Impact of Geological and Geo-Mechanical Controls in Creating Various Drilling Problems*

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Abstract

The exploration and exploitation of oil and gas resources of the Middle East by creating boreholes into the Earth's crust often trigger various drilling problems such as borehole instability, pipe sticking, loss of circulation, etc. These drilling hazards often result in high non-productive time with a drastic increase in well construction cost. Hence, elimination or mitigation of the severity of these drilling challenges is very important for safe and economic drilling operation. Loss of circulation is one of the major drilling challenges of this region. Some of the loss circulation events may be associated with large vugs and pre-existing cavities and thus may not be controlled by fluid design alone. In this case a mechanical or chemico-mechanical solution may be necessary to control such losses. However, review and analyses of drilling information and the onsite observations made by the mud and drilling engineers suggest that some of the loss circulation problems can be recognized and demarcated by analyzing the geological, geophysical and geo-mechanical signatures associated with the troublesome formations and their neighborhoods. For example, unconformities, consolidation history, poorly consolidated and over-consolidated formations, presence of open and closed fractures, narrow MW window, etc., in the post-Jurassic succession may provide an apparent relation to lost circulation and borehole problems encountered while drilling. This article describes the geological, geophysical and geo-mechanical controls and their likely effect in causing various drilling problems with emphasis on loss circulation problems that are frequently encountered in the Middle East region.

Introduction

Loss of circulation while drilling is a major drilling problem in the oil and gas industry. This is one of the major drilling challenges faced by the region since the inception of drilling operations and is also one of the major drilling problems that increases the NPT dramatically (Amanullah, et al. 2017). Even a single loss circulation event can lead to huge monetary loss by triggering a series of other drilling problems that could cost up to a million dollars or more (Kumar and Savari, 2011). Hence, prevention of loss of circulation in the first place is the best drilling strategy than curing a loss circulation problem after it happens. However, due to the huge number of uncertainties and unknown factors associated with subsurface formations and loss zone characteristics, it is often difficult to prevent loss of circulation in the first place. Hence, drilling strategy should adopt all measures and arrangements for corrective/curative approaches of loss control to eliminate or minimize any scope of losses while drilling or cementing a wellbore.

In the preventive approach of loss control, appropriate loss circulation materials or a suitable LCM blend is incorporated into an active mud system to take action immediately after the appearance of a loss circulation event. The main objective of this type of loss control strategy is to reduce the scope of induced loss of circulation arising due to the presence of various unfavorable geological and geo-mechanicals controls by strengthening the near wellbore formations and widening the mud weight window to increase the fracture gradient of the formation (Salehi and Nygaard, 2012). These geological and geo-mechanical controls are vulnerable points that can easily trigger loss circulation due to the failure of the rock under the action of wellbore pressure and/or alteration of in-situ stresses. Adequate strengthening of the near wellbore weak formation by physical, mechanical and chemical methods or by a combination of them can improve the pressure tolerance of the near wellbore formation significantly and thus can reduce the scope of induced loss of circulation dramatically.

The industry has developed several models to predict the strengthening effect of a mechanically weak near wellbore formation for preventative method of loss control. One of the models that predicts the near wellbore strengthening effect is the stress cage model described by Alberty and McLean (2004). This model is based on the linear elastic fracture mechanic theory. According to this model, an increase in the near wellbore hoop stress due to the bridging or wedging effect of loss control materials will improve the fracture gradient of the formation to avoid induced loss of circulation. There are other models such as Fracture Closure Model described by Dupriest (2005) and the Elastic-Plastic Fracture model described by Aadnoy and Belayneh (2004). These models also highlighted the increase in the fracture gradient of near wellbore formations while drilling using appropriate loss control materials to improve the success rate of preventive method of loss control.

In the event of failure of a preventive approach of loss control, a corrective or curative strategy of loss control is adopted in eliminating or controlling the loss of circulation encountered while drilling. This method of control is applied after the appearance of a loss circulation event. Hence, a considerable volume of drilling mud may be lost before the initiation of the LCM treatment job. The volume of mud lost per hour varies depending on the variation of the size, shape and concentration of the geological controls such as the porosity-permeability characteristics, fracture sizes and orientation, fracture density, status of the fractures, nature and size of the vugs and cavities, etc. Other than the geological controls, the geo-mechanical controls such as fracture gradient of the matrix material of intact formation, fracture opening pressure of formations with closed fractures, fracture gradient of cementing materials of partially cemented fractures and formation fluid pressure acting in the open fractures play an important role in creating induced and natural loss of circulation while drilling. Other geo-mechanical properties such as the anisotropic characteristics of near wellbore formation, in-situ stresses acting at the wellbore, stress regime acting in the region, lithological variation and mineralogical composition of rock matrix materials, etc., have significant effect in inducing loss of circulation while drilling.

Traditionally four placement methods are adopted in combating loss of circulation while drilling. One method is the incorporation of a suitable LCM product or a combination of LCM products into an active mud system to take action immediate after the initiation of a loss circulation event. Another placement method is the design of a LCM pill using various LCM products to place it using the drill string containing the drill bit close to the loss zone. Yet another method is the placement of the LCM pill using an open-ended drill pipe if the pill is unable to pass through the bit nozzles. One more method is the in-situ mixing and blending of two or more components close to the loss zone to create a gel like sealing and plugging material. Sometimes an especially designed loss control slurry known as RDF (rapidly dehydrating fluid) is used to combat severe loss of circulation that is encountered in formations containing large fractures and variable fracture sizes, super-k channels, vugs and caves, etc. The characteristics of the loss control materials also play an important role in creating a suitable seal/plug and controlling the loss of whole mud. Hence, LCM characteristics should be considered along with the geological and geo-mechanical controls for effective planning and successful completion of a loss preventive or loss control job.

Nearly three quarters of the Earth is ocean and has high prospects of hydrocarbon resources in addition to other marine resources (Amanullah and Yu, 2005). Hence, there is a progressive shift of drilling activities from onshore to offshore and from shallow water to deep water environments. Various types of drilling problems such as borehole instability, shallow water/gas flow, shale-drilling fluid interactions, loss of circulation, tight hole, pipe sticking, etc., are very common in offshore and in deep water environments. Loss of circulation while drilling and cementing in deep water environments is one of the major drilling challenges for current and future drilling operations due to complex subsurface geology, unusual geological features, abnormal subsurface conditions, poor geo-mechanical properties, etc. Variation of these geological and geo-mechanical controls has direct influence in triggering various types of mud losses. The success of the LCM treatment job will improve significantly if we can acquire a prior knowledge of the geological and geo-mechanical controls associated with loss of circulation. This article describes the significance of various geological, geophysical and geo-mechanical controls associated with loss of circulation while drilling.

Geological, Geophysical and Geo-Mechanical Controls – Their Significance

Geological, geophysical and geo-mechanical characteristics of subsurface formations play an important role in creating various drilling problems. These characteristic features are rock matrix fabrics and structural units, lithological composition and mineralogical variation, structural geology and associated defects, mechanical integrity, geotechnical characteristics, load bearing and pressure tolerance capacity, fluid conductivity and hydrogeological behavior, etc. These factors, either alone or in combination can create one or more drilling problems and thus can delay the drilling operation significantly. The severity of these problems is associated with the inherent geological features such as depositional history, sedimentation environment and post depositional mechanical, chemical, physical, hydrological and thermal weathering and also the diagenetic effect along with the past and present tectonic activities of a region. Due to the combined and progressive action of all these factors, subsurface formations may generate various signatures and controlling factors to influence their behavior. Figure 1 shows a schematic diagram of various characteristic signatures of subsurface formations that can directly influence the near wellbore and far field formation behavior while drilling. Prior knowledge of these dominant geological and geo-mechanical characteristics, lithological composition, nature of unconformities, karst and cavities, in-situ stress conditions, rock mechanical properties, formation fluid pressure profile, nature of rock matrix joints, fractures and faults, pressure tolerance and load bearing capacity, etc. can provide valuable information in preventing or controlling some of the drilling challenges encountered while drilling.

Careful review of the subsurface geological information of a particular hydrocarbon basin can provide the indication of existence of various faults, defects, discontinuities along with the lithological variation of the stratigraphic column to predict the nature of various problems and types of potential losses that can be encountered while drilling from the surface to the bottom of the reservoir and thus can be used as a guiding tool to mitigate the probability and the likelihood of occurrence of various drilling problems.

Mitigation by Well Site Selection

Figure 2 shows a cross-section of various overburden formations of a hypothetical well-site location. The central part of the formations clearly indicates some anomalies associated with washed away and removed rock mass due to the post-depositional geological events. This indicate the potential of existence of a severe loss zone at the central part of the cross section. Hence, site selection at the central part of the cross section will trigger severe loss of circulation. It will also create borehole instability problems if the unsupported or poorly supported rock bordering the loss zone is degraded significantly due to rock fluid interactions. The presence of shale or stringers of shale in the formation will cause severe mechanical degradation due to strong physio-chemical effects of swelling and softening of shale layers. Hence, site selection away from the central part of the deposited rock formations will either reduce or eliminate the loss of circulation while drilling along with other drilling problems. If loss is encountered in two side wells, it will be easier to control using most of the conventional LCMs or their blends.

Rubble Zone Effect

Rubble zone is a zone of fragmented, loose and rough pieces of rock mass with high porosity-permeability characteristics and fracture conductivities. It is created due to the collapse, disintegration and fragmentation of subsurface rocks as a result of the action of some external forces and changes in geologic conditions of the rock matrix. The subsurface rubble zone encountered at shallow depth at the early stage of a drilling a wellbore may be created due to several reasons. One of the major reasons is the changes in the water saturation zone due to the movement of water table and alteration of the in-situ effective stress acting on the subsurface rock mass.

There is an unsaturated zone just below the surface to the top of the water table. This unsaturated zone is not constant and may vary significantly from time to time due to the movement of the water table up or down, depending on the natural geological events such as change in climate condition, sea level alteration, rain water recharge, seasonal variation, or man-made events such as excessive withdrawal of subsurface water, etc. The movement of the water table up and down changes effective stress conditions and thus the mechanical loading of the subsurface formation. Moreover, the water movement may cause the dissolution of soluble minerals and removal of soluble and insoluble minerals and particles and thus may enhance the rock matrix porosity and permeability significantly along with the reduction of load bearing capacity. The in-situ stress effect on rock formations with scattered solution cavities can cause collapse of the subsurface formation creating a rubble like rock mass as shown in Figure 3. When this type of rock formation is encountered, moderate to severe mud loss can happen. Hence, consideration of these geological controls in the planning of a well can avoid or minimize the scope of loss of circulation and other drilling problems while drilling. The information will also provide the mud engineer appropriate information to design the drilling mud using appropriate preventive loss control materials to reduce the scope of loss of circulation.

Super-K Formation Effect

Subsurface geological formations containing super-K flow channels can trigger severe loss of circulation with huge volumes of mud loss per hour. Figure 4 shows a schematic diagram of a subsurface formation with highly distributed super-K channels. Prior knowledge of the presence of super-K zones can help design a drilling fluid and LCM treatment process to minimize mud losses while drilling and maximize hydrocarbon production while producing a well. These narrow channels and pathways within the rock matrix have very high fluid conductivity. The channel gaps and voids are usually much larger than the largest particles of conventional water and oil-based muds. Hence, the super-K loss zone has the ability to allow the flow of whole mud without depositing any mudcake at the formation face. The large voids, gaps and channels of super-K formation have a detrimental effect on core recovery. Hence, the core recovery information of offset wells can provide an indication of this geological control. According to Schon and Head (2007) the presence of large voids in the super-K zones usually shows poor core recovery. The authors further highlighted that the super-K zones can be considered as naturally fractured, well connected, multi-layer wells with capacity to allow the escape of a huge volume of drilling mud. A prior knowledge of the presence of any subsurface flow channels with massive fluid flow capacity will allow to take preventive and/or curative measures to avoid or control loss of circulation while drilling.

Fractured Formation Effect

Subsurface geological formations may have open, closed or cemented fractures depending on the geological age, acting effective stress, in-situ stress magnitude, fracture fluid pressure, rock matrix characteristics and diagenetic histories of the formation materials, post fracture sealing and cementing by precipitation, etc. (see Figure 5). These inherent geological features significantly affect the rock mechanical properties, geo-mechanical behavior, fluid flow characteristics under the action of external forces and pressure and thus can trigger various drilling problems including severe loss of circulation. The presence of fractures of different sizes with various morphological characteristics, fracture openness and closeness status, fracture opening and propagation pressure have tremendous effect in creating loss of circulation while drilling. Hence, prior knowledge of the fracture sizes, their openness and closeness characteristics, fracture distribution patterns along with the extend of inter-fracture connectivity can provide useful information for well site selection, well planning, mud programming, etc., to eliminate or minimize the loss of whole mud in the fractured loss zone. According to Adachi et al. (2004) the natural fracture of subsurface geological formation has pre-existing patterns of frequency and fracture width in the loss zones and thus prior information about these characteristic features of a fractured loss zone can provide adequate guidelines to control or mitigate the loss of whole mud in the fractured loss zone.

Several categories of fractures may be present in the subsurface conditions. Depending on the status of the subsurface fractures, the wellbore pressure that can trigger loss of circulation may vary significantly. As for example, the presence of subsurface formation with closed fractures as shown in Figure 5 will not create any loss circulation event if the mud pressure (P_m) or the pressure due to ECD effect (P_{ECD}) is below the fracture closing pressure (σ_{fc}) of the formation. It will only trigger loss of circulation if the wellbore pressure exceeds the fracture opening pressure. Mathematically, it can be expressed by inequality (1).

$$P_{\mathbf{m}} \text{ or } P_{\mathbf{ECD}} > \sigma_{\mathbf{fc}} \qquad \textbf{(1)}$$

It highlights that the prior knowledge of the nature of fractures and the fracture opening pressure, i.e. the geological and the geo-mechanical controls can provide valuable information and useful guidelines for mud design to avoid loss of circulation while drilling. It may be mentioned that the formation fracture gradient and fracture opening gradient of a closed fracture may differ significantly. Hence, conclusions drawn based on formation fracture gradient will be totally misleading.

In the presence of subsurface formation with open fractures as shown in Figure 5, whole mud loss can occur easily if the mud pressure (Pm) or the pressure due to ECD effect (PECD) exceed the fracture fluid pressure (σ_{ff}), i.e. the formation fluid pressure. The fracture gradient of the formation as determined by rock mechanical test using intact cores has no significance in this case and hence totally irrelevant in defining the upper limit of the MW. In this case, the lower and upper limit of MW could be the same, i.e. there could be no virtual difference in these two limit values. Mathematically, the condition causing loss of circulation can be expressed by inequality (2).

$$P_{m} \text{ or } P_{ECD} > \sigma_{ff} \qquad \textbf{(2)}$$

Again, the prior knowledge of the geological control associated with the status of subsurface fractures can play an important role in preventing or minimizing the loss of whole mud while drilling.

Presence of subsurface formation with cemented fractures due to the precipitation of some cementation materials in the fractures during the geological period may cause cementation and sealing of two fracture surfaces as shown in Figure 5. In this condition, whole mud loss can occur if the mud pressure (P_m) or the pressure due to ECD effect (P_{ECD}) exceeds the fracturing pressure of the inter-fracture cementation materials. ($\sigma_{fcement}$). Hence, the fracture gradient of the formation as determined by rock mechanical testhas no significance in the mud design. In this case, upper limit of MW is defined by the fracture gradient of the cementation material, not the rock matrix material. Mathematically, the condition causing loss circulation can be expressed by inequality (3).

$$P_{m} \text{ or } P_{ECD} > \sigma_{fcement} \qquad \textbf{(3)}$$

The above discussion clearly demonstrates the role of geological controls such as the status of subsurface fractures and the geo-mechanical controls such as the magnitude of the fracture gradients of the intact rock and cementation materials, or the opening pressure of closed fractures can play an important role in preventing or controlling loss of circulation while drilling.

Vugular Zone Effect

Another geological characteristic feature of subsurface formation that can trigger moderate to severe loss of circulation is the presence of vugs of various sizes (see Figure 6). Depending on the vug sizes, their inter-connectivity and areal extent of the vugular loss zone, moderate to severe mud loss with partial or no return can occur. Hence, prior information about the presence of vugular loss zone in the subsurface formation based on geological, geophysical or off set well information can provide useful guidelines to mitigate or control loss of circulation while drilling. In case of vugular zones with the potential to cause severe loss of circulation, the chemical/additive method may not work. Hence, alternative loss control strategy such as well site location selection, mechanical isolation of loss zone, chemical-mechanical and/or physio-chemical method of control should be explored to overcome the challenges.

Cavernous Zone Effect

The formation of a cavernous loss zone is the result of long term geological processes of progressive dissolution, solution and removal of water soluble minerals along with the removal of weakly bonded minerals and rock materials that are washed away easily by percolating and/or running water. The voids or empty spaces created by removing soluble and weakly bonded minerals and rock materials during the geological time period can form a cavernous loss zone with large areal extend and storage volume (see Figure 7). Based on the void space or storage volume capacity, caves can be classified as small, medium, large and very large. Even the loss trigger by a small cavernous loss zone is very difficult to control. According to Ganson (1985) the subsurface cavernous loss zone may extend horizontally, vertically or diagonally to create extensive and well-connected network of potentially high loss zones by inter-connecting various loss zones such as high permeable, super-K, fractured, vugular and/or other cavernous loss zones. Hence, this type of loss zone can swallow a colossal volume of drilling mud without any indication of return of mud flow.

The presence cavernous loss zone in the subsurface formation creates extremely difficult drilling conditions due to the loss of a huge volume of drilling mud within a short period of time with no return of drilling mud to the surface. This type of loss zone can cause a quick drop of mud level in the wellbore due to massive loss of drilling mud and thus can trigger other drilling problems. The combined effect of these drilling problems can increase the total drilling cost dramatically and the NPT exponentially. It is impossible to control this type of loss of circulation by chemical means. Selection of well site location based on the geological and geophysical information of the subsurface formation is the best preventive measure to eliminate the scope of massive loss of circulation while drilling.

Narrow Mud Weight Window Effect

Geo-mechanical factors such as in-situ stress, overburden load, effective stress, stress direction and anisotropy, etc., have a big impact in creating loss of circulation and other drilling problems such as borehole instability, pipe sticking, hole reduction, borehole collapse, etc. Due to the impact of these factors and poor rock mechanical properties, the safe mud weight window is usually very narrow in this drilling environment. Hence, the upper and lower mud weight limits are very close to each other. In extreme cases, the difference could be virtually zero. This dictates the design of a drilling mud with no or negligible ECD effect or incorporation of a formation strengthening materials into the mud system to improve the near wellbore formation strength. The augmentation of the compressive hoop stress due to wedging effect of formation strengthening materials increases the fracture gradient of the formation (see Figure 8) and thus the resistance to induced loss of circulation.

Unconformity Effect

The presence of unconformities in the stratigraphic sequence of the geological formations indicate the discontinuation in the geological record of depositional history for a period of geologic time due to one or more geological episodes such as deformation and uplifting of formation due to tectonic activities, erosion and removal of materials due to physical, chemical and mechanical weathering of surface materials, subsidence and collapsing of formation due to sink hole creation, effective stress increase and drop of subsurface fluid level, under water burial of formation due the sea level variation, re-deposition of new and geologically young formation materials on top of the eroded surface, etc.

Figure 9 shows the depositional, erosional and re-depositional episodes of creation of a subsurface unconformity. The interface between two formations of different geologic age indicate a substantial break in the geologic record for a period of geologic time and thus indicate a drastic difference in the geo-mechanical properties such as compressive, tensile and shear strength, stiffness, ductility and toughness, density, consolidation, etc. Careful review and analyses of geological information and stratigraphic sequence of subsurface geology of a region can easily indicates the presence of unconformities and thus a potential loss zone.

The depth of unconformity also plays an important role in creating loss of circulation while drilling. The part of the unconformity that is located at shallower depth have higher possibility of causing loss of circulation than the part of the unconformity that is located at greater depth. This is due to the lower consolidation effect of formation at shallower depth compared to the formation at greater depth. The rock materials above and below a shallow unconformity has poor geo-mechanical properties than the rock in the vicinity of a deeper unconformity. Hence, the mud weight window is very narrow at the shallow depth unconformity compared to greater depth unconformity. This means that the ECD, surge and swabbing pressure can easily exceed the fracture gradient of the formation bounding the shallow depth unconformity, especially the formation above the unconformity. Drilling experience in various fields and geological locations containing same unconformity at different burial depths strongly supports it.

Fault Zone Effect

The Earth's crust along with the part of the mantle of the Earth is composed of rigid plates called tectonic plates. The whole Earth is composed of several such plates with inter-plate dynamic boundary at the junction of two plates. These boundaries are vulnerable locations due to frequent action of boundary plate movement that is known as earthquakes. When these plates collide with great force, then severe Earthquakes happen. During the collision and movement, they grind past each other and spread apart from the boundary to some distance and thus create a fault zone with poor rock integrity, loose rock consistency, rubble like rock mass, high fracture density, extreme fluid conductivity and enormous fractures, voids, pores and gap connectivity in the vicinity of the fault line. Due to the action of tectonic forces, some formation is lifted up, dropped down or dislocated horizontally or diagonally as indicated by the nature of subsurface formations at the fault-line (fault surface). The fault surface shown in Figure 10 clearly indicates upward displacement of the subsurface formation.

The fault zones also have very weak formation with poor mechanical strength, complex structural geology, very bad matrix integrity and high fluid conductivity and thus prone to cause severe loss of circulation. Well planning and site selection based on the subsurface fault zone geology and geo-mechanical properties will minimize the probability and likelihood of causing loss of circulation while drilling.

Karst Effect

Karst topography is a landscape formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum. It is characterized by the presence of an underground drainage systems with inter-connected sinkholes and solution cavities of various sizes by a network of fractures and permeable channels (see Figure 11). It may be mentioned that karstification of subsurface formation may result in a variety of solution cavities of various sizes with distinct characteristics both in the surface and subsurface geological structures. Due to the creation of a series of underground solution cavities with strong inter-cavity connection, this type of thief zone can accommodate huge volumes of drilling mud. Selection of well site location away from the karstified formation will reduce the scope of massive loss of circulation while drilling.

Formation in the vicinity of a karst or solution cavity is mechanically weak due to the degradation of the rock matrix and removal of some minerals from the rock matrix. The cavity/karst area of subsurface formation has high fluid conductivity due to the creation of a complex and massive underground drainage systems by creating highly inter-connected solution cavities. The rock in the vicinity of the karst has much lower fracture gradient and thus a narrow mud weight window. This is due to the serious mechanical degradation of near karst formation. According to Abd El-Aal and Masoud (2017) the mechanical characteristics of karstic limestone usually decreases with increasing amount of karst. Hence, the presence of karst in the subsurface is a direct indication of causing massive natural and/or induced loss of circulation. Avoidance of this type of loss zones is the best strategic tool to prevent loss circulation in the first place.

Subsurface geology and geophysical information can provide adequate information about the existence of karstified formation and thus can provide useful guidelines to select a well site for reducing the probability and likelihood of causing loss of circulation. The geo-mechanical information of the rock formation in the vicinity of a karst can also predict the likelihood of causing induced loss of circulation.

Conclusions

- The geological and geo-mechanical features of subsurface rock formations have strong relation in creating different drilling problems including loss of circulation. Hence, diagnosis and application of these characteristics features in well planning can reduce the probability and likelihood of creating various drilling problems.

- The information available from subsurface geological map, stratigraphic column or seismic data of a geophysical survey of a hydrocarbon basin may provide information about the existence of faults, karst, and unconformities along with the lithological variation and thus can predict the nature of geo-hazards likely to encounter while drilling.

- Geological formations with open fractures are highly vulnerable to trigger loss of circulation as the wellbore pressure can easily exceed the fracture fluid pressure during drilling and tripping operation.

- The upper mud weight limit of the mud weight window of subsurface formations containing closed fractures is defined by the fracture opening pressure, not the pressure required to induce fracturing of the intact rock matrix.

- Fracture gradient of the cementing material of cemented fractures is the appropriate mud design parameter to prevent induced loss of circulation in loss zone containing cemented fractures.

- Geological information indicating the fracture sizes and density, inter-connectivity of fractures along with the sizes of solution cavities, sinkholes and collapse zone can provide useful information in predicting the nature of loss circulation problem.

- Technical guidelines prepared based on the geological, geophysical and geo-mechanical information of subsurface formations can play an important role in mitigating various drilling problems including moderate to severe loss of circulation.

- Lithological characteristics and the in-situ stress conditions adjacent to a fault zone have high impact on the fracture conductivity and fluid flow paths. Hence, consideration of the coupling effect of these factors may provide a prognosis of subsurface problems including loss of circulation.

- The presence of a highly damaged and fractured zones in the vicinity of a fault plane indicate an extremely conductive rock mass to the escape a large volume of drilling mud. Hence, well location near the damaged zone should be avoided to reduce the probability of borehole instability and likelihood of causing induced loss of circulation.

- Multi-disciplinary research combining geology, geophysics, geo-mechanics and along with the chemical-mechanical characteristics of mud additives and loss circulation materials can provide reliable and highly effective predictive tool to reduce the subsurface geo-hazards faced by the oil and gas industry.

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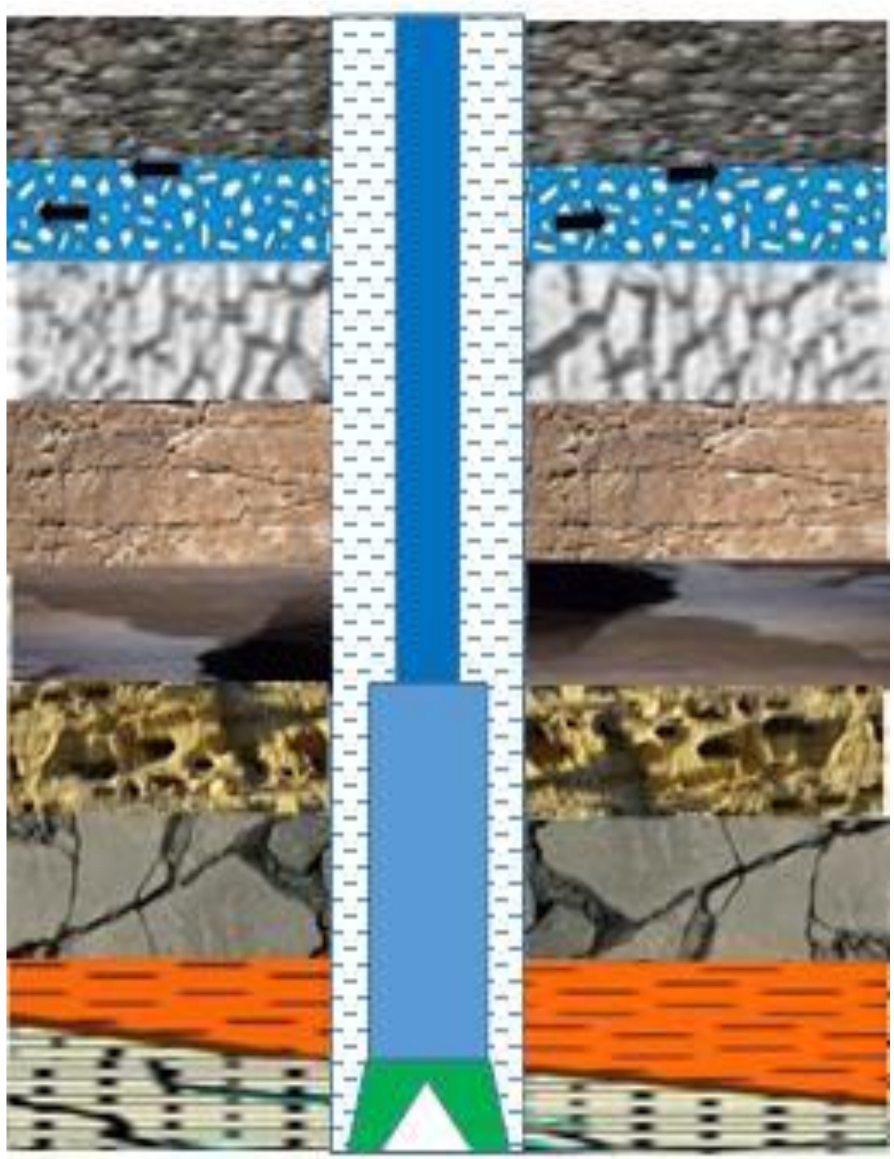

Figure 1. Schematic of a wellbore showing various types of intercepted loss zones.

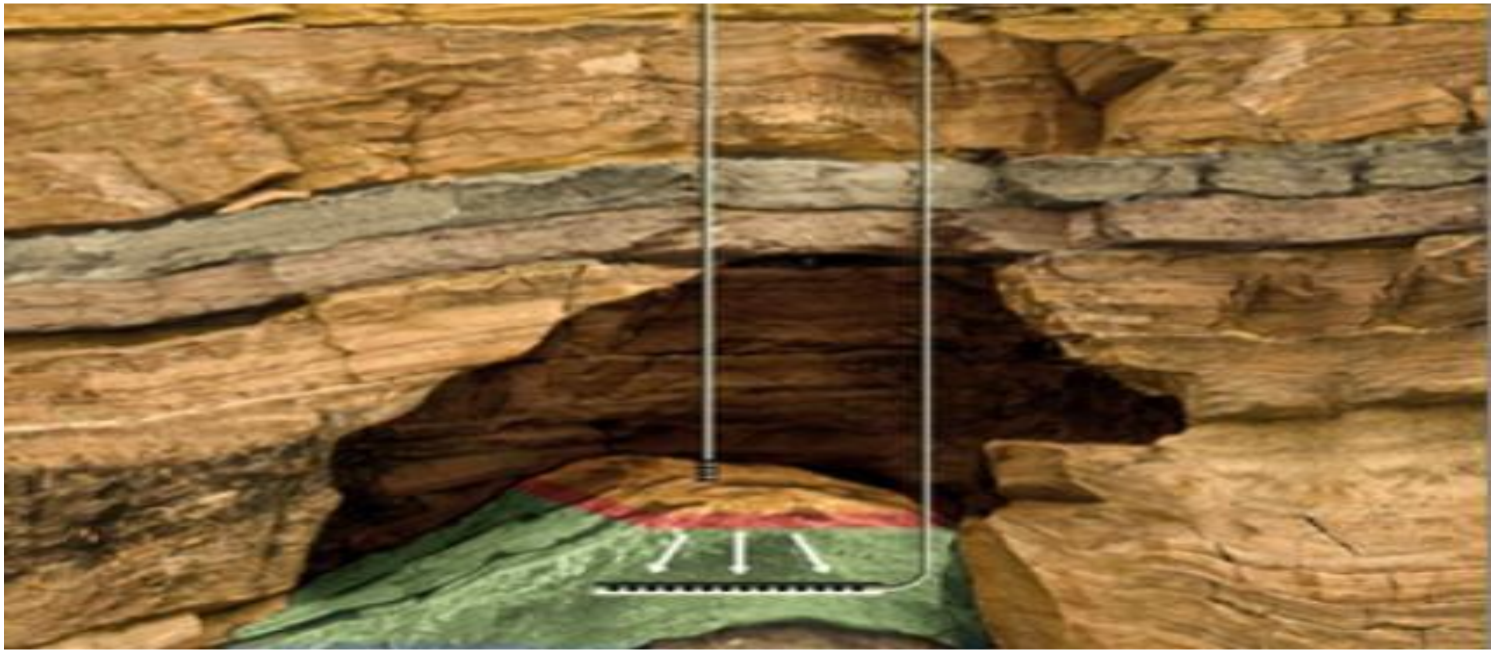

Figure 2. Subsurface formation with high geological and mechanical anomalies.

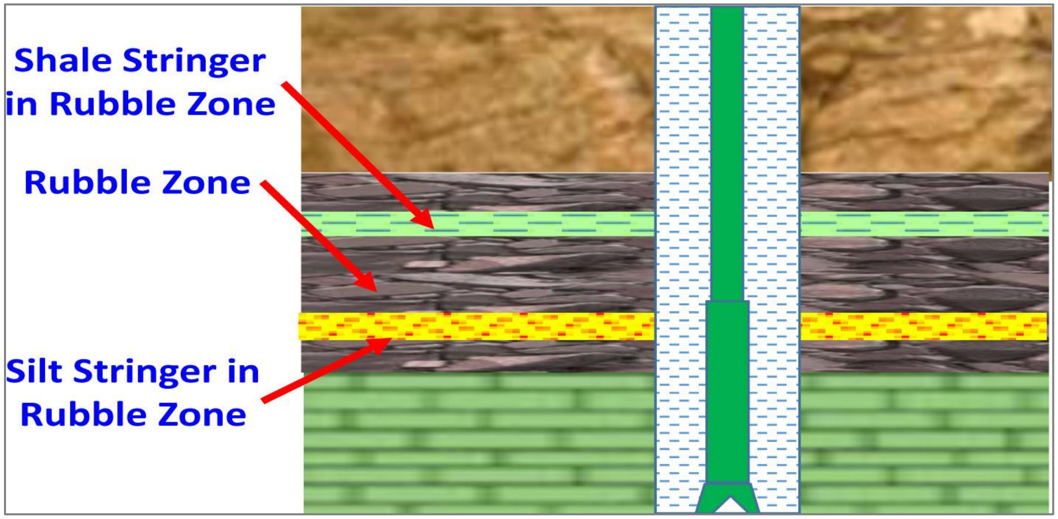

Figure 3. Schematic diagram of loss zone created due to the presence of subsurface rubble zone.

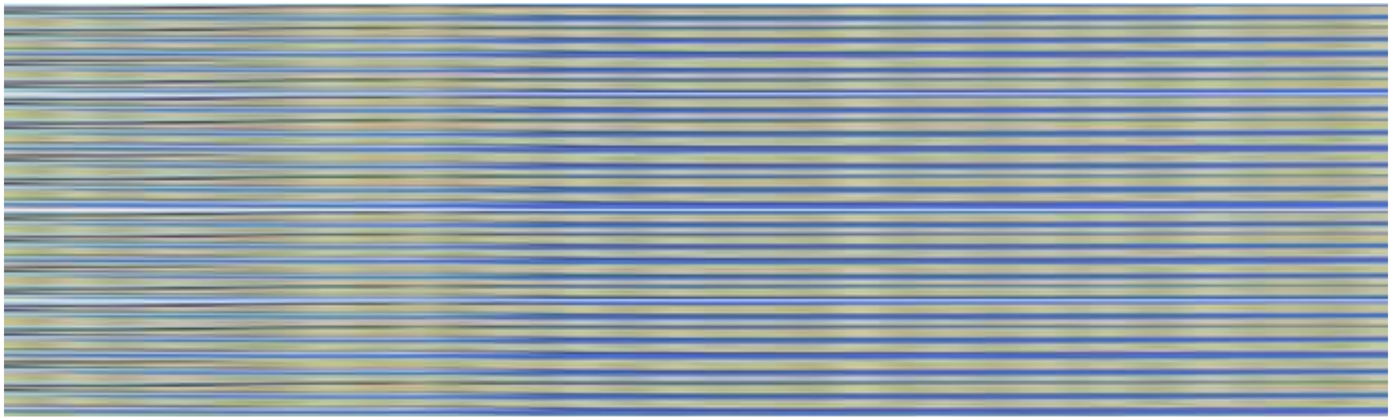

Figure 4. Loss zone created due to the presence of high fluid conductivity channels.

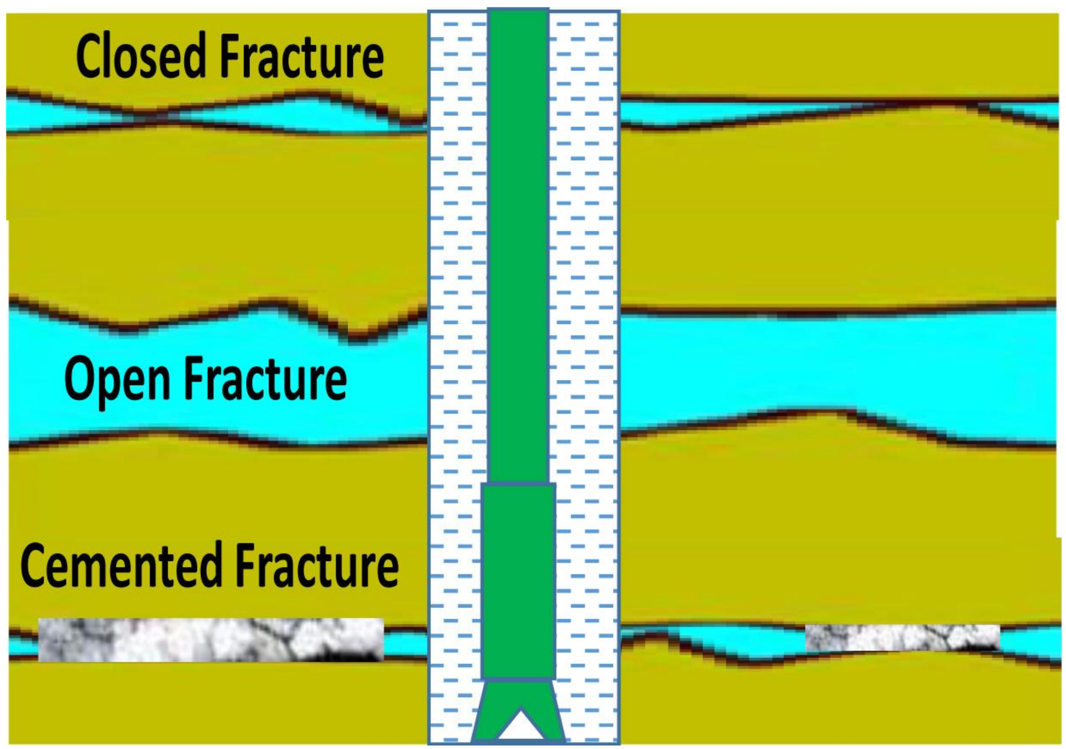

Figure 5. Loss zone created due to the presence of closed or open fractures.

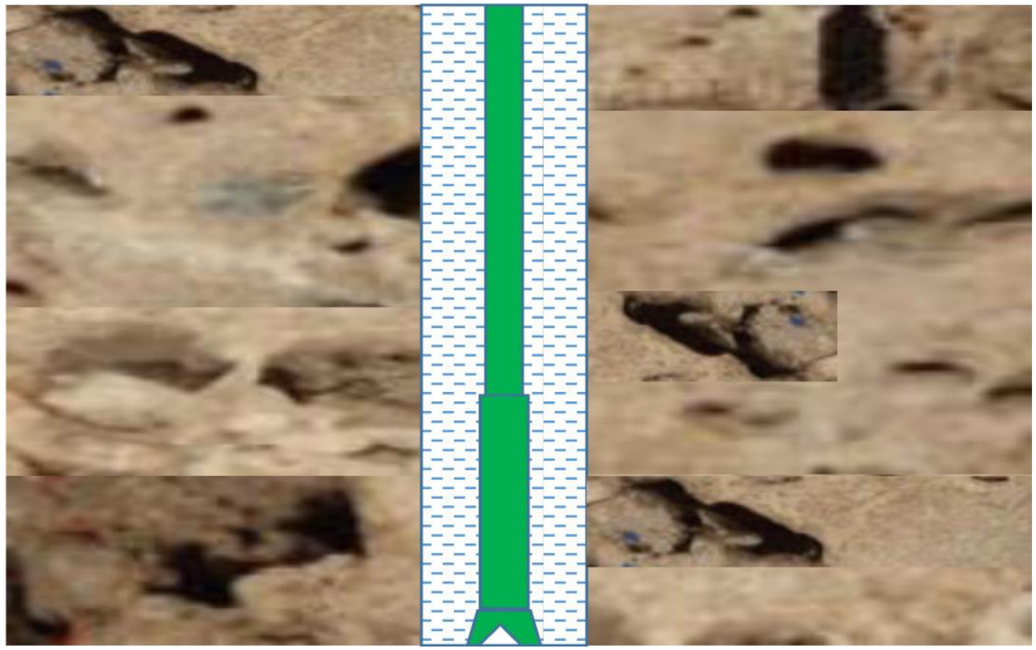

Figure 6. Loss zone created due to the presence of vugs.

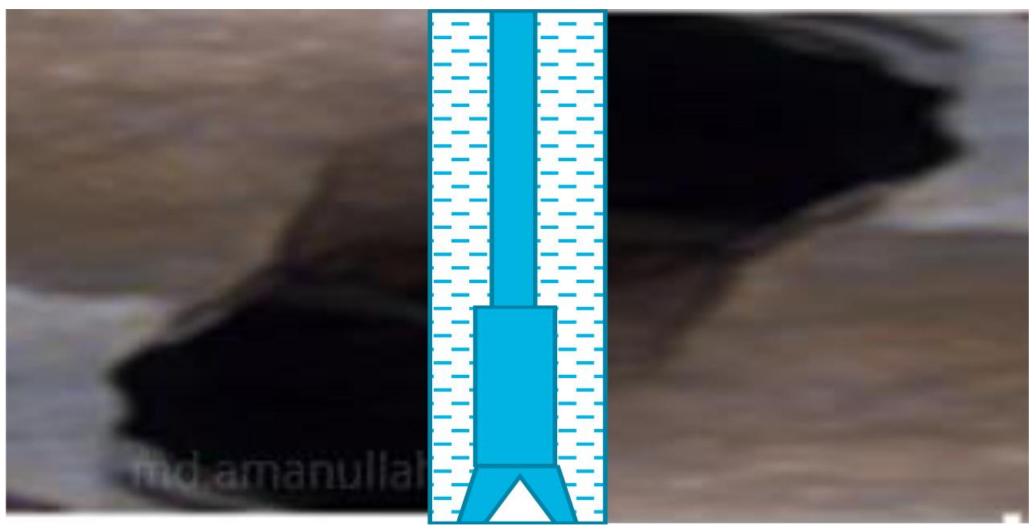

Figure 7. Loss zone created due to the presence of caves.

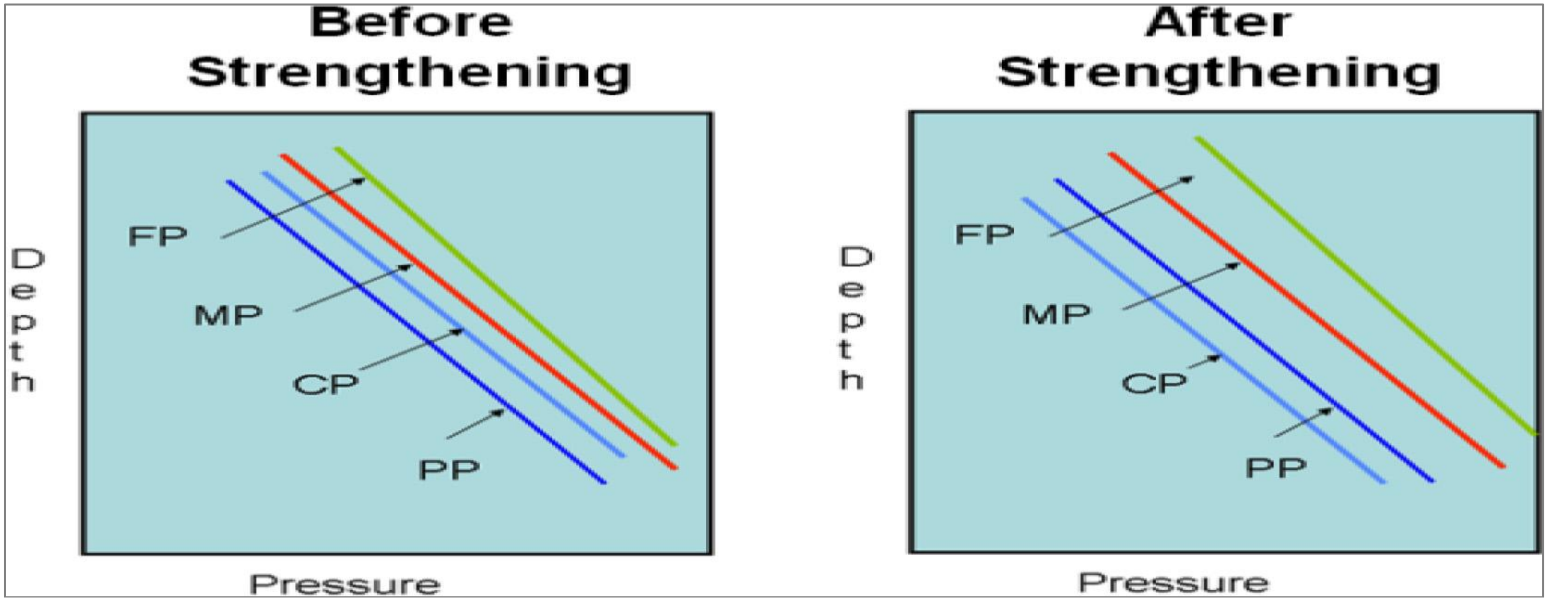

Figure 8. Loss zone created due to the presence of formation with narrow Mud Weight window.

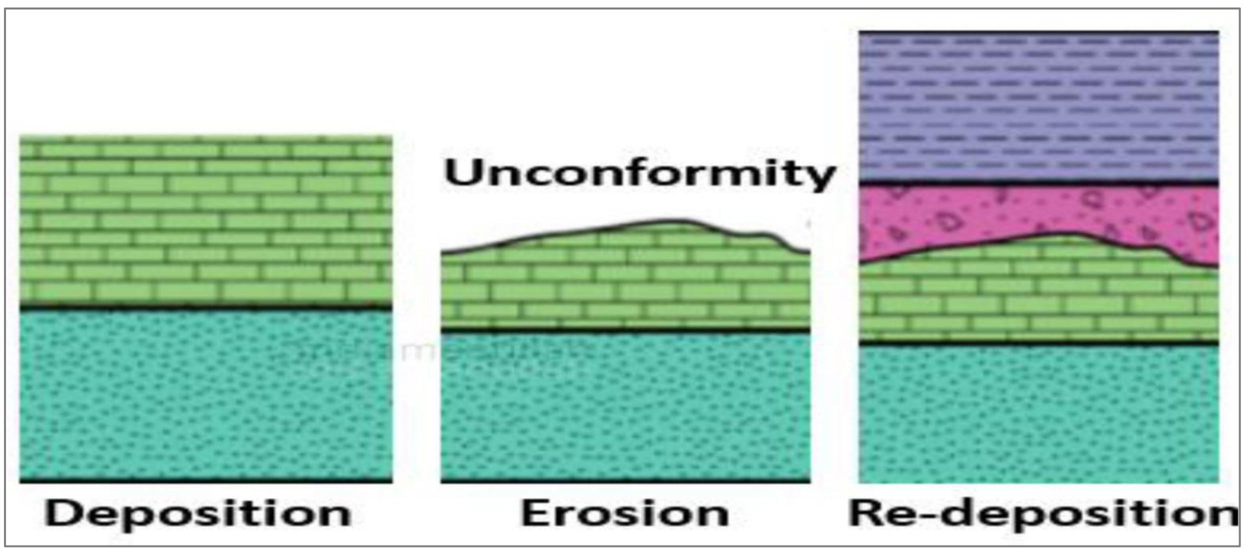

Figure 9. Loss zone created due to the presence of an unconformity.

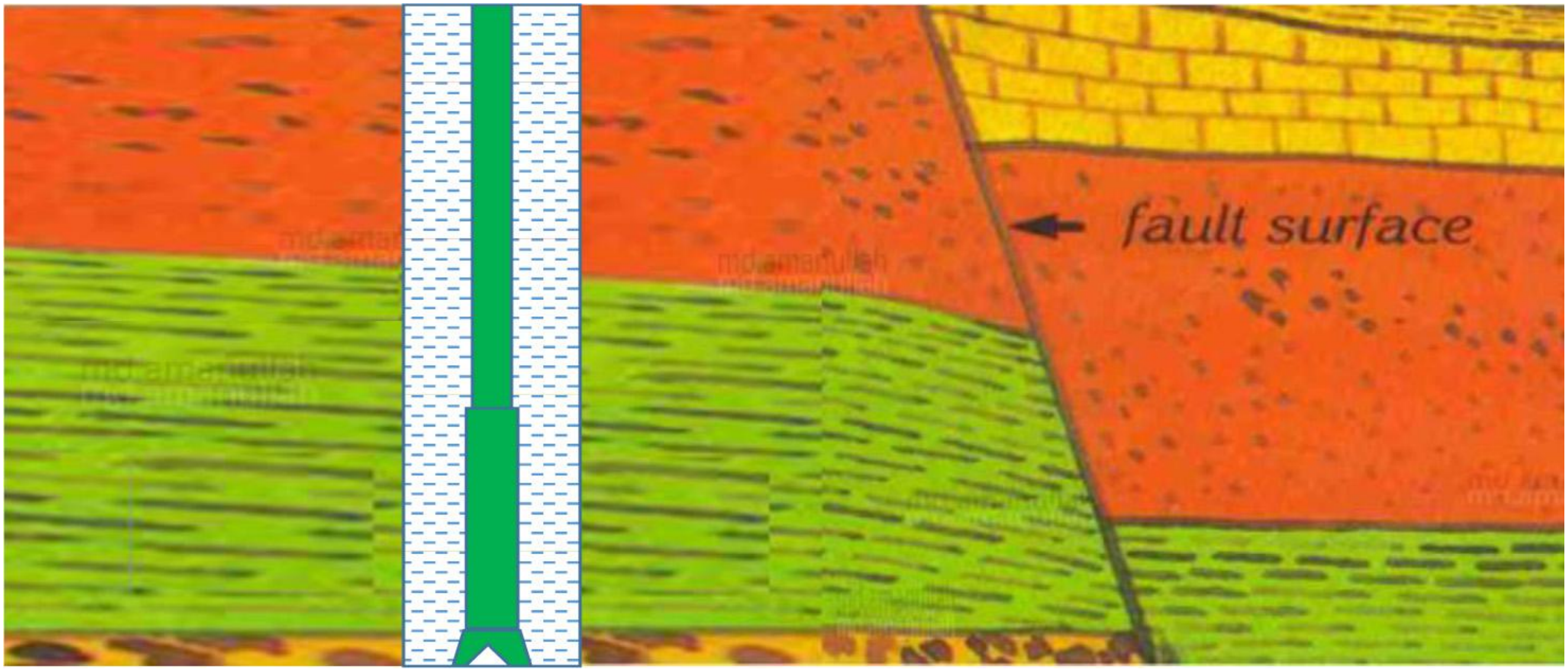

Figure 10. Loss zone created due to the presence of unsealed fault.

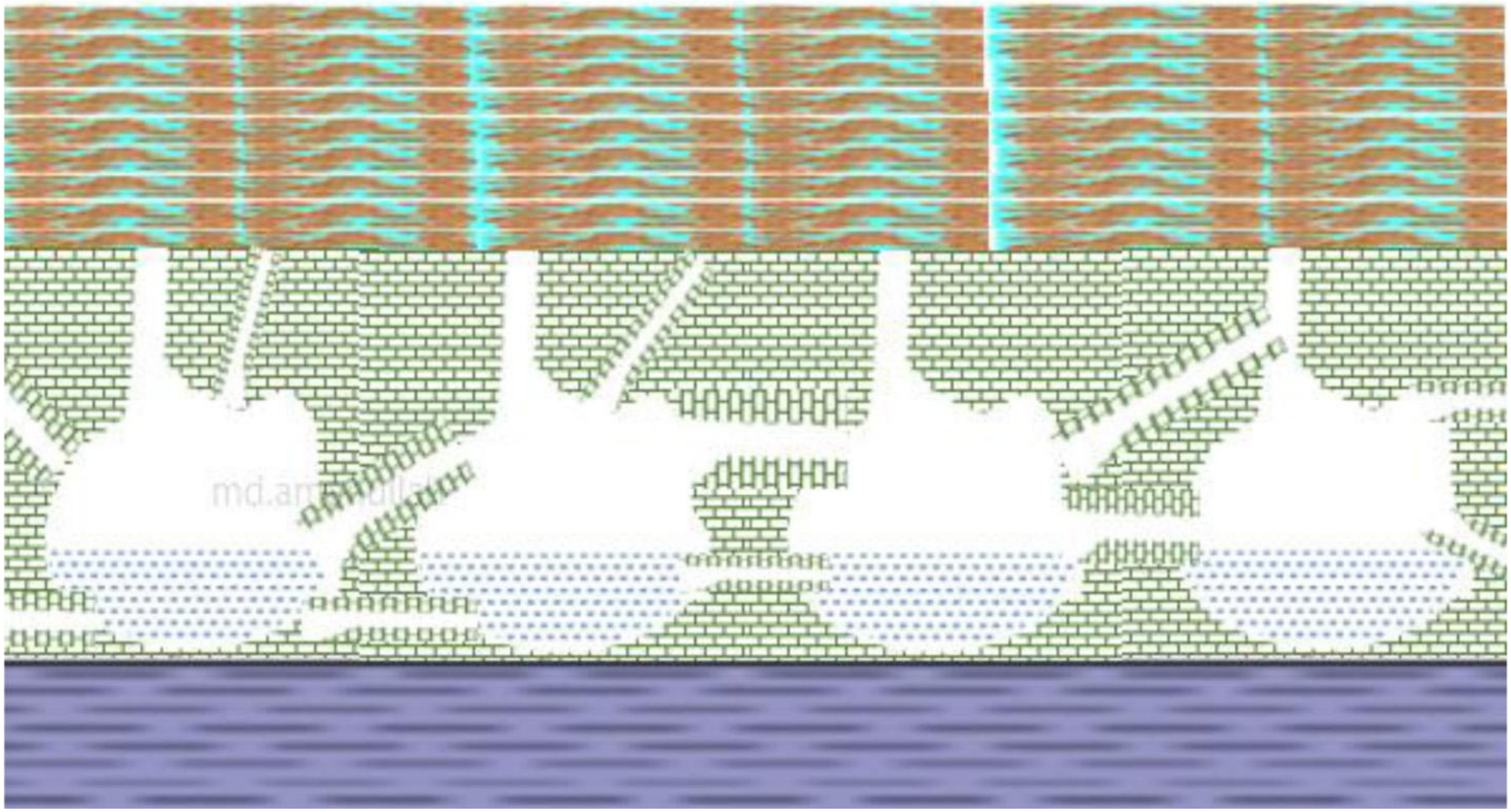

Figure 11. Karstified limestone formation with inter-connected solution cavities.