults. These regions are prone to constant tectonic readjustments which results in frequent earthquakes. Shown below is a major subduction line (in blue) which moves 18 mm per year and lies on the Eastern region of the Caribbean archipelago (Lesser Antilles). Other identifiable tectonic regions are oceanic transform fault, oceanic convergent boundary, and oceanic rift illustrated by the green, pink, and red lines respectively.

From Figure 3 an understanding of the complexity of the Caribbean plate can be grasped. It can be described as a geologically complex region that displays a variety of plate boundary interactions.

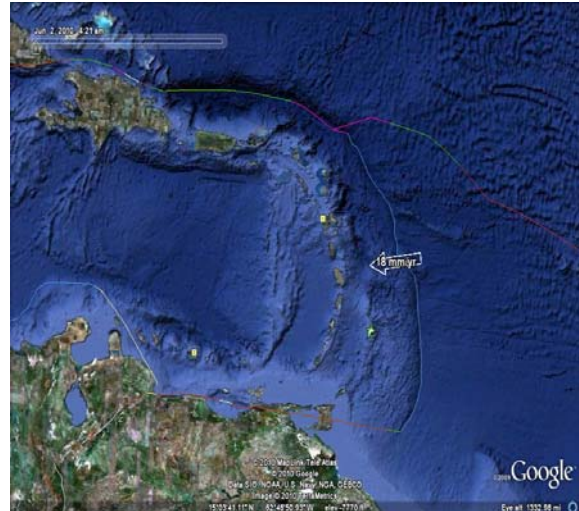


Figure 3: Caribbean Plate Tectonics (Source: Google Earth)

The friction created as a result of constant plate tectonic readjustments causes rock fracturing which allows water to circulate at depth and transport heat toward the Earth's surface. Accordingly, the plate-boundary zones and hot spot regions are prime target areas for the discovery and development of high-temperature hydrothermal-convection systems. In this way, existing and possible geothermal reservoirs of significant size as well as fracture conduits that may be present under the islands are kept open and permeable, thereby conducting meteoric recharge waters from the surface to appreciable depths that are then heated into super-heated temperatures.

### MINERALOGY AND GEOTHERMAL EXPLORATION

The primary source of permeability in crystalline rock is made possible by faults and fractures. Yet in many hydrothermal systems the active precipitation of minerals and chemical alteration, implies that fractures conducting fluids in the subsurface will often seal and permeability will be lost. In contrast, recurrent brittle fractures and frictional failure in low porosity crystalline rocks produce dilation owing to surface roughness along the fracture walls (Brown, 1987) and the formation of breccias and micro-cracks during fault slip (Lockner and Beeler, 2002).

The precipitation of common vein-filling minerals such as quartz or calcite that seals fault and fractures retains the brittle (dilatant) behavior, as demonstrated by crack-seal textures in the layered veins. The frictional strength of the fractures is maintained by

these minerals and also enhances their cohesion. These processes lead to the periodic permeability enhancement associated with reactivation of optimally oriented and critically stressed fractures, which has been shown to be an important mechanism in maintaining high reservoir permeability in some geothermal systems (Hickman *et al.*, 1998; Barton *et al.*, 1998).

On the contrary, dissolution of crystalline rock by hydrothermal fluids reduces the strength of grain contacts and increases porosity in fracture walls (Boitnott, 2002). Furthermore, chemical alteration yields an increase in proportions of clay and other phyllosilicates, which promotes ductile behavior and reduces frictional strength (Lockner and Beeler, 2002) and which also reduces fault permeability (Crawford *et al.*, 2002; Tembe *et al.*, in press). Hence increased ductility of fault rocks that minimizes dilation accompanying slip and the mitigation of fracture regeneration is potentially an outcome of these processes.

In low porosity crystalline rocks where brittle fracture and frictional slip exist, there is dilation owing to surface roughness along fracture walls, brecciation, and micro-cracking. Rapid sealing is evident for fractures that are generated by active precipitation and alteration in geothermal system. The brittle dilatant behavior responsible for permeability generation as revealed by crack-seal textures and brecciated cements are facilitated by precipitated calcite and silica.

Figure 4 is a map of the mineralogy of Nevis. It can be observed that the mineralogy of the island is diverse. The North North West region of the island at Round Hill is concentrated with hornblende-pyroxene and phyrlic dacite. At Hurricane Hill, Cades Bay, Saddle Hill Red Cliff, Butler's Mountain, and Nevis Peak there are pyroxene-phyric dacite, porphyritic dacite, pyroxene-phyric dacite, volcanic breccias, porphyritic and orthopyroxene-phyric dacite respectively (Hutton and Nockolds 1978, Petrology of Nevis). This mineralogy is evident of geothermal resources in Nevis.

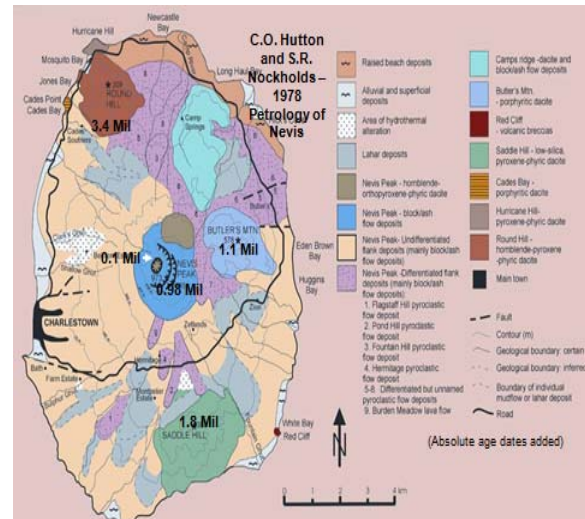


Figure 4: Mineralogy of Nevis (Source: Hutton and Nockolds 1978)

## GEOLOGY OF NEVIS

The island of Nevis is one of particular interest to the Caribbean when it comes to geothermal energy development. Nevis is an ellipsoidal island which is situated at the Northern end of the Lesser Antilles archipelago. The island consists of a single volcanic complex comprised of a series of volcanic domes or centres. The oldest outcropping rock on the island is a conglomerate containing blocks of crystallized limestone that contain fossils of mid-Eocene age (Hutton 1965). The majority of the island is composed of Upper Pliocene to Lower Pleistocene volcanic rocks, dominated by ash and block flow deposits. The volcanic rocks of Nevis are classified according to the composition of silicon oxide concentration that they are comprised of. The three volcanic rocks are dacite, andesite and basalt. Seven volcanic centres have been identified on Nevis: Hurricane Hill, Cades Bay, Saddle Hill, Red Cliff, Butler's Mountain and Nevis Peak (Hutton 1965; Hutton and Nockolds 1978).





Figure 5. This represents a simple illustration of the locations of the seven volcanic centres along the NW to SE of the island of Nevis.

The main volcanic centre on the island is Nevis peak. It is a single volcanic complex, comprising of a series of other volcanic centres and domes. This is the only potentially active centre, as it is a Peleen type volcano- andesite to dacite (58-65wt%; Hutton and Nockolds 1978). The formation of Nevis peak is due to effusive eruptions of lava that also produced the numerous other nested lava domes which form the bulk of the main cone.

There exists a 1000 m-wide, semi-circular depression that is open to the west and northwest, of the northwestern quadrant of Nevis Peak. This was referred to as a breached crater by previous researchers (Martin-Kaye 1959; Hutton and Nockolds 1978). The cause of this depression is unclear; however, its formation is credited to the collapse of the northwestern summit of the volcano during dome collapse events.

Violent eruptions at these centres have displayed remnants of lava domes. Saddle Hill and Butler's Mountain have radiometric ages of 1.80 and 1.10Ma respectively, and are therefore somewhat younger. The Nevis peak volcanic centre is believed to be the youngest on the island, based on its youthful appearance and an age estimate of 0.98 – 0.10 Ma (Hutton and Nockolds 1978; Geothermica Italiana 1991).

Table 1: The relative ages of the seven volcanic centres on the island of Nevis.

Volcanic Centres	Relative ages/ Ma
Hurricane Hill	$3.43 \pm 0.17$
Cades Bay	$3.22 \pm 0.16$
Round Hill	$2.70 \pm 0.50$
Saddle Hill	$1.80 \pm 0.30$
Butler's Mountain	$1.10 \pm 0.16$
Nevis Peak	$0.98 \pm 0.10$
Red Cliff	$\approx 1.00$

## GEOTHERMAL ACTIVITY IN NEVIS

Large areas of pervasively hydrothermally altered rock present throughout the island (e.g. Clarks Ghut) are interpreted as areas of past/extinct fumarolic activity. Presently geothermal activity is heavily concentrated on the Western half of the island of Nevis. In the nineteen fifties the two areas of main interest in Nevis were Cades bay Soufriere and Farm estate Soufriere.

Cades bay Soufriere is an area of warm, hydrothermally altered ground approximately 900 square metres. Soil temperatures of up to 100°C were reported for these early stages (Robson and Willmore 1955). As a result of the response to local readjustments in the groundwater system brought about by severe earthquakes between 1950 and 1951, it is likely to have formed Cades bay Soufriere. Farm estate Soufriere on the other hand, is also a hydrothermally altered ground (part of the Sulphur Ghut stream valley). Temperatures of up to 100°C were also obtained from within small crevices at Farm estate Soufriere when visited by Robson and Willmore in 1953.

### 1.0 Fractured Reservoirs

A natural geological system can be described as highly complex when the geological structure and physical processes occurring within them are considered. For investigation into such a system, it is vital to understand the natural processes, and the interactions with geological structures. The system structure and the processes occurring within it are therefore represented by conceptual models, designed to meet the requirements of certain types of problems on a given scale Dietrich, P et al. 2005

The level of complexity is inversely related to the level of simplicity when moving from a natural system to a numerical model that describes this system. Specifically a conceptual model is satisfied by the following three areas:

- Conceptual representation of the structure.
- Selection of relevant physical processes
- Conceptual representation of the physical processes.

It is essential to note when model results are being interpreted, that model is merely an approximation of nature.

A hydrothermal system or reservoir can be considered as one in which the rock matrix is highly fractured, to facilitate the ease of fluid flow throughout the system. Fractured porous rock is generally divided into three components, these include: (1) a fractured network - a system of partially intersecting single fractures. Its hydraulic properties are typically characterized by the distribution of fracture size, permeability, orientation, distance and density, (2) fractured filled networks - filling material consisting of mineral deposits can be found at these fractures, and (3) the matrix blocks between the fractures – these have a spatially varying texture and porosity. The permeability contrast between fractures and matrix is important for the flow and transport processes.

It is not possible to generate a model that is an exact representation of reality; however, conceptual models are developed to describe the relevant structures and physical processes of a problem. The choice of a model concept for the description of fractured media strongly depends on the scale of the problem, the geological characteristics of the area of investigation, and the purpose of the simulation.

It is a necessity to have different model concepts of varying characteristics, in order to generate models of systems. According to Helmig (1993), two principal approaches are possible:

1. Provided that the scale of the investigation area is sufficiently large and that the concept of representative elementary volume (REV) is valid the model can then be described as a heterogeneous, anisotropic continuum.
2. If shear zones dominate the flow and transport processes in the fractured media, the rock matrix can be neglected and the features specifically described, using a discrete fracture network model. (Dietrich P. et al., 2005)

The size of a potential REV is linked to the reliability of hydraulic properties of fractured reservoirs (Bear, 1972; De Marsily, 1986), and is fundamental to the

mathematical description of fluid flow and transport in porous media. It is the smallest volume over which a measurement can be made yielding a value representative of the whole (Blocher, M. G. 2010).

1.1 Mathematical considerations of fluid flow

The main concepts of the stress and strain tensor are fundamental in approaching more useful forms of the Navier-Stokes equation, continuity equation, parallel plate concepts of fractured systems, and Darcy’s law. The fluids under discussion can be assumed to have no internal forces between the fluid particles, therefore for these inviscid fluids, the equation of motion is given by Euler’s equation

$$\bar{F} - \frac{1}{\rho} \nabla p = \frac{\delta \bar{q}}{\delta t} \dots \dots \dots (1)$$

where the external force  $\bar{F}$ , the density, pressure and rate of fluid flow are represented by  $\rho$ ,  $p$ , and  $\frac{\delta \bar{q}}{\delta t}$  respectively. The associated fluids are known as Newtonian or viscous fluids. A further property of these inviscid fluids is the stress tensor  $\bar{\tau}$ , sometimes referred to as the traction or Cauchy stress tensor.

A general case where S can be any surface with unit normal,  $\hat{n} = n_1 \hat{i} + n_2 \hat{j} + n_3 \hat{k}$ , ( $n_1, n_2$ , and  $n_3$  are the direction cosines of  $\hat{n}$ ) can be considered. The traction can be represented by

$$\bar{\tau}^{(n)} = \bar{\tau}^{(1)} n_1 + \bar{\tau}^{(2)} n_2 + \bar{\tau}^{(3)} n_3 \dots (2)$$

Hence the traction  $\bar{\tau}^{(n)}$  on any surface with unit normal  $\hat{n}$  can be expressed as a linear combination of the three basic tractions  $\bar{\tau}^{(1)}, \bar{\tau}^{(2)}$ , and  $\bar{\tau}^{(3)}$ . In addition by considering an infinitesimal part of a fluid as a cuboid the stress components can be observed:

$$\tau_{11}, \tau_{12}, \tau_{13}, \tau_{21}, \tau_{22}, \tau_{23}, \tau_{31}, \tau_{32}, \tau_{33};$$

where  $\bar{\tau}$  is a second order tensor as shown below

$$\bar{\tau} = \begin{pmatrix} \tau_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \tau_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \tau_{33} \end{pmatrix}$$

If  $i = j$  then  $\tau_{ij}$  is called the normal component of the stress tensor i.e.  $\tau_{11}, \tau_{22}, \tau_{33}$ , when  $i \neq j$  then  $\tau_{ij}$  is called the shear stress component of the stress tensor i.e.  $\tau_{12}$ .

Furthermore, a useful form of Euler’s equation is shown below:

$$\bar{F} + \frac{1}{\rho} \nabla \cdot \bar{\tau} = \frac{\delta \bar{q}}{\delta t} \dots \dots \dots (3)$$

$$\text{Using, } \nabla \cdot \bar{\tau} = \nabla \cdot \bar{\tau}^{(1)} \hat{i} + \nabla \cdot \bar{\tau}^{(2)} \hat{j} + \nabla \cdot \bar{\tau}^{(3)} \hat{k}$$

$$\text{and, } \nabla \cdot \bar{\tau} = \tau_{ij,j} \hat{i},$$

equation (2) can be written as

$$\bar{F}_i + \frac{1}{\rho} \tau_{ij,j} = \frac{\delta q_i}{\delta t} \dots \dots \dots (4)$$

1.2 Strain Tensor

The strain tensor, otherwise known as the Rate of Deformation tensor, is established when the stress

forces have the effect of deforming a volume of fluid. A measure of this deformation is given by the *deformation tensor D*.

$$\text{It is defined by } \bar{D} = D_{ij} = \frac{1}{2} (q_{i,j} + q_{j,i}) \dots (5)$$

Here it is observed that  $\bar{D}$  is a second order symmetric tensor which is dependent on the fluid velocity gradients of the fluid.

Let  $\bar{q} = u\bar{i} + v\bar{j} + w\bar{k}$  then

$$\begin{aligned} D_{kk} &= D_{11} + D_{22} + D_{33} \\ &= \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \nabla \cdot \bar{q} \\ &= \epsilon_r \bar{D} = \nabla \cdot \bar{q} \dots \dots \dots (6) \end{aligned}$$

The trace of  $\bar{D}$ ,  $\epsilon_r \bar{D}$ , is the summation of all the elements of  $D_{ij}$  along the leading diagonal of a matrix containing all the elements of  $D_{ij}$ .

A particular medium is characterized by the *constitutive equation*, which is the relationship between stress  $\bar{\tau}$  and strain  $\bar{D}$ . This stress-strain relationship is given by:

$$\bar{\tau} + p\bar{I} = f(\bar{D}) \dots \dots \dots (7)$$

When this relationship is linear, the fluid is said to be viscous, classical and Newtonian, and is shown by

$$\bar{\tau} + p\bar{I} = \bar{A} + \bar{B}\bar{D} \dots \dots \dots (8)$$

where A and B are constants (tensors), and  $\bar{I}$  is the identity matrix.

By further analysis of the equation and using the facts that both  $\bar{\tau}$  and  $\bar{D}$  are symmetric, and that the frame-indifference principle, (the constitutive equation does not depend on the orientation of the frame of reference), the eventual field equation, known as *Navier-Stokes equation*, is obtained as stated below.

$$\bar{F} + \frac{\mu}{\rho} \nabla^2 \bar{q} - \frac{1}{\rho} \nabla p = \frac{\partial \bar{q}}{\partial t} \dots \dots \dots (9)$$

where the viscous coefficient is represented by  $\mu$ . This equation is very useful when investigating fluid flows, since it is solved together with the continuity equation for incompressible flow, i.e.

$$\nabla \cdot \bar{q} = 0 \dots \dots \dots (10)$$

### 1.3 Special case: Parallel Plate Concept

The rock matrix bounds naturally occurring fractures on all sides. An identical profile does not exist for the fracture walls, hence the normal tension is carried by contact zones between the walls. A frequently used model for fracture representation is the parallel plate concept.

Tsang and Tsang 1987 showed that preferential flow paths exist, hence channeling effects may have significant influence on the flow and therefore also on the transport processes.

For the application of the parallel plate concept it is assumed that the length scale,  $l$ , of the plates is much larger than the distance between them  $b$  ( $l \gg b$ ). Furthermore, hydraulically smooth walls and laminar

flow are assumed, corresponding to the *POISEUILLE fluid model* (Wollrath, 1990).

Between the parallel plates the velocity profile has a parabolic shape, indicating laminar flow. The upper and lower plates have values of  $Z = +H$ , and  $Z = -H$ , respectively, whilst the vertical distance between, the plates,  $b$ , can be considered to have a value of  $b = 2H$ .

The NAVIER-STOKES equation (NSE) for the laminar single-phase flow of an incompressible Newtonian fluid yields the following equation for the velocity profile between two parallel plates (Snow 1969; White 1999).

$$v(z) = \frac{\rho g}{2\mu} \left[ -\frac{\delta}{\delta x} \left( \frac{p}{\rho g} + z \right) \right] (H^2 - z^2) \dots (11)$$

where  $g$ , is the acceleration due to gravity. The mean three-dimensional velocity  $\bar{v}$  can be determined by stating that the maximum velocity  $v_{max}$ , is reached at  $z = 0$ , and for parabolic shaped profiles, the mean velocity  $\bar{v}$  is given as  $\bar{v} = \frac{2}{3} v_{max}$ . (Dietrich P *et al.*, 2005) therefore,

$$\bar{v}_i = -\frac{b^2 \rho g \delta h}{12 \mu \delta x_i} = -K \frac{\delta h}{\delta x_i} \dots \dots \dots (12)$$

It can then be seen that the hydraulic conductivity  $K$ , and the permeability  $k$ , have the following relationship:

$$K = k \frac{\rho g}{\mu} \dots \dots \dots (13)$$

$$\text{and } k = \frac{b^2}{12} \dots \dots \dots (14)$$

Now the flow field can be determined by assuming there is steady flow between the parallel plates and no external forces act on the plates. We can now introduce Cartesian co-ordinate system, where the plates can be taken to be  $Z = -H$  and  $Z = +H$ . Allow the lower plate to be fixed while the upper plate moves with a velocity  $v_i$ .

Hence we need to solve the NSE and the Continuity equation, respectively. These are given by:

$$\bar{F} - \frac{1}{\rho} \nabla p + v \nabla^2 \bar{q} = \frac{\partial \bar{q}}{\partial t} \dots \dots \dots (15)$$

$$\nabla \cdot \bar{q} = 0 \dots \dots \dots (16)$$

$$\text{where the kinematic velocity } v = \frac{b}{\rho} \dots (17)$$

Equations (14) & (15) simplify to

$$-\frac{1}{\rho} \nabla p + v \nabla^2 \bar{q} = \bar{q} \cdot \nabla \bar{q} \dots \dots \dots (18)$$

$$\nabla \cdot \bar{q} = 0 \dots \dots \dots (19)$$

The above equation are then subjected to the following boundary conditions

$$q = 0 \text{ at } Z = -H$$

$$q = u\bar{i} \text{ at } Z = +H$$

where  $\bar{q} = u\bar{i} + v\bar{j} + w\bar{k}$  is the velocity field of the fluid at any point  $P(x, y, z)$  in the flow field.

It is then assumed that

$$\bar{q}(P) = u(z)\bar{i} \dots \dots \dots (20)$$

Where  $u$  is a function of  $z$ .  
 Substituting (19) into (18) yields  
 $\frac{\partial u}{\partial z} = 0$ , since  $u = u(z)$

From further simplification it is shown that

$$u = \left(\frac{U}{H} + \frac{P_0 H}{2\mu}\right)z - \frac{P_0 z^2}{2\mu} \dots \dots \dots (21)$$

where  $P_0$  is a constant, from (20) it is seen that the velocity profile is parabolic.

The stress field is finally determined from the following:

$$\tau_{ij} = -p\delta_{ij} + 2\mu D_{ij} \dots \dots \dots (22)$$

$$\tau_{ij} = -p\delta_{ij} + \mu(q_{i,j} + q_{j,i}) \dots \dots \dots (23)$$

Solutions show that  $\tau_{11} = \tau_{22} = \tau_{33} = -p$ .

The only other two non-zero components are

$$\tau_{13} = \tau_{31} = \mu \left[ \frac{U}{H} + \frac{P_0 H}{2\mu} - \frac{P_0 z}{\mu} \right] \dots \dots \dots (24)$$

Hence the stress on the plates is:

For the lower plate  $Z = -H$ . Hence

$$\begin{aligned} \tau_{13} &= \mu \left[ \frac{U}{H} + \frac{P_0 H}{2\mu} + \frac{P_0 H}{2\mu} \right] \\ &= \mu \left[ \frac{U}{H} + \frac{3P_0 H}{2\mu} \right] = \tau_{31} \dots (25) \end{aligned}$$

For the upper plate  $Z = +H$ , yielding

$$\begin{aligned} \tau_{13} &= \mu \left[ \frac{U}{H} + \frac{P_0 H}{2\mu} - \frac{P_0 H}{\mu} \right] \\ &= \mu \left[ \frac{U}{H} - \frac{P_0 H}{2\mu} \right] = \tau_{31} \dots \dots \dots (26) \end{aligned}$$

## 2.0 Representation of the Physical Geometry

A conceptual model can be used to simplify the understanding and prediction of physical processes occurring in a complex fractured geological system. With the use of COMSOL Multiphysics software, it provides solutions for multiphysics modeling. A clear representation of the geometry and conceptualized models of the different processes within the fractured system can be achieved using COMSOL Multiphysics 4.0.

The model represented in this paper is the discrete fracture model. Fluids travel through tiny pores within the rock matrix and the fracture; furthermore, fluid exchange can occur between them. Hence with this method the fractures are represented as boundaries between adjacent matrix blocks, and are considered as an interior boundary. This model takes into account that the fractures may not be perfectly parallel to each other, hence some vertical variation or inclination is possible for the path of the fracture. A representation of such a fracture is shown below.

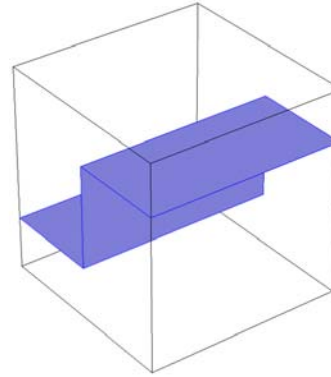


Figure [6] : Geometry of a discrete fracture represented by COMSOL Multiphysics 4.0

### 2.1 Model Definition, coefficients and parameters

The block of porous material illustrated by Figure 7[b] can be considered to have a 1m measurement on each side. The fracture thickness has a standard value of 0.1mm, with the fracture being more permeable than the matrix block. Ideally the walls of the block are impermeable except for the fracture edges, hence the fluid flows along the fracture path with minimum to no leakage to the matrix block. Darcy's law governs velocities in the system from which the velocity paths (arrow heads) can be shown to be ideally perpendicular to the fluid field.

Coefficient and parameters include: porosity of the matrix block  $\epsilon$ , compressibility of the fluid  $X_f$ , and of the solid  $X_p$ , permeability of the matrix block  $k$ , thickness  $d_f$ , storage coefficient  $S_f$  and permeability of the fracture  $k_f$ , viscosity  $\mu$ , fluid density  $\rho$ , inlet  $P_{inlet}$  and outlet  $P_{outlet}$ , pressures.

Within the matrix block the fluid flow is described time-dependently (simulation period), through Darcy's law as shown below:

$$\rho S \frac{\delta p}{\delta t} - \nabla \cdot \left( \rho \frac{k}{\mu} \nabla p \right) = 0 \dots \dots (27)$$

where the linearized storage model

$$S = \epsilon X_f + (1 - \epsilon) X_p \dots \dots \dots (28)$$

In the matrix block, the predefined velocity variable,  $u_{dl}$ , gives the Darcy velocity, which can be described as the volume flow rate per unit area of the porous material:

$$u = -\frac{k_{ij}}{\mu} \frac{\delta p}{\delta x_{ij}} \dots \dots \dots (29)$$

Parallel to all faces of the block the zero flow boundary is applied where

$$n \cdot u = 0$$

The outward-pointing normal to the boundary is given as  $n$ , hence this means no flow across the boundary. (COMSOL Multiphysics 4.0 Model library)



The fluid flow within the fracture is then observed as a model in which it is a sequence of interior boundaries. The velocity in the fracture is modified to that within the matrix block. This is achieved by altering the equation coefficient of the time-dependent fluid flow Darcy's law, to account for the relatively small resistance to flow on the fracture. (COMSOL Multiphysics 4.0 Model library)

Hence equations (27) and (29) becomes

$$\rho S_f d_f \frac{\delta p}{\delta t} - \nabla_T \cdot \left( \rho \frac{k_f}{\mu} d_f \nabla_T p \right) = 0$$

$$u = -\frac{k}{\mu} d_f \nabla_T p$$

where  $\nabla_T$  denotes the gradient operator restricted to the fracture's tangential plane,  $S_f$  is the fracture-storage coefficient,  $k_f$  is the fractures permeability and  $d_f$  is the fracture's thickness.

### 2.2 Model representation using COMSOL 4.0

The conductive heat flow of the fluid can be represented by Figure 7[a], where at the inlet of the fracture there exists high pressure and temperature shown in red, and at the outlet there exist a lower pressure and temperature illustrated in blue.

In Figure 7[b] the fracture is represented by four parallel slabs along the y-z axes. Furthermore, it shows discrete vertical decrease in temperature as the fluid travels from the inlet to outlet of the fracture. This decrease in temperature does not significantly affect the overall fluid temperature. It does assist to illustrate thermal distribution vertically across the parallel slabs.

Figures 7[c] and 7[d] illustrate isosurfaces which show the contours of fluid pressure throughout the rock matrix. As mentioned before, Darcy's law governs velocities in the block. The fluid moves from the inlet to the outlet along the fracture with a velocity field that is uniform across the block.

Figure 7[d] in particular illustrates the velocity field of the fluid at an instantaneous point along the path that is perpendicular to the isosurfaces. The contour lines follow the fluid flow and are highly dense at the inlet and outlet of the discrete fracture, in addition, illustrating the parabolic shaped velocity field.

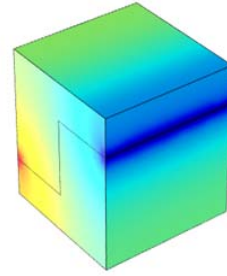


Figure 7[a]: The conductive heat flow of the fluid throughout the rock matrix.

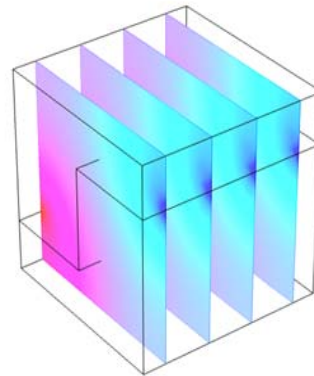


Figure 7[b]: Parallel slabs along the y-z axes across the rock fracture.

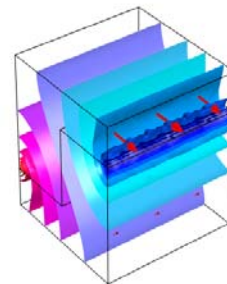


Figure 7[c]: The isosurfaces with contours of fluid pressure.

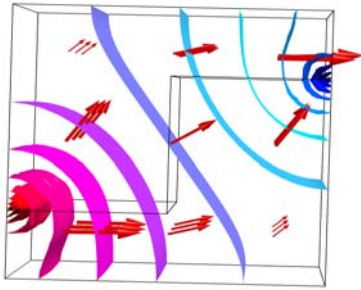


Figure 7[d] Illustrates the velocity field of the fluid flow.

Through the use of COMSOL Multiphysics 4.0 a rational understanding and appreciation of the fractured system is achieved. Furthermore, by performing the necessary field and experimental studies to determine the required model parameters as list in 2.1, multiple simplistic models of the research areas can be developed. As Darcy's velocity can be determined and modeled to illustrate highly prospective regions for fluid flow with the reservoir. The most efficient site location for drilling aspects and further geophysical surveys will then be identified through this manner.

### LIMITATIONS

A key assumption made into the investigation of the fluid flow along the geometry shown by Figure [1], was laminar flow through the discrete fracture path. However, turbulent flow was not considered in particular at the junctions from the horizontal to vertical fractured plates. Furthermore, COMSOL Multiphysics 4.0a did not take into account a temperature component as this can generate significant knowledge into the thermal distribution of heat transfer along the fracture path.

### CONCLUSION

Many uncertainties about future energy supplies in the world are being faced presently. Most of the energy currently used comes from fossil-fuel resources such as coal, oil and gas. The characterization of a fractured rock system is one of the most challenging problems faced by hydrogeologists. The prediction of hydraulic behavior of fractured porous geological systems is determinant upon the assessment of fractures as barriers or hydraulic conductors. Furthermore, mathematical models are critical for detailed

understanding and to determine fluid flow behavior. Therefore, as a result of this conceptual model an understanding of the geometry and mathematical flow processes occurring within the fractured reservoir is attained. This fundamental step is crucial, for more advanced approaches towards fully describing an understanding the complex nature of the system. Hence through field and laboratory studies on the mineralogy of research areas on Nevis, this conceptual model can be developed to fully generate a mathematical and numerical model. Due to the diverse nature of the rock mineralogy of Nevis, specific models can be produced to represent the characteristic of that individual location. Future work into the fluid flow and its characteristics can be investigated to further enhance this model to fully develop a better understanding of the flow with the fracture path.

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