A methodology for geomechanical modelling of in situ recovery (ISR) in fractured hard rocks

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Abstract

The extraction of geothermal energy, in situ minerals, liquid and gas hydrocarbons, and subsurface water are all constrained by the flow of fluid through fractured media in the earth's crust, as is the viability of projects involving CO_2 sequestration, nuclear and hazardous waste storage, hydrocarbon storage, and subsurface cavities. Subsurface fractures are the main fluid pathways as the matrix permeability is negligible in most rocks. In situ recovery (ISR) or in situ leaching (ISL), particularly in hard rock, poses some challenges currently. One of the main problems is the modelling of fluid flow in fractured rock masses, and this was the primary focus of this project. Modelling fluid flow in fractures can be done in many ways. The modelling showed that ISL in hard rock demonstrates potential. However, the modelling also exhibited the need for advancements in the fluid flow in fractures modelling area. In this paper comprehensive review of developed approaches for subsurface fracture mapping, processing and characterisation to build a fractured rock mass geometry and fluid flow simulation and mineral leachability along with examples were illustrated.

Keywords: Fracture flow, In situ Leaching (ISL), In situ Recovery (ISR), Discrete Fracture Network

1. Introduction

The extraction of geothermal energy, in situ minerals, liquid and gas hydrocarbons, and subsurface water are all constrained by the flow of fluid through fractured media in the earth's crust, as is the viability of projects involving CO_2 sequestration, nuclear and hazardous waste storage, hydrocarbon storage, and subsurface cavities. Also, fluid flow through fractured media affects the health and stability of the subsurface environment, and the populations that live above. Subsurface fractures are the central fluid pathways as the matrix permeability is negligible in most rocks. So, the presence and nature of subsurface fractures play a fundamental role in many human activities.

Mining in future will be more challenging, because of declining ore grades associated with deeper mining and finely disseminated target minerals in heterogeneous ore bodies, as well as complex mineral association with gangue material, often in locations that are difficult or risky to access. In many areas, ore grades declined by almost 50% over the last 30 years, making mineral processing mostly uneconomical for such minerals. Under these circumstances, innovation in in situ recovery could be a suitable alternative to unlocking resources. The idea of in situ recovery first started with solution mining to extract salt, potash or other minerals as shown in Figure 1(a). It was subsequently developed for recovery from porous media such as sedimentary soil and rock or heavily jointed rock masses as illustrated in Figure 1(b). In situ recovery from porous media has become well established during the last few decades, owing to the presence of void spaces and their connectivity, which facilitate fluid flow from injection wells to recovery wells. In situ recovery of target metals from hard rock is challenging, due to a lack of knowledge about fracture conditions, their connectivity and consequently rock mass conductivity and target metal recoverability, as shown in Figure 1(c).

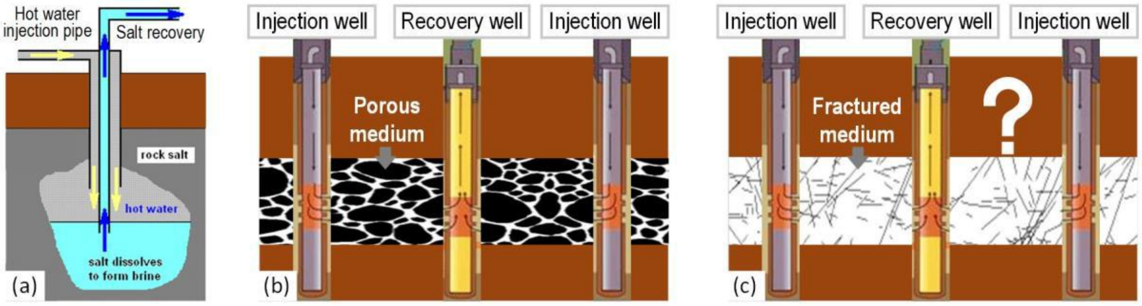


Figure 1. In situ recovery trend from (a) solution mining in the past, (b) porous medium leaching in the present, and (c) future recovery from hard and fractured rocks.

In situ leach mining can be applied to different metal deposits such as copper, uranium and gold deposits. However, existing application of in situ leach mining is mainly limited to soft rock uranium deposits and some copper deposits mainly in the USA (Dershowitz, 2011). Moreover, there have been recent advances regarding the in situ recovery of gold and copper deposits which further outline the potential of in situ leach mining in hard rock. Martens et al. (2018) combine the electro kinetics (EK) and ISR method. It shows the possibility of electro-kinetics application, electrodes, and low voltage current in low permeability media (intact rock). Zammit et al. (2014) mention that ISR method is increasingly used globally, it could be more economic benefit as it can be combined with microorganism involvement.

In the current mining climate, some metal deposits cannot be mined economically using conventional mining methods, but can be mined economically using in situ leach mining. For example, in Australia, most of the uranium deposits can only be mined economically using in situ leach mining (Mudd, 1998). It is therefore essential that the use of in situ leach mining is increased with higher efficiency and less environmental impacts. Some of the deposits occur in hard rock or non- permeable deposits which require fracturing. In this paper, several individual models will be combined to generate a logical processing model to guide the pre-production analysis of in situ leaching mining. The procedure for discrete fracture network modelling contains the following steps;

- Characterisation of fractured subsurface rock mass and its hydraulic conductivity
- Evaluation of rock fracture networks
- Generation of fracture network models
- Determination of whether fracture networks are adequate for mining production - if not, fracture conductivity enhancement is required
- Once the fracture network is acceptable, engineers can start to design injection wells.

The methodology of ISR and advances on each item are illustrated in the following sections.

2. Methodology for in situ recovery through fractured rocks

ISR or ISL mining in hard rock deposits has its challenges, hence it is still not being used. The rock fracturing demanded by ISL mining presents challenges particularly in hard rock ore bodies at a depth where there is no permeability, to begin with, and where pumping solution past the minerals targeted for recovery is problematic. The permeability or hydraulic conductivity of a deposit is essential in hard rock in situ leaching. Whereas, in hard fractured rocks, the fractures are usually closed are tight, resulting in very low hydraulic conductivity, due to micron scale fracture apertures. The issue here is mainly due to the rock mass permeability. If ISL mining is going to be successful, there has to be sufficient permeability or hydraulic conductivity in the ore body. For this purpose, the fracture condition of the rock and its potential permeability need to be assessed. If the permeability is low, enhanced fracturing of the rock would be required, to act as a pathway for the leaching solution recovering the desired mineral. Also, fluid flow through the fractures would have to be simulated to estimate the suitability of ISL in the rock mass.

The methodology for in situ recovery in fractured rocks is illustrated in Figure 2. To achieve the in situ recovery goals, innovative exploration data characterisation and analytical tools are required. Figure 2 schematically shows the overall methodology and detailed techniques that need to be employed in in situ recovery projects. The first step is exploration, data collection, analysis and interpretation. Second, the rock mass permeability and recoverability need to be determined. Third, representative laboratory and field tests and modelling are done, and in the final step, test results need to be scaled up and modelled, considering various potential scenarios of ISR.

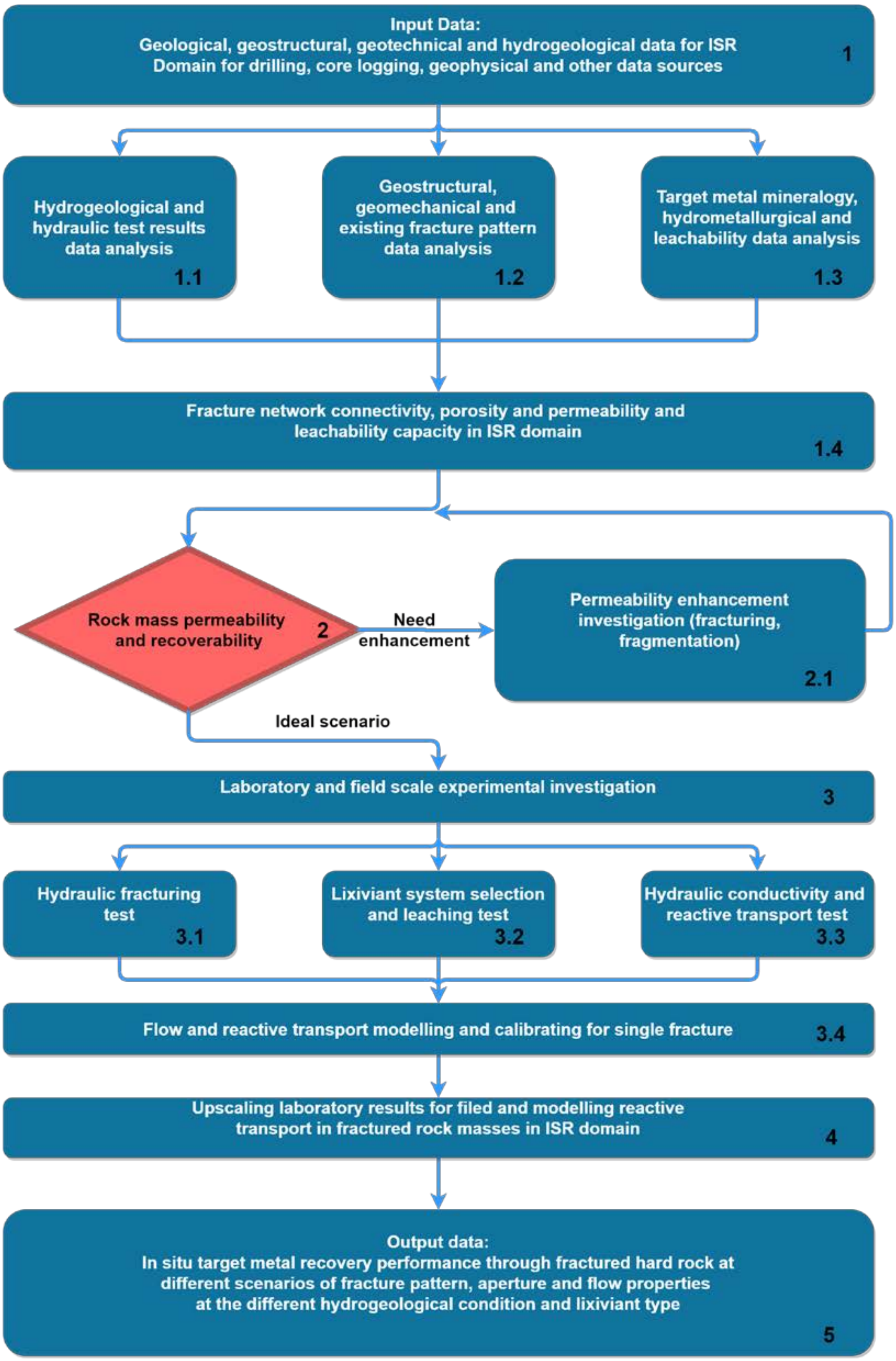


Figure 2. A methodology for in situ recovery (ISR) investigation through fractured hard fractured rocks in metalliferous deposits.

3. Subsurface fracture characterisation

3.1 Subsurface fracture data collection

Fractures are main fluid pathways in deep underground rock mass. To achieve satisfactory in situ recovery, a reasonable number of connected fractures in the ore body is desired. However, neighbouring rock must be impermeable to prevent the escape of deleterious fluids into the environment. Therefore realistic subsurface fracture characterisation plays a crucial role in ISR performance. Subsurface fracture detection, mapping, or predicting the occurrence and origin of the fractures is the most fundamental step in evaluating fracture networks and fluid flow modelling in many applications (Nelson, 2001). Previous work has primarily focused on employing fracture characterisation methods using traditional direct and indirect mapping methods, such as (a) outcrop imaging and mapping, and core logging using line (one-dimensional) surveying or aerial (two-dimensional) mapping with a limited number of measured parameters (Zhang and Einstein, 1998, Zeeb et al., 2013) (b) well and borehole logs and images, which also give limited information about the subsurface fracture characteristics (Rohrbaugh et al., 2002), and (c) geophysical approaches such as seismic, magnetic and gravity, which give spatial distributions of major structures only (Mauldon et al., 1999). There are many reported cases of failure in well recovery, due to the direct application of measured fracture characteristics. Proper interpretation of measured data against global mineralogical, lithological and tectonic information and fractures could yield better insight into positive or negative impacts on fluid flow.

The procedure for fracture data collection is shown in Figure 3. Considering that the ore body is laid in depth and covered by the sequence of geological formations over the target mineral, therefore direct exposure mapping from the surface could not represent the rock mass condition in depth. To overcome these difficulties, subsurface mapping methods such as well logging, core logging and geophysical investigation methods are needed. These mappings could be conceptualised by combining field geological, mineralogical, lithological, structural conditions, such as rock origin, as well as cooling, faulting and folding regimes and fracture origin. New methods in fracture mapping using aeromagnetic field maps could facilitate the fracture correlation along with other collected data. Additionally, the seismic and gravity maps could also be investigated to obtain further fracture properties at different scales. Laboratory tests on specimens, such as uniaxial and true three-axial tests along with acoustic emission monitoring and testing will support the crack initiation, propagation, and fracturing patterns in a larger scale. All collected data integrated into a database and sophisticated approaches must be considered to check for possible bias.

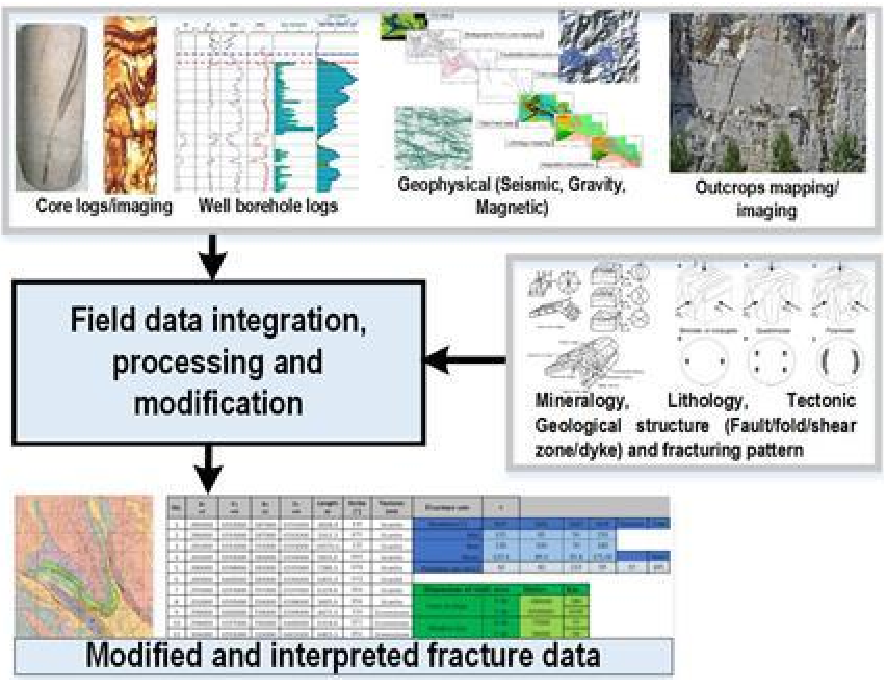


Figure 3. Procedure for data collection and processing.

3.2 Subsurface fracture data analysis

After extracting the most reliable fracture data from the previous step, the individual fractures and the fracture characteristics such as orientation, shape, size, length (persistence), aperture, number of sets, density, intensity, block size, shape and volume, as depicted in Figure 5, can be analysed. At present, fracture characterisation has not been widely investigated. Most studies focus on fracture data mapped directly from outcrop mapping (Priest, 1993), core logging, or indirectly from geophysical (magnetic, gravity, seismic) methods (Mauldon et al., 2001). Depending on the fracture mapping method, limited fracture properties are obtained, and many other characteristics such as fracture length, shape, size and pattern remain unmapped or uncertain (Holland et al., 2009). Despite the importance of fractures, a systematic approach to fracture characterisation, including the diligent integration of mapped data with in-depth geological realism, has not been established yet. Understanding the distribution and connectivity of fractures within fractured media has considerable potential to improve fluid flow simulation, based on the availability of reliable input data for modelling.

Most current studies of fracture properties are based on statistical, geostatistical or artificial intelligence methods. It is noteworthy that different rocks under specific fracturing conditions, such as cooling or tectonic forces, show particular modes of fracturing (see Figure 4) and consequently different distribution functions. For example, Fisher's distribution (Kemeny and Post, 2003) is used for fracture orientation; exponential (Sari et al., 2010), lognormal (Gumede and Stacey, 2007), and gamma (Kulatilake et al., 2003) distributions are used for fracture trace length distribution. Similarlym negative exponential and lognormal (Sari et al., 2010) distributions are used for fracture spacing distribution. In this project, the research is aimed at conceptualising and classifying the relationship between rock type, the tectonic regime and the most suitable approach to express fracture properties and their distribution.

Determining the origin of stresses that cause fracturing, as shown in Figure 4, increases the precision of structural interpretation at all scales. Considering their origin and occurrence before analysis of the data from fracture systems could help significantly to remove abnormal (outlier) data or give them a proper weighting in the analysis. This data analysis makes more sense statistically and is consistent with regional stress, and tectonic evidence. The fracture properties (specifically fracture orientation, trace length, and aperture) that govern fluid flow and that are obtained from this step are used as input to module 2 (the geometrical model). Thus, the outcome of this module is significant and several measures from advanced technical and experimental methods, along with engineering experience and judgement, can be used to achieve reliable results.

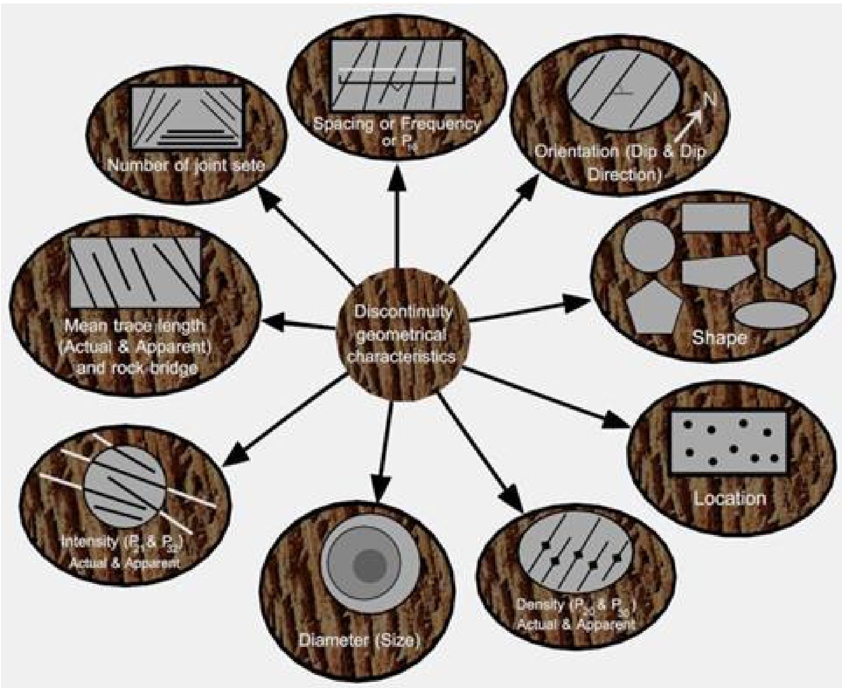
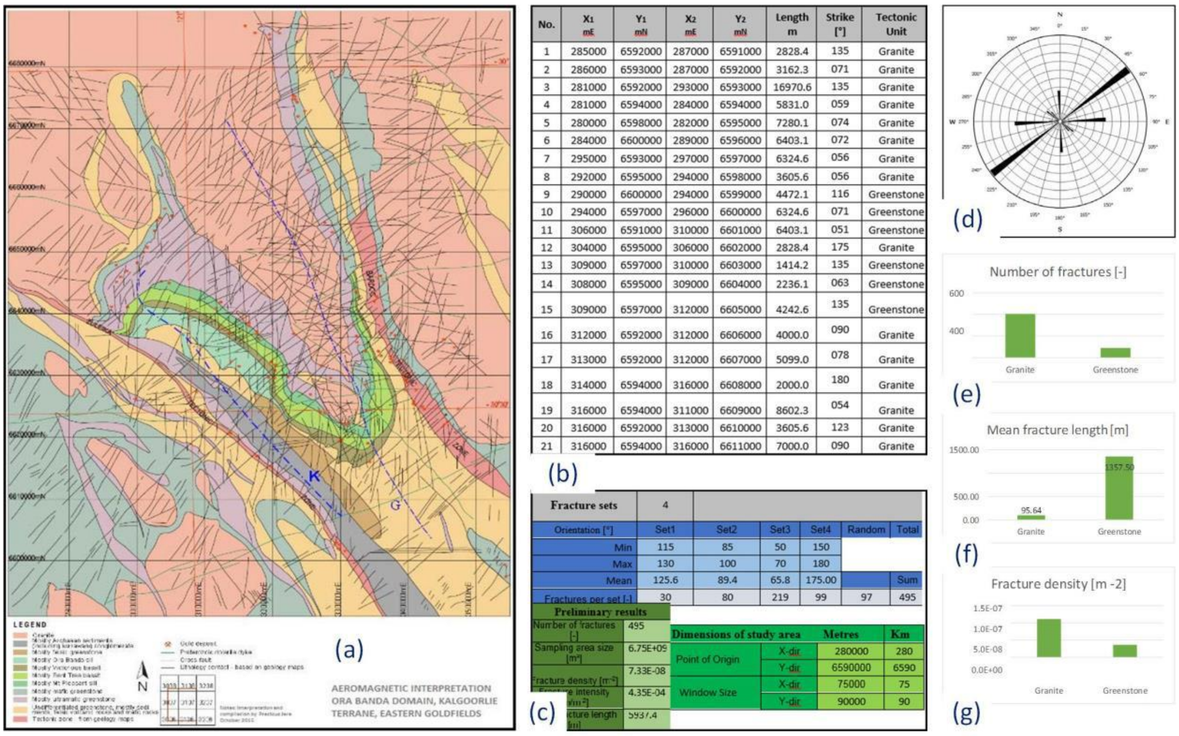


Figure 4. Schematic view of the geometrical properties of fractures (Kamali et al., 2017).

As a case example, The Eastern Goldfield, in the Yilgarn Craton of Western Australia is well known for its economic value and complex geodynamic and structural formation. To further understand these formations, a two-dimensional structural analysis of the Ora Banda region in the Kalgoorlie terrane was conducted. Using an aeromagnetic interpretation map of the structures, spatial and orientation data of 495 stress-induced fractures were collected. The data were statistically analysed, and the fracture distributions among the granite and greenstones were derived. The fracture density, intensity and mean length supported the observation of a distinction between the two tectonic units. The data show that the formations had been subjected to similar late deformations, but behaved differently. It was concluded that the fracture data could be used to predict the foliation or planes of weakness among the specific regions of rock mass within the area of study from observing the surrounding structures. If the brittle fracturing displacement directions of two fractures on either side of a region is known, the foliations between these two fractures can be derived. This displacement can be modelled in a sandbox and is a proven structural geological principle.

To analyse the structural distribution of this region, an interpretive map had to be generated. Information could be extracted and consolidated from a large available data set. This led to the generation of a consolidated structural geology map that was used in the analysis.



No.	X1 mE	Y1 mN	X2 mE	Y2 mN	Length m	Strike [°]	Tectonic Unit
1	285000	6592000	287000	6591000	2828.4	135	Granite
2	286000	6593000	287000	6592000	3162.3	071	Granite
3	281000	6592000	293000	6593000	16970.6	135	Granite
4	281000	6594000	284000	6594000	5831.0	059	Granite
5	280000	6598000	282000	6595000	7280.1	074	Granite
6	284000	6600000	289000	6596000	6403.1	072	Granite
7	295000	6593000	297000	6597000	6324.6	056	Granite
8	292000	6595000	294000	6598000	3605.6	056	Granite
9	290000	6600000	294000	6599000	4472.1	116	Greenstone
10	294000	6597000	296000	6600000	6324.6	071	Greenstone
11	306000	6591000	310000	6601000	6403.1	051	Greenstone
12	304000	6595000	306000	6602000	2828.4	175	Granite
13	309000	6597000	310000	6603000	1414.2	135	Greenstone
14	308000	6595000	309000	6604000	2236.1	063	Greenstone
15	309000	6597000	312000	6605000	4242.6	135	Greenstone
16	312000	6592000	312000	6606000	4000.0	090	Granite
17	313000	6592000	312000	6607000	5099.0	078	Granite
18	314000	6594000	316000	6608000	2000.0	180	Granite
19	316000	6594000	311000	6609000	8602.3	054	Granite
20	316000	6592000	313000	6610000	3605.6	123	Granite
21	316000	6594000	316000	6611000	7000.0	090	Granite

Fracture sets	4					
Orientation [°]	Set1	Set2	Set3	Set4	Random	Total
Min	115	85	50	150		
Max	130	100	70	180		
Mean	125.6	89.4	65.8	175.00		Sum
Fractures per set [-]	30	80	219	99	97	495

Preliminary results	
Number of fractures [-]	495
Sampling area size [m²]	6.75E+09
Fracture density [m⁻²]	7.33E-08
[illegible] intensity [illegible]	4.35E-04
[illegible] length [m]	5937.4

Dimensions of study area		Metres	Km
Point of Origin	X-dir	280000	280
	Y-dir	6590000	6590
Window Size	X-dir	75000	75
	Y-dir	90000	90

Figure 5. Rock mass characterisation from aeromagnetic maps; a) Aeromagnetic interpretation map of the Ora Banda domain, Kalgoorlie terrane, b) Sample data collected from structural analysis 21 of 495, c) rock mass properties achieved from the results, d) Rose diagram of the fracture strike orientation, and e),f),g) are fracture numbers, mean trace length, and density respectively (modified after Jere, 2016).

3.3 Fractured rock mass geometrical model

It is essential to establish a reliable geometrical model of fractured media based on measurements and geological realism, detection of fractures' connectivity and estimation of fluid flow quantities through the integration of measured, tested and acquired data. Several successful approaches have been proposed to model fluid flow using numerical, stochastic and empirical methods (Javadi et al., 2016, Sharifzadeh and Javadi, 2011). Modelling based on discrete fracture networks (DFN) is one of the primary methods for simulating a fracture network (Dershowitz and Lapointe, 1995) in rock mass. Two-dimensional computational code called "FNETF" and attempts towards three-dimensional DFN modelling has recently been initiated (Sharifzadeh and Javadi, 2011, Karimzade et al., 2017). These DFN codes use a Monte Carlo approach to generate two-dimensional DFN realisations based on the statistical parameters of the geometrical properties of fractures. A schematic view of procedures involved in the generation and regularisation of a DFN model is shown in Figure 6. In both models, a fracture network is created in an area called the generation region. Fractures are presented as linear features. Their geometrical properties are defined with respect to their location in the generation region, their orientation relative to coordinate axes and lengths determined by a cumulative probability density function. After generating all fractures, a flow domain is selected for fluid flow analysis that is laid entirely within the generation region. In the next step, the excavation (well, tunnel) boundaries are generated through the flow domain (Figures 6-a-a'). Then, the hydraulically inactive fractures (red fractures in Figures 6-b) are removed from the flow domain, and the "dead-ends" of the interconnected fractures are deleted (Figures 6-c-c'). After regularisation, the flow simulation is applied to evaluate recovery. As shown in Figures 6-b-b', most fractures are hydraulically inactive, and most fluid flows from a small percentage of discontinuities. This constitutes the first stage of the discrete fracture fluid flow modelling. In this stage, both the geometric and network models were developed using realistic fracture properties, such as the fracture length, aperture and number of sets, in multi-scale and in three dimensions, which have not been considered properly to date. DFN models have rarely been validated on the basis of the linear, areal and volumetric intensity of three joint sets surveyed in a tunnel using circular and rectangular window sampling. Likewise, in in situ recovery, fracture network generation code in 3D taking into account most fracture properties, such as realistic fracture length, spacing, number of sets and aperture could be considered.

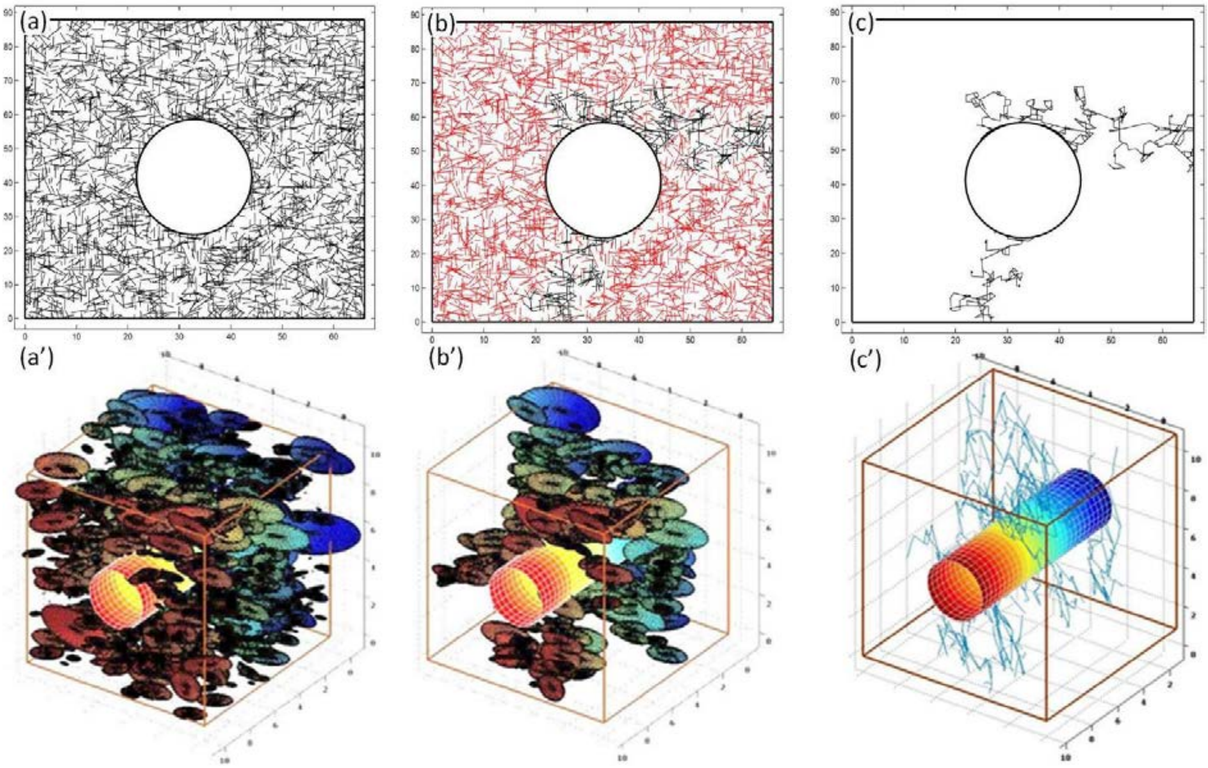


Figure 6. Schematic representation of the generation and regularisation of the DFN model: (a, a') generation region and excavation, (b, b') finding the hydraulically inactive fractures, (c, c') deleting the hydraulically inactive and "dead-ends" fractures (Modified after Sharifzadeh and Javadi, 2011, Karimzade et al., 2017).

4. Fluid flow modelling approaches in fractured rocks

In reality, fluid flow in fracture networks is complicated. Fluid often flows in a small fraction of the fractures only, and most fractures remain hydraulically inactive. Considering the rock mass condition and its proportion to modelling zone scale, different conceptual models have been proposed. Hydraulic modelling approaches are illustrated in Figure 7. According to Figure 7, in small-scale fluid flow simulation, it could be considered both as porous media or single fracture flow. However, large-scale fluid flow simulation depends on the rock mass size to modelling volume size, and both continuum and discontinuum modelling approaches could be applied. The main difference between continuum and discontinuum modelling methods of hydraulic behaviour of fractured rocks is the way that fractures contribute to fluid flow. In continuum methods, the fractured rock mass is treated as an equivalent porous medium characterised by equivalent hydrogeological properties. On the other hand, in discontinuum methods, the rock mass is explicitly represented by individual discrete fractures as a geometrically well-defined hydraulic feature.

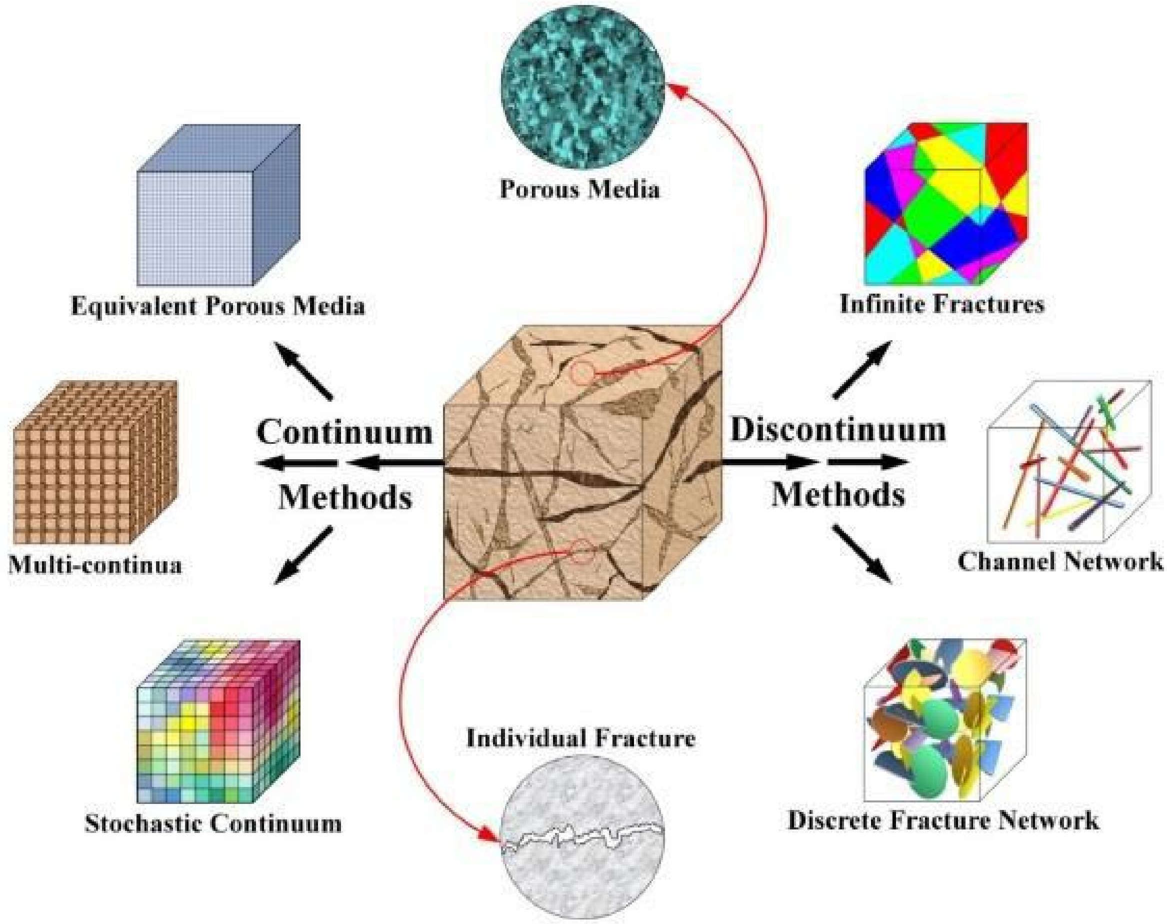


Figure 7. Different hydraulic processes in fractured media with a classification of modelling methods f (Sharifzadeh et al., 2012).

An example of fluid flow simulation in fractured rocks for a mine in Western Australia is presented here. The fracture data for the mine were extracted from borehole data at a depth of 1500m to 2000m. It is also supported with some additional hydrogeological information to run fluid flow simulations. The natural condition was modelled using a discrete fracture network utilised in FracMan® software package (Figure 8). The preliminary model including investigation domain and the location of injection and production wells are illustrated in Figure 8-a. To study the in situ recovery performance, at first, the naturally fractured rock mass was modelled, and fluid flow distribution was then investigated (Figure 8-b). Subsequently the effect of key factors variation such as fracture set orientation, aperture, fracture intensity, fracturing or fracture number increases were simulated (Figure 8-d). Obviously increasing the number of fractures leads to more fracture connectivity and intersection with production walls, thereby enhancing in situ recovery performance. Results show that aperture increases lead to remarkable increases in flow rates, and that injection and production well patterns should be designed based on fracture orientations. In tight rock formations, hydraulic conductivity can be performed to optimise the flow. Furthermore, it is also suggested that the distance between injection and production wells should be based on fracture locations.

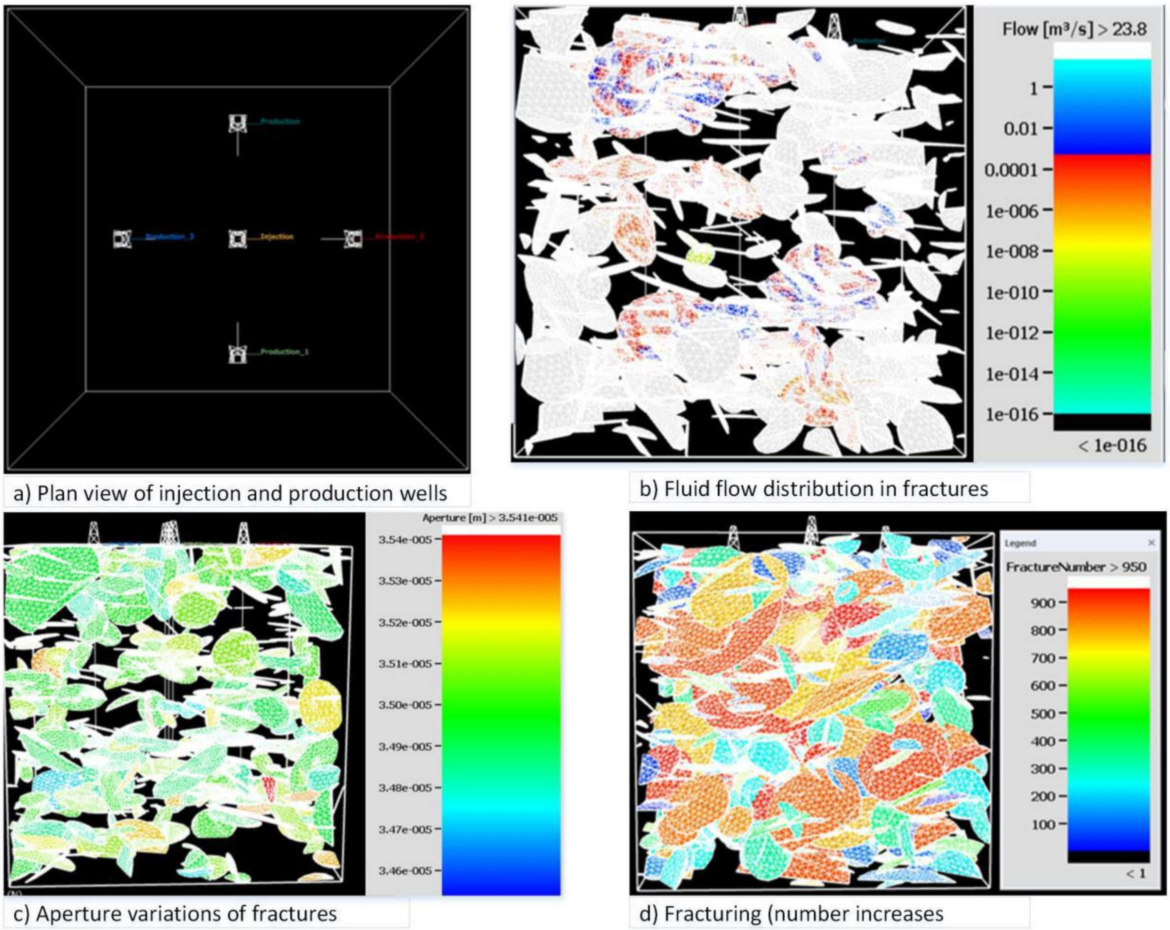


Figure 8. Fluid flow modelling in discrete fracture network to simulate in situ recovery in hard fractured rocks (Modified after Waheed, 2017).

5. Mineralisation pattern and leachability of target mineral

The distribution and style of mineralisation are other key factors, since they have a major impact on leachability. It is undesirable, if the target minerals are completely occluded in an inert rock matrix. It is also undesirable if the rock is highly absorptive. More desirable situations arise when the mineral is located in open pores, fissures and strongly altered rock. Selective leachability of target compounds is another key factor of ISL mining. Leaching of harmful components can prove to be a serious issue in ISR. It is therefore essential that the right lixiviant is selected and calibration of the leaching and acidification is essential for the dynamics involved in leaching and extraction (Seredkin et al., 2016).

6. Conclusion

In situ recovery (ISR) has many advantages over conventional mining. The main ones are that ISR mining results in considerably less surface disturbance than conventional open cut or underground mining methods due to the fact that no open pits, waste dumps and tailings are involved. In terms of ISR in hard rock deposits, permeability was identified as the main governing factor. Therefore, accurate characterisation and processing of the fracture data could significantly increase the success of ISR recovery. Artificially inducing fractures could be considered as an alternative approach to creating a pathway for fluids to flow from injection wells to production wells. From a metallurgical viewpoint, selective leachability of target compounds and the distribution of mineralisation is required.

Acknowledgements

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